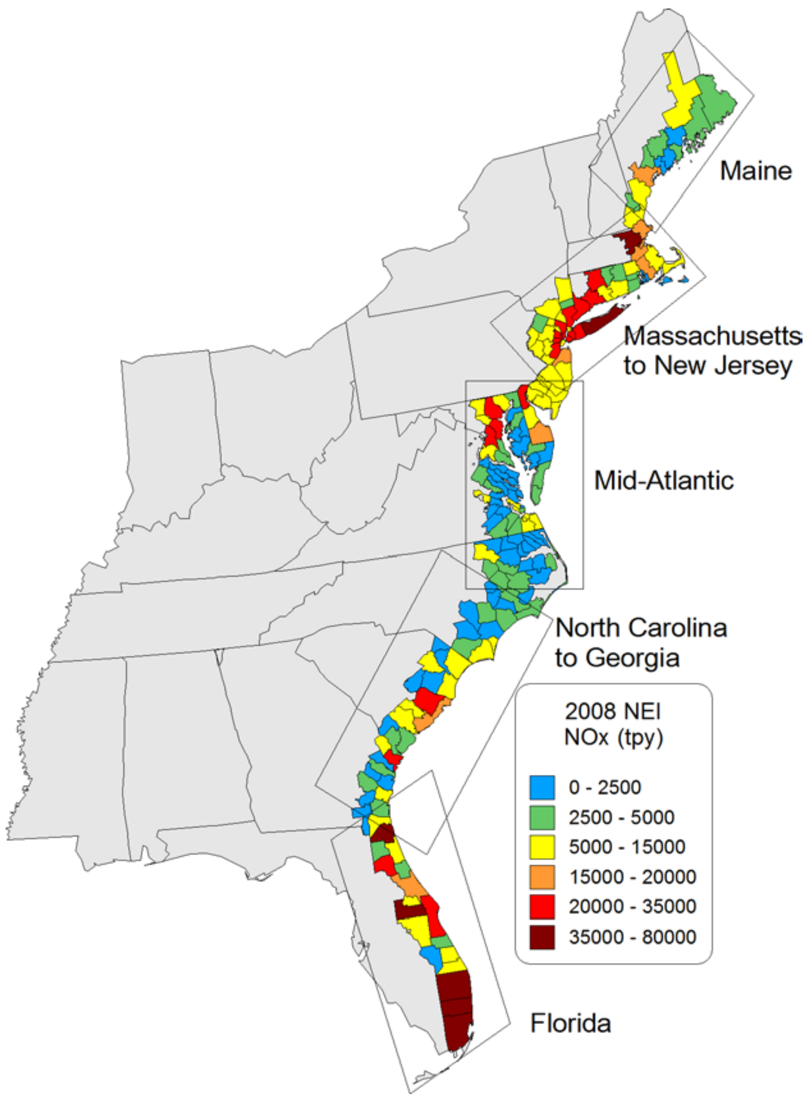
AR Study
BOEM 2014-008

Synthesis, Analysis, and Integration of Meteorological and Air Quality Data for the Atlantic Coast Region

Volume III: Data Analysis



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Synthesis, Analysis, and Integration of Meteorological and Air Quality Data for the Atlantic Coast Region

Volume III: Data Analysis

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ABOUT THE COVER

The graphic on the cover depicts county level emissions of nitrogen oxides (NO_x) for key port/harbor areas along the Atlantic Coast. The emission data are included in the Atlantic Region Air Quality Database (ARAQDB) tool.

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1.0 INTRODUCTION

In establishing offshore wind-based energy generation areas offshore of the Atlantic Coast, BOEM and its partners must consider any potential impacts on air quality in nearby coastal areas. This requires an understanding of the relationships between meteorology, emissions, and air quality within each area of interest. Federal, state and private organizations have collected a variety of meteorological, air quality, and emission inventory data for the Atlantic Outer Continental Shelf (OCS) region and nearby onshore areas. These data have been used to support various air quality related data analysis and modeling activities. The focus of this data synthesis study was to assemble these data into a coherent dataset, so that an integrated analysis of the data could be conducted. The dataset includes data from the Environmental Protection Agency (EPA), the National Weather Service (NWS), the National Buoy Data Center (NBDC), and other sources. It is expected that this integrated dataset will provide new information about meteorological and air quality conditions in the Atlantic OCS region, including the relationships between meteorology, emissions, and air quality revealed by the data.

The data synthesis study included some basic analysis of the data, which was conducted in order to ensure the integrity and usability of the dataset. The analyses were also intended to provide new information about meteorological and air quality conditions in the Atlantic OCS region, including the relationships between meteorology, emissions, and air quality revealed by the data. The specific goals of the data analysis task were to use the integrated dataset to 1) examine the relationships between meteorology, emissions, and air quality in the Atlantic OCS region, 2) confirm and/or advance prior conceptual descriptions related to ozone, particulate matter, and regional-haze air quality issues along the Atlantic coast, 3) identify gaps in the data/knowledge bases, and 4) recommend future data analyses.

In addition, as part of the data synthesis study, meteorological data from selected onshore and offshore monitoring sites for the period 2005–2009 were formatted and processed for input to the Offshore Coastal Dispersion model (OCD5). The model-ready input data are expected to support future modeling studies focused on selected portions of the coastline in which the OCD5 model is used to examine the effects of changes in emissions on coastal air quality.

This document presents the methods, results, and key findings from the data synthesis and analysis tasks. Two companion reports (a User's Manual and a Technical Reference Manual) summarize the preparation and workings of the integrated meteorological, emissions, and air quality dataset and associated database tool.

1.1. OVERVIEW OF THE STUDY REGION

The data synthesis study area is shown in Figure 1. It encompasses the entire eastern seaboard of the U.S. and the Atlantic Region OCS area. The map axes indicate latitude (left axis), longitude (bottom axis), and distance in kilometers (km) from the center of the Lambert conformal map projection (40 degrees north latitude/97 degrees west longitude – or roughly the center of the U.S.). While all offshore areas are potential wind energy areas (WEAs), several areas have been formally designated by BOEM as of November 2013 as being of particular interest, based on available wind observations, currents, ocean depths, and other considerations related to access and energy transmission. These are discussed in the following section.

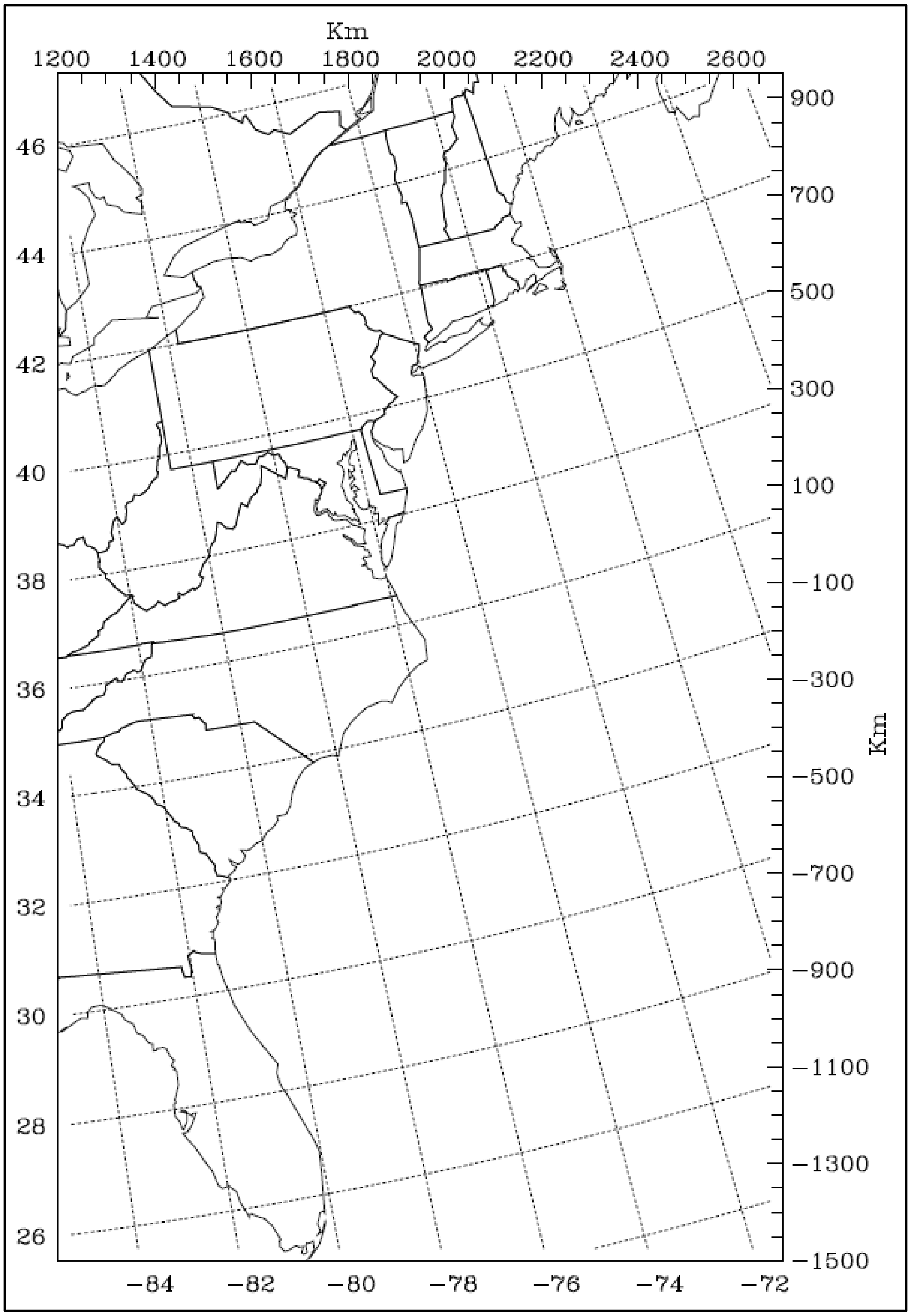

Figure 1. BOEM data synthesis study area.

Geographically, the region is quite diverse. For this study we are most interested in the coastal areas, since they are most likely to be influenced by emissions from wind energy development activities in the Atlantic OCS region. The area spans approximately 20 degrees of latitude (from 26 to 46 degrees North latitude) and includes coastal and offshore areas from Florida to Maine. The geography of a given coastal area is determined in part by location and onshore/inland topographic features, but also by the contours of the coastline, and presence of islands, bays, and inland waterways.

Key port and harbor areas along the Atlantic Coast include:

- Portland, ME
- Gloucester, MA
- Port of Boston, MA
- Provincetown, MA
- Martha's Vineyard, MA
- Nantucket, MA
- Providence, RI
- New York, NY
- Newark-Elizabeth, NJ
- Wilmington, DE
- Baltimore, MD
- Newport News, VA
- Norfolk, VA
- Morehead City, NC
- Wilmington, NC
- Charleston, SC
- Savannah, GA
- Brunswick, GA
- Port Canaveral, FL
- Port of Miami-Dade, FL

The analysis region spans several climate zones: "Cold" from Maine though Central New Jersey, excluding Long Island, "Mixed Humid" from Central New Jersey to Central North Carolina plus Long Island, and "Hot Humid" from Central North Carolina through Florida.

A meteorological feature that occurs along most coastal areas is the "sea breeze." This meteorological circulation system develops in coastal areas as a result of differential heating of the land and water surfaces (due primarily to differences in specific heat, thermal conductivity, and reflectivity of these surfaces). For the northernmost areas, this feature is most likely to occur during the summer months, while for the southernmost areas it can occur year round. During the daytime hours the air temperature above the land surface is typically higher than that over the water surface (land surfaces heat up faster than water). During the nighttime hours the air temperature above the water surface is typically higher than that over the land surface (the land surface cools faster than the water surface). These temperature differences set in motion a circulation system that tends to cause the air nearest the surface to move offshore during the nighttime hours and onshore during the daytime hours.

The development and characteristics of a sea breeze can be influenced by many factors, such as prevailing regional-scale wind direction, temperature variations, and the shape of the coastline. A sea breeze is generally characterized in terms of timing (time of onset), strength (associated wind speeds), and inland extent (distance inland over which its influence is apparent). The sea breeze circulation is important to air quality because it provides a mechanism for the recirculation of pollutants. By this we mean that primary and precursor emissions and secondary pollutants may be carried offshore by the offshore-directed flow (either near the surface during the nighttime hours or as part of a daytime return flow aloft). Due to low vertical mixing (as a result of cooler temperatures) and relatively lower deposition rates over the water, pollutants may build up or pool over the water surface. With the onset of the sea breeze, the pollutants may then be carried onshore.

1.2. Current Wind Energy Prospects for the Atlantic OCS Region

In November 2010, the Department of Interior (DOI) announced its Atlantic Wind "Smart from the Start" initiative (formally published in the Federal Register (76 FR 7226-7228)), which includes a plan to accelerate the development of offshore wind energy in the United States. The objectives of the initiative are to diversify the energy supply, stimulate local economies, and reduce greenhouse gas emissions. Having primary jurisdiction over the review and approval of offshore wind projects in federal waters, the DOI has set up the regulatory framework for reviewing such projects, and the initiative facilitates the review of the siting, leasing, and construction phases of development. Working directly with the Department of Energy (DOE), a coordinated Strategic Work Plan was developed that focuses research, development, and planning efforts between the agencies in an effort to help expedite offshore wind energy development projects. As summarized in the report A National Offshore Wind Strategy: Creating an Offshore Wind Energy Industry in the United States (DOE, 2011), prepared jointly by DOI and DOE's Office of Energy Efficiency and Renewable Energy (EERE) Wind and Water Power Program, an Offshore Wind Innovation and Demonstration (OSWinD) initiative has been developed to "promote and accelerate responsible commercial offshore wind development in the U.S. in both federal and state waters." The objectives of the initiative are to address the technical challenges related to the siting of wind turbines and other forms of alternative energy generation in offshore waters, including technology, engineering, permitting and grid connections issues, and reduce both the cost of offshore energy development and the time it takes for construction and full implementation. Working cooperatively through Smart from the Start and OSWindD, the DOI and DOE will provide complementary planning, siting, and infrastructure support.

As part of the Smart from the Start initiative, DOI's Bureau of Ocean Energy Management (BOEM), working with state agencies, identified potential offshore Wind Energy Areas (WEAs) along the Atlantic coastline. The initiative called for the identification of WEAs that would be "most suitable for commercial and wind energy activities, while presenting the fewest apparent environmental and user conflicts." From the evaluation of environmental data, initial WEAs were identified offshore of Massachusetts, Rhode Island, New Jersey, Delaware, Maryland, and Virginia. Based on the initial specification of these general areas, in 2010 the BOEM issued Requests for Interest (RFI) and Calls for Information (CFI) to learn more about these areas and gauge the level of interest for the commercial development of offshore wind resources, and to refine the specifications of these areas. From the information gathered in these RFIs/CFIs, in 2012 formal Environmental Assessment (AE) reports were prepared and the specifications of the WEAs were finalized for Massachusetts (BOEM, 2012a), Massachusetts/Rhode Island (BOEM, 2012b), and combined for New Jersey, Delaware, Maryland, and Virginia (BOEM, 2012c), as depicted in Figure 2.

The BOEM is currently working with the State of North Carolina to identify potential offshore wind development areas, and in December 2012 issued a CFI for the Wilmington-West, Wilmington-East, and Kitty Hawk offshore areas (Federal Register, 77 74204-74213). The BOEM is working with the State of South Carolina on the designation of potential wind development areas, but nothing has been finalized to date. BOEM is also working with the State of Georgia regarding the installation and operation of a meteorological tower and/or buoy off the coast of Tybee Island to examine the potential for wind development in that area. For the State of Florida, the BOEM's Office of Renewable Energy is working with interested parties on the development of an offshore hydrokinetic energy development project, but to date there is no activity with the state to identify and develop potential offshore wind energy development areas along their Atlantic coast.

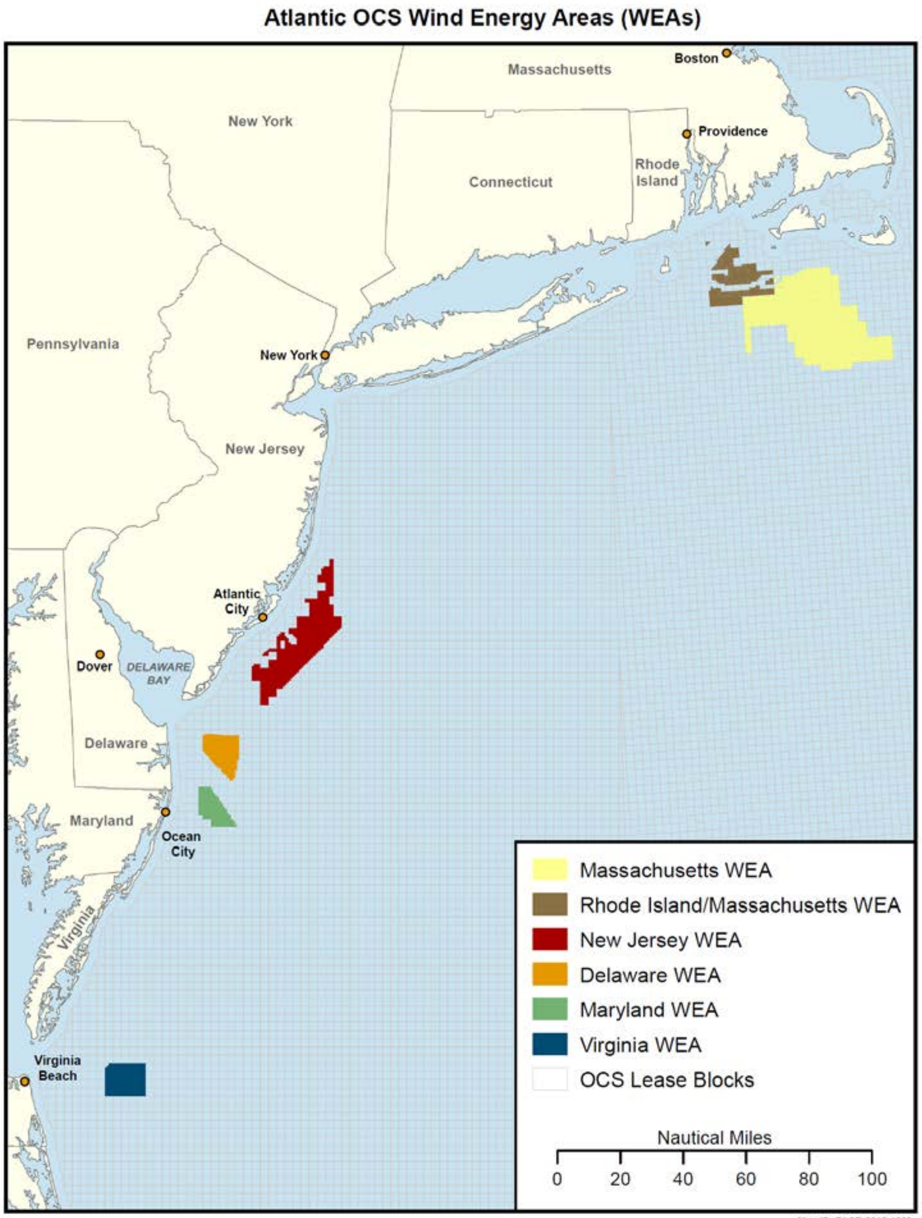

Figure 2. Atlantic WEAs.

(Source: http://www.boem.gov/Renewable-Energy-Program/Smart-from-the-Start/Index.aspx)

1.3. EMISSIONS CHARACTERISTICS OF THE ATLANTIC OCS REGION

Emissions influencing air quality in the Atlantic OCS region originate from a variety of anthropogenic and biogenic sources located in both onshore and offshore areas of the region. The overwhelming majority of emissions influencing the coastal region are from sources located onshore or in state waters. The U.S. Atlantic coast, situated between southeastern Florida to northeastern Maine, includes the large urban areas of Miami, New York, and Boston; several mid-size urban areas including Jacksonville, Florida; Norfolk, Virginia; Providence, Rhode Island; and Portland, Maine; as well as a number of smaller cities. As listed above, there are numerous ports and harbors situated along the Atlantic coast that contain facilities for commercial marine vessels, cruise lines, commercial fishing operations, recreational vessels, and maritime military bases for the U.S. Coast Guard and U.S. Navy. Unlike the Gulf of Mexico OCS area, there are currently no oil or gas development activities or alternative energy facilities (e.g., wind farms) occurring/situated offshore in the Atlantic OCS, but commercial shipping, recreational boating, fishing, military, and other activities occur offshore from Florida to Maine.

For this study, ozone and PM precursor emission estimates were acquired, examined, and used to infer the effects on observed air quality conditions. These estimates were obtained from EPA's latest 2008 National Emission Inventory (NEI) (version 2) (USEPA, 2010), which only contains emissions for onshore and nearshore (ports, state waters) sources. Unlike for the Gulf of Mexico OCS region, where a comprehensive inventory of offshore oil and natural gas development activities, sources, and emissions has been developed and maintained, there is no corresponding emission inventory for the Atlantic OCS region. It should be noted that the emissions tables and charts presented in this report are also included in the Atlantic Region Air Quality Database (ARAQDB) tool developed as part of this study.

1.3.1. Onshore Emissions for the Atlantic Coastal Areas

The Atlantic coastal onshore areas include population- and industry-based sources of criteria pollutants including oxides of nitrogen (NO_x), volatile organic compounds (VOC), sulfur dioxide (SO_2), carbon monoxide (CO), ammonia (NH_3), and particulate matter (coarse – PM_{10}, and fine - $PM_{2.5}$) from a variety of on-road mobile, area, industrial point, and non-road sources. Levels of emissions of these pollutant species vary among the major emission source types and by region along the coast. Transportation-related sources make up the largest percentage of the onshore NO_x and CO emission inventory in the major metropolitan areas, at the coastal ports, and along the Interstate highway system, especially the I-95 corridor that runs north-south from Maine to Florida, and the coastal termination points (major ports and harbors) for a number of the east-west Interstates, namely I-10 (Jacksonville), I-16 (Savannah), I-26 (Charleston), I-40 (Wilmington), I-64 (Norfolk), I-70 (Baltimore), I-80 (New York), and I-90 (Boston). Other emission contributions of NO_x and CO are associated with minor transportation/freight movement highways that service the smaller ports and cities, and the numerous railway corridors along the coast that run north-south or terminate at the coastal port cities. The major contributors to emissions of NH_3, PM_{10}, and $PM_{2.5}$ are area sources associated with population centers/activities. Area sources include home heating units, solvent utilization (architectural coatings/painting, auto refinishing, metal/wood refinishing, de-greasing, dry cleaning), petroleum storage and transport (gas stations, fuel terminals), solid waste and wastewater treatment facilities, landfills, small boilers, restaurants, outdoor grills, road dust, agricultural operations, and open burning. Major contributors of SO_2 emissions are from large industrial point sources, such as electric generation units and other smaller industrial sources situated in a variety of locations along the Atlantic coast. The on-road, non-road, and area source sectors are equal contributors to anthropogenic VOC emissions, while forests, wetlands, crops, and other vegetation are contributors to biogenic VOC emissions along the Atlantic coast.

1.3.2. Offshore Emissions of the Atlantic OCS

The offshore areas of the Atlantic coast (beyond state waters) contain a variety of anthropogenic sources associated with commercial marine vessels, recreational boating, military, and commercial fishing operations. By far, the largest contributors to criteria pollutant emissions are commercial marine vessels. The highest density of emissions from these vessels are in areas offshore of the large commercial ports/harbors, major bay entrances (e.g., Chesapeake Bay) and river channels, and along designated commercial shipping lanes that run predominantly north-south along what is referred to as the M-95 Marine Highway Corridor, which includes the Atlantic coastal waters. This corridor was established in 2010 by the U.S. Department of Transportation's Maritime Administration as part of America's Marine Highway Program (75 FR 18095; April 9, 2010; MARAD-2010-0035) to "serve as extensions of the surface transportation system…" and "to offer relief to landside corridors that suffer from congestion, excessive air emissions or other environmental concerns and other challenges." (USCG, 2012). Figure 3 depicts commercial marine vessel traffic density along the Atlantic coast. The colored areas are individual traces of marine vessel traffic paths with the "warmer" colors in the figure depicting higher vessel density and corresponding higher emissions, especially offshore of southern Florida near Miami, and near each of the major port cities. As estimated by the U.S. Coast Guard, "there are about 156,000 movements of major vessels along the Atlantic Coast each year, and at any given time there are 4,500 vessels off the east coast." (USCG, 2012). Although not quantified in this analysis specifically for the Atlantic OCS area, commercial marine vessels burning diesel or other fuel oil will primarily emit larger quantities of NO_x, CO, and SO_2 emissions and smaller quantities of VOC, PM_{10}, $PM_{2.5}$, and NH_3 emissions.

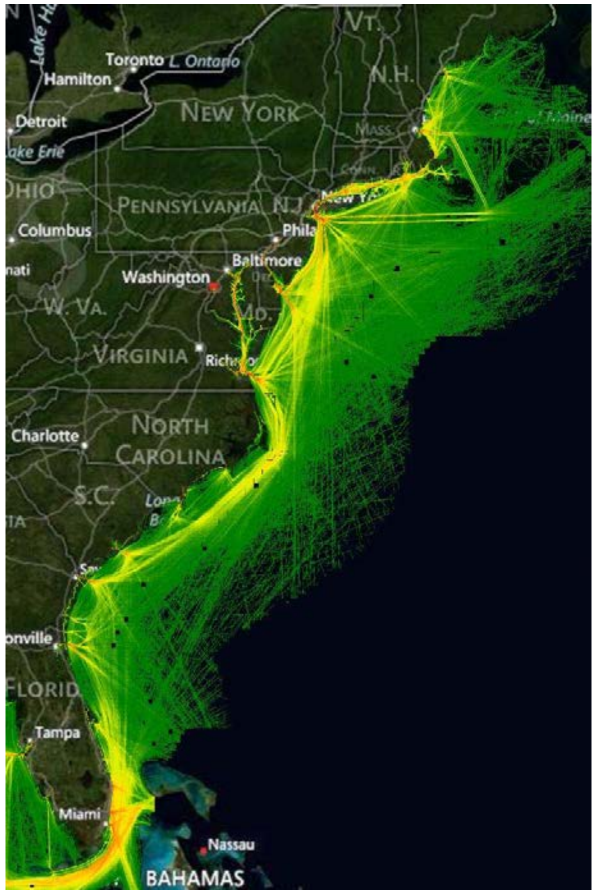

Figure 3. Depiction of commercial marine vessel traffic density off the Atlantic Coast
(Source: USCG, 2012).

1.4. Current Air Quality Issues for the Atlantic OCS Region

A summary of current air quality issues for key port/harbor areas and Class I areas along the Atlantic Coast is presented in this section. Air quality is affected by local geographical, meteorological and emissions characteristics. Due to the predominance of westerly winds (characteristic of North American weather patterns), air quality for most areas along the Atlantic coast is also influenced by pollutant transport from other areas in the continental U.S.

1.4.1. 8-Hour Ozone

Ozone is a secondary pollutant that is not directly emitted into the atmosphere but instead is formed in the lower atmosphere by a series of reactions involving ultra violet (UV) radiation and precursor emissions of oxides of nitrogen (NO_x) and volatile organic compounds (VOCs). NO_x consists of nitric oxide (NO) and nitrogen dioxide (NO_2), which are primarily emitted from anthropogenic sources. VOCs consist of thousands of individual hydrocarbon and oxygenated hydrocarbon species emitted from anthropogenic, biogenic, and geogenic sources. Ozone formation in the troposphere is affected by local weather conditions: winds, temperature, solar radiation, and horizontal and vertical dispersion characteristics, which influence precursor concentrations, reaction rates, formation, transport, and deposition. Because the primary ozone-forming reaction is photochemically driven (i.e., by the sun), ozone concentrations typically peak during the daylight hours and then decrease after sunset.

Health effects studies have determined that exposure to ozone can reduce lung function and increase the incidence and severity of respiratory illnesses such as asthma. Repeated exposure to ozone may also damage vegetation and trees. To protect public health, the U.S. Environmental Protection Agency (EPA) established the first National Ambient Air Quality Standard (NAAQS) for ozone in 1971 and has since revised the level and form of the standard several times. The most recent revision occurred in March 2008 and set the 8-hour ozone standard to 75 parts per billion (ppb). To attain this standard, the three-year average of the annual fourth highest daily maximum 8-hour ozone concentration at all sites within a designated area must be less than 75 ppb. The three-year average or "design value" is calculated for each site and then the maximum value over all sites within an area determines the design value for the area. EPA issued attainment/non-attainment designations in April 2012. For most areas, compliance with the new standard was determined using data collected during the period 2008–2010.

To provide perspective on the recent 8-hour ozone concentrations and trends along the Atlantic Coast region, Table 1 lists the maximum 8-hour ozone design values (calculated as indicated above) for sites within key port and harbor areas for the four consecutive three-year periods ending in 2010 through 2012. Of the areas included in the table, the New York, Newark-Elizabeth, Wilmington (DE), and Baltimore areas are currently designated non-attainment areas for ozone. All of the other areas included in the table are designated unclassifiable or attainment.

Table 1
8-Hour Ozone Design Values (ppb) for the Four Consecutive Three-Year Periods Ending in 2010 through 2012 for Selected Areas Along the Atlantic Coast.

Compliance with the 8-Hour Ozone NAAQS Requires the Design Value to be Less than or Equal to 75 ppb; Current EPA Determinations Were Based on the 2008–2010 Values.

Area (Counties, State)	**2007–2009 8-Hour Ozone Design Value (ppb)**	**2008–2010 8-Hour Ozone Design Value (ppb)**	**2009–2011 8-Hour Ozone Design Value (ppb)**	**2010–2012 8-Hour Ozone Design Value (ppb)**
Portland (Cumberland County, ME)	74	70	70	69
Gloucester (Essex County, MA)	79	74	71	71
Boston (Middlesex, Norfolk and Suffolk Counties, MA)	78	73	72	73
Provincetown (Barnstable County, MA)	76	74	72	75
Martha's Vineyard/Nantucket (Bristol and Dukes Counties, MA)	77	78	76	80
Providence (Providence County, RI)	77	72	71	75
New York (Bronx, Kings, Nassau, New York, Queens, Richmond and Suffolk Counties, NY)	84	84	84	85
Newark-Elizabeth (Essex, Hudson and Union Counties, NJ)	80	77	76	82
Wilmington (New Castle County, DE)	78	76	77	80
Baltimore (Baltimore City and Baltimore Counties, MD)	85	78	78	84
Newport News/Norfolk (Newport News City, Norfolk City, Hampton and Suffolk Counties, VA)	73	72	71	76
Wilmington (New Hanover County, NC)	70	66	62	63
Charleston (Berkeley and Charleston Counties, SC)	67	67	65	66
Savannah (Chatham County, GA)	64	64	64	64
Brunswick (Glynn County, GA)	62	63	61	61
Port Canaveral (Brevard County, FL)	66	65	64	65
Miami-Dade (Broward, Miami-Dade and Palm Beach Counties, FL)	69	68	65	65

The calculated design values are above the 8-hour standard for all three design-value periods for Martha's Vineyard/Nantucket, New York, Newark-Elizabeth, Wilmington (DE), and Baltimore; for the 2007–2009 and 2010-2012 periods for other areas in Massachusetts and Rhode Island, and for the 2010-2012 period for Newport News/Norfolk. The design values either decrease with time or stay about the same for the first three three-year periods, but there are some increases for 2010-2012.

1.4.2. PM2.5

The recent emphasis on $PM_{2.5}$ as an air pollutant of concern is based primarily on epidemiological studies that have indicated a cause and effect relationship between exposure to fine particles and health effects, including respiratory and cardiovascular disease and premature mortality. Particulates are also a primary constituent of regional haze, which limits visibility and the attainment of visibility goals, and ultimately diminishes the natural beauty of the environment.

Fine particulates in the atmosphere consist of primary particles that are emitted directly from sources and secondary particles that form in the atmosphere through chemical and physical processes. Pollutants that contribute to the formation of secondary aerosols include SO_2, $NO_{x,}$ and ammonia (NH_3). Natural sources of fine particulates and precursor pollutants include organic aerosols from vegetation, wind-blown dust, sea salt, and forest fires. Anthropogenic contributors include numerous agricultural, mobile, and industrial sources. Meteorology plays an important role in particulate formation and transport and in determination of the ambient particulate concentration levels.

The U.S. EPA established new standards for fine particulate matter in 1997, and subsequently revised the 24-hour standard in 2006 and the annual standard in 2012. Under these standards, fine particles are defined as those with a diameter of less than 2.5 microns; particles of this size are also referred to as $PM_{2.5}$. The annual $PM_{2.5}$ NAAQS requires the three-year average annual mean concentration to be less than 12 micrograms per cubic meter (μgm^{-3}). The daily $PM_{2.5}$ standard requires the three-year average of the 98^{th} percentile daily average concentration to be less than 35 μgm^{-3}. The averages or "design values" are calculated for each site and then the maximum value over all sites within an area is the design value for the area.

Table 2 lists the annual and 24-hr $PM_{2.5}$ design values for key port and harbor areas along the Atlantic coast for the four consecutive three-year periods ending in 2010 through 2012. Designations for the annual $PM_{2.5}$ standard are expected to be issued in 2014. Of the areas included in the table, the New York, Newark-Elizabeth, and Wilmington (DE) areas are currently designated non-attainment areas for 24-hour $PM_{2.5}$. All of the other areas included in the table are designated unclassifiable or attainment.

Table 2a

Annual $PM_{2.5}$ Design Values (μgm^{-3}) for the Four Consecutive Three-Year Periods Ending in 2010 through 2012 for Selected Areas along the Atlantic Coast.

Compliance with the Annual $PM_{2.5}$ NAAQS Requires the Design Value to Be Less than or Equal to 12 μgm^{-3}.

Area (Counties)	**2007–2009 Annual PM2.5 Design Value (μgm^{-3})**	**2008–2010 Annual PM2.5 Design Value (μgm^{-3})**	**2009–2011 Annual PM2.5 Design Value (μgm^{-3})**	**2010–2012 Annual PM2.5 Design Value (μgm^{-3})**
Portland (Cumberland County, ME)	9.1	8.4	8.2	8.4
Gloucester (Essex County, MA)	9.0	8.5	8.2	8.0
Boston (Middlesex, Norfolk and Suffolk Counties, MA)	11.1	10.5	10.2	9.9
Martha's Vineyard/Nantucket (Bristol and Dukes Counties, MA)	8.8	8.3	7.9	7.6
Providence (Providence County, RI)	10.5	9.6	9.4	8.1
New York (Bronx, Kings, Nassau, New York, Queens, Richmond and Suffolk Counties, NY)	13.9	12.5	11.9	11.8
Newark-Elizabeth (Essex, Hudson and Union Counties, NJ)	12.6	11.6	11.4	11.2
Wilmington (New Castle County, DE)	13.0	11.7	10.7	10.4
Baltimore (Baltimore City and Baltimore Counties, MD)	12.9	11.7	11.1	11.1
Newport News/Norfolk (Newport News City, Norfolk City, Hampton and Suffolk Counties, VA)	11.5	11.1	10.0	9.6
Wilmington (New Hanover County, NC)	8.7*	8.2*	8.3*	7.7
Charleston (Berkeley and Charleston Counties, SC)	9.9	9.1	9.2	8.9
Savannah (Chatham County, GA)	11.3	10.7	10.7	10.7
Brunswick (Glynn County, GA)	10.4	10.1	9.7*	--
Port Canaveral (Brevard County, FL)	7.1	6.9	6.6	6.5
Miami-Dade (Broward, Miami-Dade and Palm Beach Counties, FL)	8.0	7.8	7.5	7.5

* = Incomplete data

Table 2b

24-Hour PM2.5 Design Values (μgm-3) for the Four Consecutive Three-Year Periods Ending in 2010 through 2012 for Selected Areas Along the Atlantic Coast.

Compliance with the 24-Hour PM2.5 NAAQS Requires the Design Value to be Less than or Equal to 35 μgm-3.

Area (Counties/Parishes)	2007–2009 24-Hour $PM_{2.5}$ Design Value (μgm^{-3})	2008–2010 24-Hour $PM_{2.5}$ Design Value (μgm^{-3})	2009–2011 24-Hour $PM_{2.5}$ Design Value (μgm^{-3})	2010–2012 24-Hour $PM_{2.5}$ Design Value (μgm^{-3})
Portland (Cumberland County, ME)	20	21	22	20
Gloucester (Essex County, MA)	24	22	20	19
Boston (Middlesex, Norfolk and Suffolk Counties, MA)	27	25	24	23
Martha's Vineyard/Nantucket (Bristol and Dukes Counties, MA)	24	23	22	20
Providence (Providence County, RI)	26	24	23	23
New York (Bronx, Kings, Nassau, New York, Queens, Richmond and Suffolk Counties, NY)	33	29	28	26
Newark-Elizabeth (Essex, Hudson and Union Counties, NJ)	32	30	30	29
Wilmington (New Castle County, DE)	32	30	27	26
Baltimore (Baltimore City and Baltimore Counties, MD)	32	30	29	27
Newport News/Norfolk (Newport News City, Norfolk City, Hampton and Suffolk Counties, VA)	25	23	26	27
Wilmington (New Hanover County, NC)	20*	18*	26*	23
Charleston (Berkeley and Charleston Counties, SC)	22	21	22	22
Savannah (Chatham County, GA)	24	23	29	30
Brunswick (Glynn County, GA)	25*	24*	25*	--
Port Canaveral (Brevard County, FL)	18	16	15	14
Miami-Dade (Broward, Miami-Dade and Palm Beach Counties, FL)	18	16	14	14

* = Incomplete data

The annual $PM_{2.5}$ design values are above the standard for four sites (New York, Newark-Elizabeth, Wilmington (DE), and Baltimore) for the 2007–2009 period, one site (New York) for the 2008–2010 period and no sites for the 2009–2011 and 2010-2012 periods. For most sites, the annual design values either decrease with time or stay about the same for these most recent three-year periods.

The 24-hour $PM_{2.5}$ design values are below the standard for all sites and all four periods. For most sites, the 24-hour design values either decrease with time or stay about the same for the four most recent three-year periods. For Newport News/Norfolk, Wilmington (NC), and Savannah, the 24-hour design values increase with time, especially between the 2008–2010 and 2009–2011 periods.

1.4.3. Visibility

Visibility impairment or light extinction can result from the scattering and/or absorption of light by particles in the atmosphere. Fine particles from both natural and anthropogenic sources (as described in the previous section), coarse particles, and, in coastal areas, sea salt can contribute to light extinction. High humidity conditions can also contribute to light extinction and reduced visibility. Visibility is sometimes expressed in terms of deciview units, which vary approximately in proportion to the human response to visibility change. Higher deciview (DV) values correspond to poorer visibility (and a lower visual range).

In 1999, the U.S. EPA promulgated regional haze regulations to prevent "any future, and remedy any existing, impairment of visibility" at 156 designated Class I areas (national parks greater than 6000 acres and wilderness areas greater than 5000 acres). The regional haze rule calls for states to establish "reasonable progress goals" for each Class I area to improve visibility on the 20% haziest days and to prevent visibility degradation on the 20% clearest days. The national goal is to return visibility to natural background levels by 2064. Using the period 2000 to 2004 as the baseline period, states are to evaluate progress in improving visibility by 2018 and every ten years thereafter. State Implementation Plans (SIPs) for the first phase of the regional haze regulation were due in December 2007. Several Regional Planning Organizations (RPOs) have been developing control strategies to guide states in meeting the regional haze goals.

There are six Class I areas located along the Atlantic coast. These are Acadia National Park, ME; Brigantine National Wildlife Refuge (NWR), NJ; Swanquarter NWR, NC; Cape Romain NWR, SC; Okefenokee NWR, GA; and Everglades National Park, FL. Table 3 lists the average visibility (deciviews) for the 20 percent worst visibility days for the periods 2000–2004, 2004–2008, and 2008–2012 for each area. Note that Cape Romain is not included in the table due to incomplete data. The values for 2000–2004 are the baseline values for implementation of the regional haze regulations. Deciviews (DV) corresponding to the 2018 goal and estimated natural conditions (USEPA, 2003) are also provided.

Table 3
Average Visibility for 20% Worst Days Based on 2000 through 2012 Data for Class I Areas Along the Atlantic Coast.

Class I Area (State)	2000–2004 Average Visibility for 20% Worst Days (DV)	2004–2008 Average Visibility for 20% Worst Days (DV)	2008–2012 Average Visibility for 20% Worst Days (DV)	2018 Glidepath Goal (DV)	Estimated Natural Conditions (DV)
Acadia National Park	23.3	22.8	19.2	20.5	11.5
Brigantine NWR	28.1	28.2	25.0	24.2	11.3
Swanquarter NWR	24.6	27.0	23.4	21.5	11.2
Okefenokee NWR	26.2	27.5	23.6	22.8	11.5
Everglades NP	22.5	21.6	18.2	19.9	11.2

Table 3 indicates that continued improvements in visibility are needed to achieve the 2018 goals for Brigantine, Swanquarter, and Okefenokee NWR and the natural conditions goals for all areas. As noted above, some measures to reduce regional haze and improve visibility at these and other Class I areas may be under consideration (or being implemented), based on the work conducted by the RPOs.

1.5. REVIEW OF PRIOR STUDIES

Over the past many years, numerous data collection, data analysis, and modeling studies have been conducted to examine air quality and related issues in the Atlantic OCS region.

Regional Air Quality Analysis and Modeling Studies: Although there have been many national initiatives that have addressed air quality issues in the Eastern U.S., including along the Atlantic coast, most air quality issues are addressed at the regional level, for example for portions of the Atlantic Coast (such as New England, the Mid-Atlantic, the Southeast), or at the State or local level, for example for areas that do not attain air quality standards (such as counties or multi-county areas containing major urban areas).

Regional Planning Organizations (RPOs) have been established within the U.S. to address air quality issues, in particular, visibility impairment, from a regional perspective. Two RPOs have been active in addressing visibility issues along the Atlantic Coast: the Mid-Atlantic/Northeast Visibility Union (MANE-VU) and the Visibility Improvement State and Tribal Association of the Southeast (VISTAS). The following Atlantic Coastal states are members of MANE-VU: Maine, New Hampshire, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Delaware, and Maryland. The remaining Atlantic Coastal states are members of VISTAS: Virginia, North Carolina, South Carolina, Georgia, and Florida. These groups have conducted numerous data analysis and modeling studies focused on understanding the causes of poor visibility and improving visibility – especially for Class I areas within their broader regions. The results of these studies provided the basis for the regional haze SIPs submitted by the States in 2006.

In addition, several multi-state organizations have conducted air quality data collection, data analysis, and modeling studies aimed at reducing inter-state pollutant transport and attaining air quality standards for a variety of pollutants. The Northeast States for Coordinated Air Use Management (NESCAUM) assists member states in implementing national environmental programs required under the Clean Air Act and other federal legislation. Its membership includes the following Atlantic Coastal states: Maine, New Hampshire, Massachusetts, Rhode Island, and Connecticut. The Mid-Atlantic Air Resources Management Association (MARAMA) is an association of state and local air pollution control agencies that work together to prevent and reduce air pollution in the Mid-Atlantic Region. The following Atlantic Coast states are members of MARAMA: New Jersey, Delaware, Maryland, Virginia, and North Carolina. The Ozone Transport Commission (OTC) is a multi-state organization specifically focused on developing and implementing regional solutions to ozone air quality issues in the Northeast and Mid-Atlantic regions and involves the Atlantic Coastal States from Maine to Virginia. These groups have conducted numerous data analysis and modeling studies and have supported the development of inter-state transport rules and SIPs.

Coastal Meteorology Studies: A few studies have examined the effects of meteorology on pollutant transport along the Atlantic Coast. In 1984, a pollution transport study with the acronym ACURATE was conducted to provide information on regional transport patterns. Kr-85 (a tracer of opportunity) from the Savannah River Plant (SRP) in Aiken, SC was sampled at five locations in North Carolina, Virginia, and New Jersey. Over an 18-month period, about 750 out of 3858 measurements were attributable to the SRP plume. Non-zero measurements account for about 30 percent of the samples at the closest site (Fayetteville, NC) and about 10 percent of the samples at the farthest site (Murray Hill, NJ).

More recently, data collection studies have focused on assessing the potential for wind energy development in OCS areas offshore of several states including Massachusetts, New Jersey, Delaware, Virginia, North Carolina, and Georgia. Although few published studies of these data are available, they are being used to identify potential areas for wind energy development.

For example, as part of the Cape Wind Project (near Martha's Vineyard, Massachusetts), a meteorological data tower was established on Horseshoe Shoal in Nantucket Sound (http://capewind.whgrp.com/). Meteorological data as well as sea temperature, current, and wave data were obtained for a multi-year period and are being used to design and engineer the planned wind energy installations in this area.

A weather buoy was established offshore of Atlantic City/Cape May, New Jersey in 2010 (http://www.fishermensenergy.com/atlantic-city-windfarm.php) and was expected to collect meteorological data for two years.

Similarly, Virginia's Department of Mines, Minerals and Energy is planning to conduct wind-energy-related research activities, including the installation of meteorological and ocean monitoring platforms, beginning as soon as 2013.

Beginning in 2011, an intensive study of wind conditions along the Virginia and North Carolina coastlines was conducted (http://www.weatherflow.com/middle-atlantic-offshore-wind-energy-studies/). The goal was to develop and improve understanding of wind conditions along the coastline, especially with regard to small-scale weather patterns. This information is expected to be used to identify optimal locations for wind installations and improve weather forecasting for these locations.

As part of a BOEM-sponsored study, Lavalee (2012) examined visibility at various locations along the North Carolina coast, including those of special interest to the National Park Service. This information is expected to be used to effectively locate offshore wind installations without compromising visibility in key areas.

Finally, Georgia Power (http://www.georgiapower.com/about-energy/energy-sources/wind-energy.cshtml) is preparing to collect wind data off the coast of Tybee Island, Georgia to assess the potential for wind power generation in the area.

Emissions Studies for Port/Harbor Areas: For coastal areas, one component of any air quality analysis or modeling exercise is accounting for emissions from marine vessels and other traffic in and around port/harbor areas. Assessing and controlling emission has been an active area of study for at least the past decade. In 2009, the U.S. and Canada became the first two countries to ask the International Maritime Organization to create an emissions control area around their coastlines extending out 200 miles (300 kilometers). This was done in order to protect North American residents from harmful ship emissions.

There have been a number of meetings and events held to present information regarding emissions related to ports and harbors along the Eastern seaboard. Most papers from these meetings relate to emissions at the ports themselves, and more specifically to the vehicle traffic and equipment used. Many indicated that going electric was the cleanest approach, but not necessarily the most cost effective. Most stressed that making incentives available to help to reduce emissions was a positive approach. The MARAMA – Mid-Atlantic Diesel Collaborative presentation: http://www.dieselforum.org/files/dmfile/Mid-AtlanticUpdate.pdf (December 2012) outlines projects implemented to date and examines current (2008) and expected (2030) emissions for Mid-Atlantic ports.

The Atlantic Coast Port Access Route Study (ACPARS) has also examined navigational safety issues associated with the development of offshore renewable energy installations. An interim report was presented in July 2012 (USCG, 2012). One goal of the study is to assist the Coast Guard in developing plans for safety fairways, traffic separation schemes, or other routing measures. Another goal is to provide data and tools to aid the determination of the suitability of specific waterways for proposed projects.

1.6. OVERVIEW OF THE DATA ANALYSIS

In this study, a variety of data analyses were conducted in order to “mine” the integrated ARAQDB dataset in a variety of ways and thus ensure the integrity and usability of the dataset. Specific goals of the data analysis were to use the integrated dataset to 1) examine the relationships between meteorology, emissions, and air quality in the Atlantic OCS region, 2) confirm and/or advance prior conceptual descriptions related to ozone, particulate, and regional-haze air quality issues along the Atlantic Coast, 3) identify gaps in the data/knowledge bases, and 4) recommend future data analyses.

The analysis consisted of several data analysis subtasks:

Data Summaries: Statistical and graphical summaries were prepared to provide an overview of the meteorological, air quality, and emissions data and highlight key features/components of the integrated dataset.

CART Analysis for Selected Port/Harbor Areas: Classification and Regression Tree (CART) analysis and other data analysis techniques were used to examine the relationships between onshore and offshore meteorological conditions and air quality in coastal areas. The CART technique is described in more detail in Section 4 of this report. This analysis examined ozone, $PM_{2.5}$, and visibility.

Air Quality Trends Analysis: Meteorologically adjusted trends for ozone, $PM_{2.5,}$ and visibility were developed based on meteorological typing provided by CART analysis.

OCD5 Input File Preparation: Data from selected onshore and offshore monitoring sites for the period 2005–2009 were formatted and processed for input to the OCD5 model.

1.7. Datasets Used for this Analysis

This analysis relied on data from the BOEM Atlantic Region Air Quality Database (ARAQDB) tool, which was prepared as part of this data synthesis study and is summarized in Volumes I and II of this report. All of the data that appear in the remainder of this report are also included in the ARAQDB. The data focus on key port/harbor areas along the Atlantic Coast (as listed in Section 1.1) as well as Class I[1] protected areas.

Air quality data from the EPA including ozone, particulate matter (PM_{10} and $PM_{2.5}$), speciated particulate matter, sulfur dioxide (SO_2), and carbon monoxide (CO) for sites within approximately 50 kilometers (km) of the Atlantic coast, as available from the Air Quality System (AQS) database, with emphasis on port and harbor areas.

Air quality and meteorological data from the Interagency Monitoring of Protected Visual Environments (IMPROVE) sites located in Class I areas along the Atlantic Coast (including Acadia National Park (ME), Brigantine (NJ), Swanquarter (NC), Cape Romain (SC), Wolf Island (GA) and others). Data from special studies IMPROVE sites were also included.

Surface meteorological data from the National Weather Service (NWS) for sites within approximately 50 kilometers (km) of the Atlantic coast and within or nearby to port and harbor areas.

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[1] Class I air quality areas include national parks larger than 6,000 acres and wilderness areas larger than 5,000 acres that existed or were authorized as of August 7, 1977. They receive the highest degree of air quality protection under the Clean Air Act.

Upper-air meteorological data from the NWS for sites within approximately 50 kilometers (km) of the Atlantic coast (U.S. portion only).

Meteorological data from buoys and C-MAN stations in the western Atlantic Ocean, from the NDBC, with emphasis on the OCS region (within approximately 40 nautical miles or about 75 km from the coast). The database consists of data from a variety of sources as follows:

Initially, all available data for the period 2000 through 2010 were included in the database and the data analysis was based on those data. At the end of the project, the database was expanded to include data from 2011 and 2012.

2.0 DATA SUMMARIES

The objective of the data summaries task was to provide an overview of the meteorological, air quality, and emissions data and highlight key features/components of the integrated dataset. Selected data summaries are presented in this section of the report. A more complete set of data summary charts (similar to those included in this section) are available in Excel format.

2.1. METEOROLOGICAL DATA SUMMARIES

One objective of the data analysis task was to summarize the key meteorological characteristics of the Atlantic OCS region, and to examine how meteorological conditions vary throughout the region and throughout the year.

Historical surface and upper-air meteorological data for the period 2000 through 2010 were used to prepare the summaries. Surface meteorological data summaries were prepared for 15 different locations along the coast and nine offshore locations. Upper-air meteorological data summaries were prepared for eight locations. For the onshore surface measurement summaries, the areas include:

- Bangor, ME
- Portland, ME
- Boston, MA
- New Bedford, MA
- Providence, RI
- New York, NY
- Newark, NJ
- Atlantic City, NJ
- Wilmington, DE
- Baltimore, MD
- Newport News, VA
- Wilmington, NC
- Charleston, SC
- Savannah, GA
- Miami, FL

For the offshore surface measurement summaries, the nine buoys/C-man stations include:

- 44007 (Portland, ME)
- 44013 (Boston, MA)
- BUZM3 (Buzzard's Bay, MA)

- ALSN6/44065 (Ambrose Light, NY/New York Harbor Entrance, NJ)
- 44009 (Delaware Bay, DE)
- 44014 (Virginia Beach, VA)
- DSLN7/41025 (Diamond Shoals Light/Diamond Shoals, NC)
- 41004 (Edisto, SC)
- FWYF1 (Fowey Rocks, FL)

The eight upper-air sites are:

- Gray, ME
- Chatham, MA
- Brookhaven, NY
- Wallops Island, VA
- Newport News, VA/Morehead City, NC
- Charleston, SC
- Jacksonville, FL
- Miami, FL

The locations are shown in Figure 4. The data summaries focus on routine monitoring sites with multi-year measurement periods. The surface and upper-air data were obtained from the NWS (NCDC, 2012) and the buoy data were obtained from the National Data Buoy Center (NDBC) (NDBC, 2012). As discussed later in this section the meteorological data sites were selected to represent the different regions of the Atlantic Coast and for pairing with air quality monitoring sites. All of the data presented in this section are included in the ARAQDB. Detailed site information is also included in the ARAQDB.

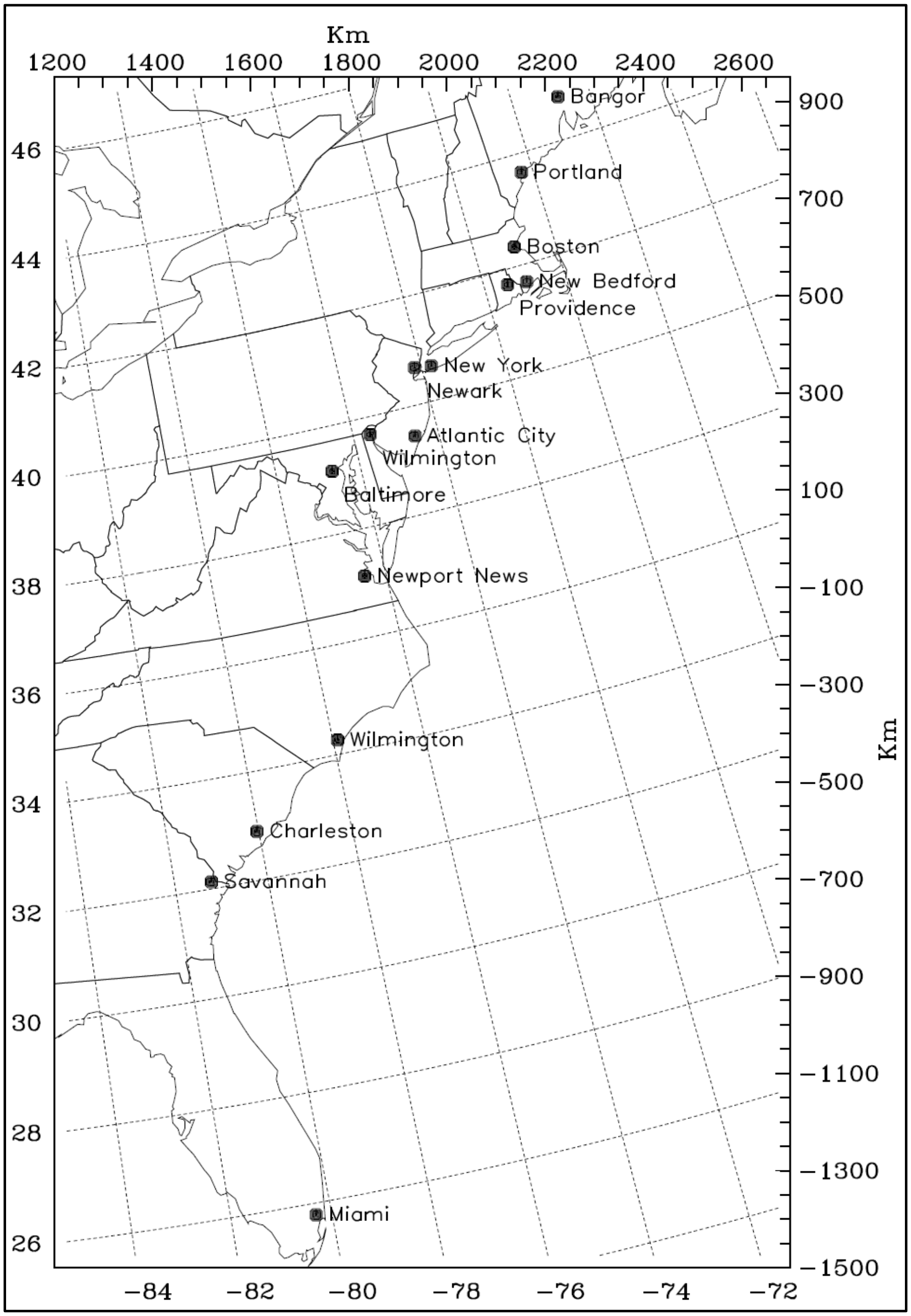


Figure 4a. Surface meteorological monitoring sites for the BOEM Atlantic OCS Region data summaries.

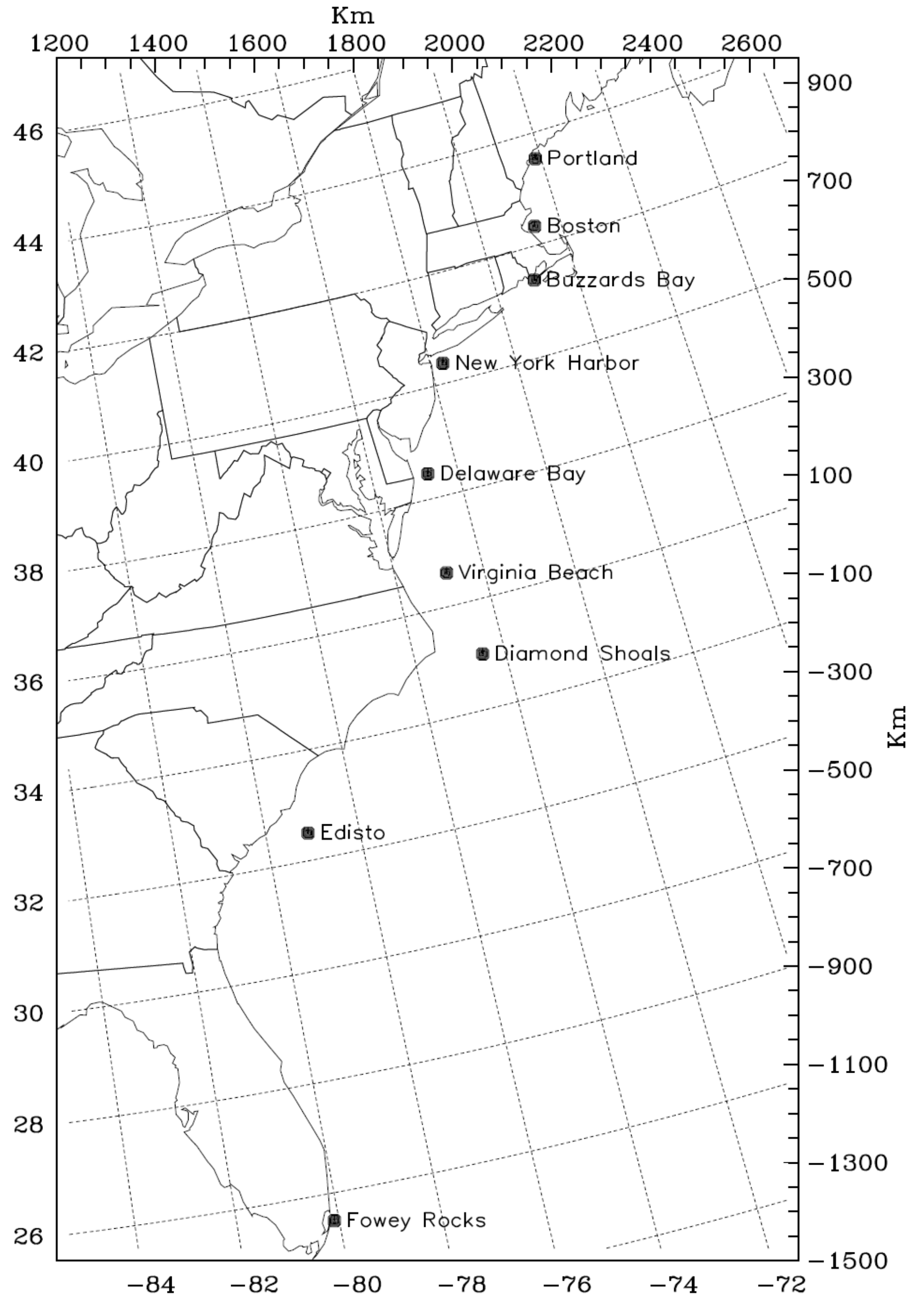


Figure 4b. Buoy meteorological monitoring sites for the BOEM Atlantic OCS Region data summaries.

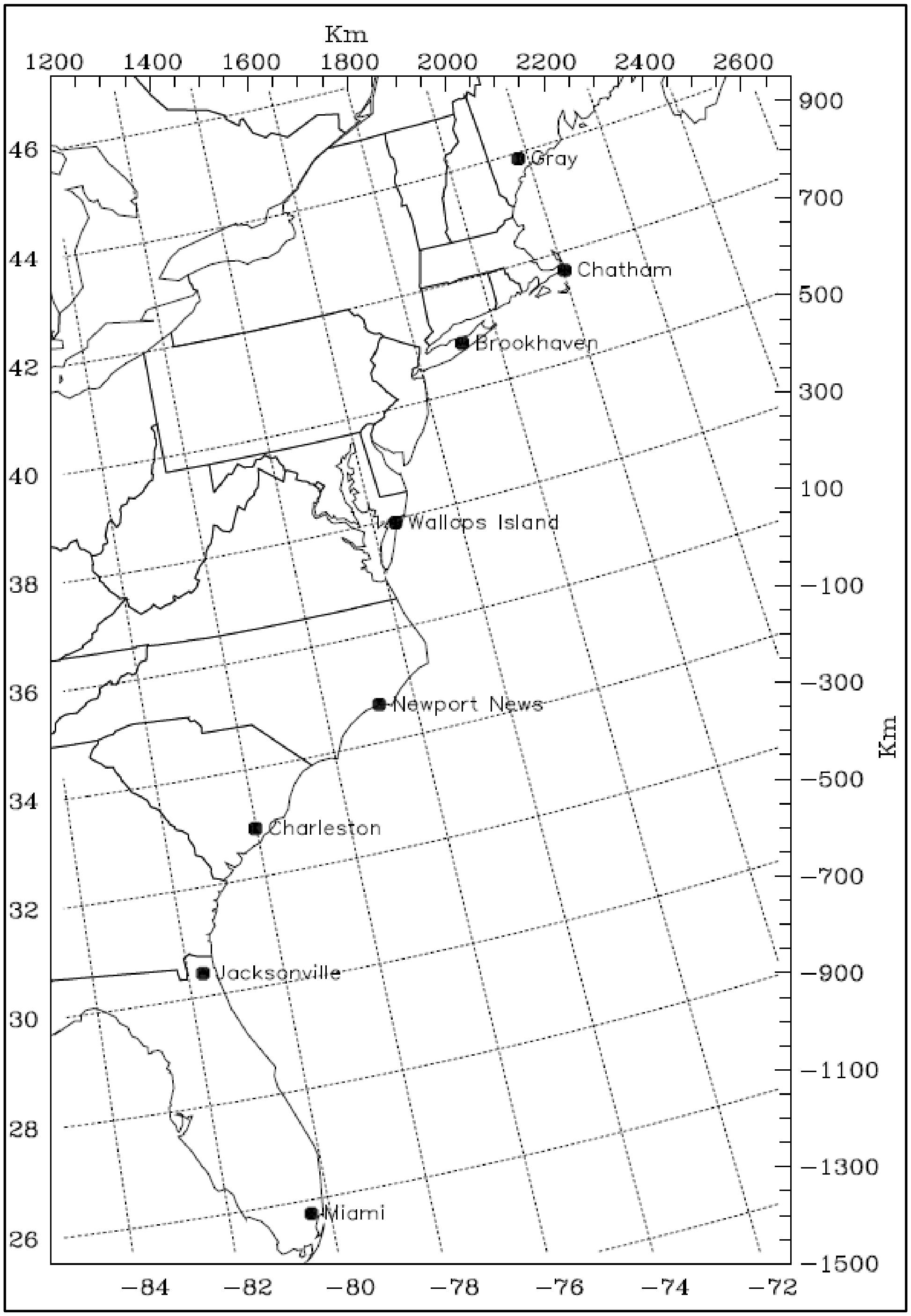


Figure 4c. Upper-air meteorological monitoring sites for the BOEM Atlantic OCS Region data summaries.

2.1.1. Selected Surface Meteorological Metrics

In this section, plots illustrating the monthly and annual variations in selected meteorological parameters for the onshore surface monitoring sites of interest are presented and discussed. The surface-based parameters include:

- Minimum and maximum temperature (°C)
- Relative humidity at noon (%)
- Wind speed at 1000 and 1600 LST (ms^{-1})
- Wind direction at 1000 and 1600 LST (degrees)
- Precipitation amount (inches)
- Persistence index (unitless).

The "persistence index" is a derived parameter and is defined for each day as the average vector wind speed divided by the average scalar wind speed. A value close to one indicates a persistent wind direction during the daily averaging period. A lower value indicates some variation in wind direction during the period, such as is expected during a sea breeze cycle. Simple calculations indicate that a classic sea breeze circulation would have a persistence index in the range of 0.1 to 0.5. Throughout this report, the persistence index is used to identify possible sea breeze conditions.

The NWS surface data typically represent temperature at three to five meters above the ground and winds at ten meters above the ground. The hours 1000 and 1600 LST were selected for these displays in order to sample different potions of the diurnal cycle. These two hours, respectively, typically represent key hours for photochemical production and pollutant transport (especially for ozone) and the initial and later (well established) phases of a sea breeze.

Figures 5 through 12 present some example meteorological data summaries for seven meteorological monitoring sites within or nearby to the following port/harbor areas: Portland, Martha's Vineyard, Newark-Elizabeth, Newport News, Wilmington (NC), Savannah, and Miami and one site nearby to a Class I area (Brigantine NWR). In each figure, the first four charts display month-to-month variations in selected parameters. The first chart (upper left-hand corner) presents the average (overall years) of the minimum (blue line) and maximum (red line) temperature (°C) for each month. The second chart (upper right hand corner) gives the average monthly precipitation. The third and fourth charts (in the middle of the page) display the average monthly wind speed and wind direction for 1000 and 1600 hours Local Standard Time (LST). The next two charts (bottom of the page) display annual variations for two key parameters - precipitation and the persistence index. Not all sites had complete data for the full period and thus some of the annual charts are for a subset of the full period. A full set of summary charts (for all sites listed above and additional meteorological parameters) is available in Excel format.

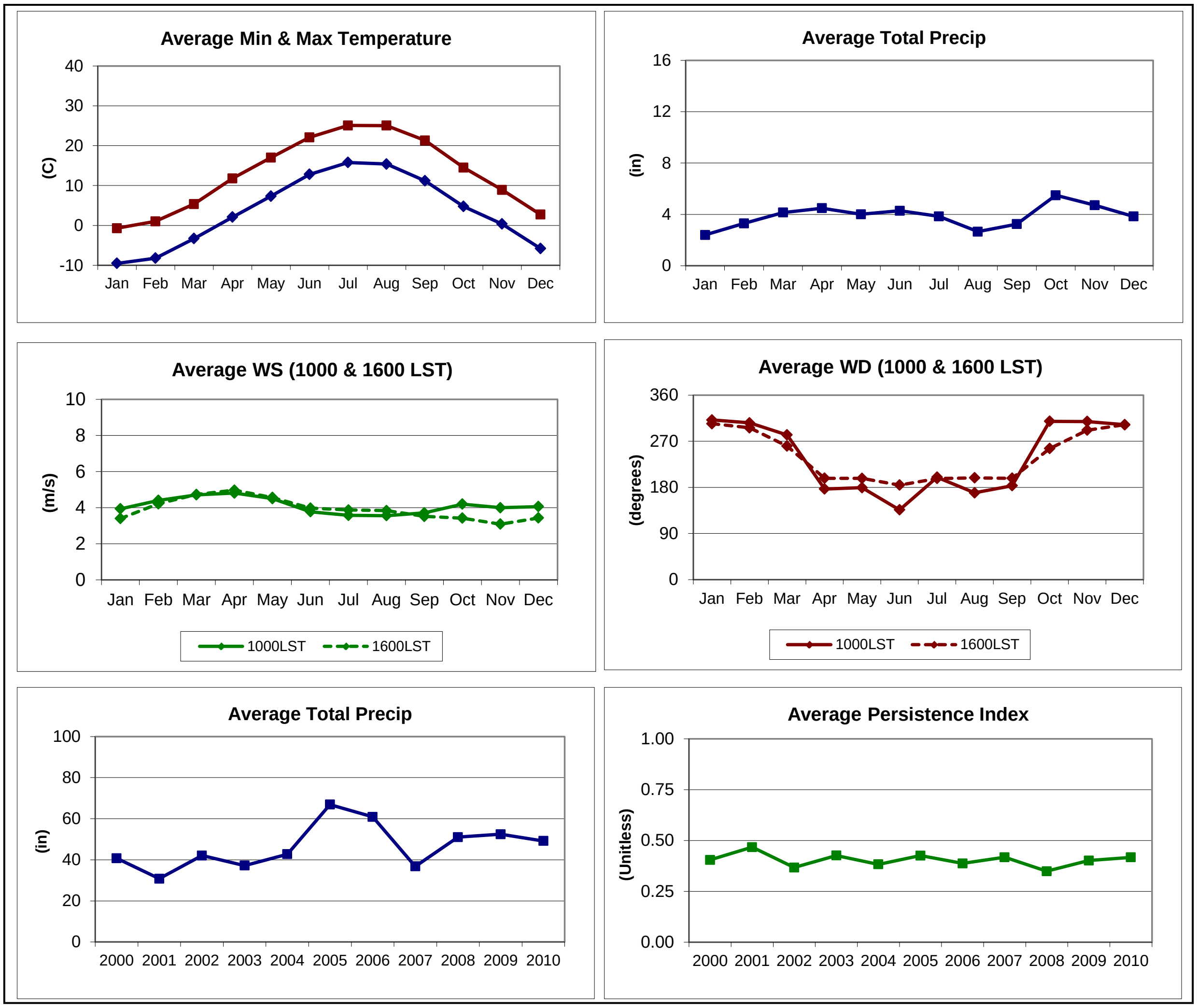


Figure 5. Surface meteorological data summary for Portland (2000–2010).

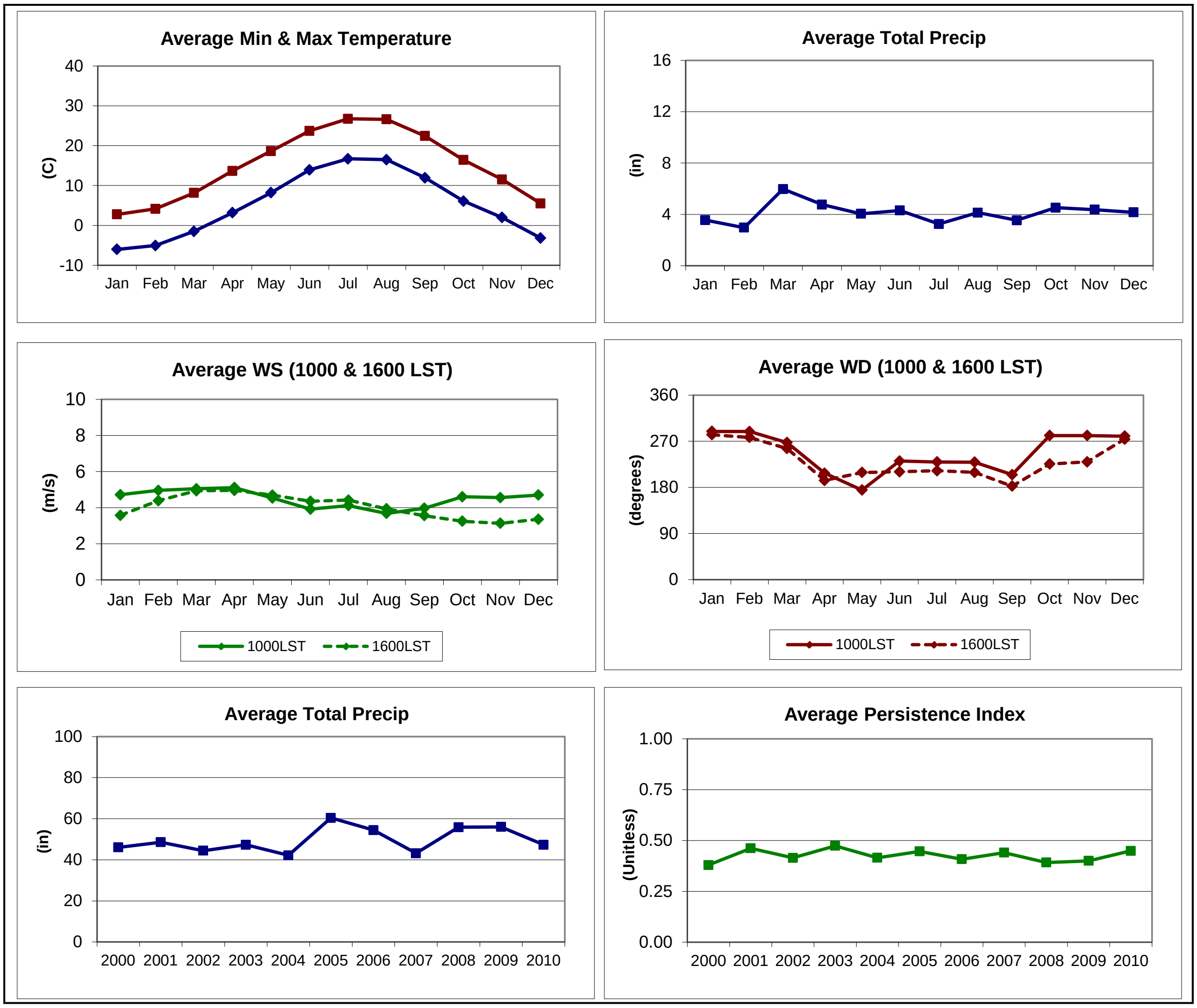


Figure 6. Surface meteorological data summary for Martha's Vineyard (New Bedford) (2000–2010).

Figure 7. Surface meteorological data summary for Newark-Elizabeth (2000–2010).

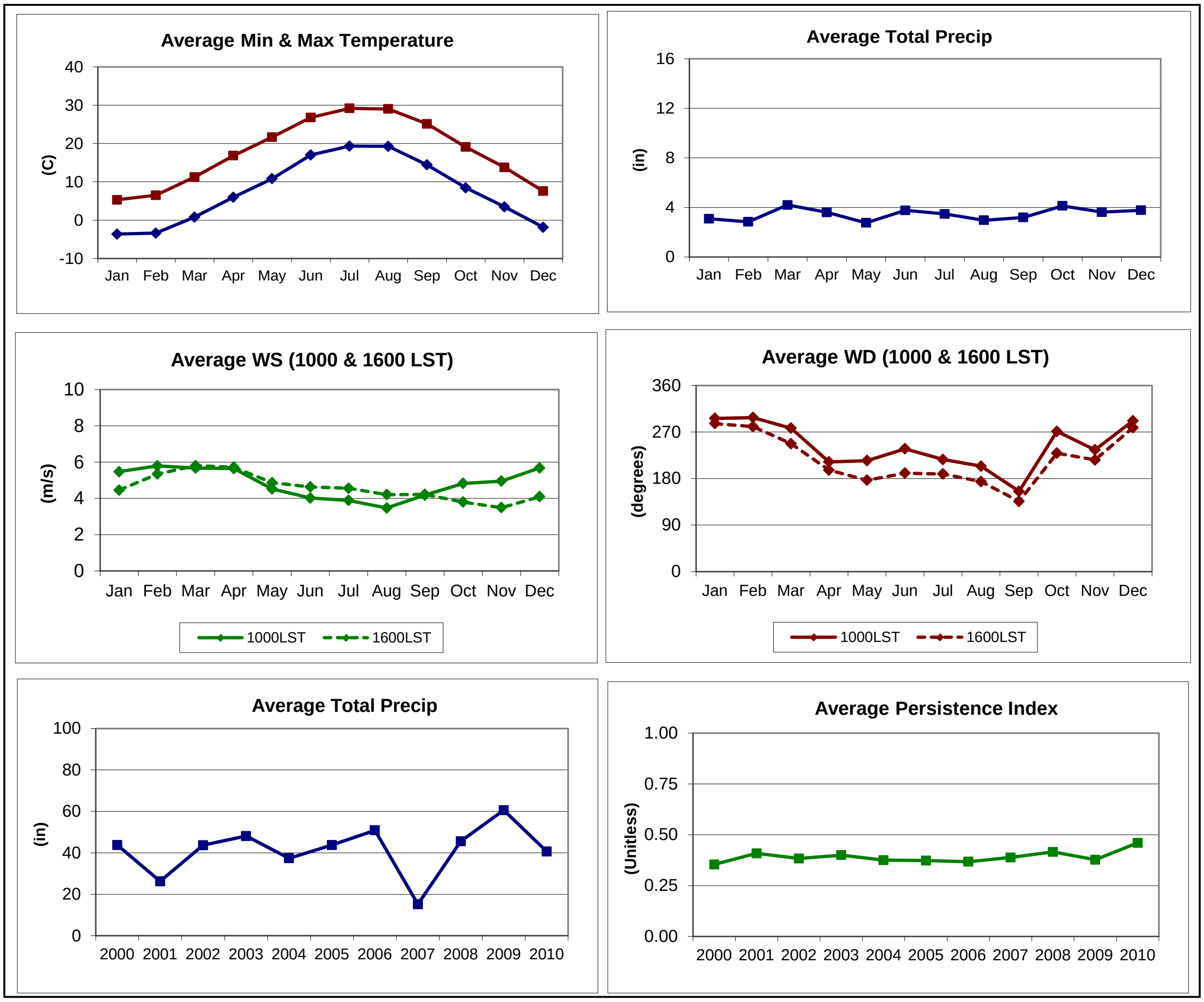


Figure 8. Surface meteorological data summary for Brigantine NWR (Atlantic City) (2000–2010).

Figure 9. Surface meteorological data summary for Newport News (2000–2010).

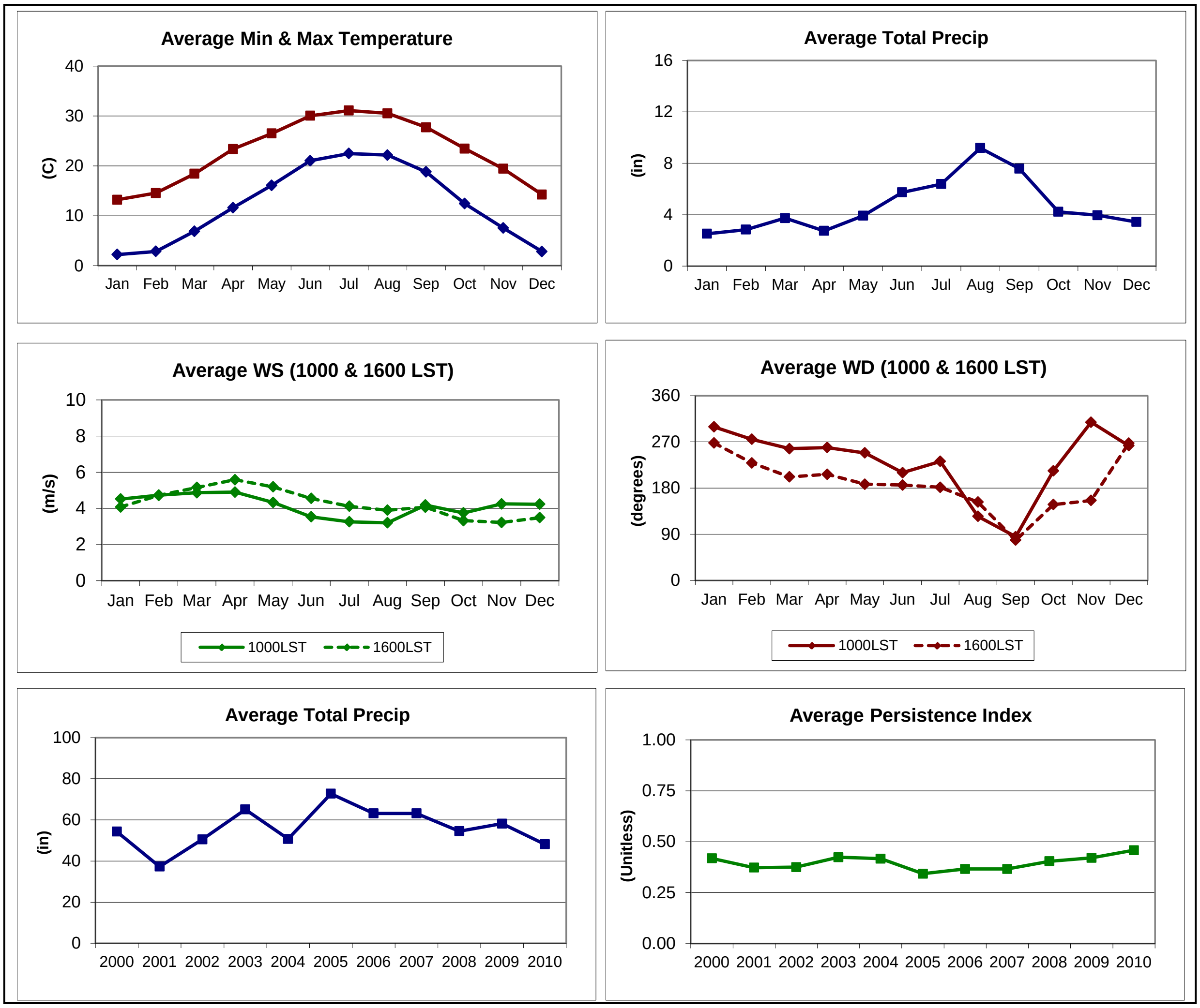


Figure 10. Surface meteorological data summary for Wilmington (NC) (2000–2010).

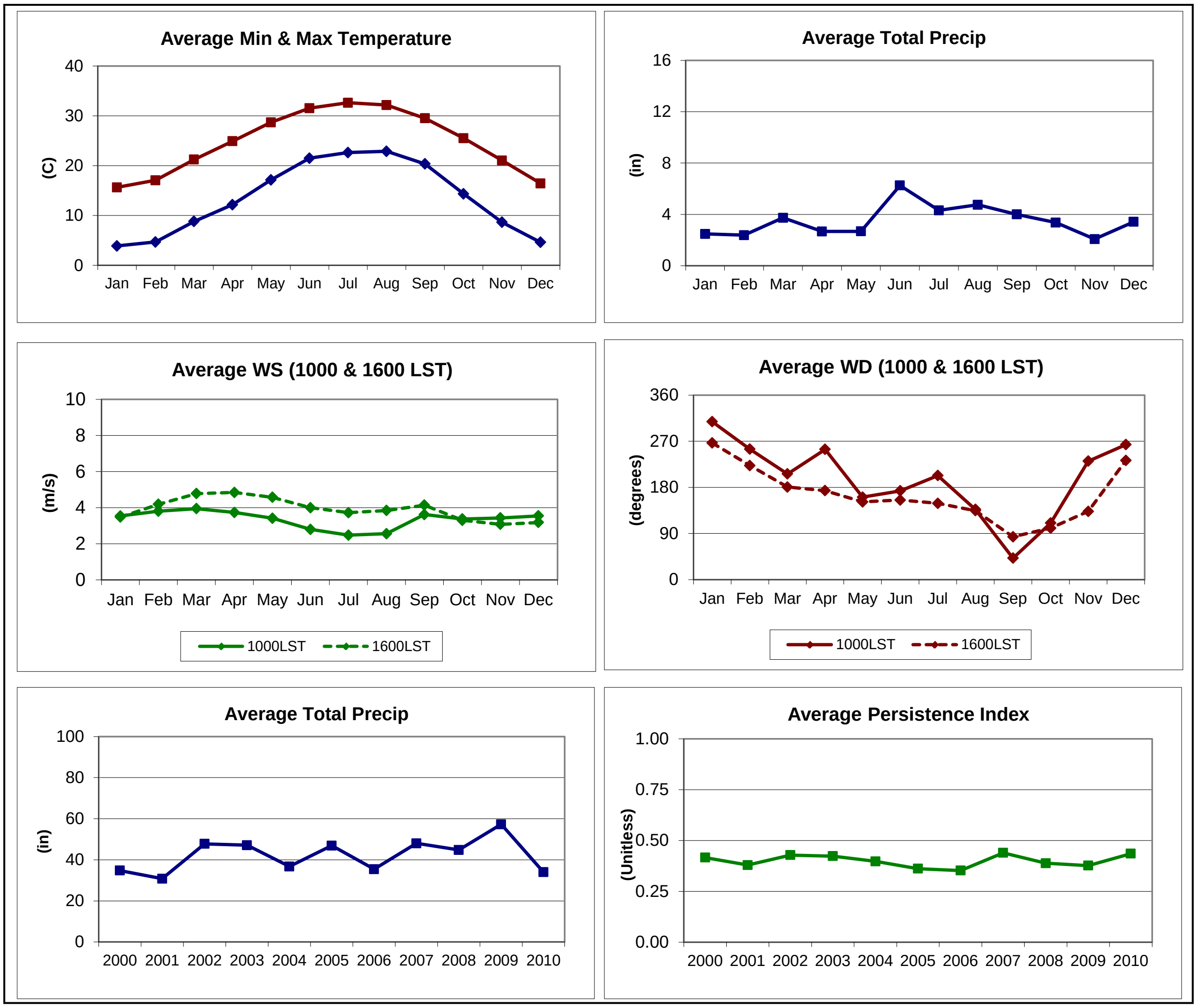


Figure 11. Surface meteorological data summary for Savannah (2000–2010).

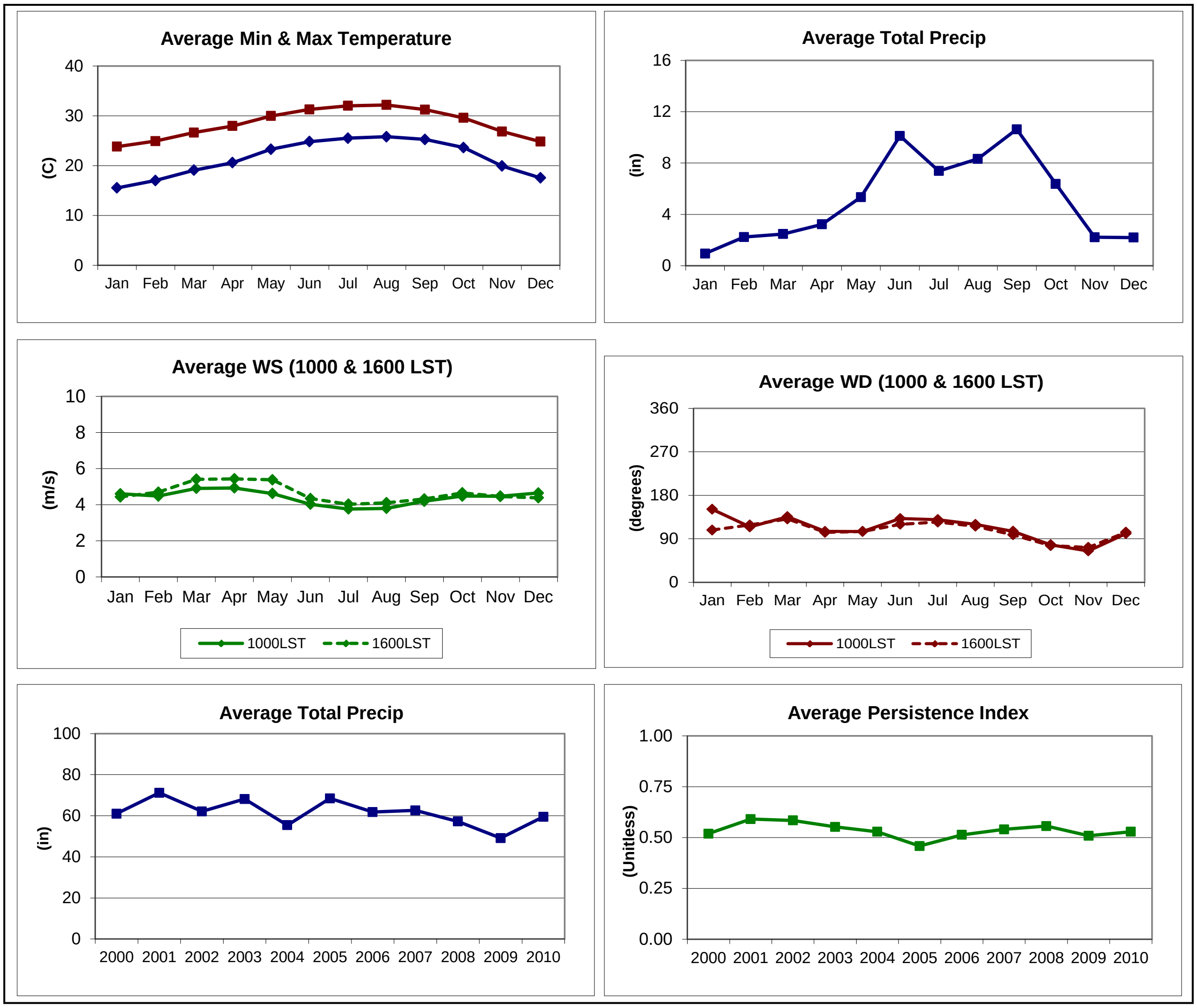


Figure 12. Surface meteorological data summary for Miami (2000–2010).

Monthly average temperatures increase from north to south. Temperatures for all sites exhibit the expected seasonal characteristics and the monthly average maximum temperatures tend to be approximately 10 degrees higher than minimum temperatures. Precipitation amounts and the month-to-month variations are different among the sites. The more southern sites (Wilmington (NC), Savannah, and Miami) are characterized by greater precipitation amounts and more month-to-month variation compared to the more northern sites. For the more southern sites, precipitation amounts are also higher during the summer months. For all sites, average wind speeds are lower during the summer months and higher during the winter months. Average wind directions have a westerly component during the winter months and a southerly component during the summer months – except for Miami which has southeasterly winds year round.

For many sites 2005 and 2009 are characterized by relatively higher precipitation compared to other years in the analysis period, but the year-to-year variations in precipitation are different among the sites. The persistence index is lowest for Atlantic City and Newport News and this suggests a greater frequency of sea breeze development for these sites. With a few exceptions, the average persistence index does not vary much from year to year, indicating that no years stand out as having a much greater frequency of sea-breeze-conducive conditions compared to other years. Note that for some sites, depending upon the local geography, this index may not be an indicator of sea breeze conditions but simply an indicator of wind direction persistence.

2.1.2. Selected Buoy Meteorological Metrics

Buoy data include many of the same parameters as the onshore meteorological monitoring data. For this study, the following parameters were reviewed and summarized:

- Minimum and maximum temperature (°C)
- Sea surface temperature (°C)
- Relative humidity at noon (%)
- Wind speed at 1000 and 1600 LST (ms^{-1})
- Wind direction at 1000 and 1600 LST (degrees)
- Persistence index (unitless).

Figures 13 through 15 present some example buoy meteorological data summaries. A full set of summary charts is available in Excel format. Three sites were selected for this example: C-man station Buzzard’s Bay (BUZM3) is located near Martha’s Vineyard, MA; Buoy #44009 is located near the entrance to the Delaware Bay; and Buoy #44025 (Diamond Shoals) is located off the coast of Cape Hatteras, NC. In each figure that follows, the first four charts display month-to-month variations in selected parameters. The first chart (upper left-hand corner) presents the average (overall years) of the sea surface temperature (°C) for each month. The second chart (upper right hand corner) gives the monthly average persistence index. The third and fourth charts (in the middle of the page) display the average monthly wind speed and wind direction for 1000 and 1600 LST. The next two charts (bottom of the page) display annual variations for two key parameters—sea surface temperature and the persistence index. Not all buoys have complete data for the full period, as indicated in the annual charts.

Figure 13. Surface meteorological data summary for Buzzard's Bay (BUZM3) (2000–2010).

Figure 14. Surface meteorological data summary for Delaware Bay Buoy #44009 (2000–2010).

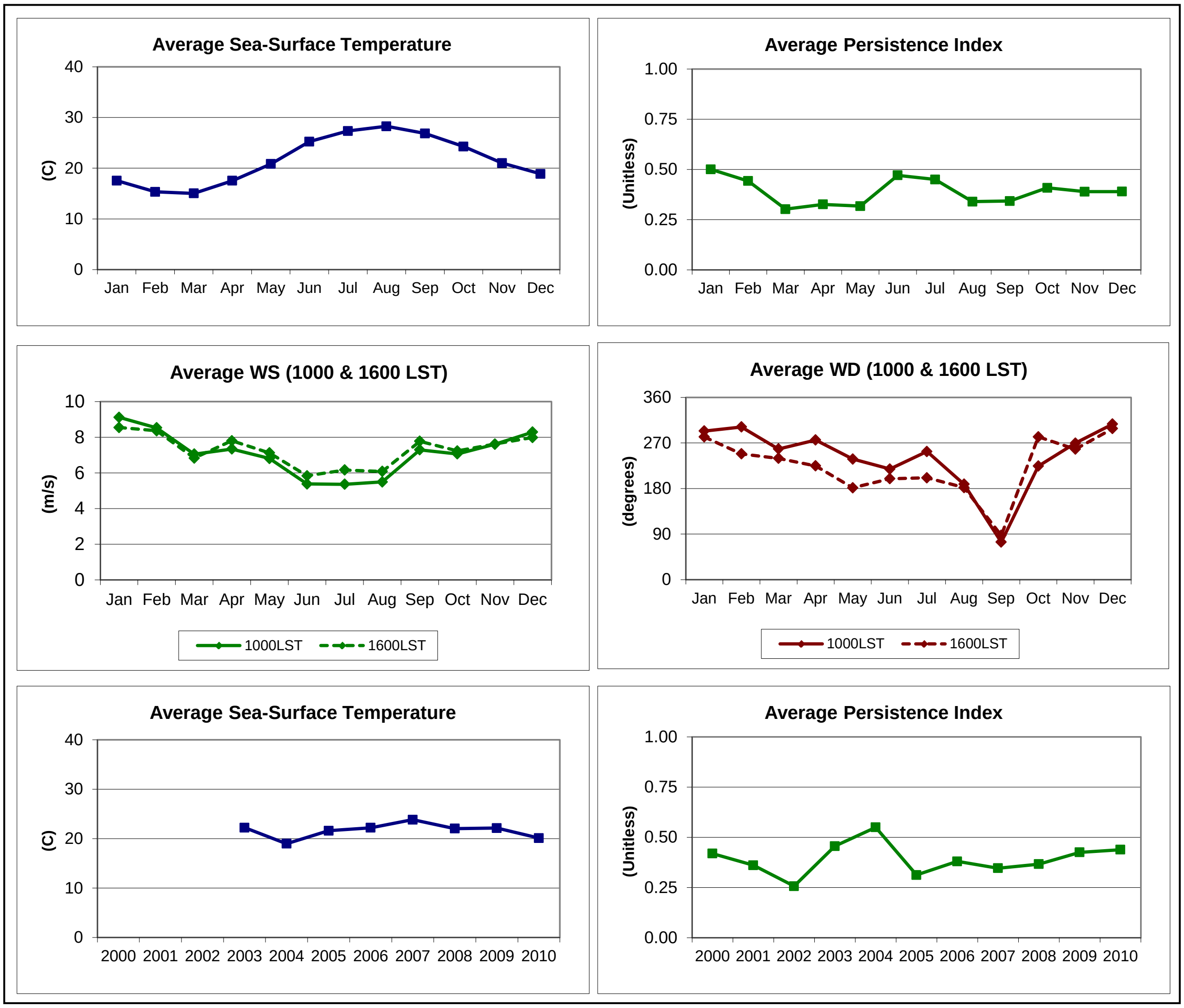


Figure 15. Surface meteorological data summary for Diamond Shoals Buoy #41025 (2000–2010).

At the buoy sites, sea surface temperature exhibits the expected seasonal variations, with the lowest average temperatures in March and the highest in August. The persistence index shows more month-to-month variability than for the onshore locations and indicates that sea breeze circulation is most frequent in spring (March, April and May) and late summer/early fall (September and October). Wind speeds are lower and daytime winds (on average) exhibit a westerly component during the winter month, a southerly component during the summer months, and, for two of the buoys (Delaware Bay and Diamond Shoals), an easterly component in September. Both the sea-surface temperature and persistence parameters exhibit some year-to-year variation and this varies among the sites.

2.1.3. Selected Upper-Air Meteorological Metrics

In this section, plots illustrating the monthly and annual variations in selected meteorological parameters for the upper-air monitoring sites of interest are presented and discussed. The parameters include:

- Temperature (°C)
- Dew-point temperature (°C)
- Wind speed (ms^{-1})
- Wind direction (degrees)
- Stability index (°C).

The upper-air measurements are taken twice daily at approximately 0700 and 1900 LST. For this analysis, we focused primarily on the 850 mb level, which is typically about 1500 meters (m) above sea level (asl). The “stability index” is defined as the difference in temperature between 900 mb (about 500 m) and the surface. The value of this parameter increases with increasing stability. Negative values (less than about -5°C) may indicate unstable (or very well mixed) conditions near the surface. Positive values indicate stable conditions (and limited mixing) near the surface.

Figures 16 through 18 present some example upper-air meteorological data summaries. These focus on three sites representing different portions of the Atlantic coast: Chatham, MA; Wallops Island, VA; and Jacksonville, FL. The examples present (in order) the month-to-month variations in temperature, dew-point temperature, wind speed, wind direction, and stability index. The year-to-year variations aloft are much less than for the surface. A full set of summary charts is available in Excel format.

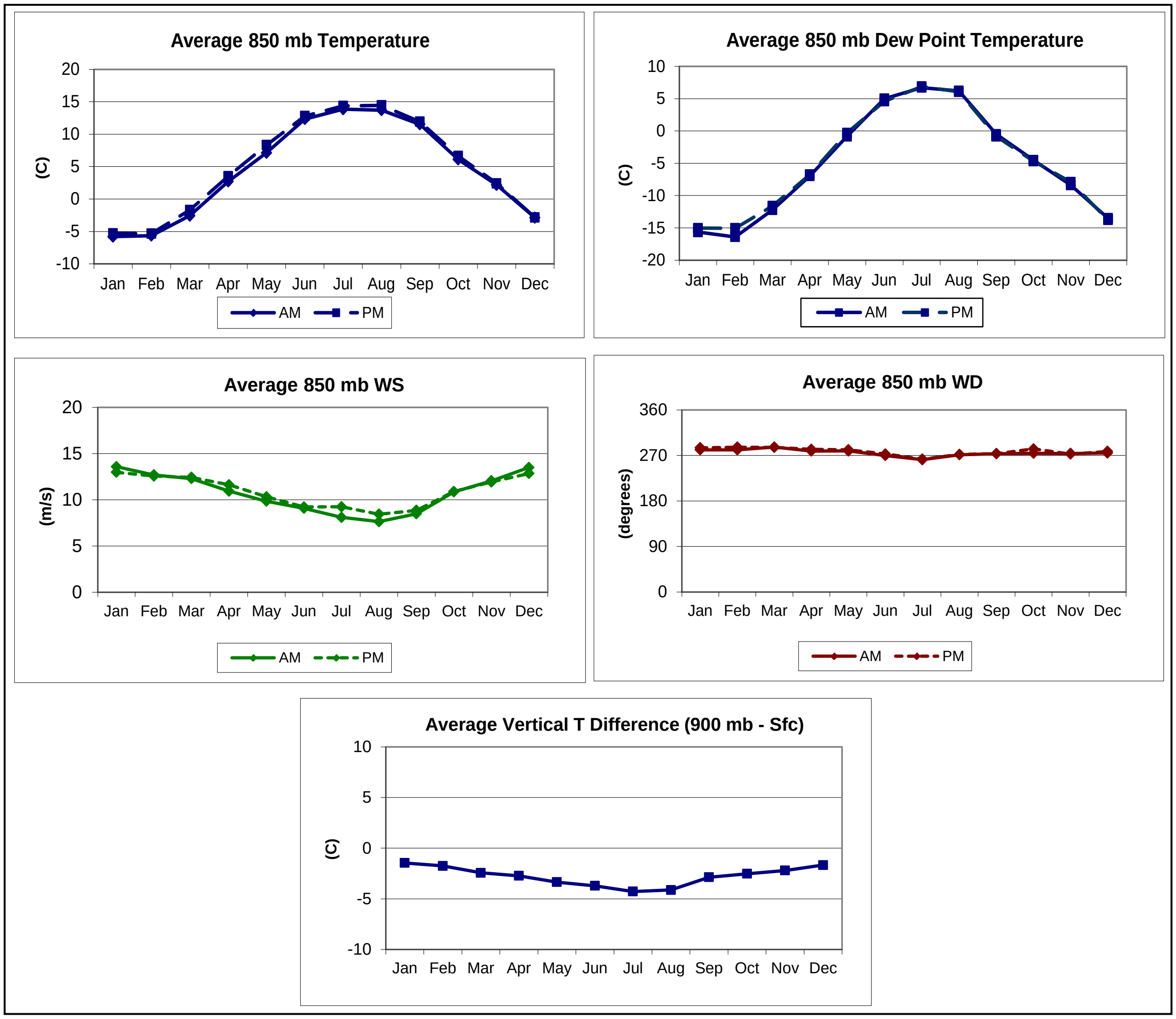


Figure 16. Upper-air meteorological data summary for Chatham, MA (2000–2010).

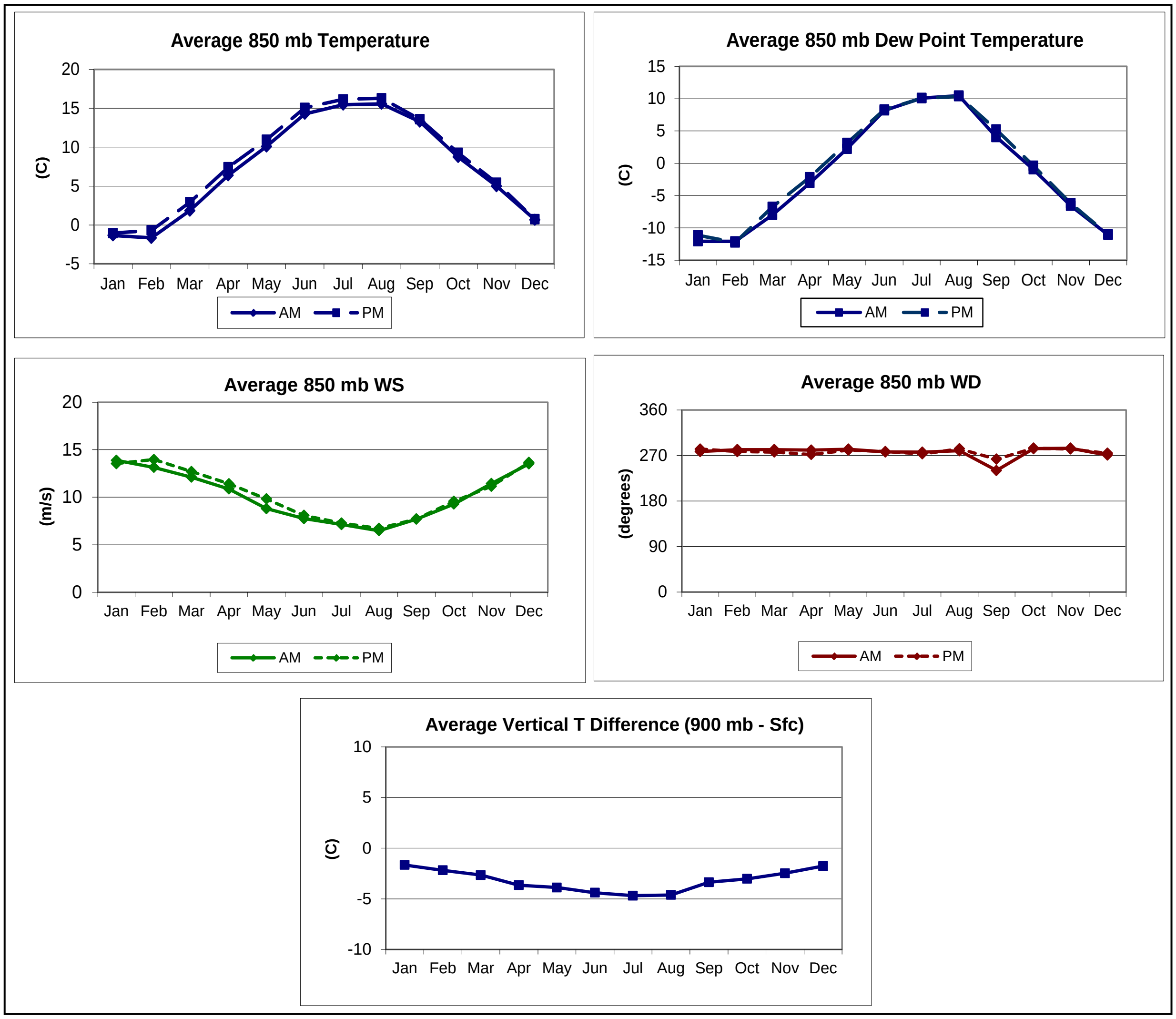


Figure 17. Upper-air meteorological data summary for Wallops Island, VA (2000–2010).

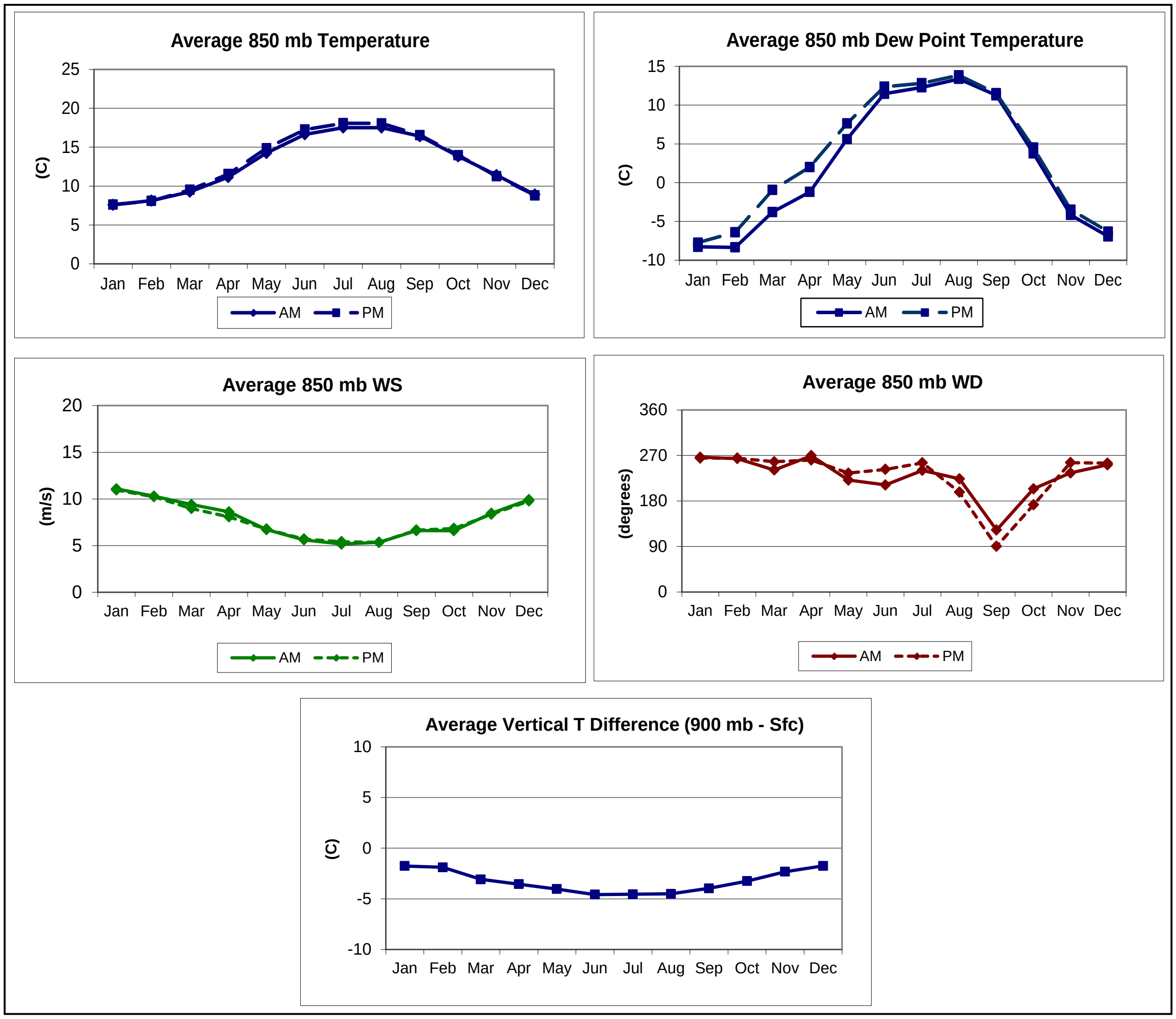


Figure 18. Upper-air meteorological data summary for Jacksonville, FL (2000–2010).

The 850 mb temperatures and dew-point temperatures exhibit strong seasonal variations. Wind speeds aloft are lowest during the summer months. Average 850 mb wind directions for Chatham and Wallops Island are westerly for all months. Average 850 mb winds directions vary by month for Jacksonville and are southwesterly during August and October, easterly during September, and westerly to southwesterly for the remaining months. For all locations, the stability index indicates greater stability during the winter months and less stability during the summer months and the values are very similar.

2.2. OZONE DATA SUMMARIES

Ozone is one of the key air quality issues affecting urban areas along the Atlantic Coast. As presented in Section 1, several coastal urban areas have ozone design values that exceed the current 8-hour ozone standard of 75 ppb.

In this study, historical ozone data for the period 2000 through 2010 were examined for selected sites within 15 different port/harbor and Class I areas along the coast. These areas include:

- Acadia National Park, ME
- Portland, ME
- Boston, MA
- Martha's Vineyard, MA
- Providence, RI
- New York, NY
- Newark-Elizabeth, NJ
- Brigantine NWR, NJ
- Wilmington, DE
- Baltimore, MD
- Norfolk, VA
- Wilmington, NC
- Charleston, SC
- Savannah, GA
- Miami, FL

The locations are shown in Figure 19. A representative ozone monitoring site from each of these areas was selected, based on calculated ozone design value and the length of the data record. Sites with average ozone concentrations near the design value for the area and longer data records were favored. In addition to the ozone data for these sites, surface and upper-air meteorological data from nearby sites were also examined with the goal of determining whether relationships between meteorology and ozone are readily apparent in the observed data. The ozone data were obtained from the EPA AQS database (USEPA, 2012). All of the data presented in this section are included in the ARAQDB. Detailed site information is also included in the ARAQDB.

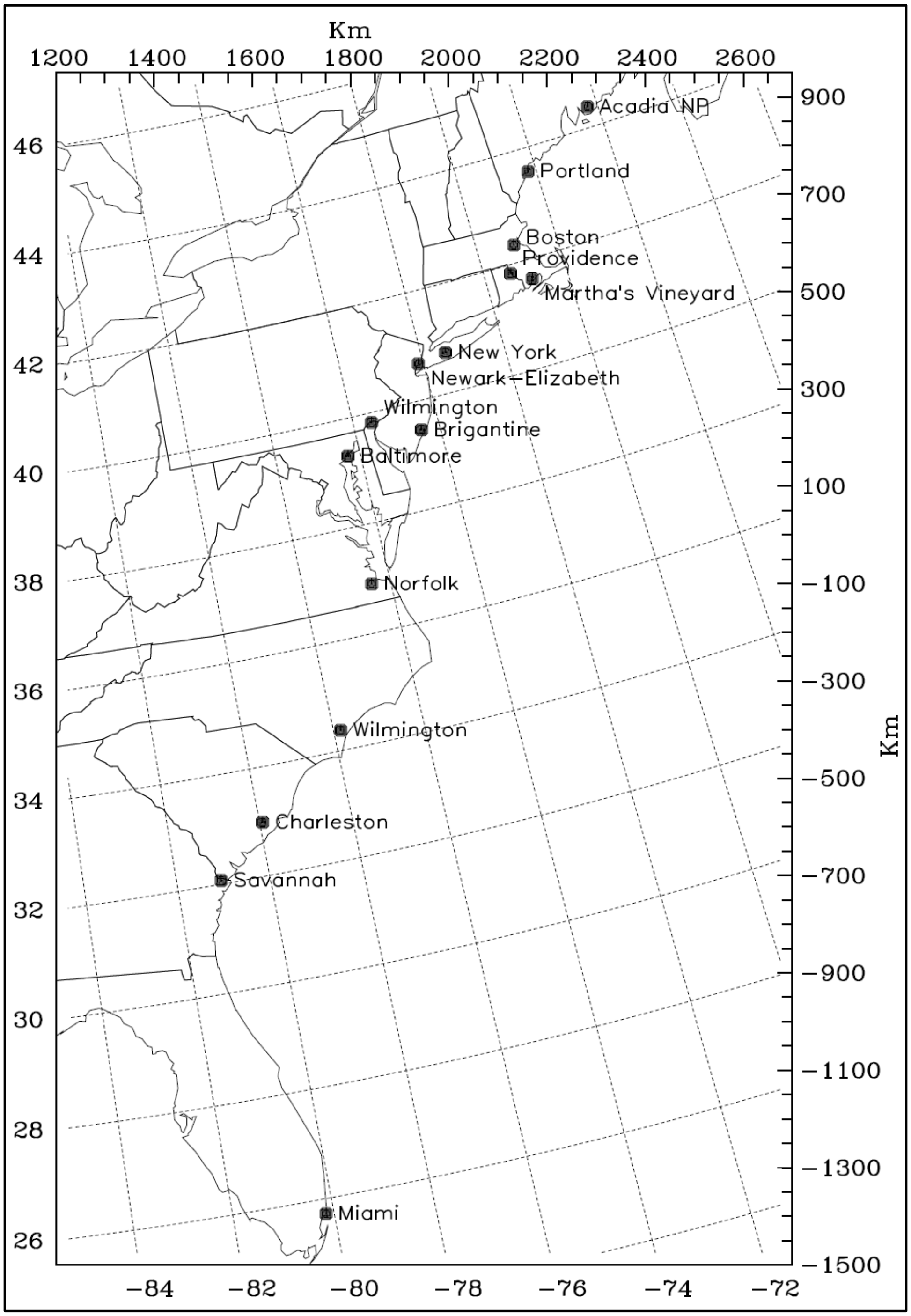


Figure 19. Ozone monitoring sites for the BOEM Atlantic OCS Region data summaries.

In this section, plots illustrating the monthly, diurnal, and annual variations in ozone concentration for the representative sites for each area of interest are presented and discussed. The metrics used to present the ozone data and derived information are as follows:

- Hourly and daily maximum (1-hour) ozone concentration.
- Daily maximum 8-hour average ozone concentration.
- Number of days on which the daily maximum 8-hour average ozone concentration exceeds 75 ppb (the current 8-hour ozone NAAQS).
- 8-hour ozone design value (the three-year average of the fourth highest ozone concentration per year).

Figures 20 through 25 present ozone data summaries for selected sites within the following port/harbor areas: Portland, Martha's Vineyard, Newark-Elizabeth, Norfolk, Wilmington (NC), and Savannah. The first chart (upper left-hand corner) presents the monthly average daily maximum 1-hour (green bar) and 8-hour (blue bar) average ozone concentration (ppb). The second chart (upper right hand corner) gives the annual maximum 1-hour and 8-hour ozone concentration. The third chart (middle of the page) displays the hourly average ozone concentration (ppb) by month for the ozone season months of May through September. The fourth chart (lower left-hand corner) gives the number of 8-hour ozone exceedances per year for each year with data (from the period 2000–2010). The final chart (lower right-hand corner) displays the 8-hour ozone design value for each three-year period with data (the end year of each three-year period is shown on the plot). The dashed, red line marks the 75 ppb NAAQS level. Not all sites have complete data for the full period and thus some of the annual charts are for a subset of the full period. A full set of summary charts (for all sites listed in Section 2.2 and including additional ozone metrics) is available in Excel format.

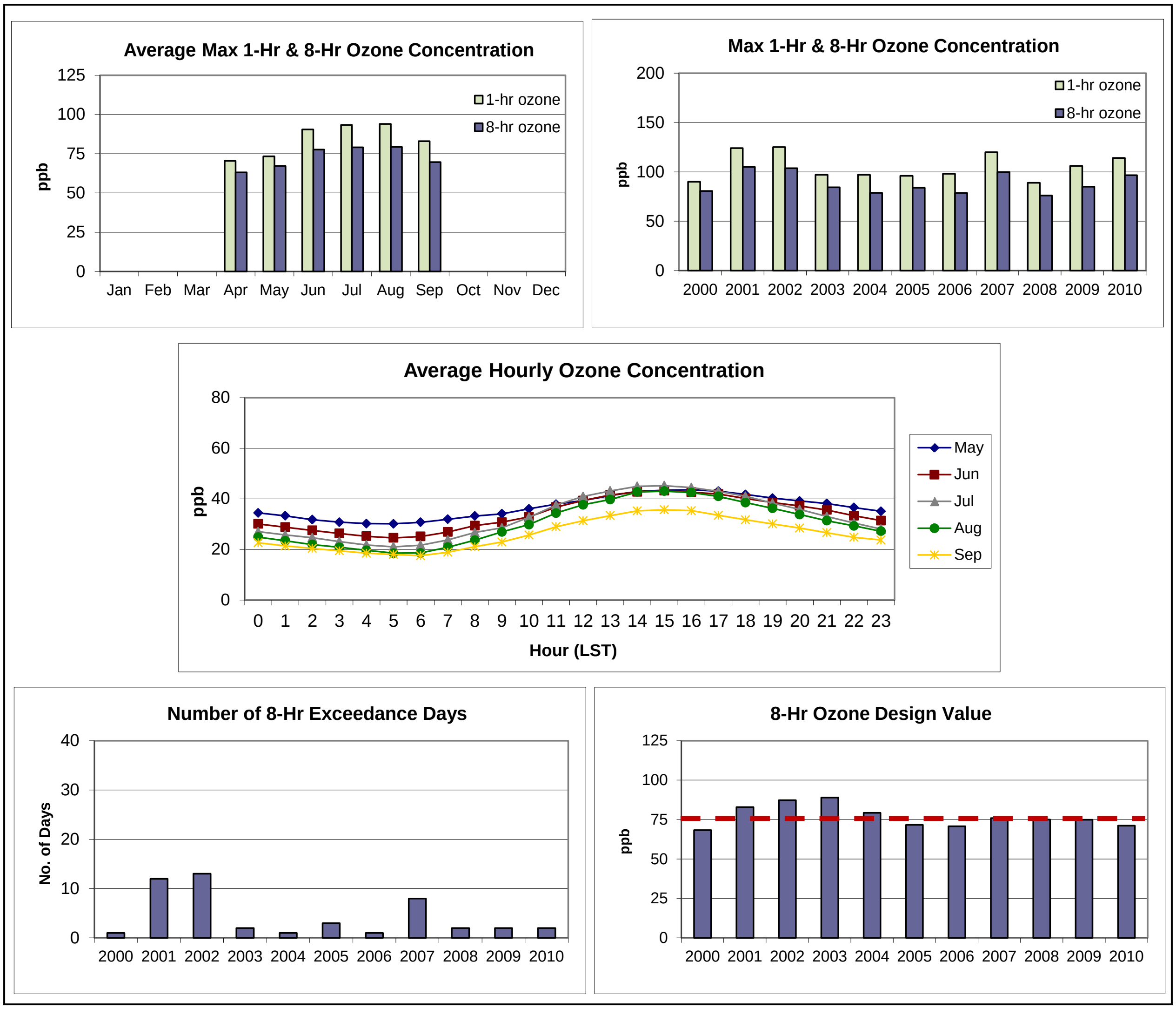


Figure 20. Ozone data summary for Portland area site (AQS # 230052003 (Cape Elizabeth)).

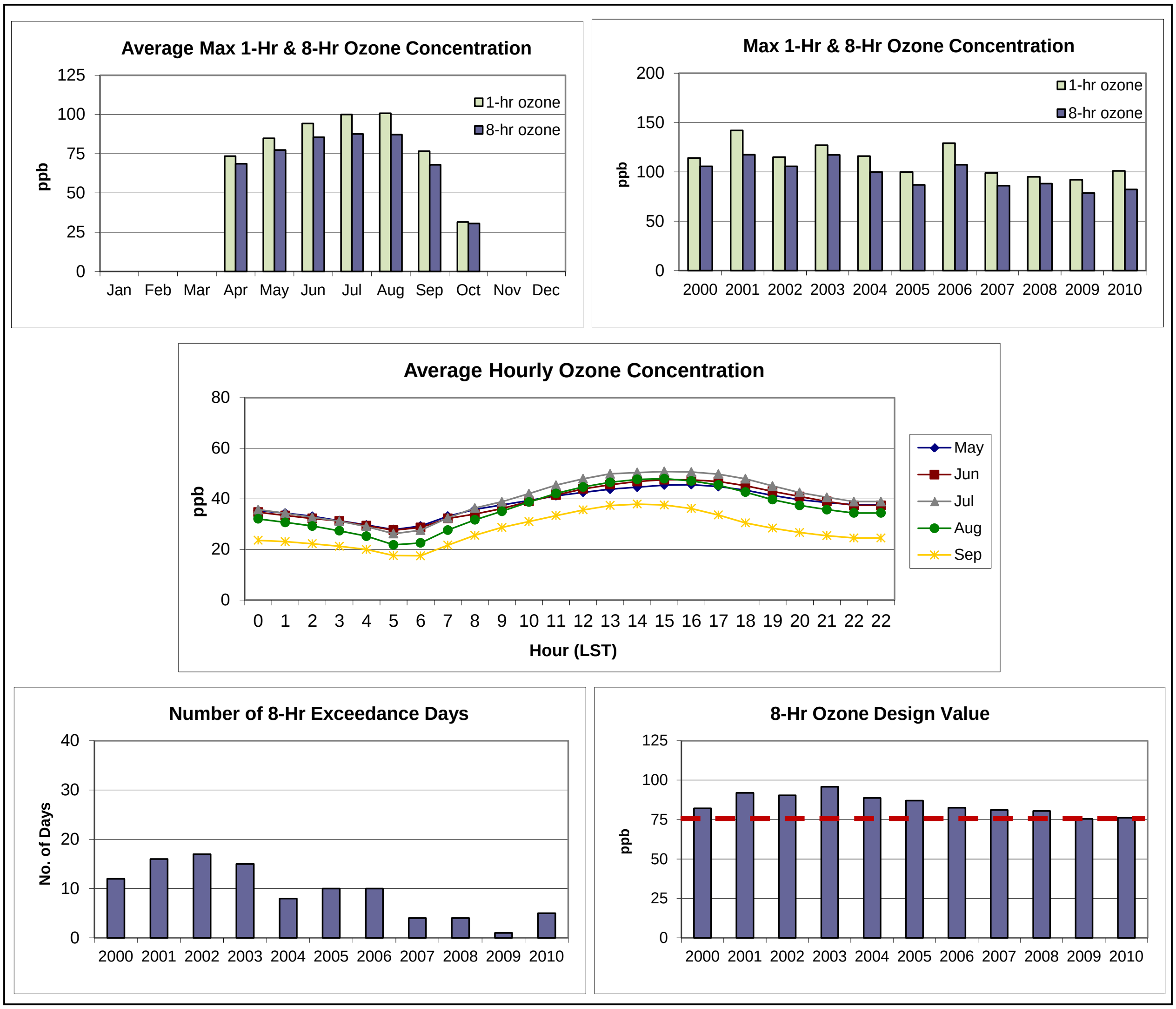


Figure 21. Ozone data summary for Martha's Vineyard area site (AQS # 230051002 (Fairhaven)).

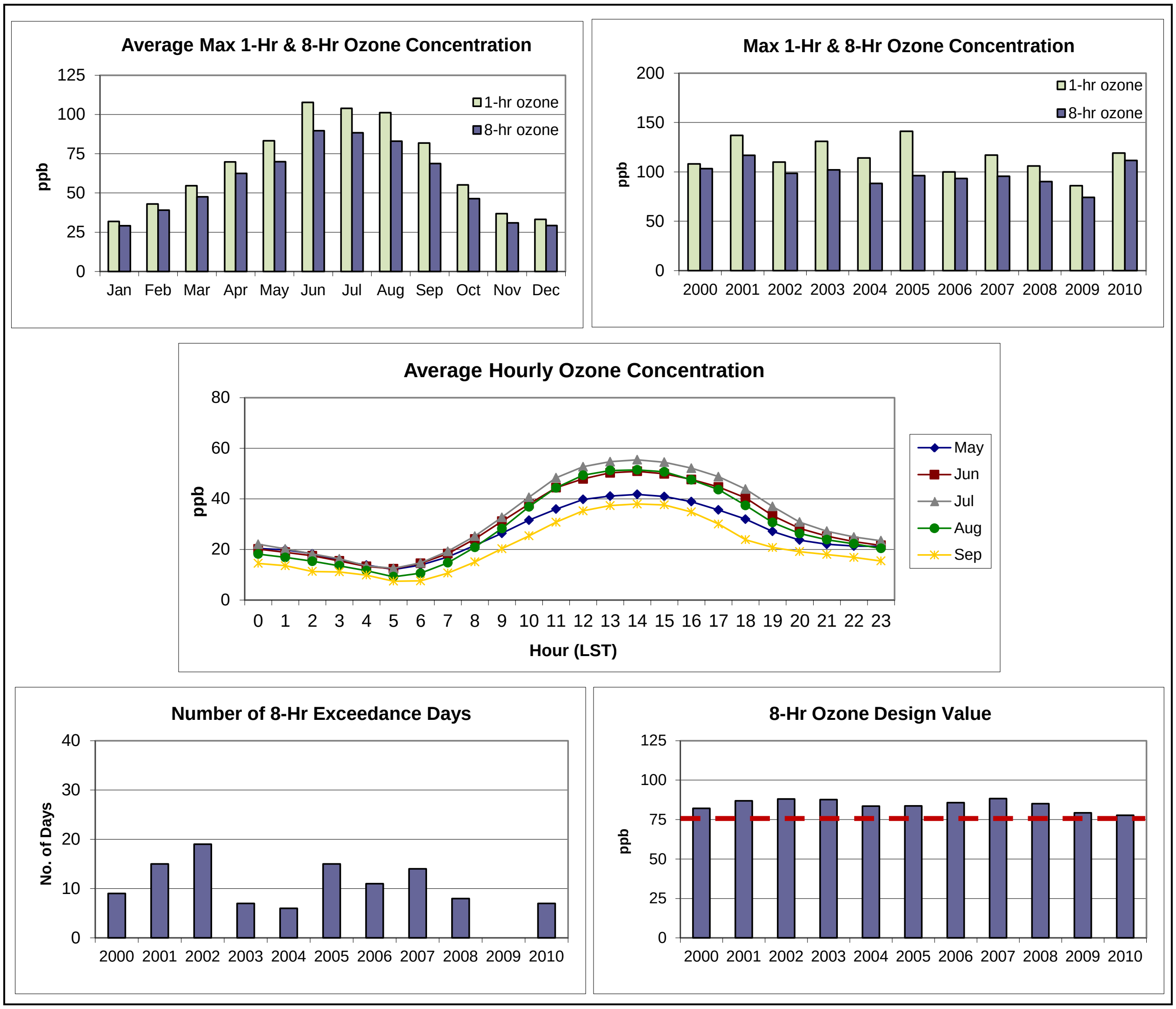


Figure 22. Ozone data summary for Newark-Elizabeth area site (AQS # 340170006 (Bayonne)).

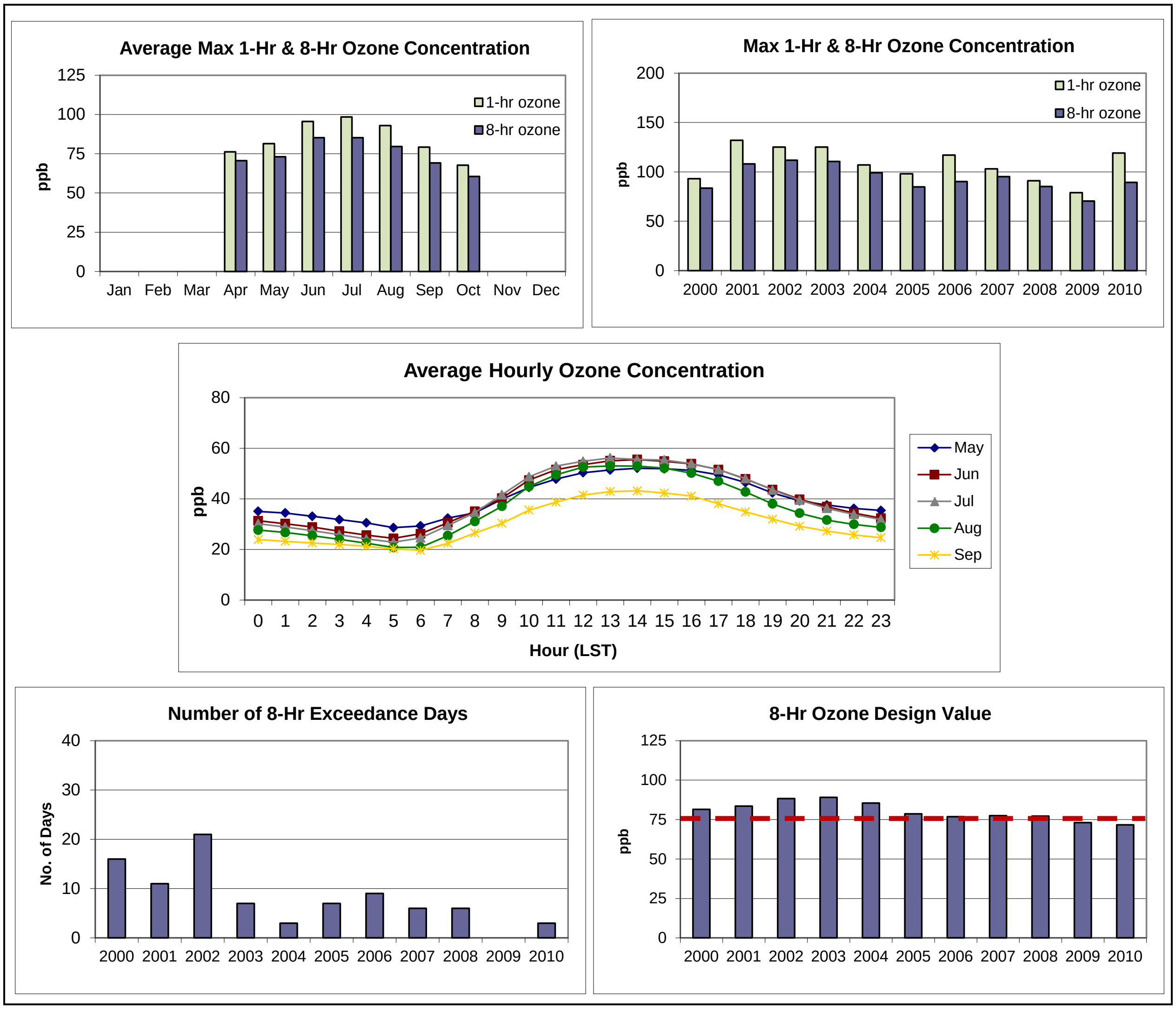


Figure 23. Ozone data summary for Norfolk area site (AQS # 518000004 (Tidewater)).

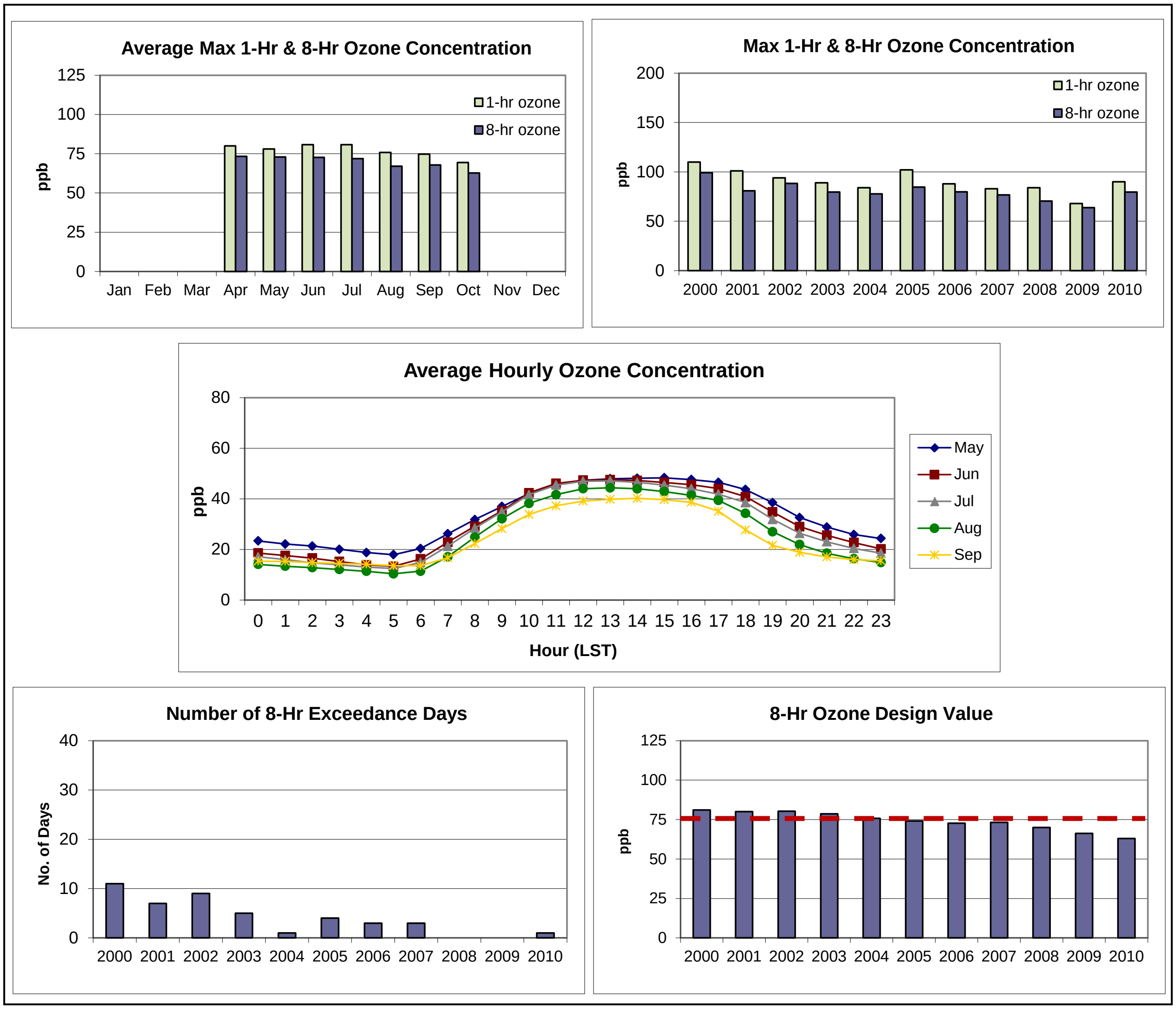


Figure 24. Ozone data summary for Wilmington (NC) area site (AQS # 371290002 (Castle Hayne)).

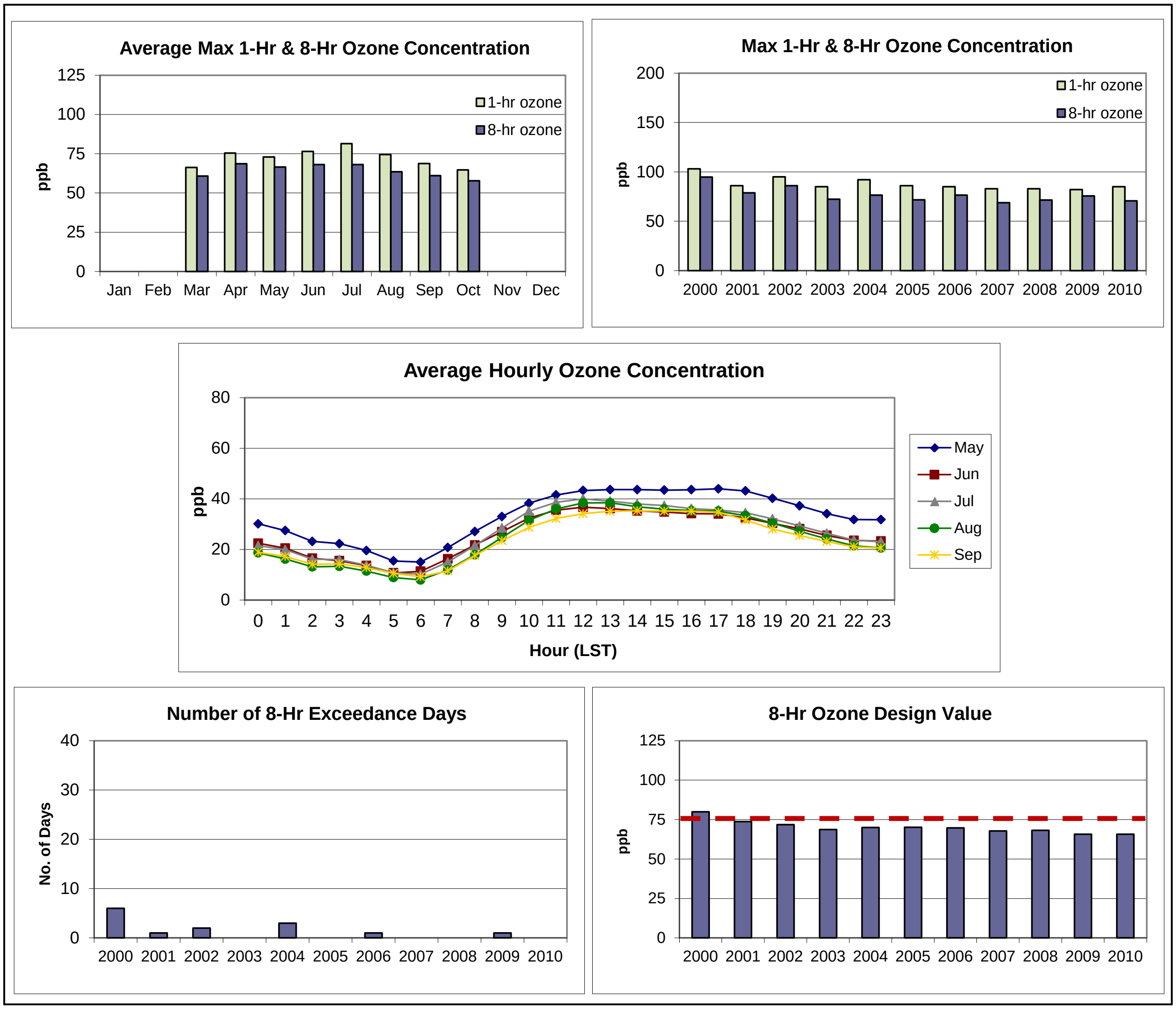


Figure 25. Ozone data summary for Savannah area site (AQS # 130510021 (Savannah-President St.)).

These figures provide an overview of ozone for the selected port/harbor areas along the Atlantic Coast and characterize ozone air quality for each area. For the sites shown in Figures 19 through 24, peak ozone concentrations occur at different times of the year and different times of the day. On average, the highest ozone concentrations occur in August for the Portland and Martha's Vineyard areas, in June and July for the Newark-Elizabeth area, and in July for Norfolk and Savannah (no single month stands out for Wilmington (NC)). The diurnal profile for the Newark-Elizabeth area site is typical of urban areas and shows a peak at approximately 1400 LST. The flatter, broader diurnal profile for the remaining sites is more typical of sites for which the ozone concentrations are influenced by a sea breeze circulation. For these sites, ozone and precursor pollutants produced early in the day are advected offshore by the offshore component of the sea-breeze circulation during the morning hours and then carried back onshore by the onshore component of the sea breeze that develops later in the day. This results in an extended period of moderate to high ozone concentrations during the afternoon and early evening hours and is thought to contribute to exceedances of the 8-hour ozone standard, even for sites that do not have very high 1-hour ozone values.

Among the sites shown, the Bayonne site (representing the Newark-Elizabeth) area exhibits the highest ozone concentrations. For all sites, the number of exceedance days and the 8-hour ozone design values decrease with time throughout the eleven year period.

2.3. PM2.5 DATA SUMMARIES

In addition to ozone, fine particulate matter ($PM_{2.5}$) is also a pollutant of concern in much of the eastern U.S. because of its effects on human health, deposition to land and waterways, and regional haze/visibility. All of the port/harbor areas listed in Section 1 are currently in compliance of both the annual and 24-hour $PM_{2.5}$ standards. However, design values greater than the annual standard were recorded for the New York area for the 2008–2010 period (based on a design value of 12.5 µg/m^3) and for several areas for the 2007–2009 period.

In this study, historical $PM_{2.5}$ data for the period 2000 through 2010 were examined for selected sites within 13 different port/harbor areas along the coast. These areas include:

- Portland, ME
- Boston, MA
- Martha's Vineyard, MA
- Providence, RI
- New York, NY
- Newark-Elizabeth, NJ
- Wilmington, DE
- Baltimore, MD
- Norfolk, VA
- Wilmington, NC
- Charleston, SC
- Savannah, GA
- Miami, FL

The locations are shown in Figure 26. For areas with more than one $PM_{2.5}$ monitoring site, a representative monitoring site was selected, based on the calculated $PM_{2.5}$ design value and the length of the data record. Sites with average $PM_{2.5}$ concentrations near the design value for the area and longer data records were favored. In addition to the $PM_{2.5}$ data for these sites, surface and upper-air meteorological data from nearby sites were also examined with the goal of determining whether relationships between meteorology and $PM_{2.5}$ are readily apparent in the observed data. The $PM_{2.5}$ data were obtained from the EPA AQS database (USEPA, 2012). All of the data presented in this section are included in the ARAQDB. Detailed site information is also included in the ARAQDB.

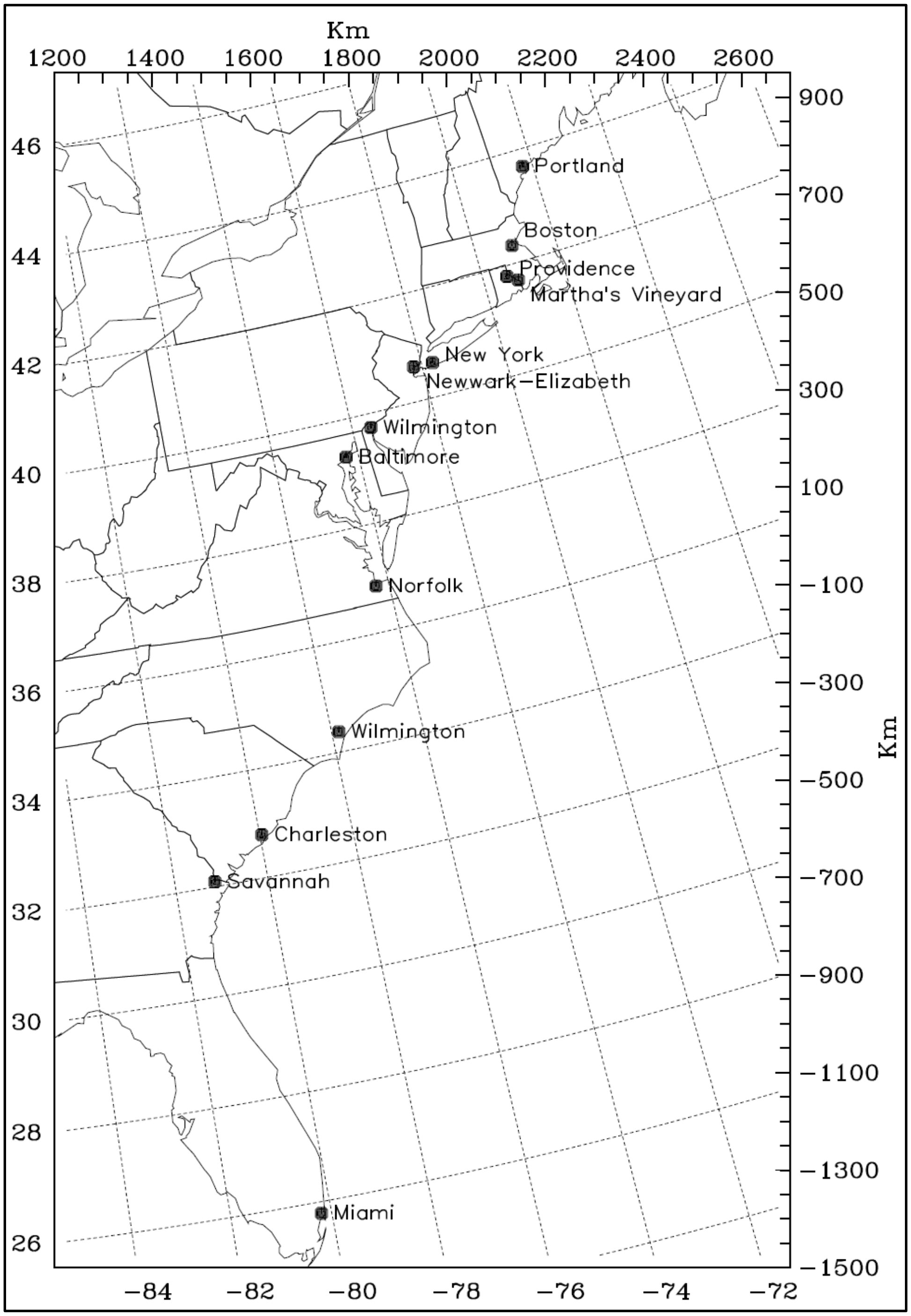


Figure 26. $PM_{2.5}$ monitoring sites for the BOEM Atlantic OCS Region data summaries.

In this section, plots illustrating the monthly, quarterly, and annual variations in total $PM_{2.5}$ concentration for the representative sites for each area of interest are presented and discussed. The metrics used to present the $PM_{2.5}$ data and derived information are as follows:

- Daily average (24-hour average) $PM_{2.5}$ concentration (μgm^{-3}) (and various monthly and quarterly averages based on this value).
- Number of days on which the daily average $PM_{2.5}$ concentration exceeds 12 μgm^{-3} (the annual NAAQS threshold).
- Number of days on which the daily average $PM_{2.5}$ concentration exceeds 35 μgm^{-3} (the 24-hour $PM_{2.5}$ NAAQS).
- Annual average $PM_{2.5}$ concentration (μgm^{-3}).
- 98^{th} percentile 24-hour average $PM_{2.5}$ concentration (μgm^{-3}).
- Annual $PM_{2.5}$ design value (μgm^{-3}) (the three-year average annual mean concentration).
- 24-hr $PM_{2.5}$ design value (μgm^{-3}) (the three-year average of the 98^{th} percentile daily average concentration).

Figures 27 through 32 present $PM_{2.5}$ data summaries for selected sites within the following port/harbor areas: Portland, Martha's Vineyard, Newark-Elizabeth, Norfolk, Wilmington (NC), and Savannah. The first chart (upper left-hand corner) presents the average (overall years) of both the daily average (gray bar) and maximum (red bar) $PM_{2.5}$ concentration for each month. The second chart (upper right hand corner) gives the average (overall years) of both the daily average (gray bar) and maximum (red bar) $PM_{2.5}$ concentration for each quarter. The third chart (lower left hand corner) gives the annual design value (the end year of each three-year period is shown on the plot). The dashed, red line marks the 12 μgm^{-3} NAAQS level. The final chart (lower right-hand corner) gives the 24-hour $PM_{2.5}$ design value (again, the end year of each three-year period is shown on the plot). The dashed, red line marks the 35 μgm^{-3} NAAQS level. $PM_{2.5}$ data collection for the selected sites began between 1998 and 2003. Thus, not all sites have complete data for the full period and some of the annual charts are for a subset of the full period. For these sites, the earlier design values may be based on one or two years of data, rather than the full three years of data. The annual $PM_{2.5}$ NAAQS requires the annual design value to be less than 12 μgm^{-3}. The daily $PM_{2.5}$ standard requires the 24-hour design value to be less than 35 μgm^{-3}.

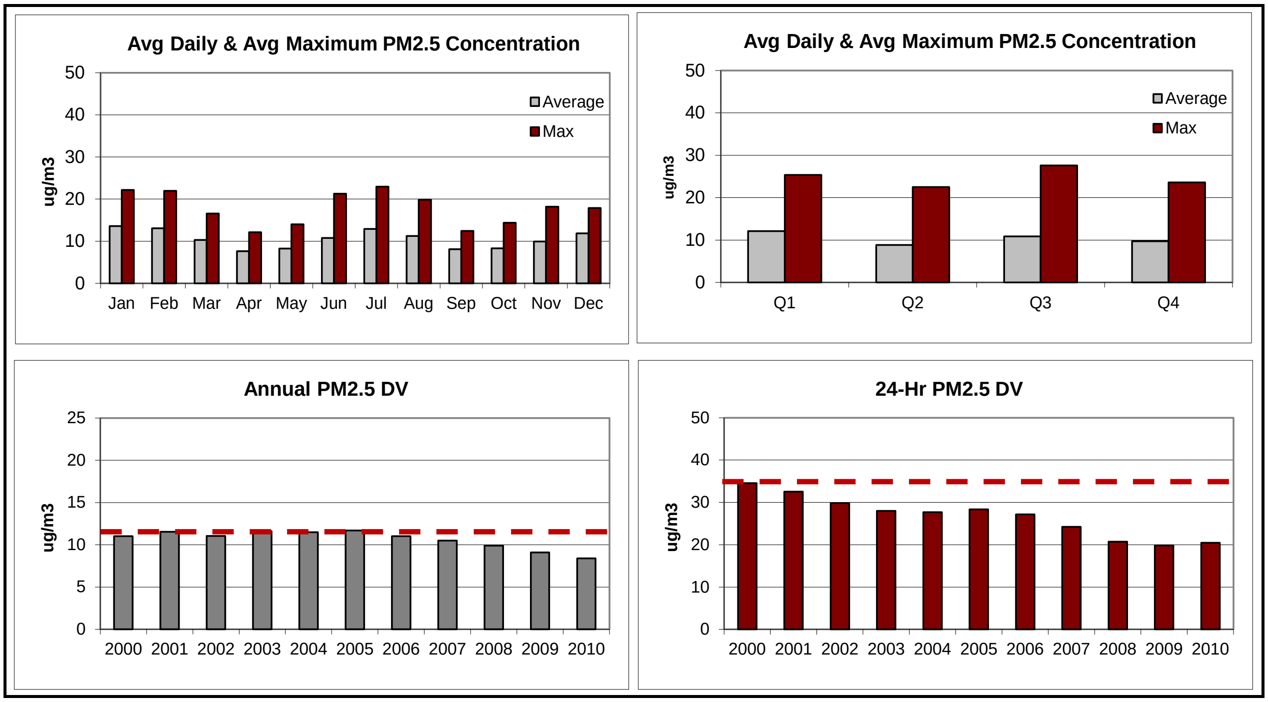


Figure 27. $PM_{2.5}$ data summary for Portland area site (AQS # 230050015 (Portland - Tukey's Bridge)).

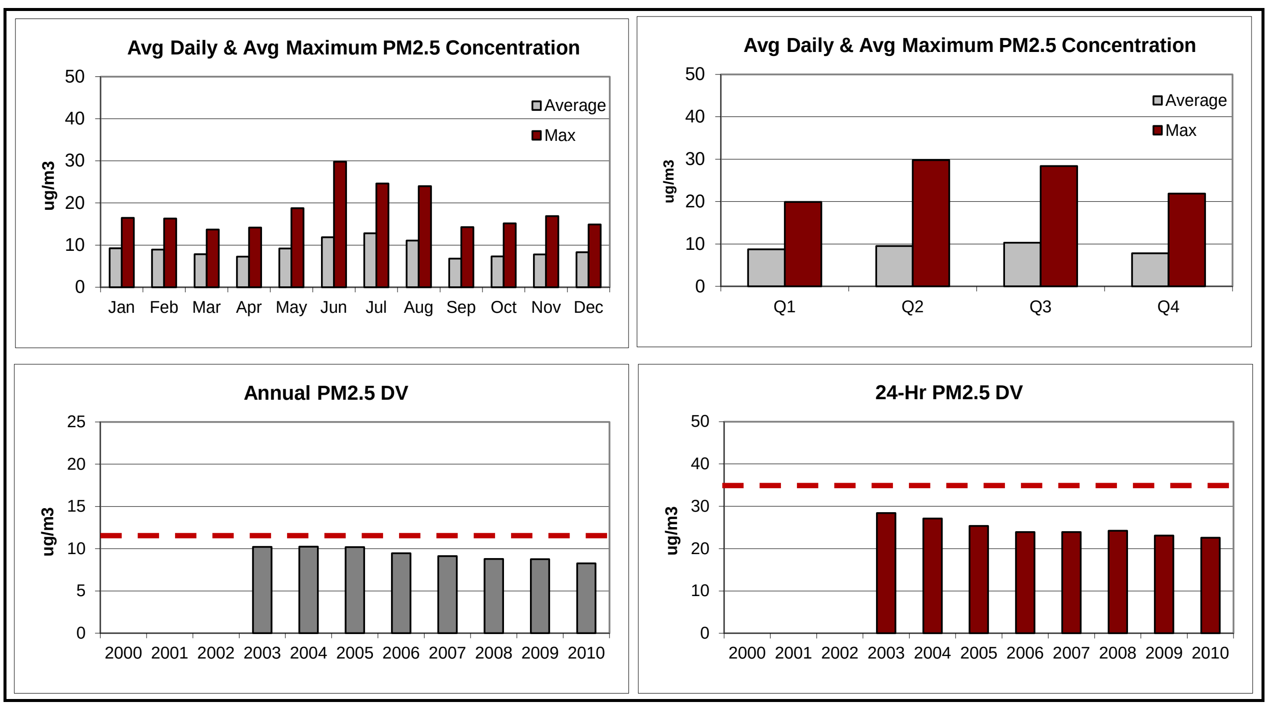


Figure 28. $PM_{2.5}$ data summary for Martha's Vineyard area site (AQS # 250051004 (Fall River)).

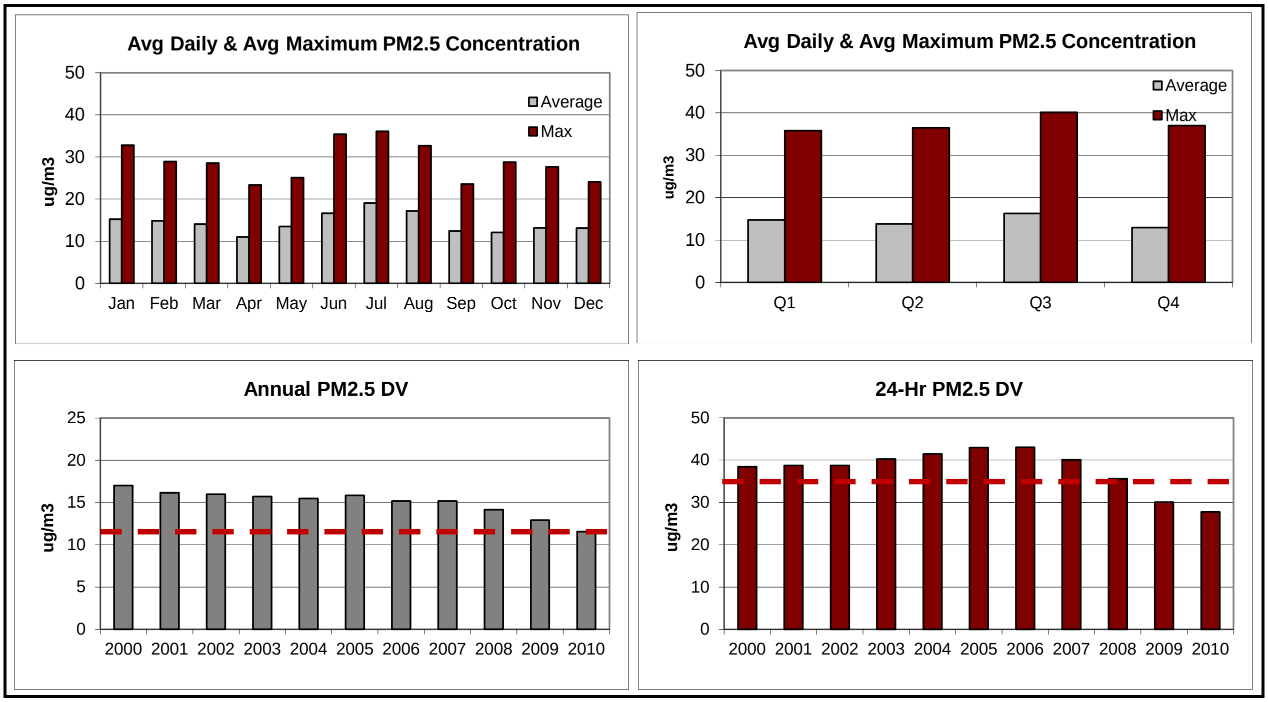


Figure 29. $PM_{2.5}$ data summary for Newark-Elizabeth area site (AQS # 340390004 (Elizabeth - Lab)).

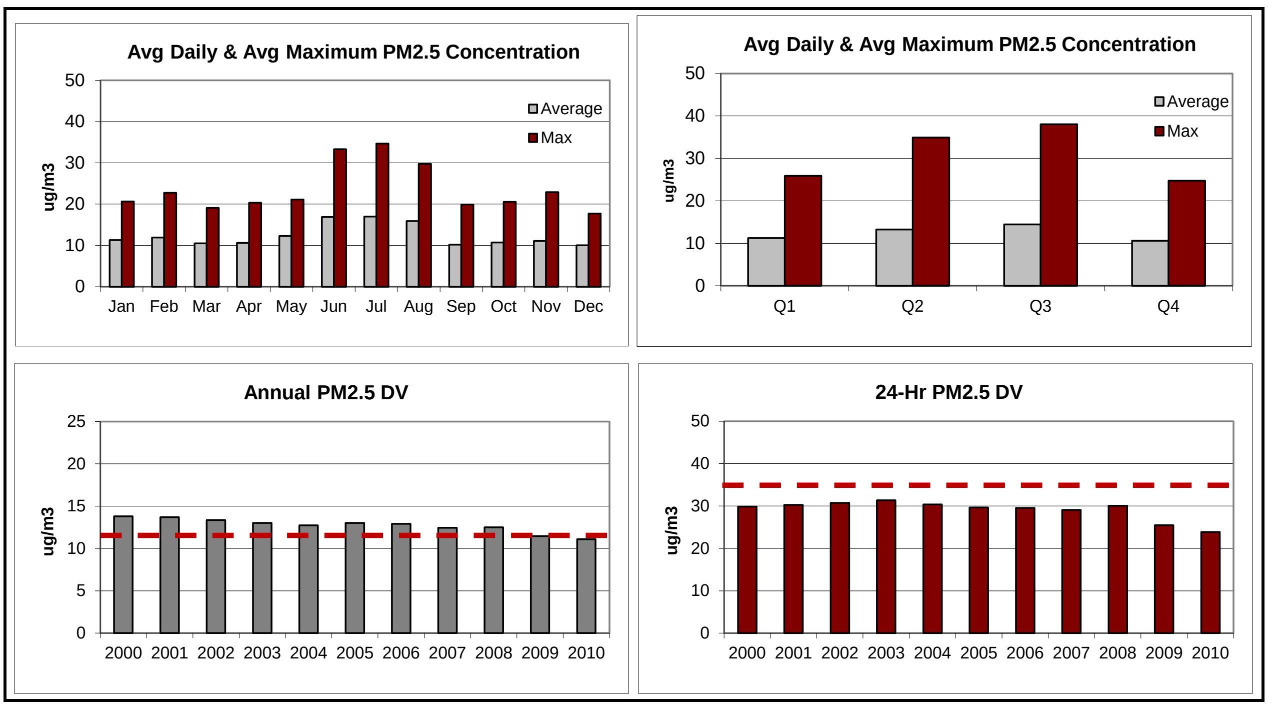


Figure 30. $PM_{2.5}$ data summary for Norfolk area site (AQS # 577100024 (Norfolk)).

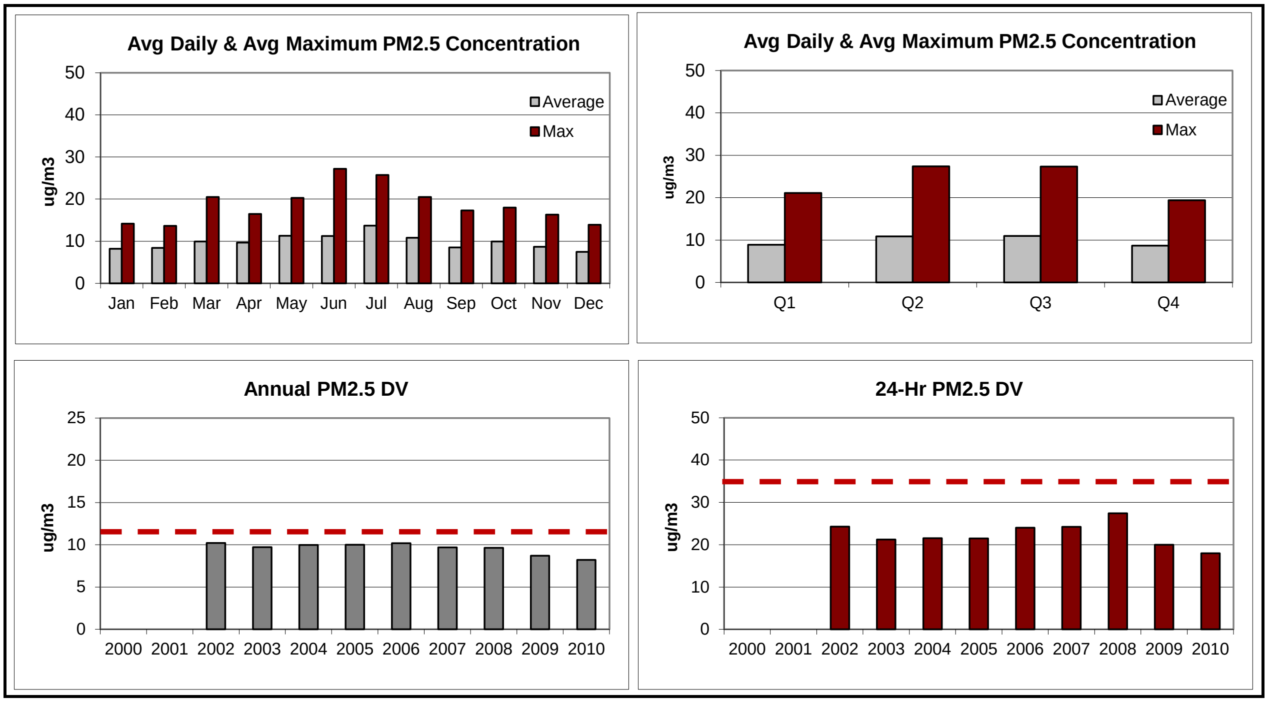


Figure 31. $PM_{2.5}$ data summary for Wilmington (NC) area site (AQS # 371290002 (Castle Hayne)). Note that data are incomplete for 2009 and 2010.

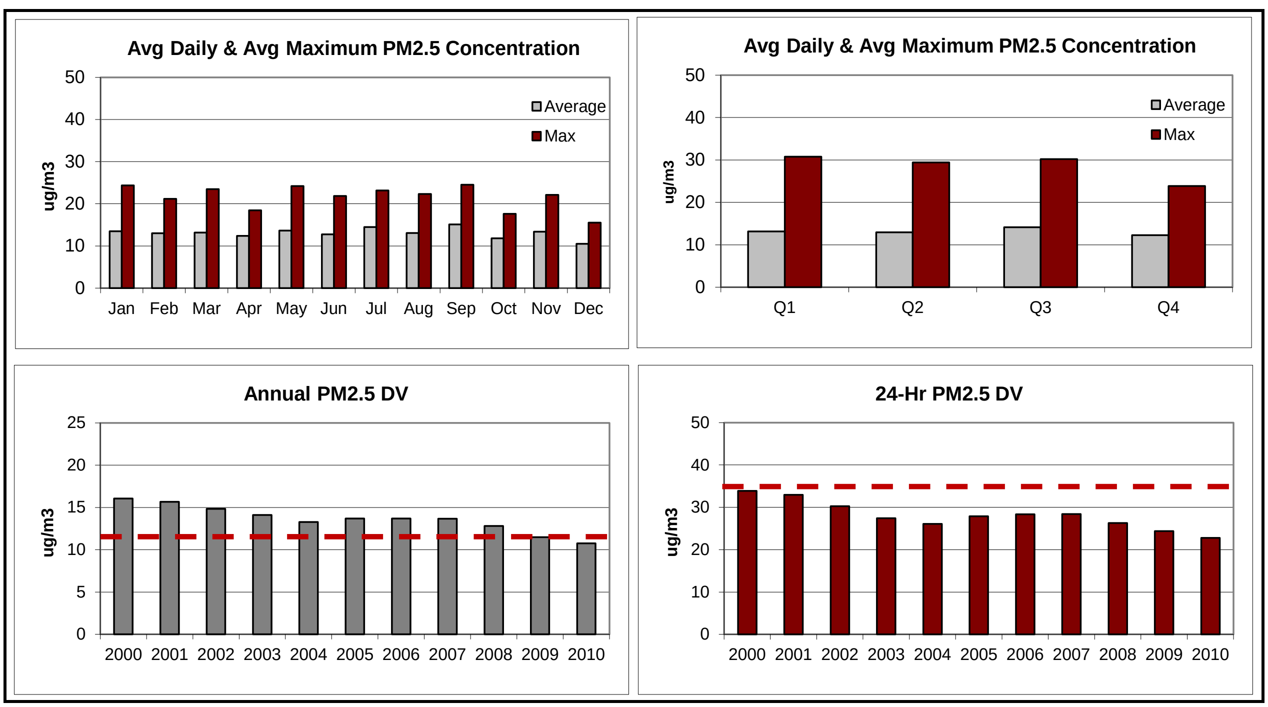


Figure 32. $PM_{2.5}$ data summary for Savannah area site (AQS # 130510017 (Savannah - Market St.)).

These figures provide an overview of particulate concentrations along the Atlantic Coast. For most of the selected area, the average maximum concentrations tend to be highest during the summer months. For the Portland, Martha's Vineyard, Newark and Norfolk areas, there are also high values during the winter months of January, February, November and December. For Savannah, the peak values do not vary much throughout the year.

For most sites, the annual $PM_{2.5}$ design values are less than the annual standard throughout the analysis period. However, for the Newark, Norfolk and Savannah area sites, the annual average $PM_{2.5}$ concentrations are greater than 12 μgm^{-3} for several design value periods, especially during the early part of the analysis period. Similarly 24-hour $PM_{2.5}$ design values are less than 35 μgm^{-3} for all sites and design value periods, with the exception of Newark for the periods ending in 2000 through 2008.

Without fully accounting for year-to-year differences in meteorology, a downward trend in both the annual and 24-hour design values is apparent for most sites for the period, with the exception of the Castle Hayne site in the Wilmington (NC) area which shows both increases and decreases in the 24-hour $PM_{2.5}$ design values in recent years.

Speciated $PM_{2.5}$ data are available for several of the selected port/harbor areas. Figures 33 through 35 present speciated $PM_{2.5}$ data summaries for: Providence, Baltimore, and Charleston. The charts display quarterly and annual average of the $PM_{2.5}$ species concentrations for each quarter. The quarterly averages are calculated overall years with speciated data. The species include sulfate (SO_4), nitrate (NO_3), ammonium (NH_4), organic carbon (OC), elemental carbon (EC), and other unidentified species such as metals (OTHER). The final value (BLANK) is the blank correction that is applied to the $PM_{2.5}$ data to account for instrument error.

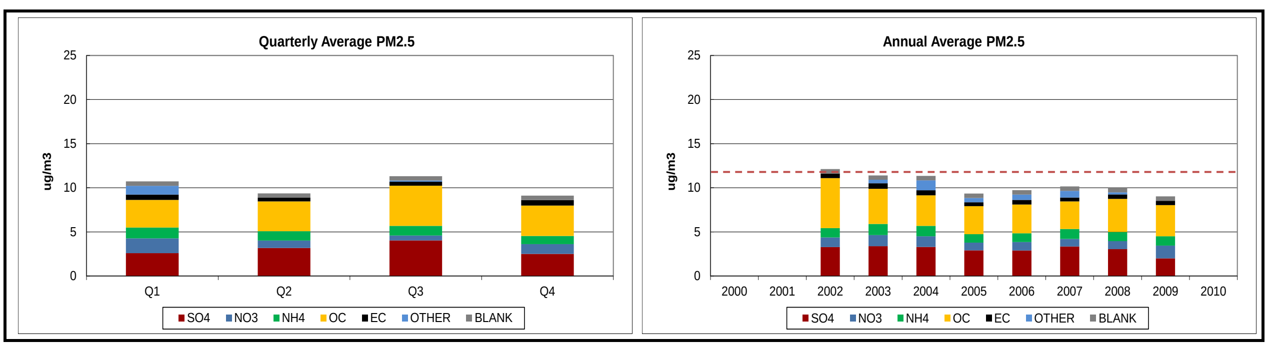


Figure 33. $PM_{2.5}$ data summary for Providence area site (AQS # 440070022 (East Providence)).

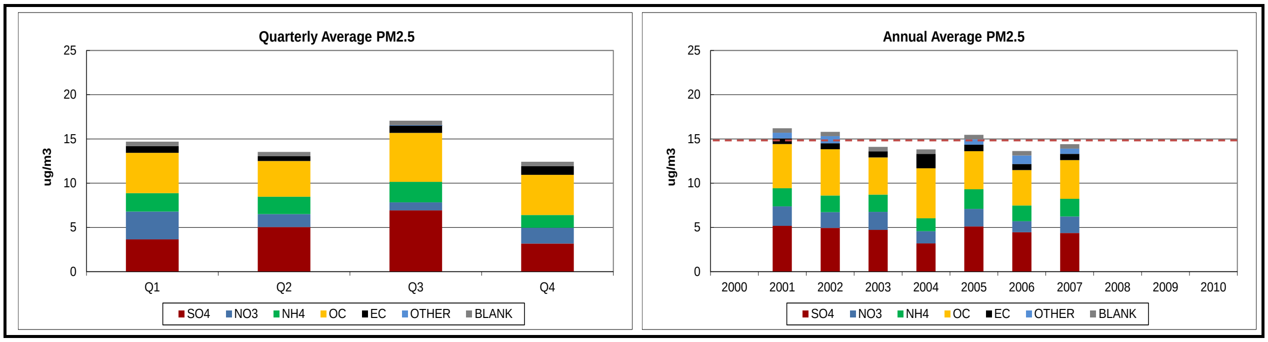


Figure 34. $PM_{2.5}$ data summary for Baltimore area site (AQS # 240053001 (Essex)).

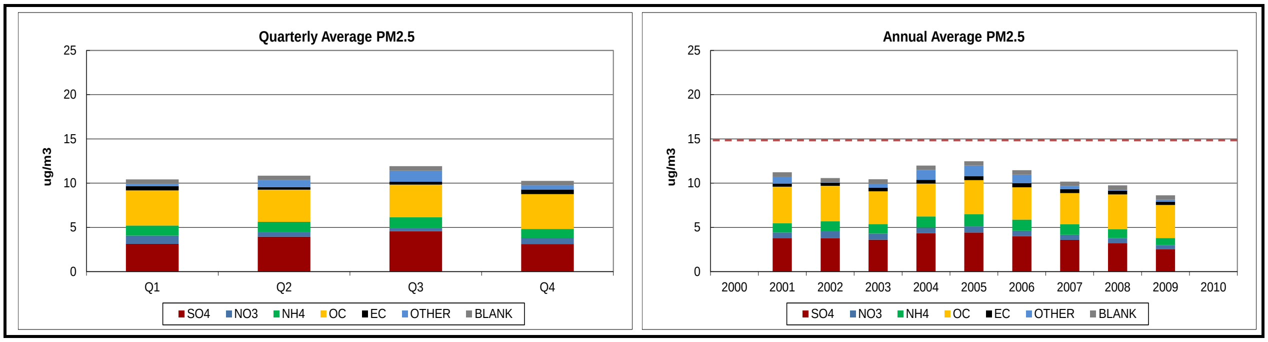


Figure 35. $PM_{2.5}$ data summary for Charleston area site (AQS # 450190049 (Charleston - Public Works)).

For all three sites, sulfate and organic carbon are the primary constituents of $PM_{2.5}$. Nitrate is also an important constituent for Baltimore and to a lesser extent Providence, especially during the winter months. Elemental carbon is a smaller but year round constituent for both Baltimore and Providence. Quarterly and annual variations in both the species concentrations and the overall $PM_{2.5}$ concentrations are quite pronounced for these three sites.

2.4. VISIBILITY CALCULATIONS

In this study, visibility was examined for six Class I areas along the Atlantic Coast. These areas are:

- Acadia National Park, ME
- Brigantine National Wildlife Refuge (NWR), NJ
- Swanquarter NWR, NC
- Cape Romain NWR, SC
- Okefenokee NWR, GA
- Everglades National Park, FL

Visibility data for these sites are collected routinely as part of the IMPROVE monitoring network. For the Class I areas, the regional haze rule calls for states to establish "reasonable progress goals" to improve visibility on the 20 percent haziest (worst) days and to prevent visibility degradation on the 20 percent clearest (best) days, with the ultimate goal of returning to natural visibility conditions by 2064.

There are also several IMPROVE Protocol monitoring sites that are located along the Atlantic Coast, but not in Class I areas. The equipment and data are the same as for the IMPROVE Class I sites and these data were also used in the analysis. The IMPROVE Protocol sites include:

- Casco Bay, ME
- Cape Cod, MA
- Martha's Vineyard, MA
- New York, NY

The areas represented by the IMPROVE and IMPROVE Protocol monitoring sites are shown in Figure 36.

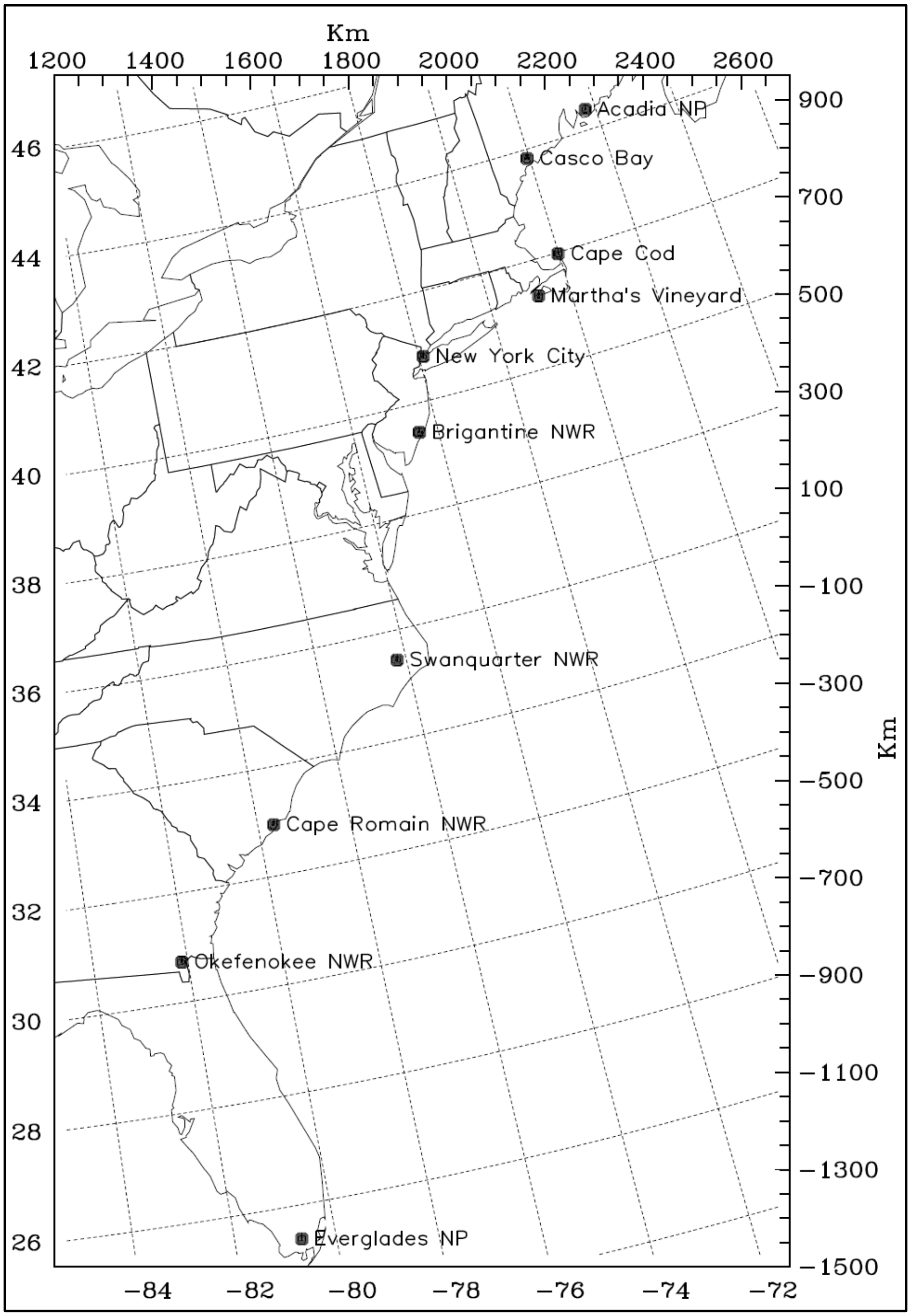


Figure 36. IMPROVE monitoring sites for the BOEM Atlantic OCS Region data.

The visibility data were obtained from the VIEWS database (CIRA, 2012). All of the data presented in this section are included in the ARAQDB. Detailed site information is also included in the ARAQDB.

In this section, plots illustrating annual variations in extinction coefficient and visibility (in deciviews) for the 20 percent best (clearest) and worst (haziest) days for each year comprising the period 2000–2010 are presented and discussed.

An estimate of the daily extinction coefficient (B_{ext}) is calculated using the current IMPROVE algorithm (IMPROVE, 2006)). Details are presented in the latest EPA guidance document on the use of models and other analyses for demonstrating attainment of the regional haze goals (USEPA, 2007). Specifically, B_{ext} is calculated as follows:

B_{ext} = 2.2 x f(RH) x [Small Sulfate] + 4.8 x f(RH) x [Large Sulfate]

+ 2.4 x f(RH) x [Small Nitrate] + 4.8 x f(RH) x [Large Nitrate]

+ 2.8 x f(RH) x [Small Organic Mass] + 4.8 x f(RH) x [Large Organic Mass]

+ 10 x [Elemental Carbon]

+ 1 x [Fine Soil]

+ 1.7 x f(rh) x [Sea Salt]

+ 0.6 x [Coarse Mass]

+ Rayleigh Scattering (site specific)

In this equation, f(rh) is a relative humidity adjustment factor. Monthly values of f(rh) are used and they differ for small and large particles and sea salt. The brackets represent concentrations of each constituent. The last term involving NO_2 concentration was not included here due to lack of NO_2 data. In applying this algorithm, sulfate, nitrate, and organic mass are apportioned into small and large size fractions using empirical formulae. The units for Bext are Mm^{-1}.

Deciviews are defined as the natural logarithm of the ratio of extinction coefficient to Rayleigh scattering (USEPA, 2007) as follows:

$$\text{Deciview} = 10 \ln(B_{ext}/10)$$

For the data summaries presented in this section, pre-calculated values of Bext by species were obtained from the IMPROVE dataset and used to prepare the summary charts.

Figures 37 through 42 summarize visibility for the following areas: Acadia NP, Martha's Vineyard, New York City, Brigantine NWR, Swanquarter NWR, and Okefenokee NWR. The first chart presents average B_{ext} by species for the 20 percent best days for each year. The second chart presents average B_{ext} by species for the 20 percent worst days for each year. The third chart gives the average deciview index for the 20 percent best and worst days for each year. The abbreviations used in the first two charts are defined as follows: SO_4 (sulfate mass), NO_3 (nitrate mass), OMC (organic carbon mass), SS (sea salt), and PMC (coarse particulate mass). The extinction coefficient attributable to each component is presented. Note that the scale is different for best and worst B_{ext}, in order to show the relative contributions from each component.

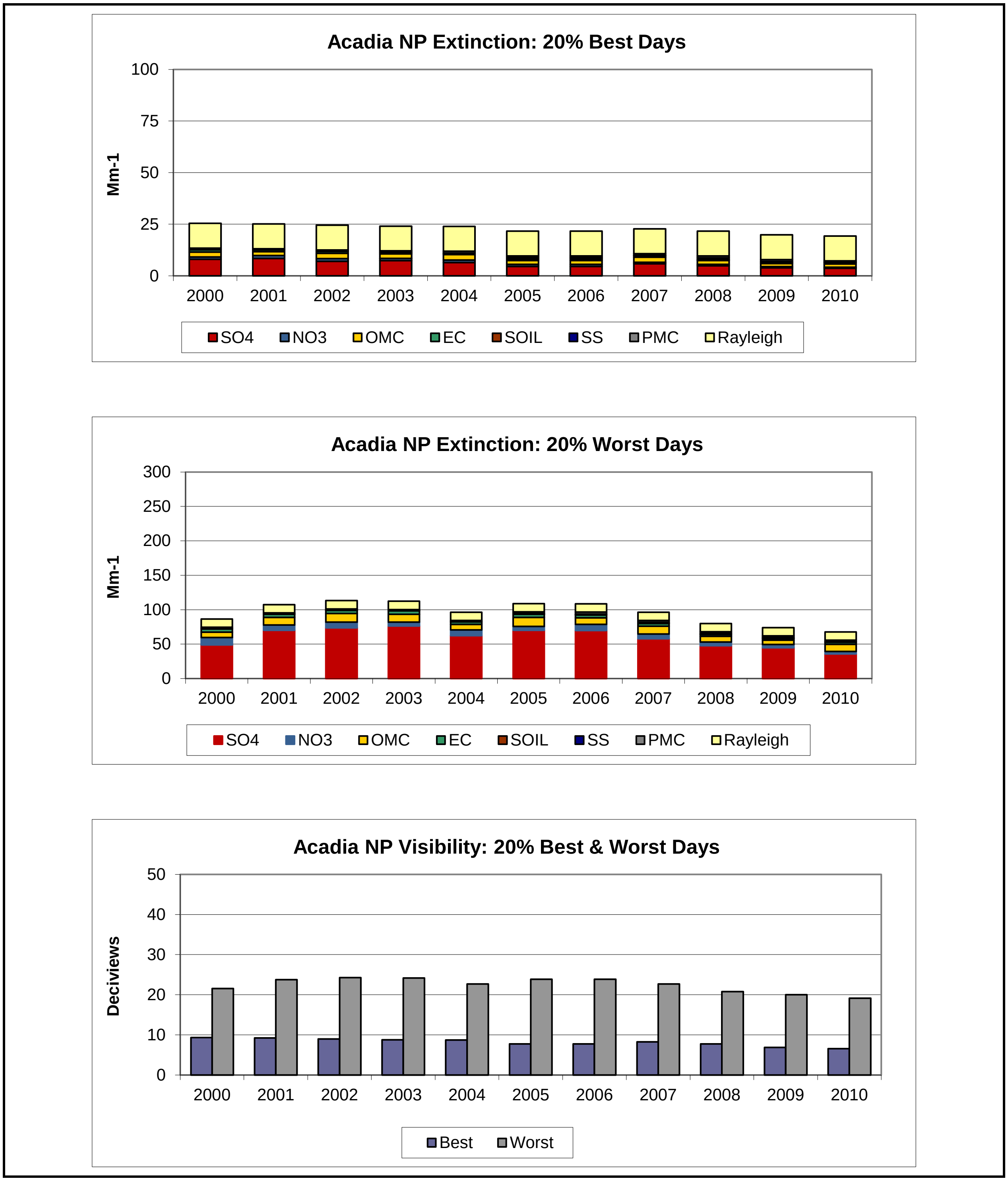
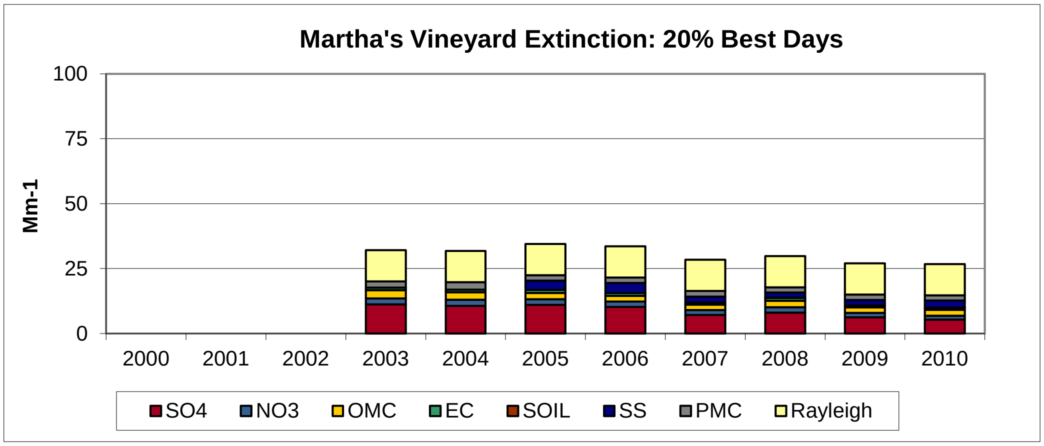
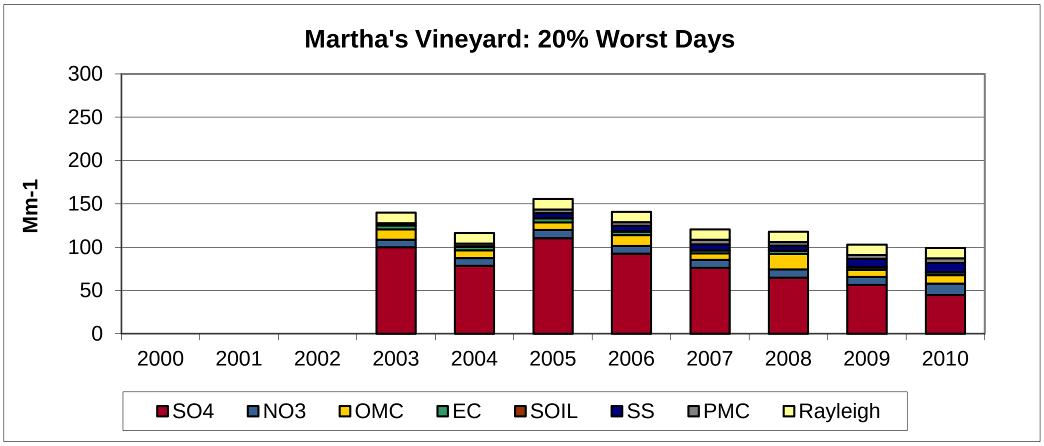


Figure 37. Visibility data summary for Acadia NP (2000–2010).





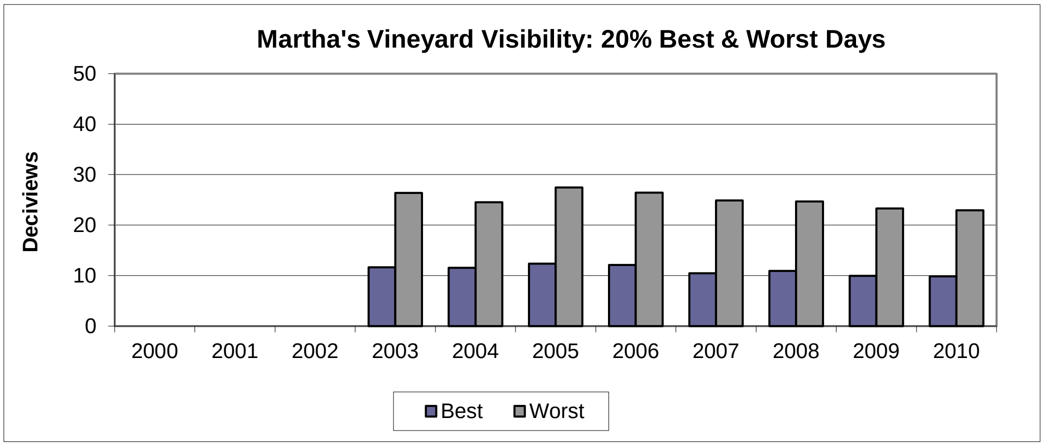


Figure 38. Visibility data summary for Martha's Vineyard (2000–2010).

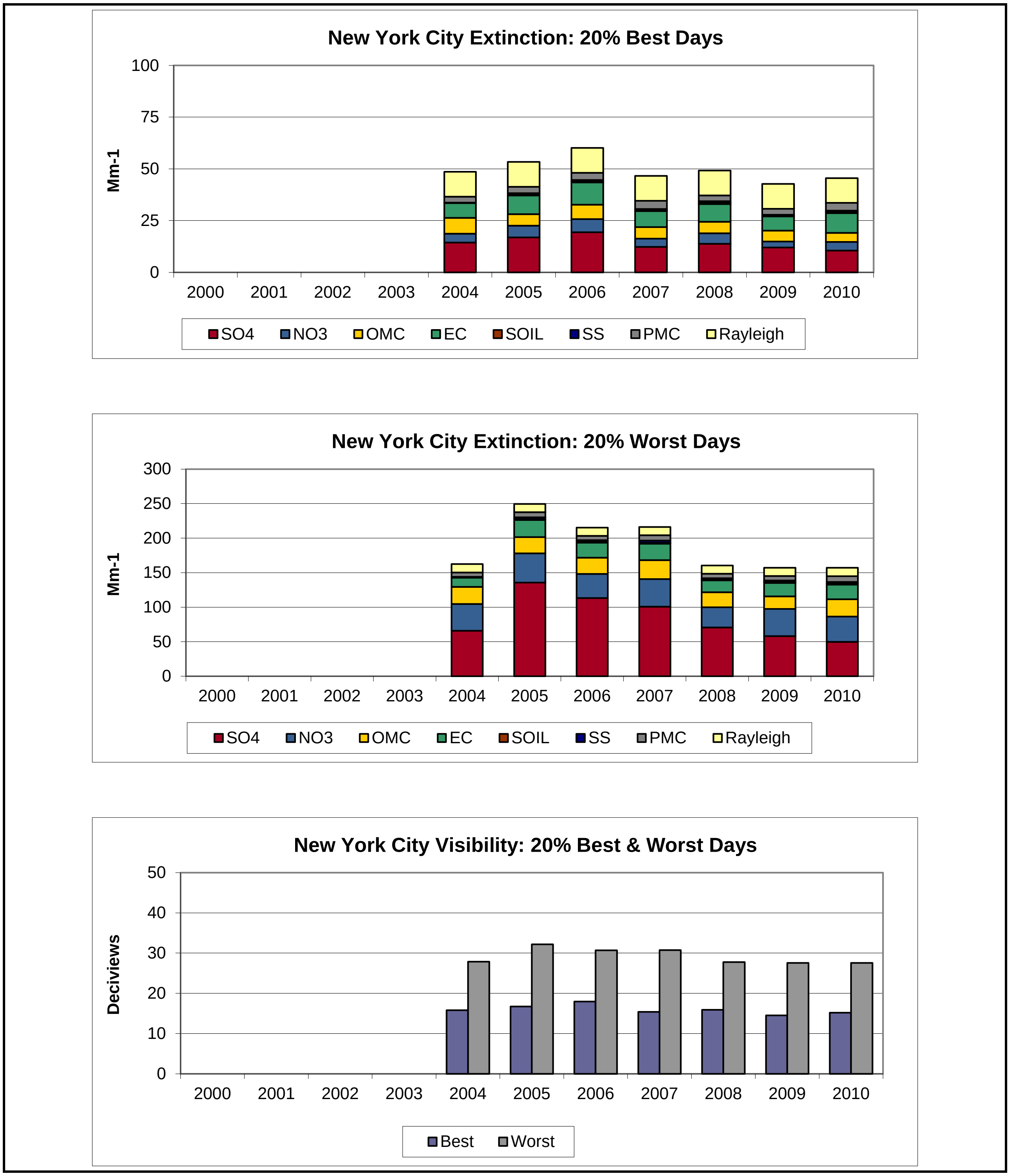


Figure 39. Visibility data summary for New York City (2000–2010).

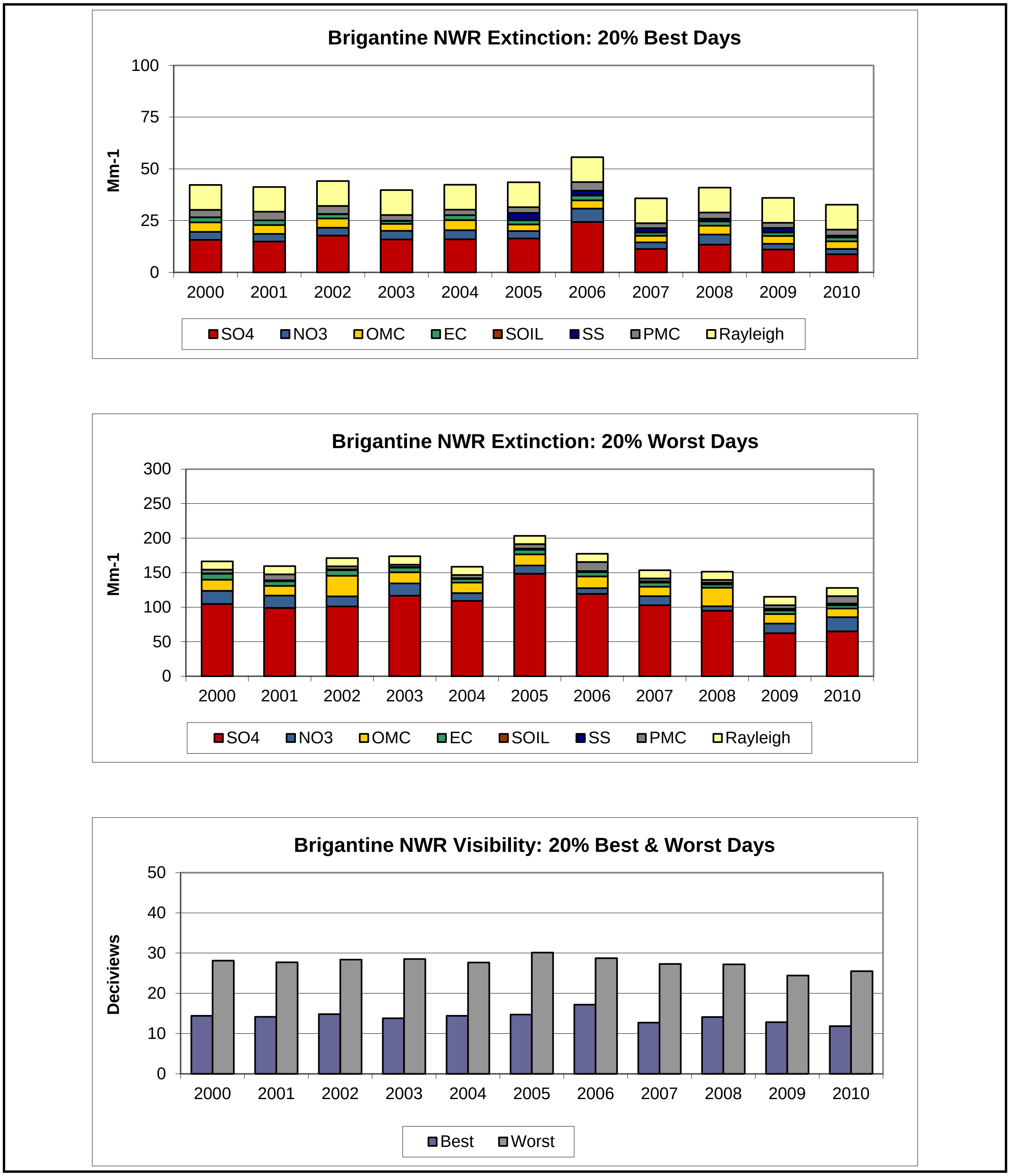


Figure 40. Visibility data summary for Brigantine NWR (2000–2010).

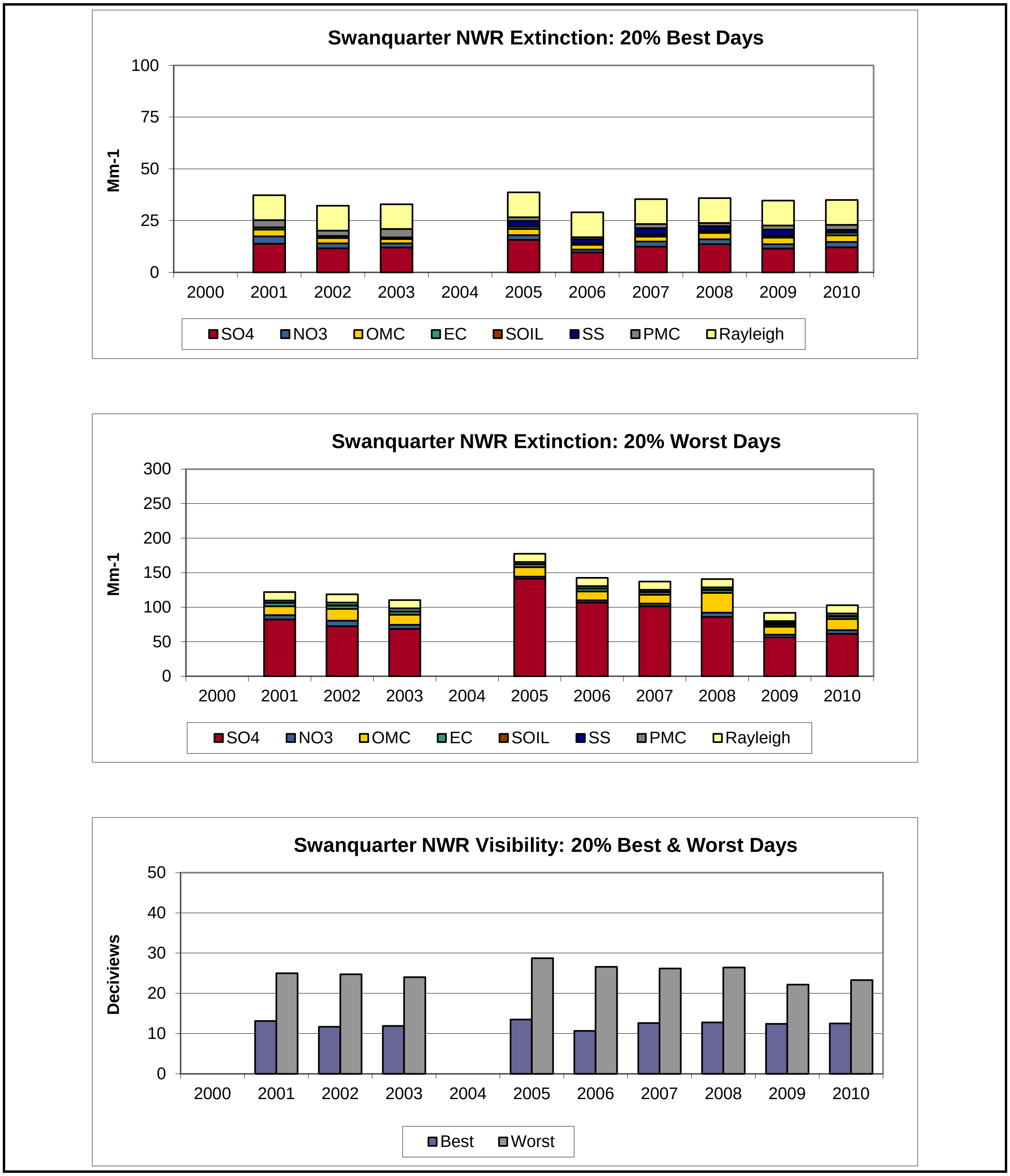


Figure 41. Visibility data summary for Swanquarter NWR (2000–2010).

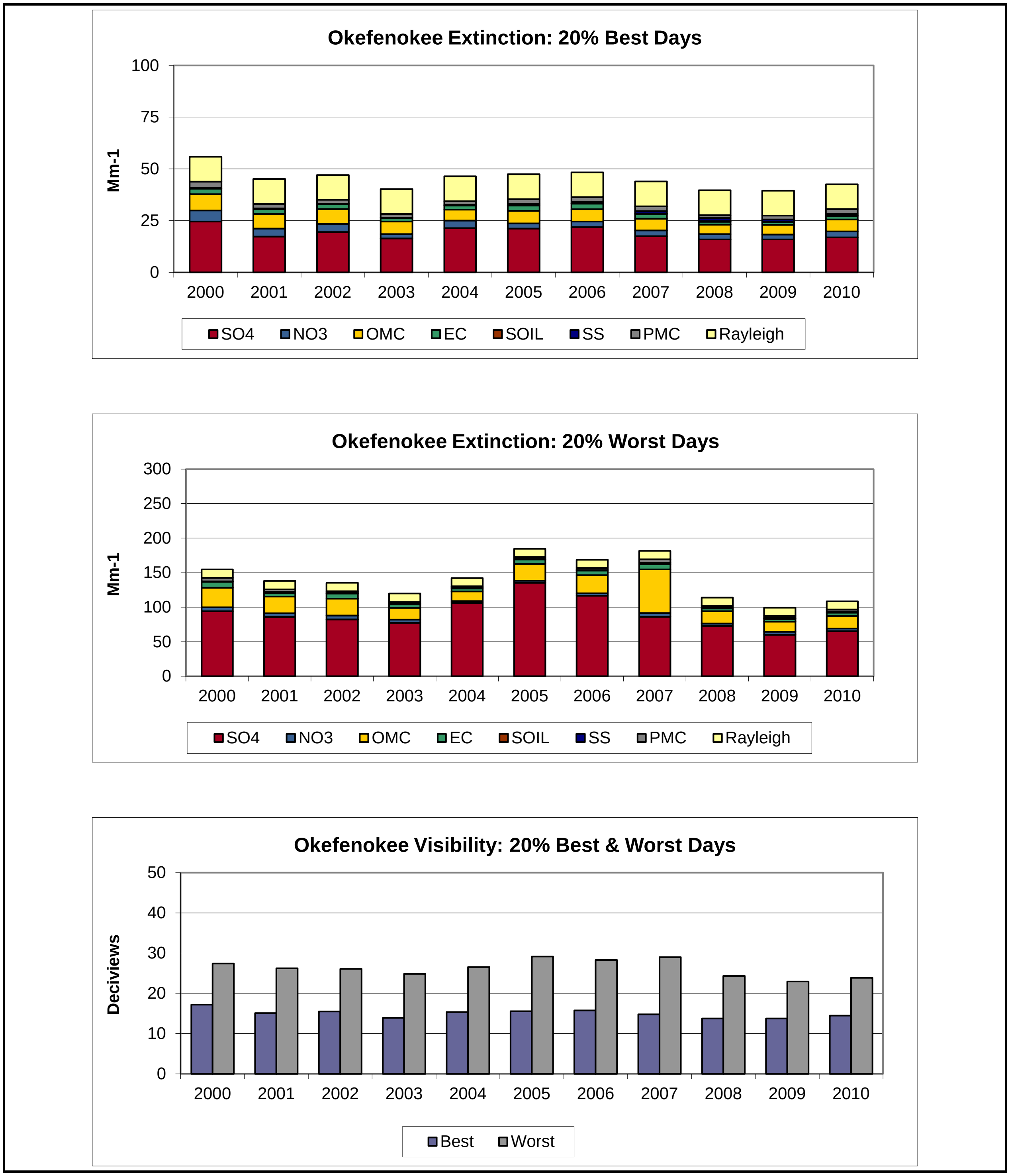


Figure 42. Visibility data summary for Okefenokee NWR (2000–2010).

For all areas, sulfate is the greatest contributor to poor visibility. Nitrate, organic carbon, and elemental carbon also contribute to visibility degradation in New York City and organic carbon contributes substantially at the Okefenokee NWR site. The data for most sites indicate a slight downward trend (improved visibility) during the analysis period, especially for the worst visibility days.

2.5. EMISSIONS DATA SUMMARIES

The study area for this analysis spans the full length of the Atlantic coast, from Florida to Maine, which includes a diverse mix of urban areas, rural areas, seashores, parks, harbors, ports, and other facilities that support a variety of recreational and commercial activities. Observed air quality along the Atlantic coast is influenced by a multitude of anthropogenic and biogenic sources emitting criteria pollutants, with the highest density of anthropogenic emissions occurring in the highly populated urban areas or at the major ports. As noted above, emission estimates for onshore areas were obtained from the latest available national inventory for 2008.

To examine recent levels of emissions for the Atlantic coastal area, county-level emissions from EPA's 2008 NEI were obtained for coastal and near-coastal counties identified for each of the states. To further examine the contributions of emissions by species and source category in more focused areas, the Atlantic coast was subdivided into five zones as follows: Zone 1 – Maine, Zone 2 – Massachusetts to New Jersey, Zone 3 – Mid-Atlantic, Zone 4 – North Carolina to Georgia, and Zone 5 – Florida. Emission density maps (by county) were prepared and used to infer potential impacts to local and regional air quality. Figures 43 through 49 present county-level anthropogenic emission density maps for NO_x, VOC, CO, SO_2, PM_{10}, $PM_{2.5}$ and NH_3, respectively. The maps clearly indicate that the highest levels of emissions are in counties with the highest population centers or at the major port facilities, including Miami, New York, and Boston.

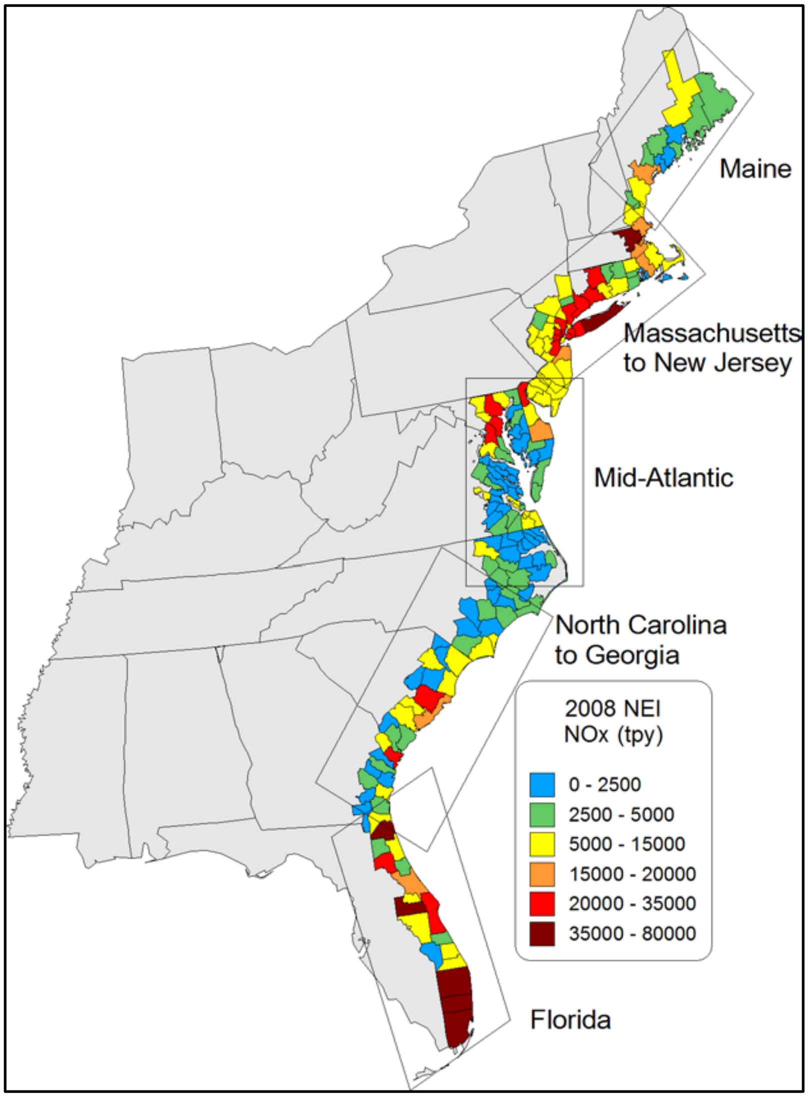


Figure 43. County-level annual NO_x emissions (tons/year) for 2008.

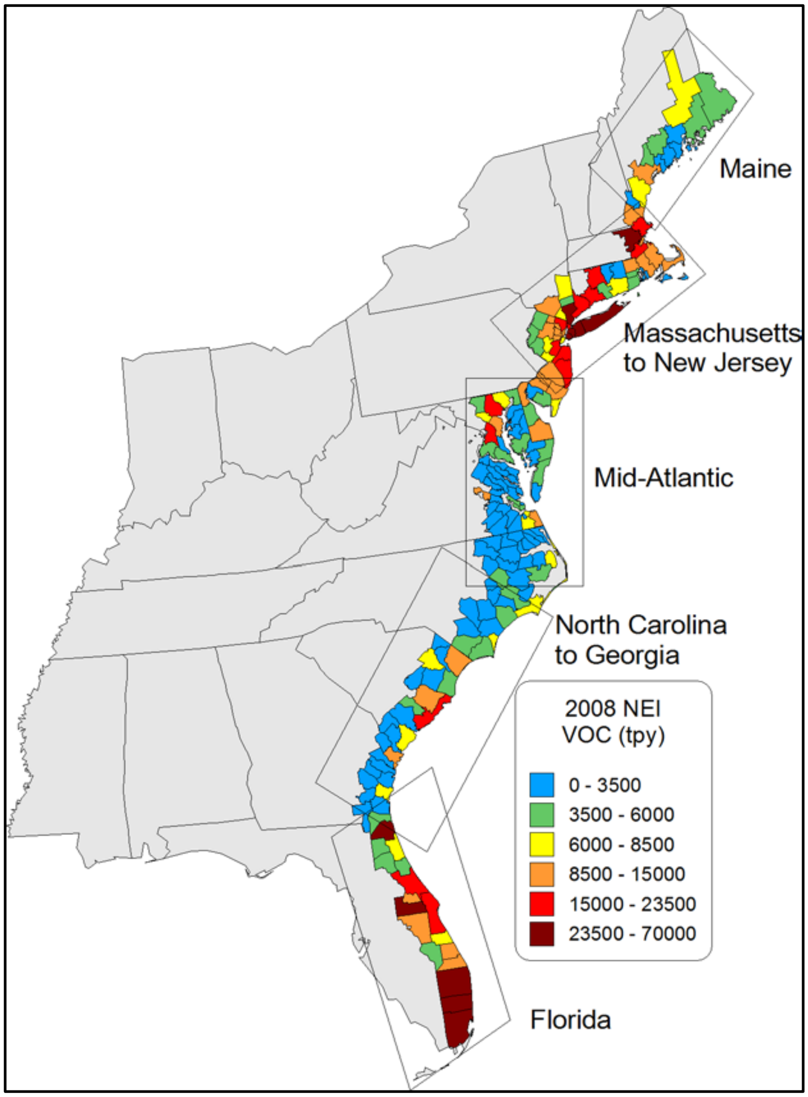


Figure 44. County-level annual VOC emissions (tons/year) for 2008.

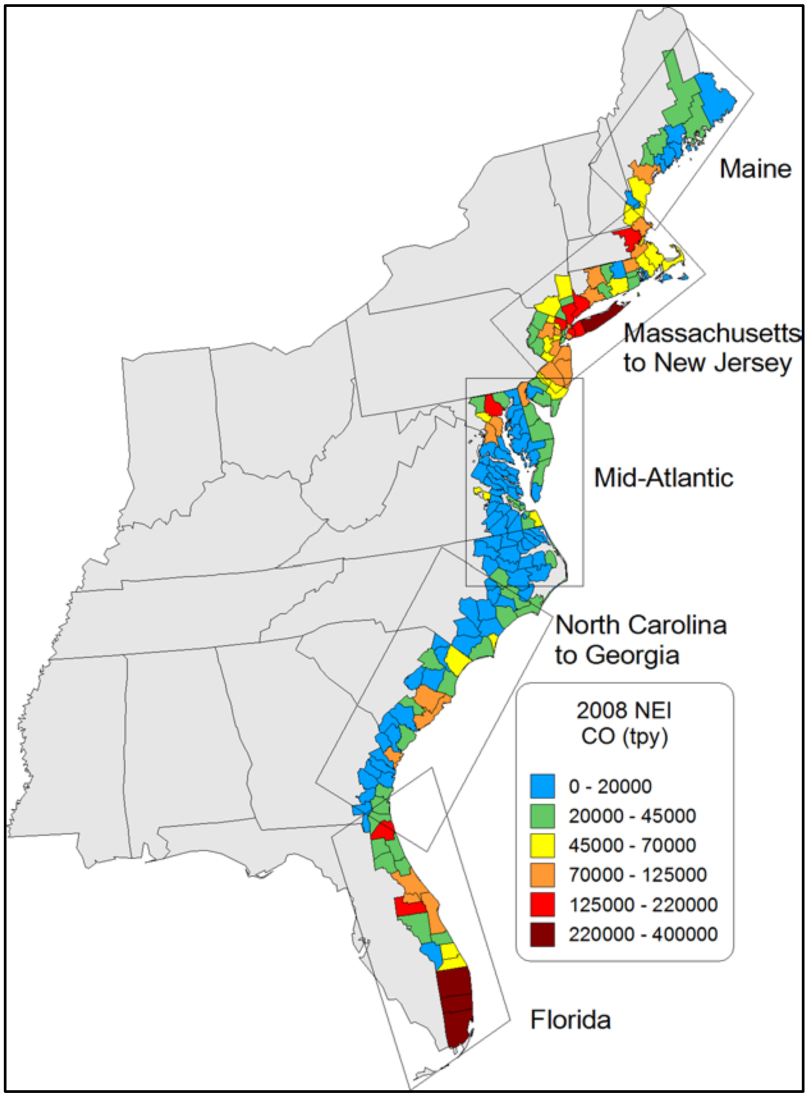


Figure 45. County-level annual CO emissions (tons/year) for 2008.

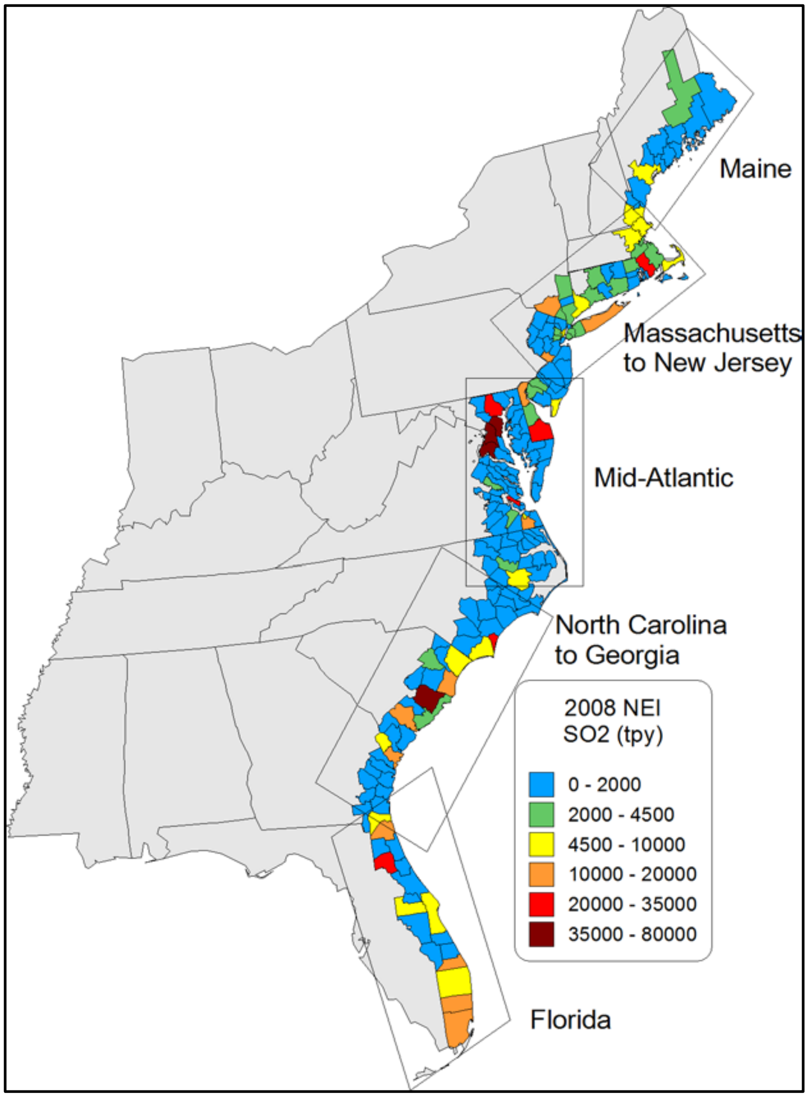


Figure 46. County-level annual SO_2 emissions (tons/year) for 2008.

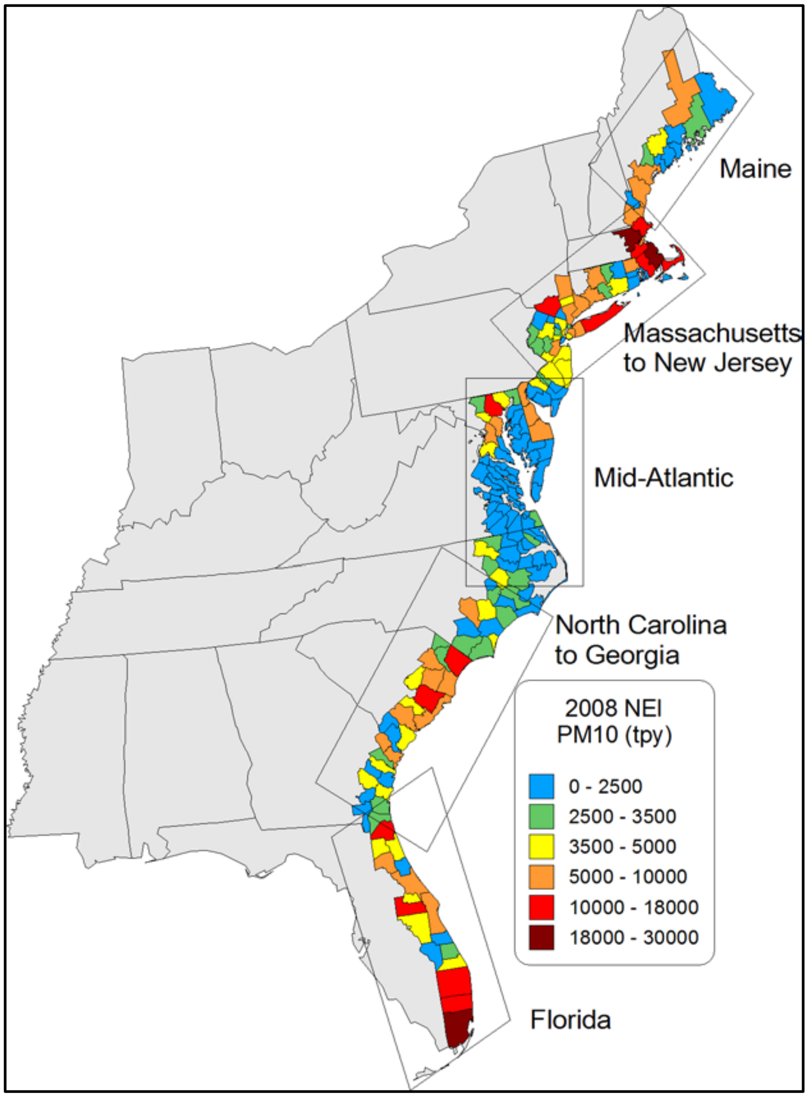


Figure 47. County-level annual PM_{10} emissions (tons/year) for 2008.

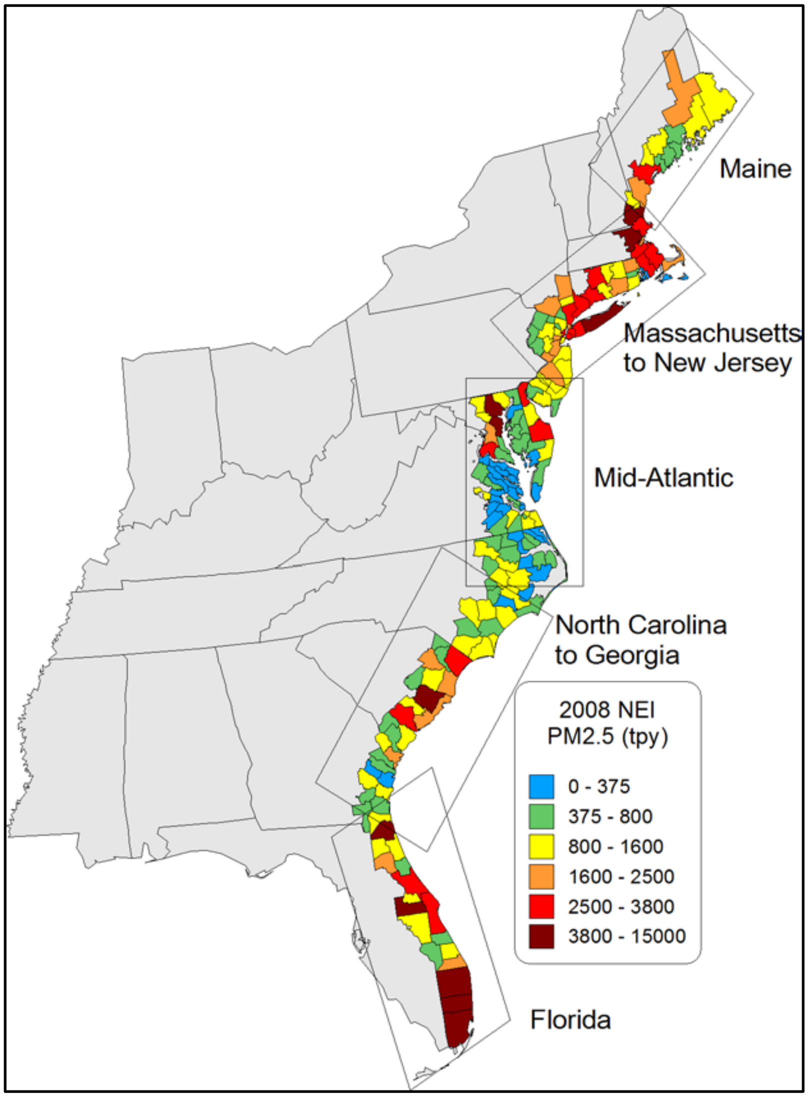


Figure 48. County-level annual $PM_{2.5}$ emissions (tons/year) for 2008.

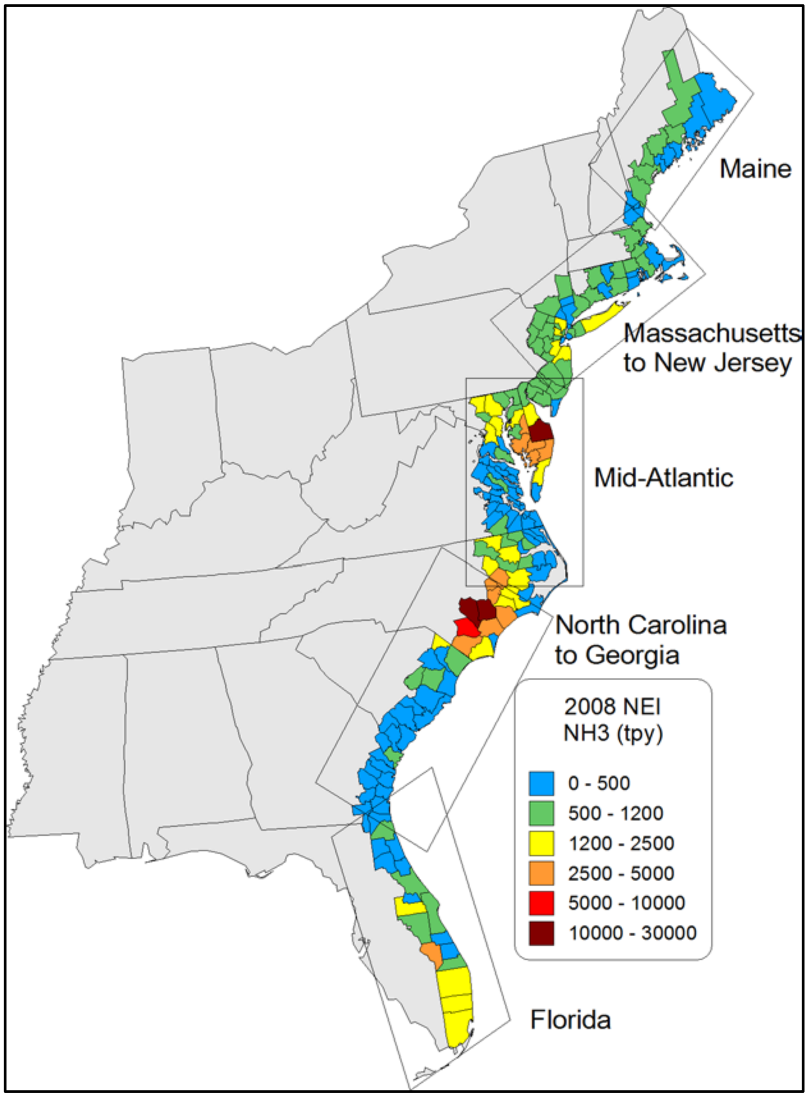


Figure 49. County-level annual NH_3 emissions (tons/year) for 2008.

Tables 4 through 8 present emission totals for NO_x, VOC, CO, SO_2, PM_{10}, $PM_{2.5}$ and NH_3 for Zones 1 through 5. The tables present a breakdown of emissions by major source category, including industrial point sources, area sources, non-road, on-road, and nearshore emissions which include commercial marine vessel emissions while they are in port, and marine vessel fuel storage emissions. The information contained in the tables is graphically depicted in two different ways in the stacked bar charts presented in Figures 50 and 51. Figure 50 compares individual species totals for all zones while Figure 51 presents all species totals for each zone. Please note the differences in scale used for each of the charts. As noted above, the major contributors to NO_x and CO emissions along the Atlantic coast are on-road mobile sources, while the major contributors to anthropogenic VOC, PM_{10}, $PM_{2.5}$ and NH_3 emissions are area sources. In the tables these are labeled, “non-point” sources. For SO_2, the major contributors are elevated point sources, such as power plants. The tables and figures show similarities and differences in the magnitude of the emissions from zone to zone and the contributions by source category for the various pollutant species. Zones 2 (Massachusetts to New Jersey), Zone 3 (Mid-Atlantic), and Zone 5 (Florida) have the highest levels of emissions, followed by Zone 4 (North Carolina to Georgia), while Zone 1 (Maine) has the lowest emissions. This is expected, given the population centers and ports located in each of the zones.

Table 4
2008 Annual Criteria Pollutant Emissions by Source Category for Zone 1 – Maine.

Source	NOx (tpy)	VOC (tpy)	CO (tpy)	SO2 (tpy)	PM10 (tpy)	PM2.5 (tpy)	NH3 (tpy)
Point	11,316	2,647	10,113	14,150	4,724	4,132	398
Non-Point	7,632	25,237	55,060	8,876	40,091	13,454	4,994
Non-road	7,678	21,726	117,630	136	970	913	11
On-road	40,060	16,692	205,513	711	2,198	1,770	715
Nearshore	8,241	854	1,511	1,722	352	336	3
Total	74,928	67,157	389,826	25,595	48,335	20,605	6,122

Table 5
2008 Annual Criteria Pollutant Emissions by Source Category for Zone 2 - Massachusetts to New Jersey.

Source	NOx (tpy)	VOC (tpy)	CO (tpy)	SO2 (tpy)	PM10 (tpy)	PM2.5 (tpy)	NH3 (tpy)
Point	81,747	15,794	69,284	97,996	11,560	9,823	2,746
Non-Point	113,536	334,034	189,477	66,139	232,714	57,409	19,461
Non-road	104,321	158,260	1,628,314	1,969	9,406	8,944	123
On-road	310,918	152,523	1,722,968	5,469	20,005	14,319	8,480
Nearshore	70,444	3,548	12,458	14,093	3,072	2,924	32
Total	680,966	664,158	3,622,501	185,666	276,757	93,420	30,841

Table 6
2008 Annual Criteria Pollutant Emissions by Source Category for Zone 3 - Mid-Atlantic.

Source	NOx (tpy)	VOC (tpy)	CO (tpy)	SO2 (tpy)	PM10 (tpy)	PM2.5 (tpy)	NH3 (tpy)
Point	103,460	19,765	134,563	320,903	19,943	15,006	1,676
Non-Point	33,562	133,317	128,618	10,763	158,136	37,544	111,184
Non-road	53,499	108,597	655,755	1,121	5,464	5,180	67
On-road	191,279	85,456	993,681	3,408	8,985	7,189	4,302
Nearshore	47,729	6,139	7,630	12,380	2,426	2,304	26
Total	429,529	353,275	1,920,248	348,576	194,954	67,223	117,255

Table 7
2008 Annual Criteria Pollutant Emissions by Source Category for Zone 4 - North Carolina to Georgia.

Source	NOx (tpy)	VOC (tpy)	CO (tpy)	SO2 (tpy)	PM10 (tpy)	PM2.5 (tpy)	NH3 (tpy)
Point	66,575	22,413	117,461	160,363	17,743	13,660	1,639
Non-Point	10,732	58,856	63,846	1,073	123,702	23,315	81,852
Non-road	19,626	40,308	248,047	376	2,080	1,973	25
On-road	91,586	38,232	464,896	1,578	4,216	3,391	1,548
Nearshore	16,127	464	2,673	4,921	783	737	7
Total	204,647	160,273	896,923	168,310	148,524	43,076	85,072

Table 8
2008 Annual Criteria Pollutant by Source Category for Zone 5 – Florida.

Source	NOx (tpy)	VOC (tpy)	CO (tpy)	SO2 (tpy)	PM10 (tpy)	PM2.5 (tpy)	NH3 (tpy)
Point	101,746	13,494	81,157	76,740	14,995	12,527	2,465
Non-Point	6,012	125,625	47,660	314	98,527	21,052	7,320
Non-road	54,663	80,175	710,040	1,075	5,557	5,293	68
On-road	234,931	102,127	1,140,483	4,609	13,252	9,744	4,541
Nearshore	31,864	876	4,149	15,614	2,238	2,094	22
Total	429,215	322,296	1,983,489	98,352	134,569	50,709	14,417

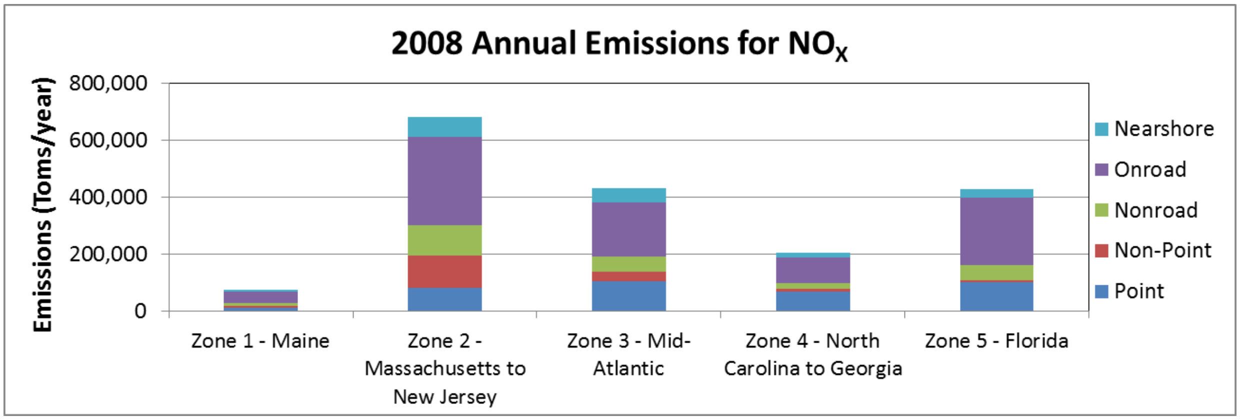


Figure 50a. Annual NOx emissions (tons/year) by source category and zone for 2008.

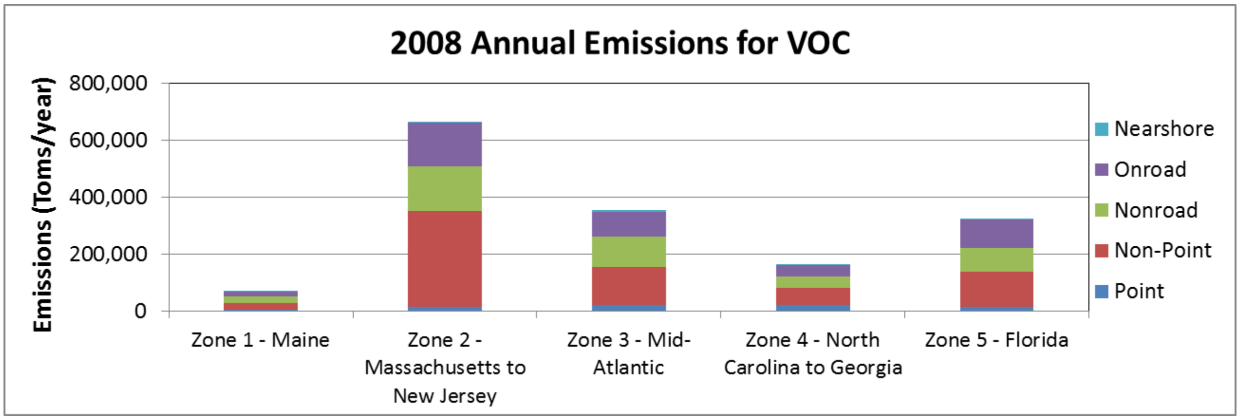


Figure 50b. Annual VOC emissions (tons/year) by source category and zone for 2008.

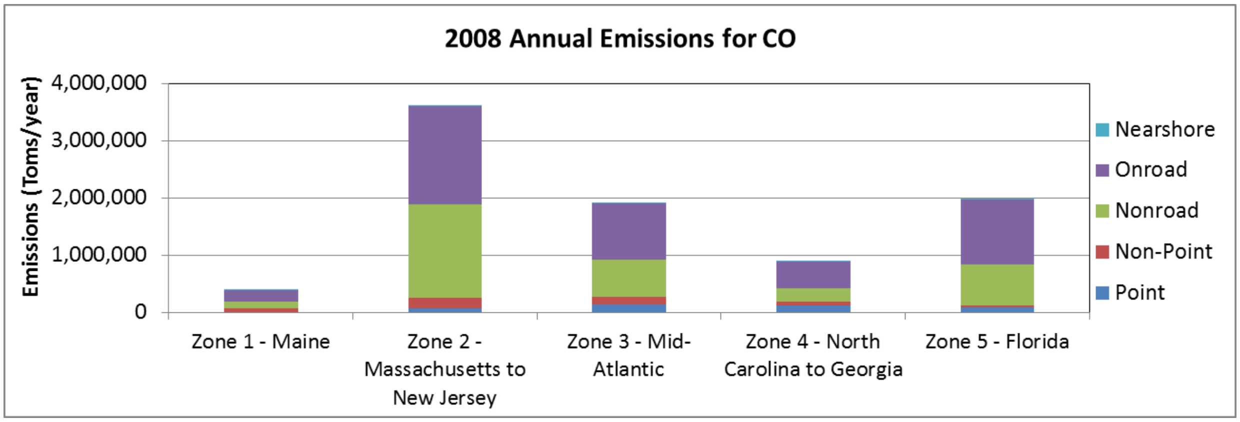


Figure 50c. Annual CO emissions (tons/year) by source category and zone for 2008.

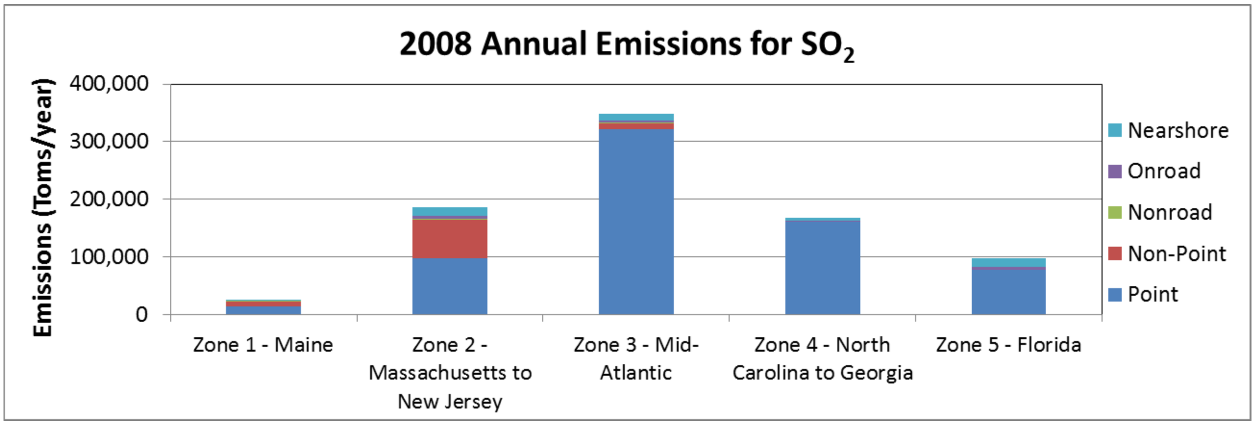


Figure 50d. Annual SO_2 emissions (tons/year) by source category and zone for 2008.

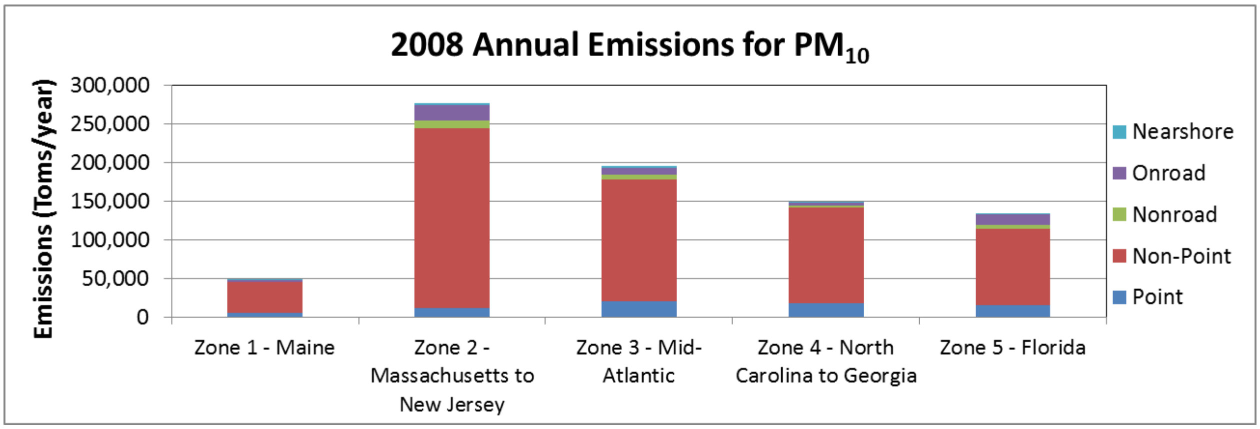


Figure 50e. Annual PM_{10} emissions (tons/year) by source category and zone for 2008.

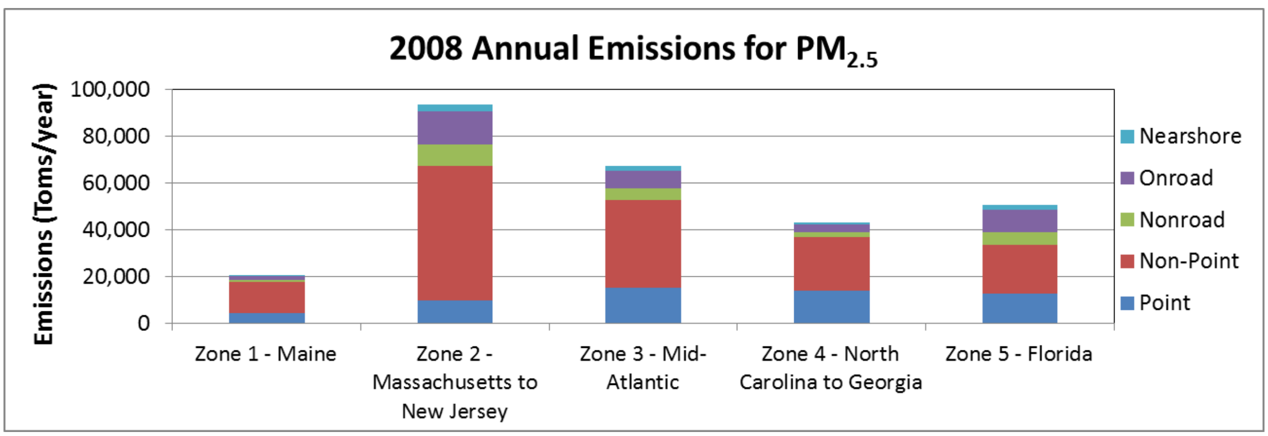


Figure 50f. Annual $PM_{2.5}$ emissions (tons/year) by source category and zone for 2008.

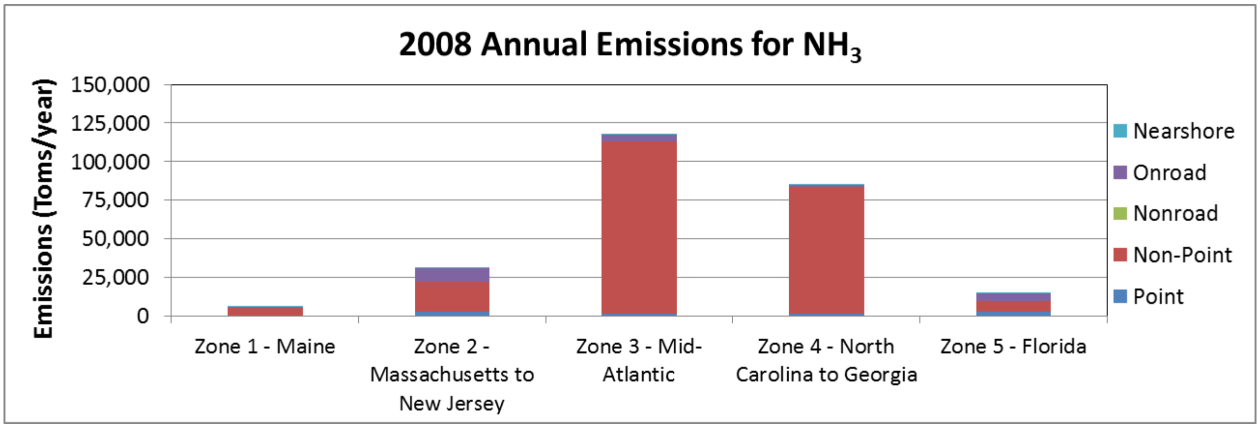


Figure 50g. Annual NH_3 emissions (tons/year) by source category and zone for 2008.

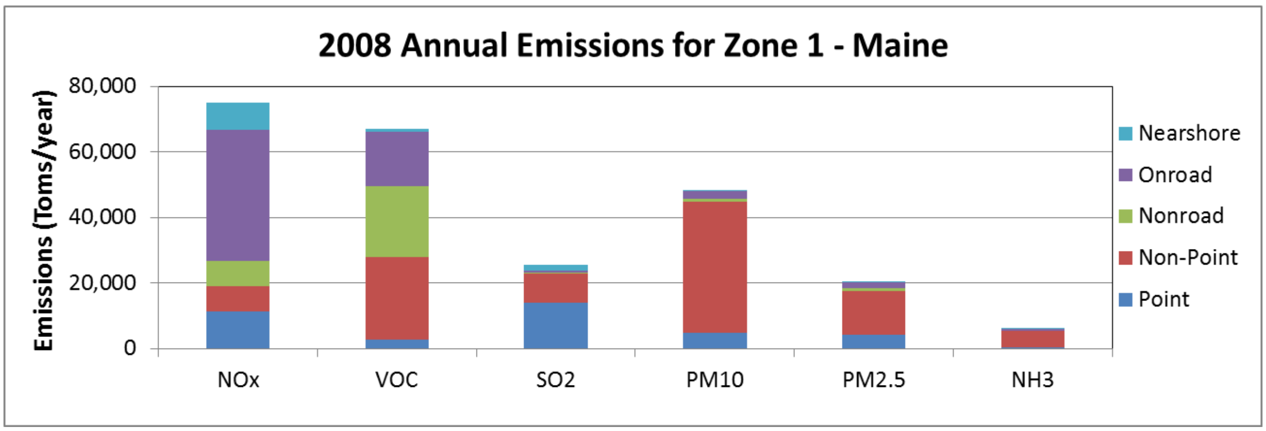


Figure 51a. Annual 2008 criteria pollutant (tons/year) by source category for Zone 1 - Maine.

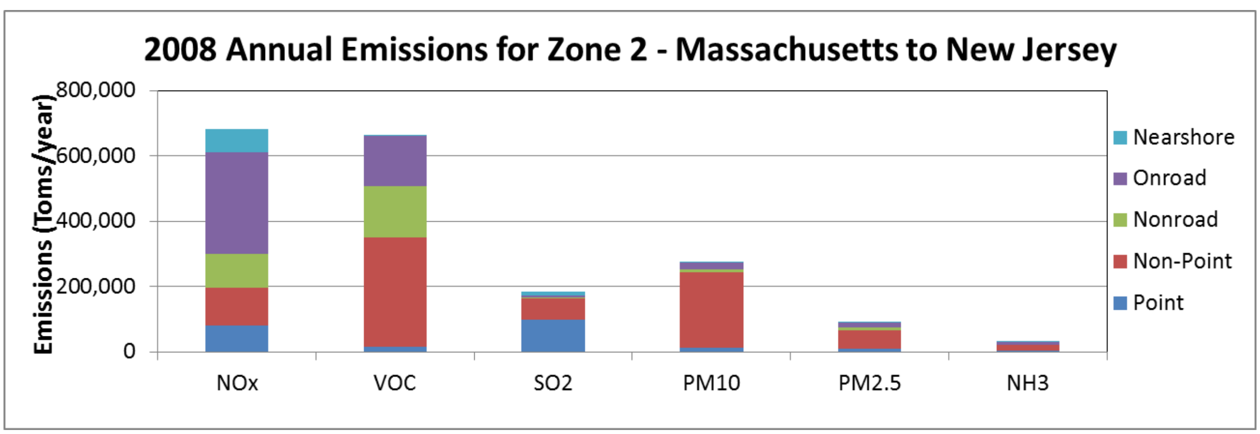


Figure 51b. Annual 2008 criteria pollutant emissions (tons/year) by source category for Zone 2 – Massachusetts to New Jersey.

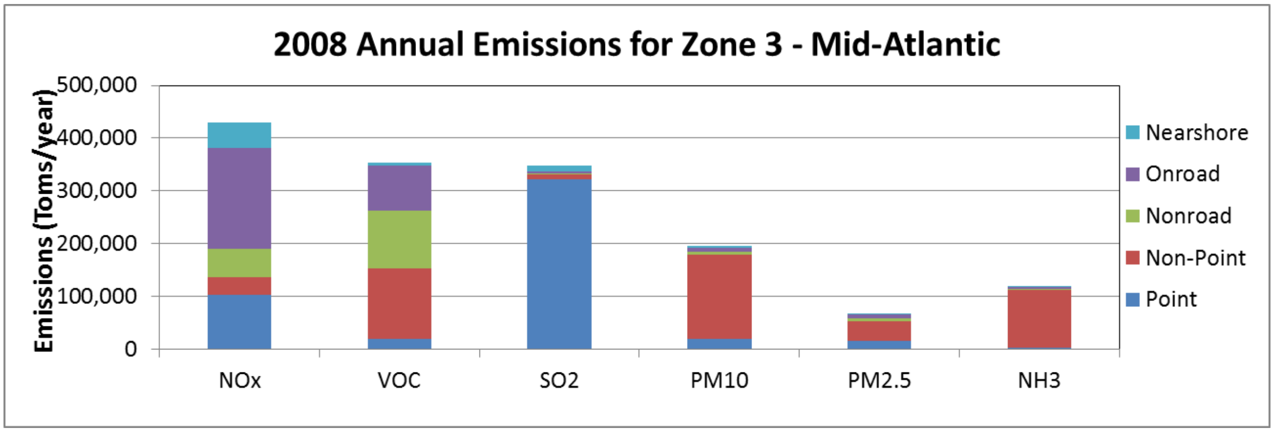


Figure 51c. Annual 2008 criteria pollutant emissions (tons/year) by source category for Zone 3 – Mid-Atlantic.

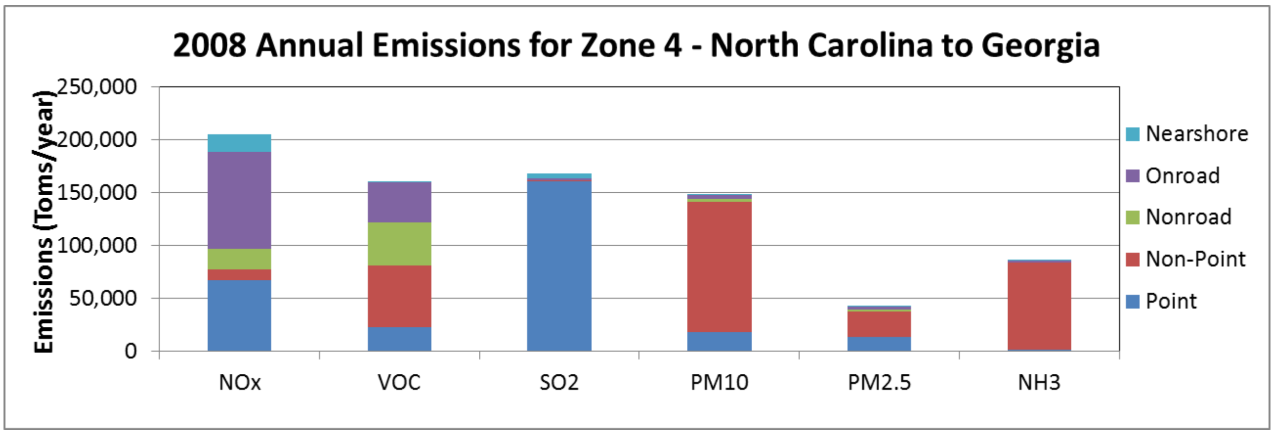


Figure 51d. Annual 2008 criteria pollutant emissions (tons/year) by source category for Zone 4 – North Carolina to Georgia.

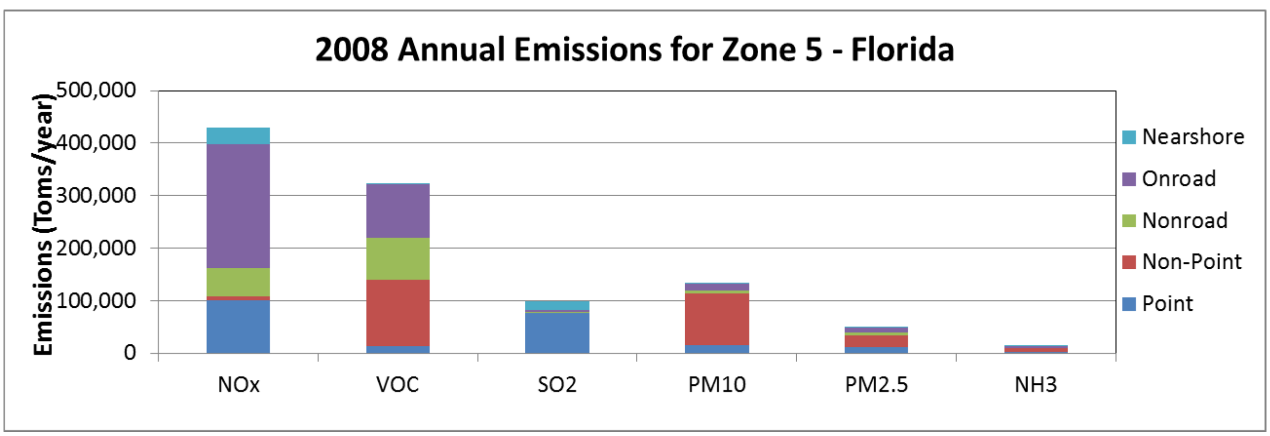


Figure 51e. Annual 2008 criteria pollutant emissions (tons/year) by source category for Zone 5 – Florida.

3.0 ANALYSIS OF WIND DATA ALONG THE ATLANTIC COAST

One objective of this data analysis was to use available data to examine the potential for emissions from offshore facilities to contribute to air quality issues in port/harbor areas along the Atlantic Coast. Combined summaries of wind and pollutant concentration data for several coastal areas are presented in this section of the report. An analysis of the effects of the sea breeze on air quality is also presented. All of the data presented in this section are included in the ARAQDB.

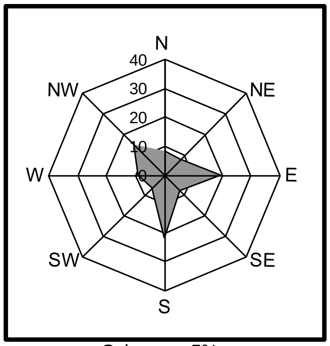
3.1. OZONE SEASON WIND DISTRIBUTIONS

Figures 52 through 59 present information about wind direction frequency, and the observed relationship between wind speed, wind direction and ozone concentration. The data used to prepare the diagrams cover the period April through October, 2000–2010. This analysis samples several areas along the Atlantic Coast including Portland, Providence, New York, Newark-Elizabeth, Brigantine NWR, Baltimore, Norfolk, and Savannah. For each area, the wind distribution/ozone summary consists of two parts. In the first part, surface wind data are used as the basis of the diagram. Specifically, the average surface winds for 1000-1300 LST, which is a key time period for daytime ozone formation, are depicted. In the second part, upper-air wind data for 850 mb and the morning (0700 LST) sounding are used as the basis of the diagram. The 850 mb pressure level (approximately 1500 m asl) was selected for this display to represent upper-level winds and possible transport conditions. The data for the morning sounding were selected because the winds at this time have the potential to influence ozone formation during the critical daytime hours. Previous analyses have also found winds for these times and the 850 mb level to be important to ozone formation. Wind data from the local surface and nearest upper-air meteorological monitoring sites were used.

Each display consists of a table that summarizes the frequency of occurrence of calm winds and winds from eight principal wind directions. Calm winds are defined as winds with zero wind speeds, but this category may also include periods with non-zero wind speeds with values up to the threshold of the sensor (typically 0.2-0.4 ms^{-1}). Each wind direction represents the 45 degree sector centered on the direction (e.g., N winds range from 337.5 to 22.5 degrees, NE winds range from 22.5 to 67.5 degrees), where the wind direction is the direction from which the winds blow. This information is then graphically displayed in a "radar" diagram, such that each ring moving outward from the center represents a ten percent increase in the frequency of occurrence of the wind from a given direction. Finally, the wind information is combined with ozone data in the wind/ozone relationship diagram. For each wind speed and wind direction combination, the 90th percentile value of 8-hour ozone concentration over all days meeting the wind criteria (as defined along the x- and y-axes) is presented. The colors correspond to the concentration ranges used by EPA for 8-hour ozone forecasting as follows: Green (< 60 ppb), Yellow (60-75 ppb), Orange (75-95 ppb), Red (≥ 95 ppb).

The displays for each area are presented in the order listed above (north to south).

WD	%
Calm	5
N	8
NE	8
E	19
SE	8
S	22
SW	6
W	9
NW	15



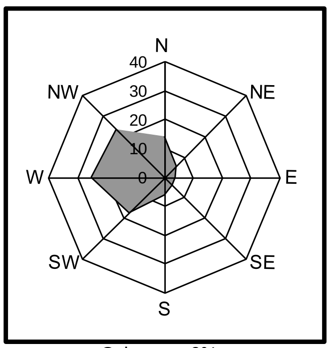
Calm: 5%

WD → WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	58							
1-2	44	57	43	58	54	53	53	52
2-3	50	44	52	69	72	63	62	57
3-4	46	47	53	61	68	68	70	53
4-5	42	45	50	68	61	64	75	53
5-6	47	45	52	55	65	76	66	50
6-7	44	48	48	46	54	66	57	45
7-8	46	44	44		58	65	52	51
8-9	42	46	43	57	53		60	50
9-10	53		54			34	32	46
>=10	43		48		45		40	51

90th percentile of daily maximum 8-hour ozone concentration (ppb) for days meeting the wind speed and direction criteria

Figure 52a. Wind direction frequency diagram and ozone concentration/wind relationship diagram based on surface wind data for 1000-1300 LST for 2000–2010: Portland.

WD	%
Calm	0
N	14
NE	6
E	4
SE	4
S	6
SW	17
W	25
NW	24



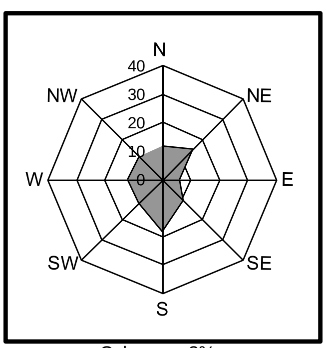
Calm: 0%

WD → WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	76							
1-2	49	47	50	47	44	46	49	63
2-3	48	52	44	43	50	54	64	52
3-4	55	39	49	40	46	56	64	51
4-5	50	53	46	50	49	68	66	60
5-6	51	43	48	45	46	69	62	53
6-7	52	40	43	37	51	55	80	64
7-8	46	45	45	49	48	67	59	65
8-9	51	51	47	44	52	56	62	52
9-10	51	42	45	37	49	61	64	55
>=10	49	51	45	54	53	60	66	58

90th percentile of daily maximum 8-hour ozone concentration (ppb) for days meeting the wind speed and direction criteria

Figure 52b. Wind direction frequency diagram and ozone concentration/wind relationship diagram based on upper-air wind data for 0700 LST for 2000–2010: Portland/Gray.

WD	%
Calm	3
N	12
NE	15
E	6
SE	10
S	18
SW	12
W	12
NW	11



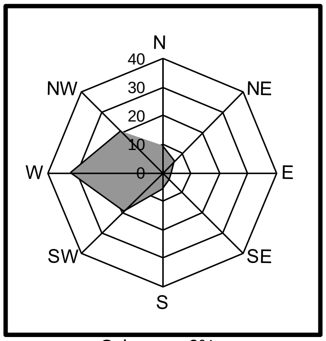
Calm: 3%

WD → WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	70							
1-2	61	63	62	68	64	56	62	51
2-3	59	59	68	65	64	70	72	56
3-4	63	51	49	78	74	79	63	69
4-5	50	52	47	79	71	81	82	62
5-6	53	50	57	72	60	69	88	54
6-7	55	47	43	51	57	77	70	56
7-8	48	52	45	45	51	74	87	56
8-9	46	50		31	27	58	47	35
9-10		49		52		56	52	46
>=10	42	43			37	58		44

90th percentile of daily maximum 8-hour ozone concentration (ppb) for days meeting the wind speed and direction criteria

Figure 53a. Wind direction frequency diagram and ozone concentration/wind relationship diagram based on surface wind data for 1000-1300 LST for 2000–2010: Providence.

WD	%
Calm	0
N	10
NE	6
E	3
SE	3
S	6
SW	19
W	32
NW	21



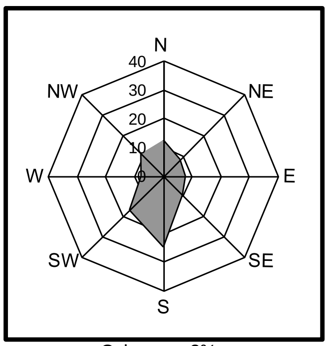
Calm: 0%

WD → WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	70							
1-2	74	68	55	62	57	43	54	56
2-3	50	58		62	56	54	78	63
3-4	65	52	59	51	53	84	75	59
4-5	56	55	45	39	57	66	73	83
5-6	51	64	55	48	66	45	74	65
6-7	57	54	44	46	43	70	78	68
7-8	66	52	51	47	57	69	71	71
8-9	52	54	51	37	40	69	69	64
9-10	67	55	45	37	40	65	79	63
>=10	54	56	45	52	52	60	72	61

90th percentile of daily maximum 8-hour ozone concentration (ppb) for days meeting the wind speed and direction criteria

Figure 53b. Wind direction frequency diagram and ozone concentration/wind relationship diagram based on upper-air wind data for 0700 LST for 2000–2010: Providence/Chatham.

WD	%
Calm	2
N	13
NE	8
E	8
SE	9
S	25
SW	17
W	8
NW	11



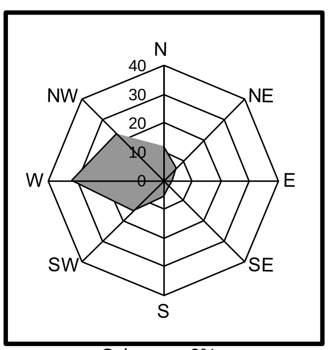
Calm: 2%

WD → WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	60							
1-2	63	46	46	58	67	80	89	58
2-3	60	44	50	71	65	67	111	52
3-4	61	60	57	56	70	80	59	64
4-5	56	47	51	69	73	76	63	59
5-6	58	51	46	55	72	76	75	63
6-7	44	49	54	46	59	84	68	51
7-8	48	47	43	41	58	79	57	48
8-9	46	45	48	42	52	70	44	51
9-10	46	42	44	38	45	53	50	47
>=10	36	38	54	45	57	37	43	49

90th percentile of daily maximum 8-hour ozone concentration (ppb) for days meeting the wind speed and direction criteria

Figure 54a. Wind direction frequency diagram and ozone concentration/wind relationship diagram based on surface wind data for 1000-1300 LST for 2000–2010: New York.

WD	%
Calm	0
N	12
NE	6
E	3
SE	3
S	6
SW	15
W	32
NW	23



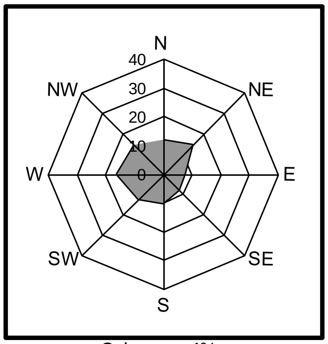
Calm: 0%

WD → WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	63							
1-2	70	55	64	49	47	45	75	59
2-3	69	58	55	50	53	51	63	75
3-4	66	73	64	42	54	57	63	85
4-5	89	49	47	50	61	69	76	68
5-6	67	52	38	41	43	61	76	82
6-7	64	69	42	61	49	58	81	76
7-8	62	49	40	42	44	55	73	80
8-9	57	50	57	38	43	61	73	64
9-10	50	46	37	37	43	58	68	66
>=10	55	49	51	39	43	58	67	63

90th percentile of daily maximum 8-hour ozone concentration (ppb) for days meeting the wind speed and direction criteria

Figure 54b. Wind direction frequency diagram and ozone concentration/wind relationship diagram based on upper-air wind data for 0700 LST for 2000–2010: New York/Brookhaven.

WD	%
Calm	4
N	12
NE	15
E	8
SE	8
S	10
SW	12
W	16
NW	14



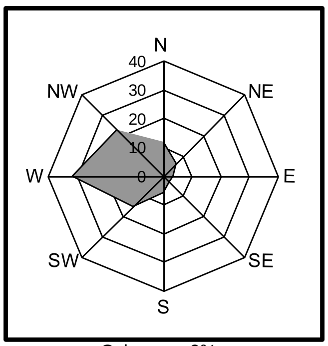
Calm: 4%

WD → / WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	66							
1-2	71	62	73	64	57	68	70	73
2-3	63	52	62	57	65	62	89	68
3-4	61	55	47	49	69	80	70	65
4-5	57	45	42	54	66	71	82	66
5-6	49	43	42	44	49	73	84	59
6-7	45	46	64	40	52	69	73	50
7-8	43	40	38	49	63	71	63	49
8-9	48	42		32	40	63	62	47
9-10	47	31	26			73	54	44
>=10	47	25				49	51	46

90th percentile of daily maximum 8-hour ozone concentration (ppb) for days meeting the wind speed and direction criteria

Figure 55a. Wind direction frequency diagram and ozone concentration/wind relationship diagram based on surface wind data for 1000-1300 LST for 2000–2010: Newark-Elizabeth.

WD	%
Calm	0
N	12
NE	6
E	3
SE	3
S	6
SW	15
W	32
NW	23



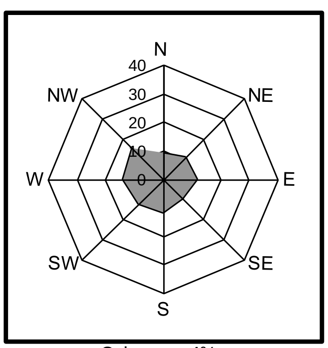
Calm: 0%

WD → / WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	58							
1-2	66	52	70	42	49	54	82	67
2-3	71	68	58	39	51	52	65	81
3-4	66	69	54	27	52	51	77	71
4-5	73	48	44	44	54	75	70	66
5-6	62	57	35	41	42	61	67	85
6-7	62	64	33	60	44	53	78	77
7-8	62	44	34	37	41	57	72	72
8-9	57	47	43	27	35	69	73	68
9-10	46	55	41	27	40	59	69	70
>=10	50	47	43	33	41	61	65	59

90th percentile of daily maximum 8-hour ozone concentration (ppb) for days meeting the wind speed and direction criteria

Figure 55b. Wind direction frequency diagram and ozone concentration/wind relationship diagram based on upper-air wind data for 0700 LST for 2000–2010: Newark-Elizabeth/Brookhaven.

WD	%
Calm	4
N	9
NE	11
E	12
SE	10
S	12
SW	12
W	14
NW	16



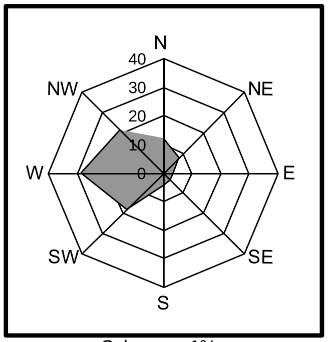
Calm: 4%

WD → / WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	66							
1-2	71	68	66	70	65	63	73	79
2-3	66	60	60	63	65	64	72	71
3-4	76	54	63	64	67	71	71	76
4-5	66	52	54	62	67	75	76	71
5-6	48	48	51	56	64	69	68	66
6-7	41	48	51	66	58	65	74	59
7-8	54	49	57	40	59	70	69	55
8-9	35	50	49	52	58	49	51	54
9-10	38	51	53		47		49	50
>=10	29	47	49	54	62	47	52	46

90th percentile of daily maximum 8-hour ozone concentration (ppb) for days meeting the wind speed and direction criteria

Figure 56a. Wind direction frequency diagram and ozone concentration/wind relationship diagram based on surface wind data for 1000-1300 LST for 2000–2010: Brigantine NWR.

WD	%
Calm	1
N	12
NE	8
E	3
SE	3
S	4
SW	18
W	29
NW	21



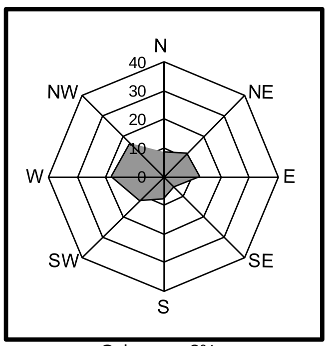
Calm: 1%

WS (m/s) \ WD →	N	NE	E	SE	S	SW	W	NW
<1	68							
1-2	62	63	57	61	70	73	62	78
2-3	81	74	71	59	79	61	65	88
3-4	67	68	48	56	51	65	73	79
4-5	75	64	61	53	55	56	72	79
5-6	74	67	58	59	61	63	79	70
6-7	71	66	75	43	43	56	69	72
7-8	63	76	59	42	58	64	68	61
8-9	63	49	67	43	50	64	76	79
9-10	63	55	45	43	38	55	62	58
>=10	56	57	48	48	53	59	64	59

90th percentile of daily maximum 8-hour ozone concentration (ppb) for days meeting the wind speed and direction criteria

Figure 56b. Wind direction frequency diagram and ozone concentration/wind relationship diagram based on upper-air wind data for 0700 LST for 2000–2010: Brigantine NWR/Wallops Island.

WD	%
Calm	8
N	9
NE	12
E	13
SE	5
S	8
SW	12
W	18
NW	17



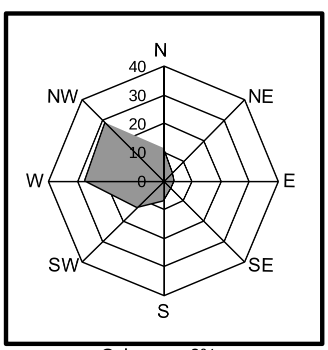
Calm: 8%

WS (m/s) \ WD →	N	NE	E	SE	S	SW	W	NW
<1	76							
1-2	80	69	65	72	79	66	75	81
2-3	79	69	75	68	68	80	78	81
3-4	70	63	65	70	69	73	80	77
4-5	53	54	59	58	63	73	71	66
5-6	62	54	54	53	56	58	75	60
6-7	54	54	52	32		66	61	54
7-8	47	42	46	37		53	58	45
8-9		42	39			48	47	48
9-10		44					49	52
>=10		27	42				46	49

90th percentile of daily maximum 8-hour ozone concentration (ppb) for days meeting the wind speed and direction criteria

Figure 57a. Wind direction frequency diagram and ozone concentration/wind relationship diagram based on surface wind data for 1000-1300 LST for 2000–2010: Baltimore.

WD	%
Calm	0
N	12
NE	4
E	4
SE	4
S	7
SW	13
W	27
NW	29



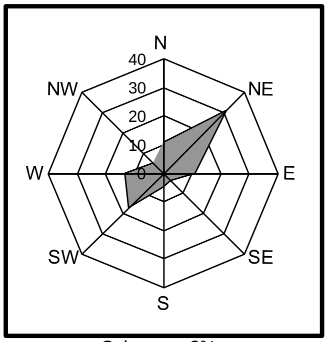
Calm: 0%

WS (m/s) \ WD →	N	NE	E	SE	S	SW	W	NW
<1	76							
1-2	62	59	74	71	69	78	65	64
2-3	83	79	68	56	76	77	77	76
3-4	83	58	58	71	68	86	80	82
4-5	98	72	63	56	70	76	74	103
5-6	80	62	78	68	58	71	86	72
6-7	65	75	61	42	57	67	77	79
7-8	63	68	50	47	47	77	69	74
8-9	61	60	72	54	50	65	71	66
9-10	66	49	53	40	59	54	71	70
>=10	58	48	52	43	47	51	63	63

90th percentile of daily maximum 8-hour ozone concentration (ppb) for days meeting the wind speed and direction criteria

Figure 57b. Wind direction frequency diagram and ozone concentration/wind relationship diagram based on upper-air wind data for 0700 LST for 2000–2010Baltimore/Dulles International Airport.

WD	%
Calm	3
N	11
NE	31
E	11
SE	4
S	5
SW	17
W	13
NW	5

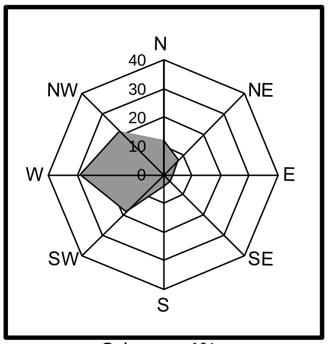


WD → / WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	66							
1-2	74	74	65	55	58	54	59	67
2-3	67	76	58	53	61	60	69	68
3-4	64	75	62	57	52	66	71	65
4-5	65	66	64	54	56	66	72	59
5-6	60	66	61	74	55	64	70	65
6-7	53	55	57	46	50	71	60	56
7-8	52	53	65		46	64	76	47
8-9	45	54	53		31	65	63	
9-10		56	37		31	70	62	
>=10	32	55	45		27	69		

90th percentile of daily maximum 8-hour ozone concentration (ppb) for days meeting the wind speed and direction criteria

Figure 58a. Wind direction frequency diagram and ozone concentration/wind relationship diagram based on surface wind data for 1000-1300 LST for 2000–2010: Norfolk.

WD	%
Calm	1
N	12
NE	7
E	3
SE	3
S	4
SW	18
W	29
NW	21

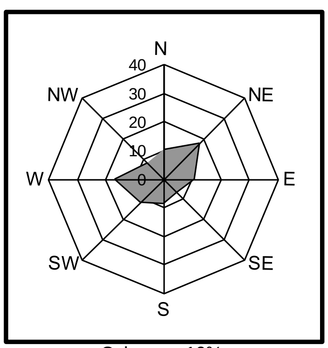


WD → / WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	65							
1-2	64	60	52	56	65	68	54	68
2-3	83	69	53	43	70	67	65	93
3-4	72	67	44	55	54	64	69	74
4-5	81	66	61	41	54	52	72	75
5-6	69	86	52	48	54	61	76	67
6-7	75	71	65	43	42	60	70	71
7-8	72	63	59	38	52	62	67	67
8-9	68	58	58	40	48	56	71	66
9-10	62	58	33	30	38	53	66	67
>=10	64	62	53	48	48	59	66	62

90th percentile of daily maximum 8-hour ozone concentration (ppb) for days meeting the wind speed and direction criteria

Figure 58b. Wind direction frequency diagram and ozone concentration/wind relationship diagram based on upper-air wind data for 0700 LST for 2000–2010: Norfolk/Wallops Island.

WD	%
Calm	10
N	10
NE	18
E	11
SE	7
S	9
SW	11
W	17
NW	8

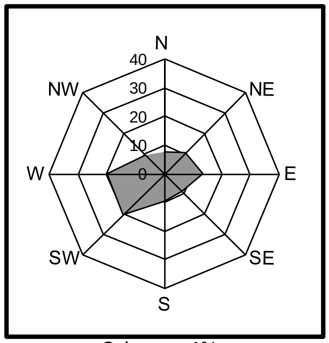


WD → / WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	64							
1-2	59	55	54	53	55	55	64	64
2-3	61	56	56	52	53	62	59	65
3-4	63	53	54	53	52	59	63	62
4-5	51	56	54	56	52	54	59	62
5-6	54	52	52	50	46	44	56	69
6-7	48	48	57	59	48	55	53	54
7-8	45	42	50	46	33	23	54	49
8-9	34		26	58		37	44	41
9-10	34				37		48	
>=10	49			31				

90th percentile of daily maximum 8-hour ozone concentration (ppb) for days meeting the wind speed and direction criteria

Figure 59a. Wind direction frequency diagram and ozone concentration/wind relationship diagram based on surface wind data for 1000-1300 LST for 2000–2010: Savannah.

WD	%
Calm	1
N	8
NE	10
E	13
SE	9
S	10
SW	20
W	20
NW	9



WD → / WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	52							
1-2	50	58	56	64	43	52	65	60
2-3	66	59	61	66	49	56	62	64
3-4	64	56	56	53	56	56	63	67
4-5	71	61	55	42	55	54	60	62
5-6	64	63	59	44	44	52	60	61
6-7	60	65	54	47	48	54	65	61
7-8	69	65	58	41	45	54	55	68
8-9	57	60	51	48	51	50	60	60
9-10	56	62	52	38	48	53	57	53
>=10	52	56	49	48	42	48	58	55

90th percentile of daily maximum 8-hour ozone concentration (ppb) for days meeting the wind speed and direction criteria

Figure 59b. Wind direction frequency diagram and ozone concentration/wind relationship diagram based on upper-air wind data for 0700 LST for 2000–2010: Savannah/Jacksonville.

The wind frequency diagrams indicate that for Portland and Providence, the higher ozone concentrations are associated with westerly and/or southerly wind components and low to moderate wind speeds. Moving southward along the coast, higher ozone for many areas is also associated with northerly wind components, in addition to westerly and southerly winds. For the mid-Atlantic areas such as Brigantine NWR and Baltimore, high ozone is associated with a wide range of wind directions. For Norfolk and Savannah, the winds are predominantly northwesterly to northeasterly on the higher ozone days. Overall, there are a wide range of patterns among the different locations, but one general finding is that moving along the coast from north to south, there is a shift from southerly to northerly wind components on higher ozone days. The lowest concentrations tend to occur with easterly winds, although this varies slightly from area to area.

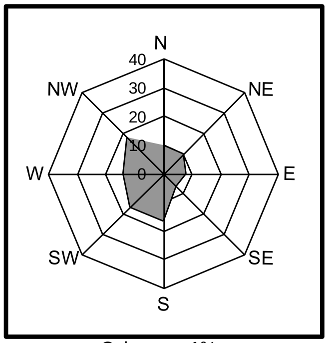
3.2. Annual Wind Distributions and PM2.5

Figures 60 through 67 present information about wind direction frequency, and the observed relationship between wind speed, wind direction and $PM_{2.5}$ concentration. The data used to prepare the diagrams cover the period 2000–2010. This analysis samples several areas along the Atlantic Coast including Portland, Providence, New York, Newark-Elizabeth, Baltimore, Norfolk, Wilmington (NC), and Savannah. For $PM_{2.5,}$ daily (24-hour) average surface winds are depicted in the first part diagram (a) and upper-air winds for 850 mb and the morning (0700 LST) sounding are used in the second part of the diagram (b). The wind data are from the local surface and nearest upper-air meteorological monitoring sites.

For each wind speed and wind direction combination in the wind/$PM_{2.5}$ relationship diagram, the 90th percentile value of the daily (24-hour average) $PM_{2.5}$ concentration over all days meeting the wind criteria is presented. The colors correspond to the following concentration range: Green (< 15 μgm^{-3}), Yellow (15–25 μgm^{-3}), Orange (25–35 μgm^{-3}), Red (≥ 35 μgm^{-3}).

The displays for each area are presented in the order listed above (north to south).

WD	%
Calm	1
N	10
NE	10
E	8
SE	6
S	17
SW	17
W	14
NW	18



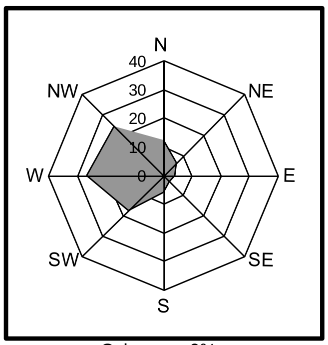
Calm: 1%

WD → WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	30							
1-2	18	14	16	21	28	31	25	22
2-3	15	13	18	13	22	17	19	20
3-4	12	12	9	12	20	26	15	12
4-5	7	6	8	17	9	14	15	10
5-6	8	7	3	7	19	18	11	10
6-7	5	13		6		8	8	15
7-8	10	3	3					8
8-9		2					4	3
9-10						4		
>=10		3						

90th percentile of 24-hr PM2.5 concentration (ug/m3)
for days meeting the wind speed and direction criteria

Figure 60a. Wind direction frequency diagram and $PM_{2.5}$ concentration/wind relationship diagram based on surface wind data for 2000–2010: Portland.

WD	%
Calm	0
N	12
NE	6
E	4
SE	3
S	6
SW	17
W	27
NW	24



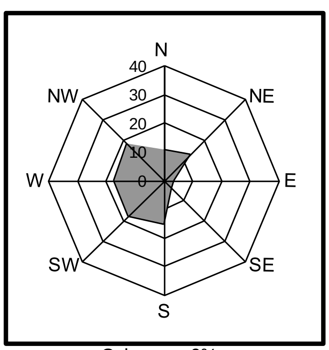
Calm: 0%

WD → WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	12							
1-2	9	7	8	16	7	3	7	10
2-3	16	7		6	14		30	8
3-4	13	8	6		8	12	15	12
4-5	9	19	13	10	7	18	22	11
5-6	19	9	12		7	20	21	19
6-7	5		8	6	21	14	31	21
7-8	8	7			24	21	14	15
8-9	12	6		14		31	20	14
9-10	17	8	12		8	26	16	14
>=10	15	9	4	8	11	21	21	19

980th percentile of 24-hr PM2.5 concentration (ug/m3)
for days meeting the wind speed and direction criteria

Figure 60b. Wind direction frequency diagram and $PM_{2.5}$ concentration/wind relationship diagram based on upper-air wind data for 0700 LST for 2000–2010: Portland/Gray.

WD	%
Calm	0
N	11
NE	13
E	3
SE	4
S	15
SW	18
W	17
NW	18



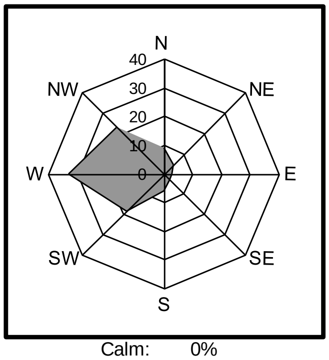
Calm: 0%

WD → WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	26							
1-2	30	20	19	18	23	26	30	19
2-3	15	17	15	19	20	21	22	19
3-4	14	14	12	22	20	24	19	13
4-5	10	12	6	16	18	23	19	11
5-6	10	8	7	14	15	22	10	9
6-7	10	8	4	6	10	13	12	9
7-8	9	6			8	11	8	5
8-9	6	5			5	5	8	6
9-10	3	1		5		6	6	4
>=10	6	3						3

90th percentile of 24-hr PM2.5 concentration (ug/m3)
for days meeting the wind speed and direction criteria

Figure 61a. Wind direction frequency diagram and $PM_{2.5}$ concentration/wind relationship diagram based on surface wind data for 2000–2010: Providence.

WD	%
Calm	0
N	9
NE	5
E	3
SE	3
S	6
SW	18
W	33
NW	23

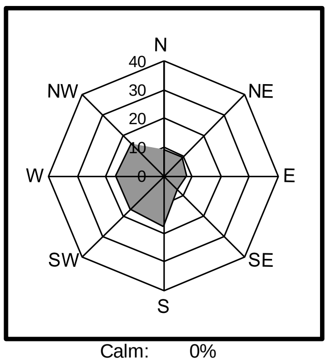


WD → / WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	13							
1-2	19	16	14	12	9	13	9	15
2-3	9	31	13	16	16	11	18	19
3-4	17	16	9	12	10	20	28	13
4-5	16	11	5	14	20	15	29	19
5-6	17	13	9	9	16	18	24	13
6-7	11	11	8	6	11	19	24	16
7-8	14	13	9	10	17	18	23	19
8-9	16	9	18	6	13	23	23	18
9-10	12	8	7	6	9	21	21	17
>=10	12	9	7	9	9	18	21	14

980th percentile of 24-hr PM2.5 concentration (ug/m3)
for days meeting the wind speed and direction criteria

Figure 61b. Wind direction frequency diagram and $PM_{2.5}$ concentration/wind relationship diagram based on upper-air wind data for 0700 LST for 2000–2010: Providence/Chatham.

WD	%
Calm	0
N	9
NE	9
E	8
SE	7
S	18
SW	16
W	17
NW	16

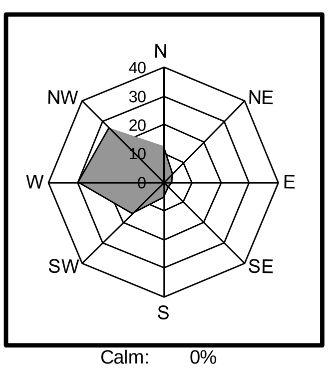


WD → / WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	16							
1-2	36	13	26	15	44	34		32
2-3	20	16	20	22	23	28	29	14
3-4	14	17	20	15	26	29	22	17
4-5	15	15	18	12	20	29	22	13
5-6	10	14	14	8	21	28	23	14
6-7	9	9	8	9	13	30	16	7
7-8	5	7	5	6	12	17	14	10
8-9	5	6		5	7	7	11	8
9-10	11	10	8		7	4	8	8
>=10			4	6	5		8	6

90th percentile of 24-hr PM2.5 concentration (ug/m3)
for days meeting the wind speed and direction criteria

Figure 62a. Wind direction frequency diagram and $PM_{2.5}$ concentration/wind relationship diagram based on surface wind data for 2000–2010: New York.

WD	%
Calm	0
N	13
NE	4
E	3
SE	2
S	5
SW	15
W	30
NW	27



WD → / WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	21							
1-2	9	11	10	4	4	8	16	22
2-3	22	13	6	5	18	17	14	21
3-4	14	12	20	36	14	18	21	25
4-5	20	15	8	5	20	15	27	17
5-6	15	14	10	8	7	23	28	22
6-7	21	9	13	10	10	18	33	23
7-8	18	12	11	10	11	16	30	31
8-9	10	7	7	6	11	22	32	22
9-10	15	13	6	5	6	19	19	19
>=10	11	6	12	6	9	19	25	17

90th percentile of 24-hr PM2.5 concentration (ug/m3)
for days meeting the wind speed and direction criteria

Figure 62b. Wind direction frequency diagram and $PM_{2.5}$ concentration/wind relationship diagram based on upper-air wind data for 0700 LST for 2000–2010: New York/Brookhaven.

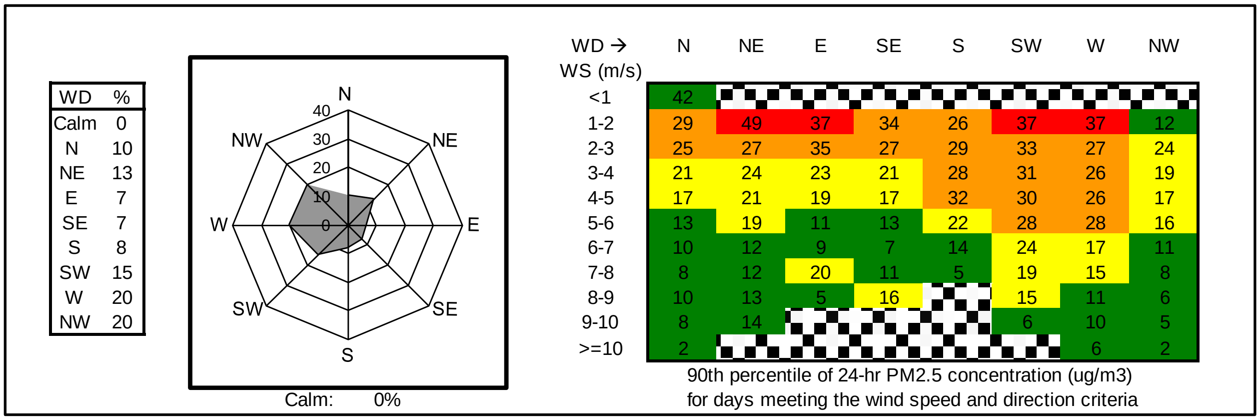


Figure 63a. Wind direction frequency diagram and $PM_{2.5}$ concentration/wind relationship diagram based on surface wind data for 2000–2010: Newark-Elizabeth.

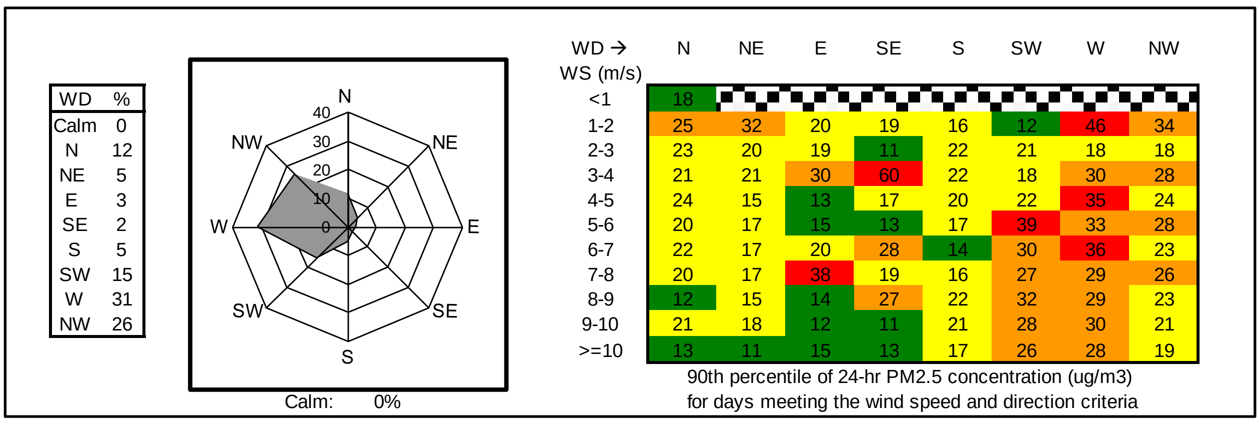


Figure 63b. Wind direction frequency diagram and $PM_{2.5}$ concentration/wind relationship diagram based on upper-air wind data for 0700 LST for 2000–2010: Newark-Elizabeth/Brookhaven.

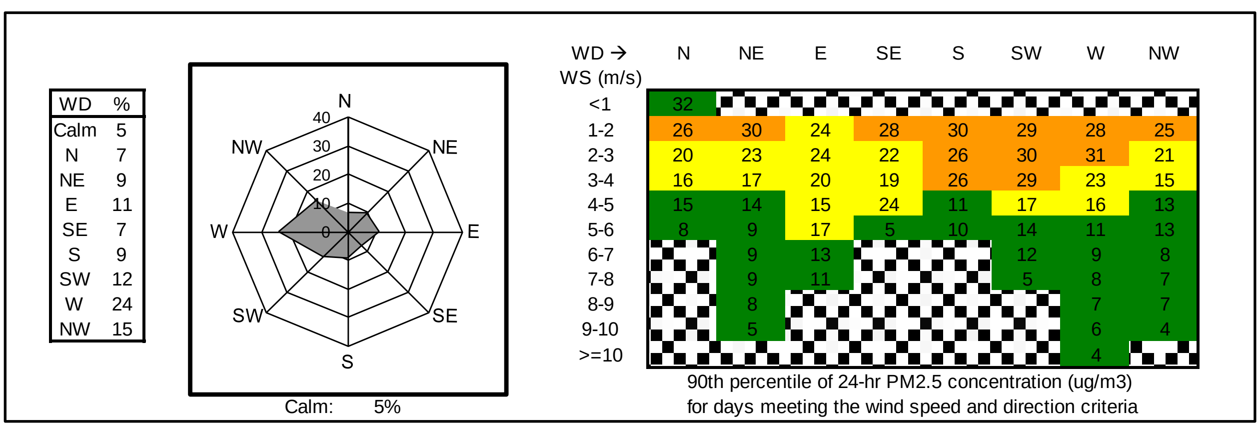
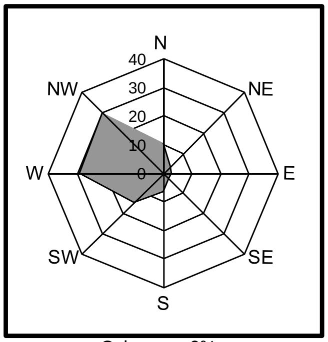


Figure 64a. Wind direction frequency diagram and $PM_{2.5}$ concentration/wind relationship diagram based on surface wind data for 2000–2010: Baltimore.

WD	%
Calm	0
N	11
NE	3
E	3
SE	3
S	6
SW	14
W	29
NW	30



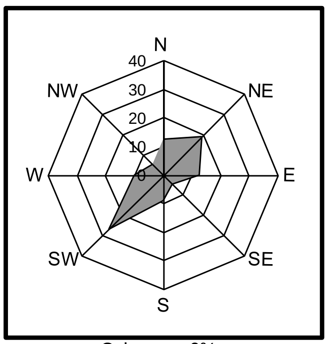
Calm: 0%

WS (m/s) \ WD →	N	NE	E	SE	S	SW	W	NW
<1	35							
1-2	16	15	25	34	24	28	22	34
2-3	37	37	24	17	25	32	29	29
3-4	29	22	16	22	23	33	29	30
4-5	26	18	15	22	25	21	32	36
5-6	28	25	16	24	18	28	34	32
6-7	19	21	21	22	27	23	31	25
7-8	25	15	29	18	18	32	27	26
8-9	23	17	12	11	20	25	27	22
9-10	19	13	12	17	20	23	29	28
>=10	13	10	10	13	16	25	25	21

90th percentile of 24-hr PM2.5 concentration (ug/m3) for days meeting the wind speed and direction criteria

Figure 64b. Wind direction frequency diagram and $PM_{2.5}$ concentration/wind relationship diagram based on upper-air wind data for 0700 LST for 2000–2010: Baltimore/Dulles International Airport.

WD	%
Calm	0
N	13
NE	19
E	13
SE	4
S	9
SW	27
W	10
NW	5



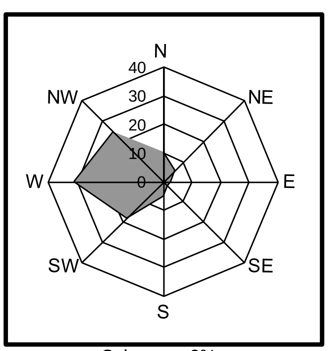
Calm: 0%

WS (m/s) \ WD →	N	NE	E	SE	S	SW	W	NW
<1	21							
1-2	22	21	27	14	23	23	22	18
2-3	22	25	25	22	28	27	22	18
3-4	16	18	18	15	22	24	20	18
4-5	14	16	16	13	17	25	20	10
5-6	15	14	11	19	12	20	14	11
6-7	14	12	11		4	21	14	6
7-8	12	11	9		6	16	8	13
8-9	4	10				9		
9-10		4	4			16		
>=10	11	5						

90th percentile of 24-hr PM2.5 concentration (ug/m3) for days meeting the wind speed and direction criteria

Figure 65a. Wind direction frequency diagram and $PM_{2.5}$ concentration/wind relationship diagram based on surface wind data for 2000–2010: Norfolk.

WD	%
Calm	0
N	10
NE	6
E	3
SE	2
S	5
SW	18
W	31
NW	25



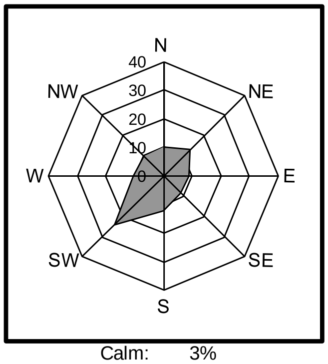
Calm: 0%

WS (m/s) \ WD →	N	NE	E	SE	S	SW	W	NW
<1	11							
1-2	17	15	21	16	17	13	17	17
2-3	20	19	13	9	23	11	19	40
3-4	20	30	18	12	12	21	27	27
4-5	29	12	19	6	10	16	27	28
5-6	17	11	8	13		20	25	25
6-7	31	21	10	15	4	20	25	20
7-8	18	17	6	6	9	20	21	22
8-9	18	4	11	6	10	15	28	24
9-10	17	10	10		16	25	19	22
>=10	15	17	12	10	12	19	21	17

90th percentile of 24-hr PM2.5 concentration (ug/m3) for days meeting the wind speed and direction criteria

Figure 65b. Wind direction frequency diagram and $PM_{2.5}$ concentration/wind relationship diagram based on upper-air wind data for 0700 LST for 2000–2010: Norfolk/Wallops Island.

WD	%
Calm	3
N	10
NE	13
E	9
SE	8
S	12
SW	24
W	10
NW	10

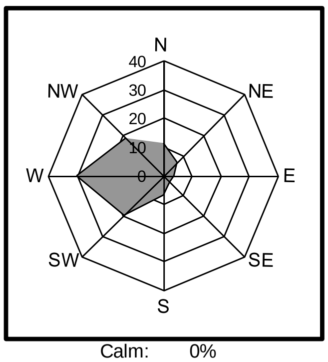


WD → WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	15							
1-2	16	16	16	15	16	18	15	16
2-3	12	15	18	13	16	18	24	15
3-4	13	14	20	13	17	23	17	13
4-5	12	15	16	11	10	19	13	11
5-6	9	13		10	10	14	14	10
6-7	10	4			8	16	7	10
7-8	8	13			6	4	8	
8-9							4	
9-10							7	
>=10								

90th percentile of 24-hr PM2.5 concentration (ug/m3)
for days meeting the wind speed and direction criteria

Figure 66a. Wind direction frequency diagram and $PM_{2.5}$ concentration/wind relationship diagram based on surface wind data for 2000–2010: Wilmington (NC).

WD	%
Calm	0
N	11
NE	7
E	4
SE	3
S	7
SW	19
W	30
NW	19

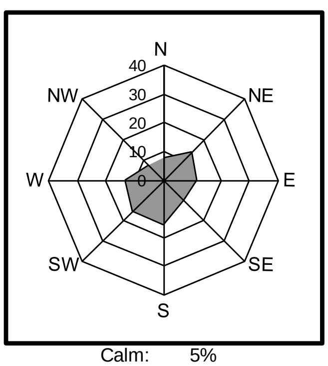


WD → WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	14							
1-2	9	11	17	10	10	13	19	13
2-3	12	10		12	10	15	13	17
3-4	19	9	16	6	8	13	16	16
4-5	17	12	13	11	12	20	23	15
5-6	22	14	2	8	10	19	20	20
6-7	13	13	12	10	13	18	23	18
7-8	25	17	6	3	32	12	17	18
8-9	15	21	14	4	15	12	17	17
9-10	17	18		9	8	18	20	22
>=10	18	13	14	5	10	14	15	13

90th percentile of 24-hr PM2.5 concentration (ug/m3)
for days meeting the wind speed and direction criteria

Figure 66b. Wind direction frequency diagram and $PM_{2.5}$ concentration/wind relationship diagram based on upper-air wind data for 0700 LST for 2000–2010: Wilmington (NC)/Newport News-Morehead City.

WD	%
Calm	5
N	8
NE	14
E	12
SE	10
S	16
SW	15
W	13
NW	7

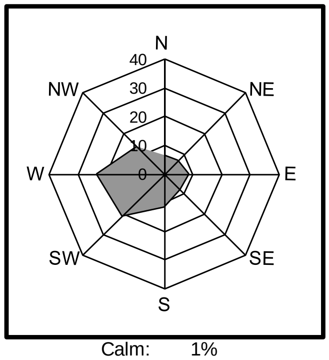


WD → WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	25							
1-2	25	18	24	24	23	25	24	22
2-3	21	20	19	18	20	19	21	20
3-4	19	19	20	12	15	17	16	17
4-5	16	16	13	17	10	18	16	12
5-6	14	14	8	11	9	7	11	15
6-7		11			10	7	7	
7-8		13				11	7	8
8-9	14			10				6
9-10								
>=10								

90th percentile of 24-hr PM2.5 concentration (ug/m3)
for days meeting the wind speed and direction criteria

Figure 67a. Wind direction frequency diagram and $PM_{2.5}$ concentration/wind relationship diagram based on surface wind data for 2000–2010: Savannah.

WD	%
Calm	1
N	7
NE	7
E	9
SE	8
S	12
SW	21
W	24
NW	14



WD → / WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	17							
1-2	13	29	26	32	24	22	22	20
2-3	20	21	27	24	19	18	23	21
3-4	25	15	16	15	17	25	24	24
4-5	26	21	11	18	15	18	24	24
5-6	21	25	19	11	19	22	23	19
6-7	26	32	15	10	12	17	20	18
7-8	20	25	20	14	18	25	23	27
8-9	10	16	23	19	21	17	23	20
9-10	21	23	17	12	18	20	22	15
>=10	14	11	17	12	13	15	18	20

90th percentile of 24-hr PM2.5 concentration (ug/m3)
for days meeting the wind speed and direction criteria

Figure 67b. Wind direction frequency diagram and $PM_{2.5}$ concentration/wind relationship diagram based on upper-air wind data for 0700 LST for 2000–2010: Savannah/Jacksonville.

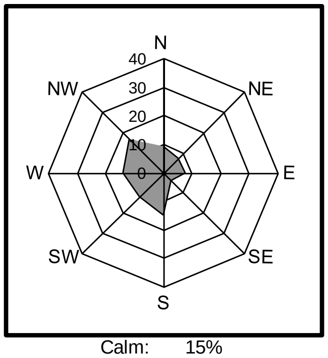
For most sites, higher $PM_{2.5}$ concentrations occur under conditions of low surface wind speeds and a wide range of conditions aloft.

3.3. Annual Wind Distributions and Visibility

Figures 68 through 73 present information about wind direction frequency, and the observed relationship between wind speed, wind direction and extinction coefficient for Casco Bay, Martha's Vineyard, New York City, Brigantine NWR, Swanquarter NWR, and Okefenokee NWR. The data used to prepare the diagrams cover the period 2000–2010, as available. Daily (24-hour) average surface winds are depicted in the first part of the diagram (a) and upper-air winds for 850 mb and the morning (0700 LST) sounding are used in the second part of the diagram (b). Again, the wind data are from the local surface meteorological monitoring site and the nearest upper-air monitoring site.

For each wind speed and wind direction combination in the wind/visibility relationship diagram, the average value of the daily extinction coefficient over all days meeting the wind criteria is presented. In this case, the colors designate whether the value shown falls approximately within the <20, 20-50, 50-80 and ≥80 percentile ranges of extinction coefficient for all days. Green is therefore representative of the "best" visibility days and red is representative of the "worst" visibility days. The percentile ranges for each site are only approximate, however, because a consistent formatting was used for all three areas with break points at 60, 90 and 120 Mm^{-1}. This allows us to compare the charts for the different areas.

WD	%
Calm	15
N	9
NE	7
E	8
SE	4
S	15
SW	12
W	14
NW	17

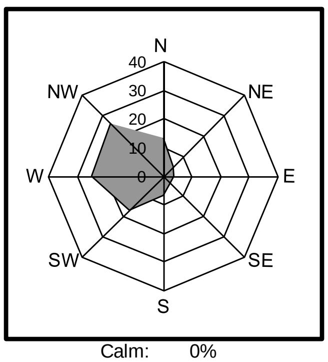


WD → WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	57							
1-2	50	48	52	55	78	59	47	44
2-3	42	41	53	45	71	69	53	36
3-4	37	53	34	41	75	81	50	35
4-5	33	32	36		64	79	42	34
5-6	31	33	25	41	32		30	33
6-7	27	32					27	31
7-8	29	30	44			23		30
8-9		19				24	22	
9-10							24	
>=10		21						

Average of daily average extinction coefficient (Mm-1)
for days meeting the wind speed and direction criteria

Figure 68a. Wind direction frequency diagram and extinction coefficient/wind relationship diagram based on surface wind data for 2000–2010: Casco Bay.

WD	%
Calm	0
N	13
NE	5
E	4
SE	3
S	7
SW	17
W	25
NW	26

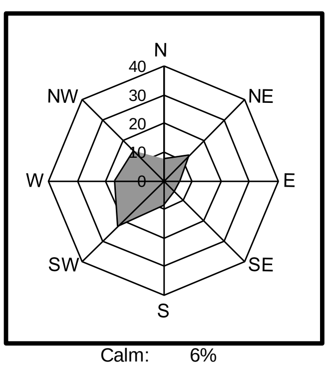


WD → WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	136							
1-2	49	35	46	72	77	67	34	53
2-3	99	36	46	39	48	48	72	48
3-4	40	44	47	51	35	61	66	53
4-5	44	63	54	59	38	81	65	51
5-6	43	34	47	40	38	57	57	52
6-7	33	47	35	40	68	55	68	54
7-8	44	36		87	63	38	77	53
8-9	34	32	52	45	35	86	80	45
9-10	40	32	31		35	67	62	38
>=10	35	31	28	48	40	65	64	38

Average of daily average extinction coefficient (Mm-1)
for days meeting the wind speed and direction criteria

Figure 68b. Wind direction frequency diagram and extinction coefficient/wind relationship diagram based on upper-air wind data for 0700 LST for 2000–2010: Casco Bay/Gray.

WD	%
Calm	6
N	8
NE	13
E	6
SE	5
S	9
SW	23
W	17
NW	15

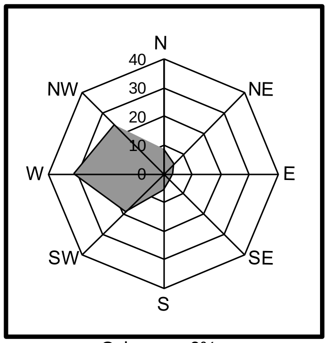


WD → WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	63							
1-2	46	51	63	62	66	72	59	44
2-3	42	45	48	53	68	80	63	51
3-4	41	45	51	52	60	104	93	39
4-5	42	50	44	42	65	108	58	38
5-6	35	40	40	52	59	101	50	38
6-7	36	32	58	67	54	81	54	36
7-8	37	34	62	68	65	108	47	43
8-9	41	39		63	54	78	38	31
9-10	41	36					47	31
>=10	51	45	96					30

Average of daily average extinction coefficient (Mm-1)
for days meeting the wind speed and direction criteria

Figure 69a. Wind direction frequency diagram and extinction coefficient/wind relationship diagram based on surface wind data for 2000–2010: Martha’s Vineyard.

WD	%
Calm	0
N	9
NE	5
E	3
SE	3
S	6
SW	19
W	31
NW	24



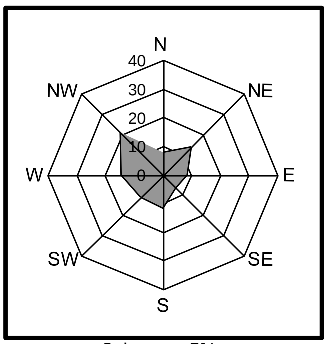
Calm: 0%

WD → / WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	50							
1-2	100		34	51		29	27	37
2-3	42	43		37	38	45	61	54
3-4	60	35	33	40	47	59	67	44
4-5	38	39	45	37	30	75	78	67
5-6	59	35		29	74	59	69	52
6-7	46	44	49	37	57	78	80	58
7-8	51	25	36	31	69	65	72	64
8-9	32	35		35	47	69	83	46
9-10	62	58	24		39	75	83	37
>=10	37	38	50	51	54	78	77	48

Average of daily average extinction coefficient (Mm-1)
for days meeting the wind speed and direction criteria

Figure 69b. Wind direction frequency diagram and extinction coefficient/wind relationship diagram based on upper-air wind data for 0700 LST for 2000–2010: Martha's Vineyard/Chatham.

WD	%
Calm	5
N	8
NE	14
E	8
SE	6
S	12
SW	11
W	15
NW	21



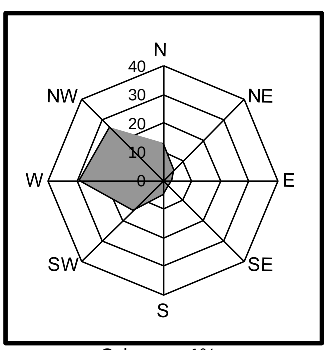
Calm: 5%

WD → / WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	113							
1-2	82	112	139	121	120	151	114	175
2-3	75	97	119	162	165	143	130	93
3-4	66	101	81	70	120	170	122	81
4-5	66	67	78	81	143	141	123	80
5-6	59	77	79		106	119	94	67
6-7	45	59	72		65	132	83	61
7-8	57	68			88		60	55
8-9	67	51						51
9-10		54					54	53
>=10		40	39					40

Average of daily average extinction coefficient (Mm-1)
for days meeting the wind speed and direction criteria

Figure 70a. Wind direction frequency diagram and extinction coefficient/wind relationship diagram based on surface wind data for 2000–2010: New York.

WD	%
Calm	1
N	13
NE	5
E	3
SE	3
S	5
SW	15
W	29
NW	26



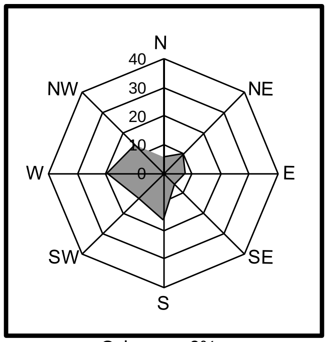
Calm: 1%

WD → / WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	149							
1-2	103					50	135	175
2-3		102	56	67	108	95	87	
3-4	78	94	150	102	129	101	137	154
4-5	103	76	96	97		152	121	106
5-6	100	68	44	69	95	104	108	85
6-7	72	95	69		67	125	165	112
7-8	73	78	56	75	93	135	125	100
8-9	68	57	59		63	139	136	99
9-10	74	87		68		130	163	86
>=10	66	61	68	54	75	108	127	82

Average of daily average extinction coefficient (Mm-1)
for days meeting the wind speed and direction criteria

Figure 70b. Wind direction frequency diagram and extinction coefficient/wind relationship diagram based on upper-air wind data for 0700 LST for 2000–2010: New York/Brookhaven.

WD	%
Calm	9
N	6
NE	10
E	8
SE	6
S	16
SW	12
W	20
NW	14



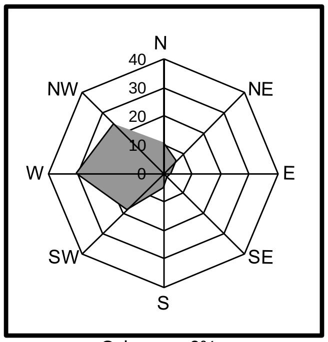
Calm: 9%

WD → WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	88							
1-2	74	81	80	78	112	109	97	87
2-3	67	69	74	85	94	132	101	78
3-4	48	64	81	65	114	116	101	64
4-5	54	57	57	71	78	111	94	57
5-6	36	41	73	80	84	82	64	58
6-7	36	72	70	83			69	44
7-8	39	55	91			46	66	42
8-9		52					54	
9-10		37					44	40
>=10		53						

Average of daily average extinction coefficient (Mm-1) for days meeting the wind speed and direction criteria

Figure 71a. Wind direction frequency diagram and extinction coefficient/wind relationship diagram based on surface wind data for 2000–2010: Brigantine NWR.

WD	%
Calm	0
N	11
NE	6
E	3
SE	2
S	5
SW	18
W	30
NW	25



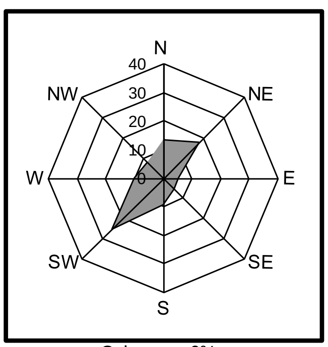
Calm: 0%

WD → WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	91							
1-2	75	74	109	88	107	66	64	81
2-3	64	86	104	126	125	95	127	88
3-4	92	108	102	73	90	127	115	108
4-5	141	67	57		81	94	143	93
5-6	73	59	72	42		129	109	78
6-7	98	97	76	80	81	80	93	85
7-8	61	107	45	37	48	97	99	78
8-9	64	50	60	43	75	94	106	99
9-10	77	38	55		77	88	95	76
>=10	61	66	58	57	60	85	91	70

Average of daily average extinction coefficient (Mm-1) for days meeting the wind speed and direction criteria

Figure 71b. Wind direction frequency diagram and extinction coefficient/wind relationship diagram based on upper-air wind data for 0700 LST for 2000–2010: Brigantine NWR/Wallops Island.

WD	%
Calm	6
N	13
NE	18
E	5
SE	5
S	9
SW	25
W	10
NW	8



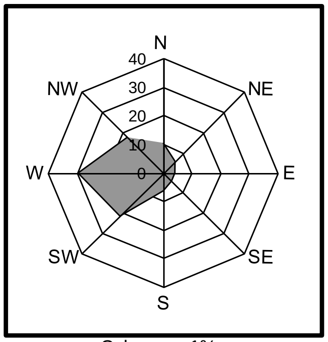
Calm: 6%

WD → WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	85							
1-2	72	76	56	63	69	76	91	88
2-3	73	69	61	47	84	74	73	62
3-4	61	83	56	60	71	84	72	53
4-5	58	54	45	45	76	94	60	63
5-6	63	54		51	53	82	55	54
6-7	73	53	61	44	55	77	44	44
7-8	57	35	35	48	60	61	35	24
8-9	72	71	59		70	51	52	
9-10						60		
>=10					83	73		

Average of daily average extinction coefficient (Mm-1) for days meeting the wind speed and direction criteria

Figure 72a. Wind direction frequency diagram and extinction coefficient/wind relationship diagram based on surface wind data for 2000–2010: Swanquarter NWR.

WD	%
Calm	1
N	11
NE	6
E	4
SE	4
S	6
SW	21
W	30
NW	18



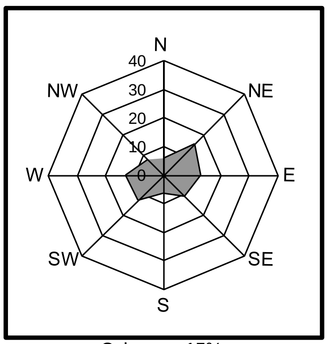
Calm: 1%

WD → / WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	90							
1-2	57	45	51	50	48	142	110	62
2-3	116	69	66	85	44	66	93	86
3-4	80	57	66	51	61	49	89	80
4-5	77	50	99	60	47	69	83	68
5-6	102	94	34		48	67	80	71
6-7	63	71	77	42	45	78	89	84
7-8	94	94	45	35	50	65	97	103
8-9	75	99	95	27	53	64	81	67
9-10	70	63	61	46	39	80	73	91
>=10	59	50	61	50	53	59	75	55

Average of daily average extinction coefficient (Mm-1) for days meeting the wind speed and direction criteria

Figure 72b. Wind direction frequency diagram and extinction coefficient/wind relationship diagram based on upper-air wind data for 0700 LST for 2000–2010: Swanquarter NWR/Newport News-Morehead City.

WD	%
Calm	15
N	6
NE	15
E	13
SE	10
S	6
SW	12
W	13
NW	8



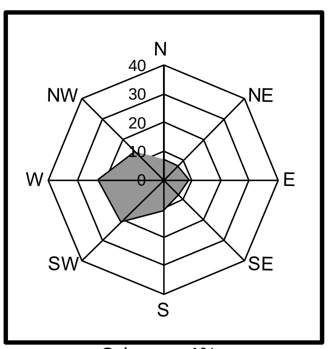
Calm: 15%

WD → / WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	86							
1-2	90	76	88	96	87	78	69	68
2-3	74	87	86	72	71	80	81	67
3-4	70	96	80	68	77	72	76	62
4-5	85	74	92	81	52	66	63	62
5-6	33	75	57	63	50	75	59	
6-7	53	79			90	74	71	54
7-8	52						56	
8-9		105						40
9-10				40				
>=10								

Average of daily average extinction coefficient (Mm-1) for days meeting the wind speed and direction criteria

Figure 73a. Wind direction frequency diagram and extinction coefficient/wind relationship diagram based on surface wind data for 2000–2010: Okefenokee NWR.

WD	%
Calm	1
N	7
NE	7
E	9
SE	8
S	11
SW	21
W	23
NW	14



Calm: 1%

WD → / WS (m/s)	N	NE	E	SE	S	SW	W	NW
<1	84							
1-2	80	85	116	76	65	97	85	125
2-3	111	113	91	88	71	88	108	89
3-4	121	63	75	104	83	88	93	103
4-5	119	89	88	71	65	76	84	86
5-6	101	124	96	63	71	97	79	89
6-7	92	100	74	65	80	79	80	77
7-8	99	100	86	63	75	80	77	103
8-9	60	106	80	89	75	72	83	91
9-10	89	117	71	69	77	73	83	78
>=10	58	61	71	56	59	63	66	66

Average of daily average extinction coefficient (Mm-1) for days meeting the wind speed and direction criteria

Figure 73b. Wind direction frequency diagram and extinction coefficient/wind relationship diagram based on upper-air wind data for 0700 LST for 2000–2010: Okefenokee NWR/Jacksonville.

Higher extinction coefficients occur under a range of wind speeds and wind directions. Poor visibility conditions for these coastal areas can be attributed to high $PM_{2.5}$ and/or high relative humidity. Days with onshore directed flow are likely to also have higher humidity, and some of the higher extinction days occur under easterly conditions.

3.4. Frequency and Characteristics of the Sea Breeze and Relationship to Pollutant Concentrations

In this section we use the persistence index together with measured pollutant concentrations to examine the frequency of the sea breeze and its relationship to pollutant concentrations for selected coastal locations. As a review, the persistence index is defined as the ratio of the 24-hour average vector wind speed and the 24-hour average scalar wind speed. It is an indicator of wind persistence. If the value is 1, this indicates that the vector and scalar wind speeds are the same, which further indicates that the wind was blowing from the same direction during the entire period. For example, a value of 0 indicates that the wind direction was from one direction for half the time and from the opposite direction the other half of the time. Thus a low value indicates the potential for recirculation. This parameter is by no means a measure of a true sea breeze since wind reversals can occur under a variety of conditions. However, along the coast, the sea breeze is an important driver of diurnal wind reversals.

For this analysis, potential sea-breeze days are defined as those with a persistence index less than 0.5. Focusing first on ozone, the ozone season is defined as April through October. Based on this definition, the number of potential sea breeze days for ozone season months for the years 2000–2010 was calculated for the following areas: Portland, Providence, New York, Newark-Elizabeth, Brigantine NWR, Baltimore, Norfolk, and Savannah. The percentage of ozone season days with a possible sea breeze is about 12 percent for Brigantine, Baltimore and Savannah; 14 percent for New York and Newark-Elizabeth; 16 percent for Providence; and 18 percent for Portland and Norfolk. For area with a complex coastline such as Baltimore and Newark-Elizabeth, the index is more likely just an indication of variable diurnal wind directions and is not necessarily a sea breeze.

To discern the relationship between the sea breeze and 8-hour ozone, the hypothesis that maximum 8-hour ozone is, on average, higher for days with a sea breeze than for days without was tested. Here the maximum 8-hour ozone is taken over all sites within a given area. Figure 74 compares the average concentrations for the non-sea-breeze and sea-breeze days.

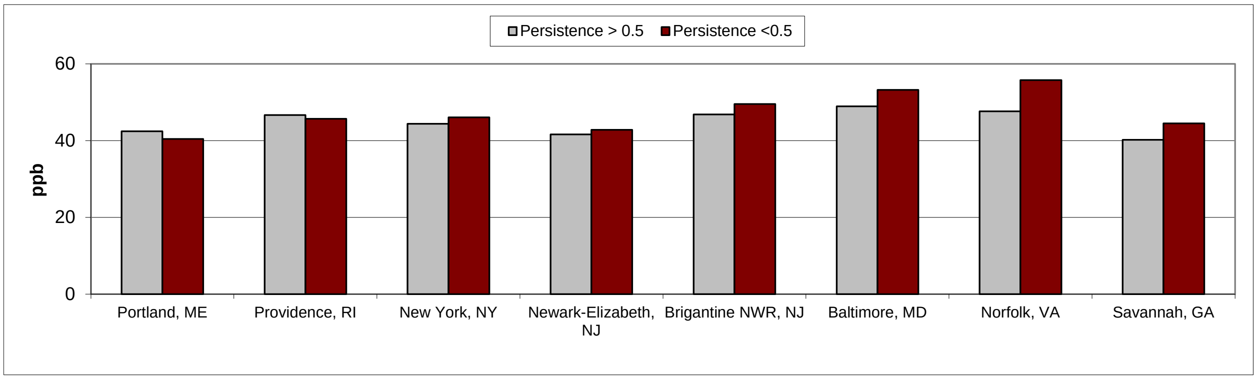


Figure 74. Comparison of average daily maximum 8-hour ozone concentration for non-sea-breeze and sea-breeze days for the 2000–2010 ozone seasons.

With the exception of Portland and Providence, the average 8-hour ozone concentration for days with a persistence index less than 0.5 and thus a possible sea breeze recirculation is higher than for days with persistent wind directions. The difference ranges from about -2 ppb for Portland to 8 ppb for Norfolk. On average, considering all locations, days with a possible sea breeze have a maximum 8-hour ozone value about 2 ppb greater than days without a sea breeze recirculation.

Similar summaries are provided for the full annual periods and $PM_{2.5}$. The number of potential sea breeze days for all months for the years 2000–2010 was calculated for the following areas: Portland, Providence, New York, Newark-Elizabeth, Baltimore, Norfolk, Wilmington (NC), and Savannah. The percentage of days with a possible sea breeze is about 10 percent for New York, Baltimore, Wilmington (NC), and Savannah; 12 to 13 percent for Newark-Elizabeth and Providence, and 15 to 16 percent for Portland and Norfolk.

To detect a relationship between the sea breeze and $PM_{2.5}$ concentration, the hypothesis that 24-hour average $PM_{2.5}$ is, on average, higher for days with a sea breeze than for days without was tested. Here the maximum value over all sites within a given area is used. Figure 75 compares the average concentrations for the non-sea-breeze and sea-breeze days.

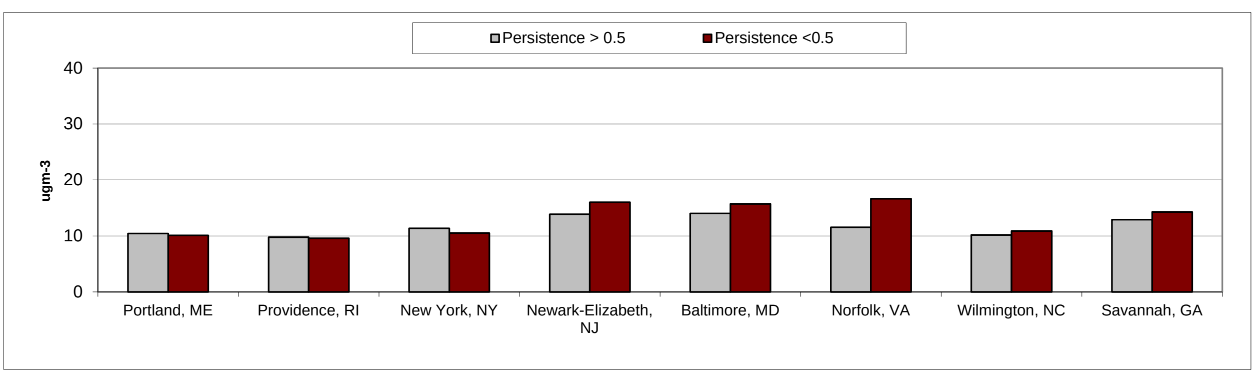


Figure 75. Comparison of average daily $PM_{2.5}$ concentration for non-sea-breeze and sea-breeze days for 2000–2010.

For Portland, Providence and New York, the average $PM_{2.5}$ concentration for days with a persistence index less than 0.5 is lower than for days with more persistent wind directions. For all other areas, the average $PM_{2.5}$ concentration for days with a persistence index less than 0.5 is higher than for days with more persistent wind directions. The difference ranges from about -1 μgm^{-3} for New York to 5 μgm^{-3} for Norfolk. On average, considering all locations, days with a possible sea breeze have a maximum $PM_{2.5}$ value about 1 μgm^{-3} greater than days without a possible sea breeze recirculation.

Finally, summaries are provided for the full annual periods and extinction coefficient for the Class I and other visibility analysis areas: Casco Bay, Martha's Vineyard, New York, Brigantine NWR, Swanquarter NWR, and Okefenokee NWR. The percentage of days with a possible sea breeze is about 9 percent for Swanquarter, 10 percent for Martha's Vineyard, 11 percent for Brigantine and Okefenokee, 13 percent for New York, and 14 percent for Casco Bay.

Figure 76 compares the average concentrations for the sea-breeze and non-sea-breeze days.

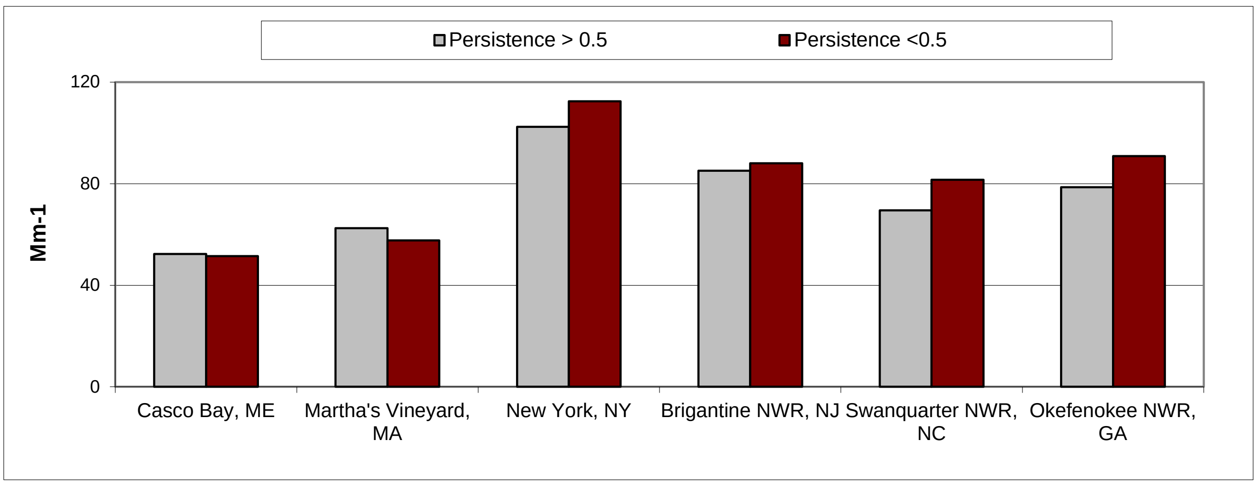


Figure 76. Comparison of average daily extinction coefficient for non-sea-breeze and sea-breeze days for 2000–2010.

With the exception of Casco Bay and Martha's Vineyard, the average extinction value for days with a persistence index less than 0.5 is higher than for days with more persistent wind directions. The differences range from approximately -5 for Martha's Vineyard to 12 Mm^{-1} for Swanquarter and Okefenokee. The average difference is 5.3 Mm^{-1}.

This analysis indicates that recirculation leads to higher pollutant concentrations and poorer visibility along the middle and southern portions of the Atlantic Coast. The findings are consistent for ozone, $PM_{2.5}$ and visibility.

4.0 CART ANALYSIS FOR SELECTED COASTAL AREAS: OZONE

The Classification and Regression Tree (CART) analysis technique was used to examine the relationships between onshore and offshore meteorological conditions and ozone air quality in selected port/harbor areas along the Atlantic Coast. The focus of this analysis was 8-hour ozone. CART was applied for Portland, Providence, New York, Newark-Elizabeth, Brigantine NWR, Baltimore, Norfolk, and Savannah.

The objective of this analysis was to explore the relationships between the offshore meteorological conditions, onshore meteorological conditions, and ozone concentrations in each of the areas of interest. Also of interest is the role of wind direction (and specifically onshore-directed flow) in determining high ozone regimes. All of the data presented in this section are included in the ARAQDB.

4.1. OVERVIEW OF CART

Classification and Regression Tree (CART) analysis (Brieman et al., 1984; Steinberg and Colla, 1997) is a statistical technique that can be used to "mine" and extract information from complex datasets. For air quality related analyses, the CART technique is used to segregate days with different values of an air quality parameter (the classification parameter) into different groups or bins and to provide information about the groupings. The input dataset is assumed to consist of a classification parameter (in this case pollutant concentration or another air quality related value) and a series of independent parameters that may be related to the classification parameter (typically a variety of meteorological input parameters). CART accomplishes the task of segregating the dataset through the development of a binary decision tree. At each split, the days are divided according to the value for one of the input parameters, in a way that best separates days with different values of the classification parameter. The end of a branch, called a bin, corresponds to a subset of days with predominantly one value for the classification parameter, characterized by input parameter ranges defined along the path to that bin.

Each value of the classification parameter may be represented by more than one bin, allowing for the possibility that different combinations of the independent parameters can be associated with a single value of the classification parameter (i.e., that different sets of meteorological conditions can lead, for example, to high ozone events). CART assumes that there is a relationship between the independent parameters and the classification parameter, and that this relationship can be extracted from the data.

The CART classification "tree" provides information about the specific parameters and values that are used by CART to distinguish one type of air quality day from another (and, thus, which parameters are the most important determinants of poor air quality).

By segregating the data values into the classification bins, CART also provides information on the frequency of occurrence of the conditions associated with each bin. The likely recurrence rate for a particular type of day and the associated prevailing conditions are obtained. A simple example of a CART classification tree diagram is given in Figure 77. In this example, 365 days are grouped into four classification bins that correspond to different ranges of 8-hour ozone concentration. In the diagram, the difference colors represent the different classification categories. The bins are distinguished by three independent input parameters: temperature, wind speed and wind direction. In this example, Bin #3 includes 15 days that are classified as belonging to the highest 8-hour ozone category (with concentrations greater than or equal to 95 ppb). Days with temperatures greater than 30°C and northerly winds are placed in this bin. Bins 1, 2 and 4 are comprised of days with different 8-hour ozone concentrations and different meteorological characteristics.

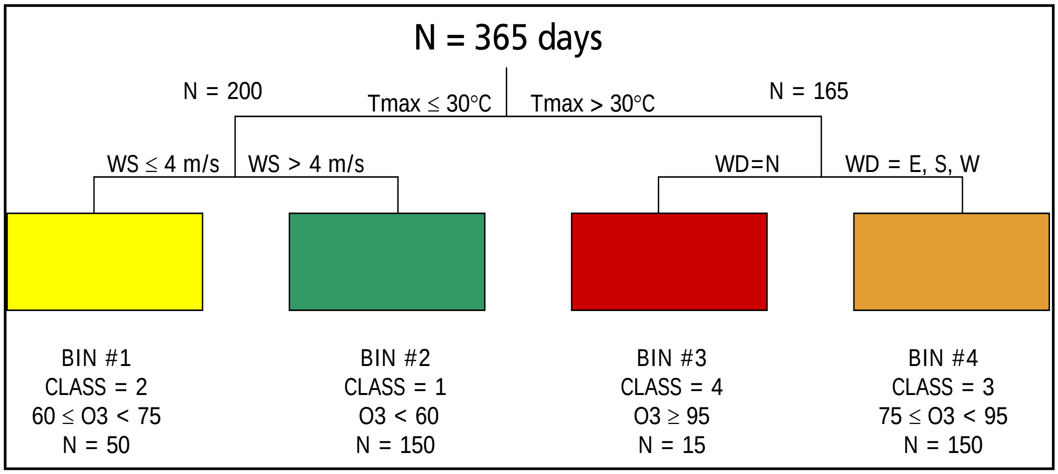


Figure 77. Simple CART classification tree diagram, with splits on temperature (Tmax), wind speed (WS) and wind direction (WD).

Note that this is a very simple example of a CART tree. For this study, most trees have approximately 25 to 35 bins and include multiple bins for each classification category.

CART also provides information about classification accuracy which can be used to assess the completeness and quality of the input parameters and the overall quality of the classification results. Misclassification can occur due to a number of reasons including monitoring network limitations, length (completeness) of the analysis period, use of discrete classification categories, and data errors or missing data. Throughout the remainder of this report, the term "classification accuracy" refers to the percentage of days that were assigned to the correct classes (that is, correctly placed into bins with ranges corresponding to their observed values).

In summary, the CART classification tree and the parameter and values used to divide the data into bins provide insight into the causal relationships between the independent parameters and the classification parameter, as well as the relative importance of the various independent parameters. In the case of air quality, this translates to the relationships between meteorology and air quality related values, and the key parameters and combinations of parameters that lead to poor air quality.

4.2. CART Application Procedures

CART was applied for the period 2000–2010. Details of the CART application for ozone are presented in this section. In addition to assembling an input dataset consisting of relevant air quality and meteorological parameters, the user must also define the classification categories, specify the "costs" associated with the misclassification of days into bins corresponding to a different category than indicated by the observed data, and select an approximate number of bins to be included in the classification tree.

As part of this analysis, CART was applied using the full set of input data and then using only the meteorological input parameters. This was done to examine the relative importance of the meteorological versus air quality parameters in determining ozone concentration and whether the selected meteorological parameters (in the absence of prior-day air quality information) are good indicators of ozone concentration.

4.2.1. Identification of CART Input Parameters

A first step in the application of CART is the identification of the input parameters. The following list includes available meteorological and air quality parameters that are expected to influence ozone along the Atlantic Coast. The list of input parameters was adapted from the CART analysis conducted for the former Minerals Management Service (MMS) as part of a similar data synthesis study for the Gulf of Mexico region (Douglas et al., 2009).

Surface Meteorological Parameters

Surface meteorological parameters were used to characterize the local meteorological conditions. The surface meteorological inputs for CART are listed below.

- **Temperature**
  - Daily maximum temperature (ºC)
  - Daily average temperature (ºC)
- **Relative Humidity**
  - Relative humidity at noon (%)
- **Wind**
  - 3-hour average vector wind direction bin; value of 1 through 5, indicating the wind direction corresponding to the 3-hour vector average wind direction for the periods 0700-1000, 1000-1300 and 1300-1600 LST. Bin definitions (in degrees) are: [315, 45), [45, 135), [135, 225), [225, 315), or calm, respectively.
  - 3-hour average scalar wind speed (ms^{-1}) for the periods 0700-1000, 1000-1300 and 1300-1600 LST
  - Persistence index (24-hour average vector wind speed/24-hour average scalar wind speed). This is an indicator of wind persistence, and a possible indicator of a sea breeze. If the value is 1, this indicates that the vector and scalar wind

speeds are the same, which further indicates that the wind is from the same direction during the entire period. A value of 0 indicates that the wind direction is from one direction for half the time and from the opposite direction the other half of the time. Thus a low value indicates the potential for recirculation.

- **Pressure**
  - Daily maximum sea level pressure (mb)
- **Precipitation**
  - 24-hour total precipitation (in)

Upper-Air Meteorological Parameters

Upper-air meteorological parameters were used to characterize the regional-scale meteorological conditions. The upper-air parameters are as follows:

- **Temperature**

  900 mb

  - 900 mb to surface temperature gradient, defined here as the difference between the temperature at 900 mb and the surface using the morning (0500 LST) temperature sounding data (ºC)

  850 mb

  - Upper-air 850 mb temperature corresponding to the morning (0500 LST) sounding on the current day (ºC)
  - Upper-air 850 mb temperature corresponding to the evening (1700 LST) sounding on the current day (ºC)
- **Wind**

  850 mb

  The following two upper-air wind variables were computed using data from the prior day's evening sounding, and the current day's morning and evening soundings for 850 mb (for a total of six input variables for each upper-air monitoring site):

  - Wind speed (ms^{-1})
  - Wind direction bin; value of 1 through 5, indicating the wind direction: (in degrees) [315, 45), [45, 135), [135, 225), [225, 315), or calm, respectively
- **Recirculation**

  850 mb

  - Recirculation index (value of 0 or 1) that is based on the difference between the average wind direction yesterday and today and/or scalar wind speed. If the difference is within +/- 15 degrees of 180 degrees or if average scalar wind speed is < 3 ms^{-1} then the index is set to 1. Otherwise the value is 0.

- **Geopotential Height**

700 mb

– Difference in the daily average geopotential height above sea level of the 700 mb surface (m) using height for the current day minus height for the prior day. Note that geopotential height differs from height above mean sea level in that it accounts for the variation of the effects of gravity with altitude and latitude. This parameter is an indicator of changing pressure patterns aloft.

- **Clouds**

700/850 mb

The cloud indicator variable combines data from both the 700 and 850 mb and was computed using data from the morning and evening soundings.

– Cloud index. Value based on relative humidity at the 850 mb (rh850) and 700 mb (rh700) levels. Ranges from 1 to 3 are based on the empirical analysis of observed data and are defined as follows:

  - if (rh850 < 80% and rh700 < 65%) then cloud = 1;
  - if (rh850 >= 80% and rh700 < 65%) then cloud = 2;
  - if (rh850 < 80% and rh700 >= 65%) then cloud = 2;
  - if (rh850 >= 80% and rh700 >= 65%) then cloud = 3

Air Quality Parameters

In addition to the meteorological input parameters, ozone concentrations for prior days as well as for the region were also used in the CART analysis.

- **Daily Maximum 8-Hour Ozone**

  – *Classification parameter for the application of CART for ozone.* Assigned a value of 1 through 5, such that each value corresponds to a different range of 8-hour ozone concentration. The concentration ranges are: less than 60 ppb, 60 to 75 ppb, 75 to 95 ppb, and greater than or equal to 95 ppb. These are the same concentration ranges that EPA uses for ozone air quality forecasting.

- **Regional Ozone Indicator Variables**

  – Prior-day daily maximum 8-hour ozone concentration for one or more nearby and thus potentially upwind sites (ppb). The specific sites and number of potential upwind sites is different for each CART region.

4.2.2. Quality Assurance Steps

Following each application, the results were assessed using statistical measures of the goodness of the classification, and then checked for physical reasonableness, as follows:

- The list of input parameters was checked for completeness.
- The CART input parameters were checked to ensure that they were specified reasonably (per the CART user's guide (Steinberg and Colla, 1997) and as intended.
- The values used to determine the branching of the CART output classification trees were checked to ensure that the values are reasonable and consistent with the input data.
- A matrix representing the statistical goodness of the classification (or classification accuracy) is created by CART, and the elements of this matrix were examined to ensure a minimum number of misclassifications. Classification accuracy refers to the percentage of days that were assigned to the correct classes (that is, correctly placed into bins with ranges corresponding to their observed values).
- Splits in the decision tree were checked to ensure that the parameters and values used to develop the classification tree are physically meaningful (i.e., consistent with basic conceptual models of ozone formation and transport).
- Splits in the decision tree were checked to ensure that CART made decisions (segregating the days) based on values of the input variables that are distinguishable in the data.
- The overall structure of the classification tree and number of classification bins were checked to ensure that the pathways to the different classification bins are distinct and that the bins provide a reasonable segregation of the days based on the daily extinction coefficient values.
- Final bins in the decision tree were checked for uniqueness, such that different bins represent different meteorological characteristics.
- One or more bins representing each classification category were selected and the decision pathways leading to those bins were explicitly checked for physical reasonableness.

4.2.3. Assessment of CART Results

The CART results were displayed in a variety of ways, both as part of the quality assurance and to aid the analysis of the results.

CART trees with approximately 25-35 bins were selected to optimize classification accuracy and physical reasonableness. The majority of the high ozone days, however, were grouped into one to four key bins.

Tabular summaries of classification accuracy were prepared and classification accuracy, by category and overall, were calculated. Overall classification accuracy ranged from approximately 80 to 95 percent.

The relative importance of the various input parameters to the CART classification tree was examined and plotted for each site.

4.3. CART DATA

The observed ozone and meteorological data used in the CART analysis are summarized in Tables 9 through 16 and provide information about the meteorological conditions associated with different levels of ozone concentration for the selected port/harbor areas.

To examine the variations in ozone versus meteorology, daily maximum 8-hour ozone was calculated for representative monitoring sites for the selected areas. Based on the observed value of daily maximum 8-hour ozone concentration, each day was then assigned to one of the four concentration categories (less than 60 ppb, 60 to 75 ppb, 75 to 95 ppb, and greater than or equal to 95 ppb). Then average values of the meteorological parameters were calculated for all days within each of the ozone concentration categories. In addition to the meteorological parameters, the average daily maximum 8-hour ozone concentration for each category is provided. Prior day average daily maximum 8-hour ozone concentrations for the area and potential upwind areas are also provided.

The combined ozone and meteorological summaries tables for each area are presented in the order listed above (north to south).

Table 9
Summary of Ozone and Meteorological Data by Ozone Concentration Category for 2000–2010: Portland.

Ozone Data are for Cape Elizabeth; Surface Meteorological Data are for Portland International Jetport. The Ranges in Ozone Concentration for Categories 1 through 4 are as follows: <60, 60-75,75-95 and ≥ 95 ppb.

	Category 1	Category 2	Category 3	Category 4
No. of Days	1961	139	30	11
Ozone Parameters				
Ozone at Cape Elizabeth (ppb)	39.4	66.5	82.5	100.6
Yesterday's Ozone - Cape Elizabeth (ppb)	40.9	52.7	62.9	75.4
Yesterday's Ozone - Regional Average (ppb)	42.3	55.5	66.0	75.7
Surface Meteorological Parameters				
Max. surface temperature (°C)	19.4	27.3	30.6	30.9
Avg. surface temperature (°C)	14.8	21.2	23.9	24.5
Relative humidity at noon (%)	61	55	51	53
Surface wind speed at 0700 - 1000 LST (ms^{-1})	3.0	2.4	2.3	1.8
Surface wind speed at 1000 - 1300 LST (ms^{-1})	3.9	3.8	3.5	3.1
Surface wind speed at 1300 - 1600 LST (ms^{-1})	4.4	4.7	4.7	5.1
Surface wind direction 0700 - 1000 LST (degrees)	332	234	259	239
Surface wind direction 1000 - 1300 LST (degrees)	118	197	207	211
Surface wind direction 1300 - 1600 LST (degrees)	165	193	198	193
Persistence	0.7	0.8	0.8	0.8
Sea level pressure (mb)	1018	1016	1016	1018
Rainfall (inches)	0.1	0.1	0.0	0.0
Upper-Air Meteorological Parameters				
Temperature AM 850 mb at Gray (°C)	7.6	14.2	16.4	17.0
Temperature PM 850 mb at Gray (°C)	8.5	15.4	17.5	18.4
Stability at Gray (°C)	-1.4	1.2	1.3	0.8
Geopotential hgt difference 700 mb at Gray (m)	0.7	-4.9	-2.8	3.3
Wind speed yesterday 850 mb at Gray (ms^{-1})	9.3	9.0	7.6	7.8
Wind speed AM 850 mb at Gray (ms^{-1})	9.0	9.1	7.6	8.4
Wind speed PM 850 mb at Gray (ms^{-1})	9.2	10.0	8.6	10.5
Wind dir. yesterday 850 mb at Gray (degrees)	288	282	282	283
Wind dir. AM 850 mb at Gray (degrees)	296	275	275	283
Wind dir. PM 850 mb at Gray (degrees)	290	272	272	270
Recirculation index at Gray	0.0	0.0	0.0	0.0
Cloud index at Gray	1.8	1.7	1.4	1.6

Table 10

Summary of Ozone and Meteorological Data by Ozone Concentration Category for 2000–2010: Providence.

Ozone Data are for East Providence; Surface Meteorological Data are for Providence T F Green Airport. The Ranges in Ozone Concentration for Categories 1 through 4 are as follows: <60, 60-75,75-95 and ≥ 95ppb.

	Category 1	Category 2	Category 3	Category 4
No. of Days	1562	217	82	11
Ozone Parameters				
Ozone at East Providence (ppb)	41.3	66.9	83.3	105.4
Yesterday's Ozone East Providence (ppb)	44.0	56.8	69.4	73.0
Yesterday's Ozone Mid-North Atlantic (ppb)	44.3	57.3	68.9	73.2
Surface Meteorological Parameters				
Max. surface temperature (°C)	21.6	29.0	31.4	33.4
Avg. surface temperature (°C)	17.1	22.8	24.8	26.9
Relative humidity at noon (%)	58	50	51	48
Surface wind speed at 0700 - 1000 LST (ms^{-1})	3.7	2.8	3.1	3.6
Surface wind speed at 1000 - 1300 LST (ms^{-1})	4.4	4.2	4.1	4.9
Surface wind speed at 1300 - 1600 LST (ms^{-1})	4.9	5.3	5.5	5.2
Surface wind direction 0700 - 1000 LST (degrees)	332	260	259	257
Surface wind direction 1000 - 1300 LST (degrees)	257	226	228	254
Surface wind direction 1300 - 1600 LST (degrees)	200	207	218	263
Persistence	0.8	0.8	0.8	0.9
Sea level pressure (mb)	1019	1017	1017	1017
Rainfall (inches)	0.2	0.0	0.0	0.0
Upper-Air Meteorological Parameters				
Temperature AM 850 mb at Chatham (°C)	9.5	14.1	16.0	16.7
Temperature PM 850 mb at Chatham (°C)	10.1	15.3	17.4	18.7
Stability at Chatham (°C)	-2.0	0.1	1.6	2.6
Geopotential hgt difference 700 mb at Chatham (m)	-1.0	4.0	1.4	1.9
Wind speed yesterday 850 mb at Chatham (ms^{-1})	10.1	9.2	8.3	9.5
Wind speed AM 850 mb at Chatham (ms^{-1})	9.4	8.7	8.2	9.5
Wind speed PM 850 mb at Chatham (ms^{-1})	9.9	9.9	9.4	9.7
Wind dir. yesterday 850 mb at Chatham (degrees)	279	289	287	323
Wind dir. AM 850 mb at Chatham (degrees)	279	278	279	276
Wind dir. PM 850 mb at Chatham (degrees)	283	281	272	270
Recirculation index at Chatham	0.0	0.0	0.0	0.0
Cloud index at Chatham	1.8	1.5	1.5	1.4

Table 11
Summary of Ozone and Meteorological Data by Ozone Concentration Category for 2000–2010: New York.

Ozone Data are for Babylon; Surface Meteorological Data are for JFK International Airport..
The Ranges in Ozone Concentration for Categories 1 through 4 are as follows:
<60, 60-75,75-95 and ≥ 95ppb.

	Category 1	Category 2	Category 3	Category 4
No. of Days	1903	259	86	17
Ozone Parameters				
Ozone at Babylon (ppb)	39.3	67.0	83.2	105.6
Yesterday's Ozone Babylon (ppb)	41.8	56.4	70.7	87.5
Yesterday's Ozone Mid-North Atlantic (ppb)	41.8	55.6	66.3	81.8
Surface Meteorological Parameters				
Max. surface temperature (°C)	21.2	28.2	31.1	33.3
Avg. surface temperature (°C)	17.4	23.4	25.8	28.2
Relative humidity at noon (%)	59	53	49	50
Surface wind speed at 0700 - 1000 LST (ms^{-1})	4.5	3.5	3.0	3.6
Surface wind speed at 1000 - 1300 LST (ms^{-1})	5.0	4.7	4.3	4.3
Surface wind speed at 1300 - 1600 LST (ms^{-1})	5.7	6.1	5.7	6.2
Surface wind direction 0700 - 1000 LST (degrees)	348	251	280	297
Surface wind direction 1000 - 1300 LST (degrees)	196	202	217	246
Surface wind direction 1300 - 1600 LST (degrees)	186	187	191	192
Persistence	0.8	0.8	0.8	0.7
Sea level pressure (mb)	1019.2	1017.3	1016.4	1015.2
Rainfall (inches)	0.1	0.1	0.0	0.0
Upper-Air Meteorological Parameters				
Temperature AM 850 mb at Brookhaven (°C)	9.2	14.2	16.1	18.4
Temperature PM 850 mb at Brookhaven (°C)	9.7	15.1	17.3	18.8
Stability at Brookhaven (°C)	-1.4	0.3	0.5	0.2
Geopotential hgt difference 700 mb at Brookhaven (m)	0.0	3.4	2.3	1.5
Wind speed yesterday 850 mb at Brookhaven (ms^{-1})	9.7	8.6	8.5	8.1
Wind speed AM 850 mb at Brookhaven (ms^{-1})	9.5	8.3	7.5	7.8
Wind speed PM 850 mb at Brookhaven (ms^{-1})	9.7	9.0	8.1	7.6
Wind dir. yesterday 850 mb at Brookhaven (degrees)	291	295	297	299
Wind dir. AM 850 mb at Brookhaven (degrees)	288	285	294	282
Wind dir. PM 850 mb at Brookhaven (degrees)	294	284	287	282
Recirculation index at Brookhaven	0.0	0.0	0.0	0.0
Cloud index at Brookhaven	1.7	1.5	1.5	1.3

Table 12
Summary of Ozone and Meteorological Data by Ozone Concentration Category for 2000–2010: Newark-Elizabeth.

Ozone Data are for Bayonne; Surface Meteorological Data are for Newark International Airport. The Ranges in Ozone Concentration for Categories 1 through 4 are as follows: <60, 60-75,75-95 and ≥ 95ppb.

	Category 1	Category 2	Category 3	Category 4
No. of Days	1933	248	893	9
Ozone Parameters				
Ozone at Bayonne (ppb)	36.3	66.7	83.2	104.1
Yesterday's Ozone Bayonne (ppb)	38.8	56.0	67.4	83.3
Yesterday's Ozone Mid-North Atlantic (ppb)	41.8	56.5	66.1	82.3
Surface Meteorological Parameters				
Max. surface temperature (°C)	22.5	31.3	33.3	35.1
Avg. surface temperature (°C)	18.2	25.7	27.6	29.6
Relative humidity at noon (%)	54	44	43	40
Surface wind speed at 0700 - 1000 LST (ms^{-1})	3.9	3.2	3.2	3.4
Surface wind speed at 1000 - 1300 LST (ms^{-1})	4.4	3.9	3.8	3.7
Surface wind speed at 1300 - 1600 LST (ms^{-1})	4.8	5.1	5.1	4.7
Surface wind direction 0700 - 1000 LST (degrees)	336	284	281	292
Surface wind direction 1000 - 1300 LST (degrees)	327	267	257	284
Surface wind direction 1300 - 1600 LST (degrees)	254	250	236	279
Persistence	0.7	0.8	0.7	0.9
Sea level pressure (mb)	1018	1017	1017	1017
Rainfall (inches)	0.2	0.1	0.0	0.0
Upper-Air Meteorological Parameters				
Temperature AM 850 mb at Brookhaven (°C)	9.2	14.4	16.1	17.8
Temperature PM 850 mb at Brookhaven (°C)	9.7	15.7	17.5	19.1
Stability at Brookhaven (°C)	-1.4	0.0	0.2	0.0
Geopotential hgt difference 700 mb at Brookhaven (m)	-0.2	1.2	7.2	1.8
Wind speed yesterday 850 mb at Brookhaven (ms^{-1})	9.8	8.0	7.6	8.9
Wind speed AM 850 mb at Brookhaven (ms^{-1})	9.5	8.2	7.0	7.2
Wind speed PM 850 mb at Brookhaven (ms^{-1})	9.7	9.0	8.0	7.7
Wind dir. yesterday 850 mb at Brookhaven (degrees)	290	293	305	321
Wind dir. AM 850 mb at Brookhaven (degrees)	288	286	289	286
Wind dir. PM 850 mb at Brookhaven (degrees)	295	281	284	297
Recirculation index at Brookhaven	0.0	0.0	0.0	0.0
Cloud index at Brookhaven	1.7	1.5	1.5	1.2

Table 13
Summary of Ozone and Meteorological Data by Ozone Concentration Category for 2000–2010: Brigantine NWR.

Ozone Data are for Brigantine NWR; Surface Meteorological Data are for Atlantic City International Airport. The Ranges in Ozone Concentration for Categories 1 through 4 are as follows: <60, 60-75,75-95 and ≥ 95ppb.

	Category 1	Category 2	Category 3	Category 4
No. of Days	1862	344	86	9
Ozone Parameters				
Ozone at Brigantine (ppb)	41.8	66.0	82.3	101.3
Yesterday's Ozone Brigantine (ppb)	44.1	57.1	69.3	86.7
Yesterday's Ozone Mid-South Atlantic (ppb)	45.4	58.5	69.2	82.1
Surface Meteorological Parameters				
Max. surface temperature (°C)	22.7	29.3	32.2	34.0
Avg. surface temperature (°C)	17.8	23.3	25.8	27.7
Relative humidity at noon (%)	60	48	44	44
Surface wind speed at 0700 - 1000 LST (ms^{-1})	3.7	3.1	3.0	3.4
Surface wind speed at 1000 - 1300 LST (ms^{-1})	4.5	3.9	3.4	4.0
Surface wind speed at 1300 - 1600 LST (ms^{-1})	4.9	4.9	4.5	5.3
Surface wind direction 0700 - 1000 LST (degrees)	347	266	294	297
Surface wind direction 1000 - 1300 LST (degrees)	110	249	283	286
Surface wind direction 1300 - 1600 LST (degrees)	164	210	217	292
Persistence	0.8	0.8	0.7	0.9
Sea level pressure (mb)	1019	1017	1016	1015
Rainfall (inches)	0.1	0.0	0.0	0.0
Upper-Air Meteorological Parameters				
Temperature AM 850 mb at Wallops Island (°C)	11.3	14.7	16.1	17.2
Temperature PM 850 mb at Wallops Island (°C)	11.9	15.9	17.3	18.9
Stability at Wallops Island (°C)	-2.3	-1.3	-1.2	-1.9
Geopotential hgt difference 700 mb at Wallops Island (m)	-1.7	9.9	4.0	-3.3
Wind speed yesterday 850 mb at Wallops Island (ms^{-1})	9.0	7.9	6.5	7.5
Wind speed AM 850 mb at Wallops Island (ms^{-1})	8.7	7.2	5.3	4.6
Wind speed PM 850 mb at Wallops Island (ms^{-1})	9.0	7.9	6.6	7.0
Wind dir. yesterday 850 mb at Wallops Island (degrees)	291	295	297	299
Wind dir. AM 850 mb at Wallops Island (degrees)	288	285	294	282
Wind dir. PM 850 mb at Wallops Island (degrees)	294	284	287	282
Recirculation index at Wallops Island	0.0	0.0	0.1	0.0
Cloud index at Wallops Island	1.8	1.6	1.5	1.6

Table 14
Summary of Ozone and Meteorological Data by Ozone Concentration Category for 2000–2010: Baltimore.

Ozone Data are for Essex; Surface Meteorological Data are for Baltimore Washington International Airport. The Ranges in Ozone Concentration for Categories 1 through 4 are as follows: <60, 60-75,75-95 and ≥ 95ppb.

	Category 1	Category 2	Category 3	Category 4
No. of Days	1612	380	129	22
Ozone Parameters				
Ozone at Essex (ppb)	41.9	66.6	82.3	107.0
Yesterday's Ozone Essex (ppb)	45.5	60.3	72.1	84.7
Yesterday's Ozone Mid-South Atlantic (ppb)	45.7	56.6	67.1	76.6
Surface Meteorological Parameters				
Max. surface temperature (°C)	23.1	30.1	32.7	33.9
Avg. surface temperature (°C)	18.3	24.0	26.4	27.7
Relative humidity at noon (%)	58	47	44	46
Surface wind speed at 0700 - 1000 LST (ms^{-1})	3.0	2.2	1.9	2.1
Surface wind speed at 1000 - 1300 LST (ms^{-1})	3.8	2.9	2.7	2.7
Surface wind speed at 1300 - 1600 LST (ms^{-1})	4.0	3.5	3.1	3.3
Surface wind direction 0700 - 1000 LST (degrees)	325	275	282	281
Surface wind direction 1000 - 1300 LST (degrees)	308	250	264	301
Surface wind direction 1300 - 1600 LST (degrees)	260	230	242	277
Persistence	0.8	0.7	0.7	0.7
Sea level pressure (mb)	0.2	0.1	0.1	0.0
Rainfall (inches)	0.2	0.1	0.1	0.0
Upper-Air Meteorological Parameters				
Temperature AM 850 mb at Dulles (°C)	10.2	14.6	16.6	17.8
Temperature PM 850 mb at Dulles (°C)	10.9	15.9	17.8	18.9
Stability at Dulles (°C)	-1.2	0.8	1.5	1.8
Geopotential hgt difference 700 mb at Dulles (m)	-2.7	5.3	4.0	12.6
Wind speed yesterday 850 mb at Dulles (ms^{-1})	8.9	6.5	5.3	5.1
Wind speed AM 850 mb at Dulles (ms^{-1})	9.3	7.1	5.3	4.7
Wind speed PM 850 mb at Dulles (ms^{-1})	8.9	6.8	5.2	5.2
Wind dir. yesterday 850 mb at Dulles (degrees)	271	281	293	305
Wind dir. AM 850 mb at Dulles (degrees)	285	289	295	299
Wind dir. PM 850 mb at Dulles (degrees)	281	267	274	259
Recirculation index at Dulles	0.0	0.0	0.1	0.1
Cloud index at Dulles	1.9	1.7	1.6	1.4

Table 15
Summary of Ozone and Meteorological Data by Ozone Concentration Category for 2000–2010: Norfolk.

Ozone Data are for Tidewater Community College; Surface Meteorological Data are for Norfolk International Airport. The Ranges in Ozone Concentration for Categories 1 through 4 are as follows: <60, 60-75,75-95 and ≥ 95ppb.

	Category 1	Category 2	Category 3	Category 4
No. of Days	1820	409	74	8
Ozone Parameters				
Ozone at Norfolk (ppb)	43.7	66.2	81.8	103.5
Yesterday's Ozone Norfolk (ppb)	46.0	59.0	68.5	78.8
Yesterday's Ozone South Atlantic (ppb)	42.8	53.1	57.7	63.6
Surface Meteorological Parameters				
Max. surface temperature (°C)	24.6	29.4	31.4	33.0
Avg. surface temperature (°C)	20.7	24.4	26.1	28.4
Relative humidity at noon (%)	63	53	51	52
Surface wind speed at 0700 - 1000 LST (ms^{-1})	4.1	3.5	3.1	1.2
Surface wind speed at 1000 - 1300 LST (ms^{-1})	4.5	3.9	3.6	3.1
Surface wind speed at 1300 - 1600 LST (ms^{-1})	4.7	4.3	3.9	2.9
Surface wind direction 0700 - 1000 LST (degrees)	315	292	289	0
Surface wind direction 1000 - 1300 LST (degrees)	26	344	342	59
Surface wind direction 1300 - 1600 LST (degrees)	74	74	31	82
Persistence	0.8	0.7	0.6	0.4
Sea level pressure (mb)	1019	1018	1018	1016
Rainfall (inches)	0.2	0.1	0.0	0.0
Upper-Air Meteorological Parameters				
Temperature AM 850 mb at Dulles (°C)	11.3	14.1	15.9	17.6
Temperature PM 850 mb at Dulles (°C)	12.0	15.1	16.7	18.8
Stability at Dulles (°C)	-2.3	-1.2	-0.9	-1.1
Geopotential hgt difference 700 mb at Dulles (m)	-1.2	6.9	5.4	-0.8
Wind speed yesterday 850 mb at Dulles (ms^{-1})	9.0	8.3	7.6	6.1
Wind speed AM 850 mb at Dulles (ms^{-1})	8.6	7.4	6.0	5.7
Wind speed PM 850 mb at Dulles (ms^{-1})	9.0	8.0	7.6	5.6
Wind dir. yesterday 850 mb at Dulles (degrees)	277	295	317	352
Wind dir. AM 850 mb at Dulles (degrees)	280	301	306	349
Wind dir. PM 850 mb at Dulles (degrees)	280	290	297	342
Recirculation index at Dulles	0.0	0.0	0.0	0.1
Cloud index at Dulles	1.8	1.6	1.5	1.6

Table 16
Summary of Ozone and Meteorological Data by Ozone Concentration Category for 2000–2010: Savannah.

Ozone Data are for Savannah; Surface Meteorological Data are for Savannah International Airport. The Ranges in Ozone Concentration for Categories 1 through 4 are as follows: <60, 60-75, and ≥ 75ppb.

	Category 1	Category 2	Category 3
No. of Days	2088	178	11
Ozone Parameters			
Ozone at Savannah (ppb)	38.4	65.1	80.5
Yesterday's Ozone Savannah (ppb)	39.2	57.4	68.7
Yesterday's Ozone South Atlantic (ppb)	43.6	57.1	68.0
Surface Meteorological Parameters			
Max. surface temperature (°C)	29.0	31.0	35.0
Avg. surface temperature (°C)	23.5	23.6	27.4
Relative humidity at noon (%)	58	42	41
Surface wind speed at 0700 - 1000 LST (ms^{-1})	2.5	1.7	2.2
Surface wind speed at 1000 - 1300 LST (ms^{-1})	3.3	2.6	2.8
Surface wind speed at 1300 - 1600 LST (ms^{-1})	3.8	3.1	2.9
Surface wind direction 0700 - 1000 LST (degrees)	318	286	254
Surface wind direction 1000 - 1300 LST (degrees)	328	290	288
Surface wind direction 1300 - 1600 LST (degrees)	134	229	259
Persistence	0.8	0.7	0.6
Sea level pressure (mb)	0.1	0.0	0.0
Rainfall (inches)	0.8	0.7	0.6
Upper-Air Meteorological Parameters			
Temperature AM 850 mb at Jacksonville (°C)	15.3	14.9	17.6
Temperature PM 850 mb at Jacksonville (°C)	15.7	16.0	18.9
Stability at Jacksonville (°C)	-1.6	1.2	1.4
Geopotential hgt difference 700 mb at Jacksonville (m)	-0.4	7.1	3.5
Wind speed yesterday 850 mb at Jacksonville (ms^{-1})	6.7	6.2	5.2
Wind speed AM 850 mb at Jacksonville (ms^{-1})	6.8	5.5	6.3
Wind speed PM 850 mb at Jacksonville (ms^{-1})	6.8	5.5	5.1
Wind dir. yesterday 850 mb at Jacksonville (degrees)	268	298	310
Wind dir. AM 850 mb at Jacksonville (degrees)	240	318	351
Wind dir. PM 850 mb at Jacksonville (degrees)	271	295	297
Recirculation index at Jacksonville	0.1	0.1	0.0
Cloud index at Jacksonville	1.8	1.4	1.6

The tabular summaries indicate that, for all areas, high ozone concentrations are associated with relatively higher temperatures, lower relative humidity, lower wind speeds, greater stability, less cloud cover, and less rainfall, compared to days with lower ozone concentrations. For most areas, wind directions also vary by category which indicates that wind direction also affects ozone concentration. The specific wind directions and variations across the categories are different for each area. For several areas (in particular, New York, Baltimore, Norfolk, and Savannah) the persistence value decreases with increasing ozone (which suggests higher ozone under possible sea-breeze conditions). High ozone days are also characterized by both local and regional buildup of ozone, as indicated by the prior-day average ozone concentrations, which increase for each higher ozone category.

4.4. CART RESULTS

The CART results for ozone are presented in the remainder of this section. As noted earlier, the CART results can provide information about the relative importance of the various independent parameters in distinguishing days with different ozone air quality characteristics as well as the combinations of parameters that lead to high ozone. This information has been extracted from the CART analysis results for ozone and is discussed in this section.

4.4.1. Classification Accuracy

CART classification accuracy ranges from 80 to 95 percent for full CART analyses, which include both meteorological data and prior-day air quality data, and from 76 to 89 percent for the meteorological data only analyses. The results for both applications are summarized in Table 17.

Table 17
Summary of CART Classification Accuracy for 8-Hour Ozone

CART Area	Classification Accuracy (%)	
	Meteorological & Air Quality Data	Meteorological Data Only
Portland	94	92
Providence	87	86
New York	87	88
Newark	89	87
Brigantine NWR	86	83
Baltimore	81	80
Norfolk	82	81
Savannah	95	93

For most of the areas, classification accuracy for the meteorological data only CART runs is lower by 1 to 3 percentage points compared to the full CART run. For one area (New York) it is 1 percentage point higher. This overall relatively small reduction in classification accuracy indicates that the selected meteorological data are good indicators of ozone concentration.

Our goal for the full data CART application for ozone for this study was 80 percent classification accuracy and this goal was met for all sites.

4.4.2. Classification Parameter Importance

Certain of the input parameters are used more frequently in the construction of the classification trees and an analysis of the important parameters provides some insight into the factors that influence air quality, and how these differ among the monitoring sites for ozone, $PM_{2.5}$ and visibility.

Parameter importance is calculated by CART based on the number of times each parameter is used, either as a split parameter or as a surrogate parameter, to construct the final classification tree. Split parameters are those that explicitly define the branches of the CART tree, and thus separate the days. Surrogate parameters represent the next best splits, and are used in the case of missing data. For example, the 850 mb temperature might be a surrogate for the 900 mb to surface temperature difference since both are indicators of stability. Several surrogates are identified for each split.

Parameter importance is assigned a value ranging from 0 to 100, based on the use of the parameter in defining the CART tree. Specifically, the importance indicates the improvement in classification accuracy that results from using the best split parameter compared to the best surrogate split parameter. The importance values are normalized such that the most important parameter has a value of 100. The values are only meaningful in a relative sense and within the context of the CART analysis. We use parameter importance in this analysis to identify those parameters that are statistically relevant to the classification and assume that these same parameters are also physically relevant to 8-hour ozone concentrations. That is, we assume that the parameters that are most important in determining the structure of the CART tree are also most important in determining ozone air quality.

Parameter importance for each area is displayed in Figure 78. In each plot, the relative importance assigned to several of the surface and upper-air meteorology categories is the maximum over the parameters that comprise the grouping (e.g., the morning and evening 850 mb temperatures comprise the upper-air temperature group). The category abbreviations are defined as follows and represent one or more of the CART input parameters:

YO3_Local = Yesterday's maximum 8-hour ozone concentration for the area of interest

YO3_Regional = Yesterday's ozone concentration for neighboring and upwind areas (average for the group)

TMAX = Daily maximum temperature

TAVG = Daily average temperature

RH = Relative humidity

WS (Sfc) = Surface wind speed (maximum for the surface wind speed parameter group)

WD (Sfc) = Surface wind direction (maximum for the surface wind speed parameter group)

PERSIST = Persistence or sea-breeze index

SLP = Sea level pressure

RAIN = Total rainfall

CLOUD = Cloud cover index

DZ700 = Daily change in geopotential height at the 700 mb level

DT900 = 900 mb to surface temperature difference

T850 = 850 mb temperature (maximum for the upper-air temperature parameter group)

WS (Upper) = Wind speed aloft (maximum for the upper-air wind speed parameter group)

WD (Upper) = Wind direction aloft (maximum over the upper-air wind speed parameter group)

RECIRC = Recirculation index

In this and subsequent plots of parameter importance, red is used for air quality parameters, blue is used for surface meteorological parameters, and green is used for upper-air parameters.

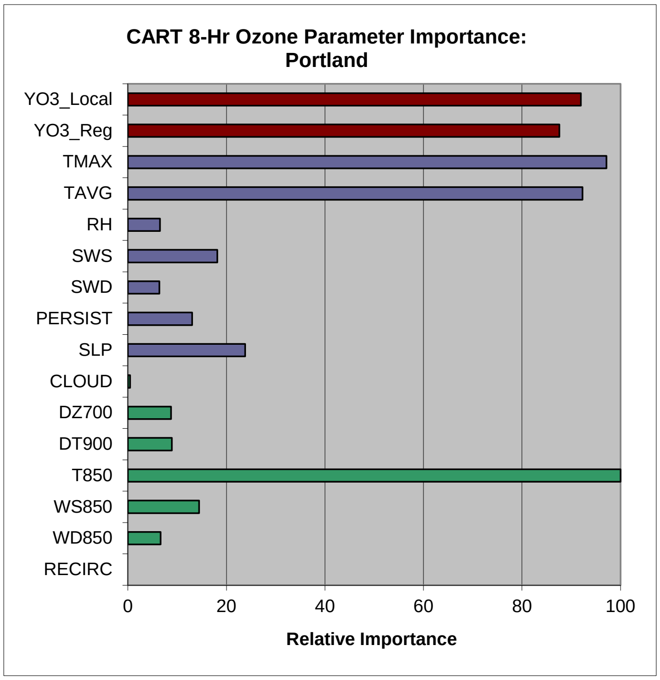


Figure 78a. Average parameter importance for the 8-hour ozone CART analysis: Portland.

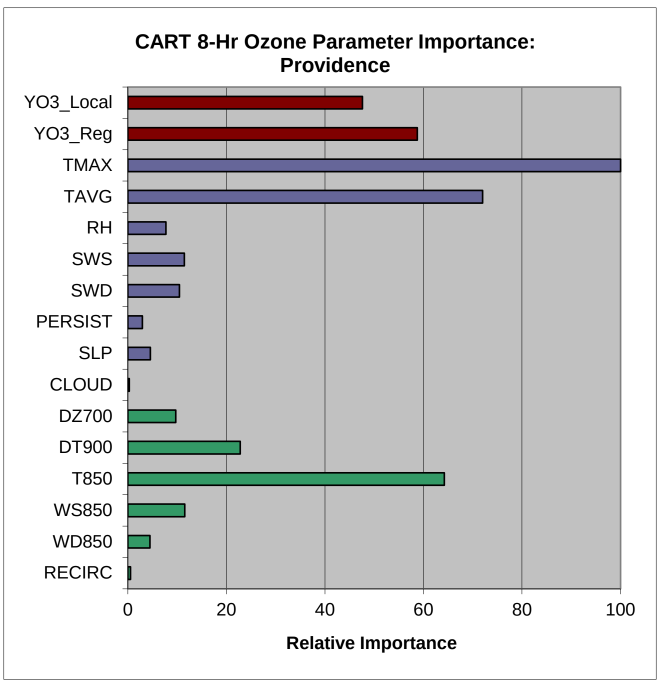


Figure 78b. Average parameter importance for the 8-hour ozone CART analysis: Providence.

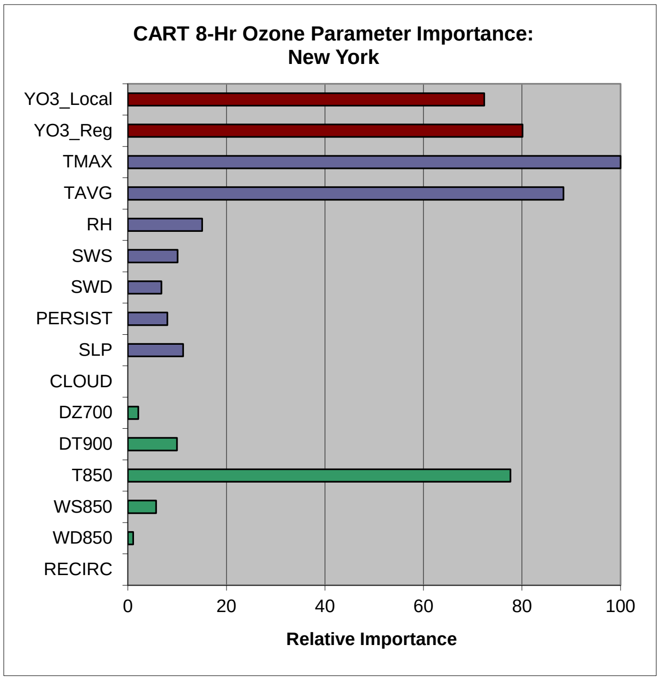


Figure 78c. Average parameter importance for the 8-hour ozone CART analysis: New York.

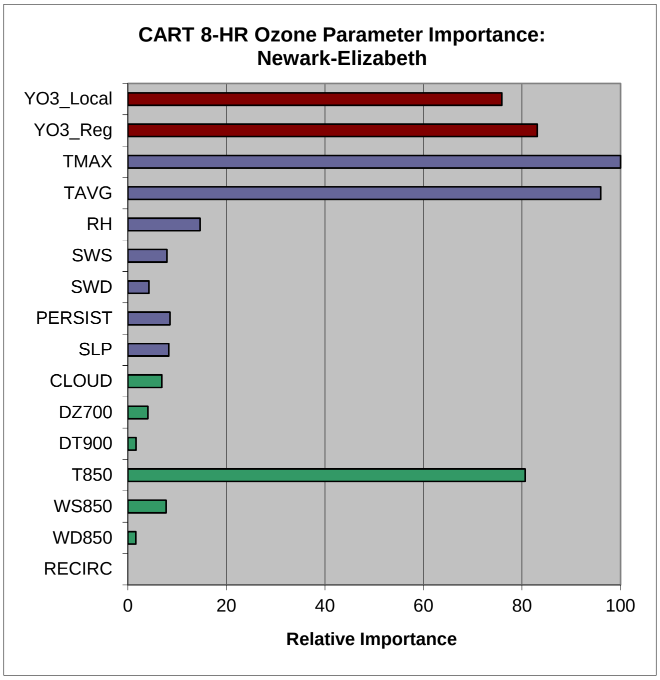


Figure 78d. Average parameter importance for the 8-hour ozone CART analysis: Newark-Elizabeth.

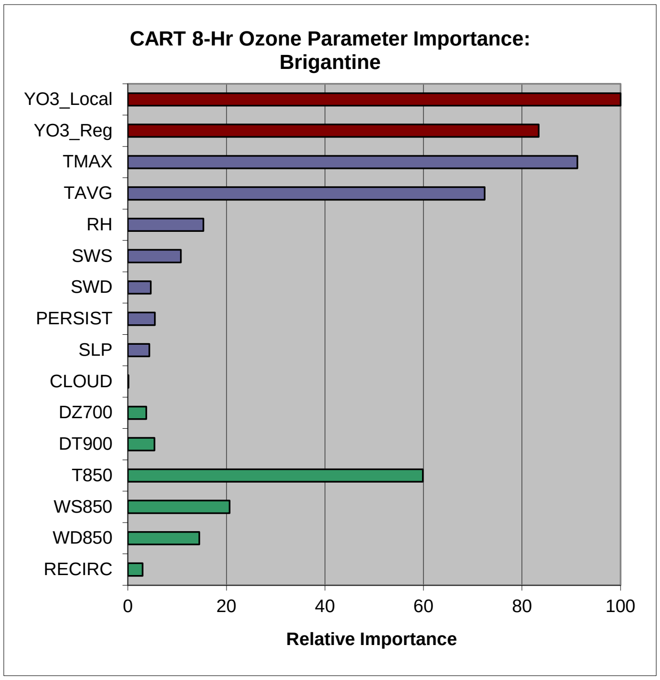


Figure 78e. Average parameter importance for the 8-hour ozone CART analysis: Brigantine NWR.

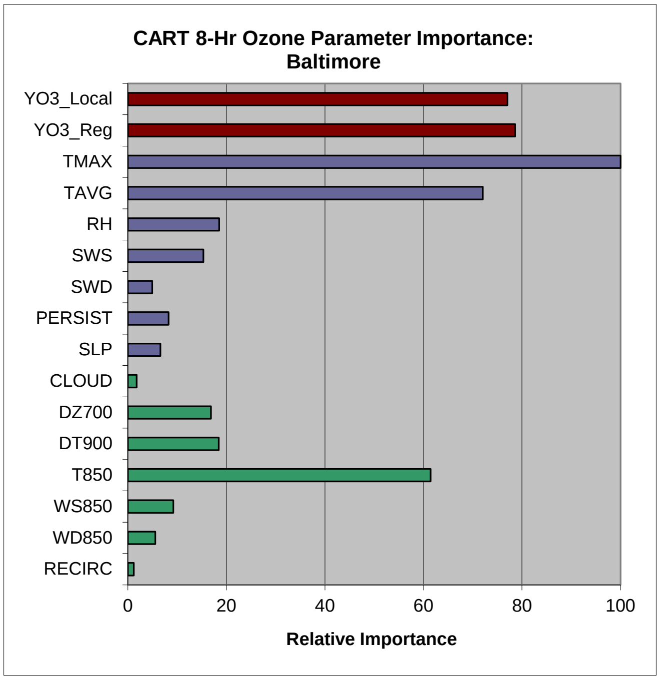


Figure 78f. Average parameter importance for the 8-hour ozone CART analysis: Baltimore.

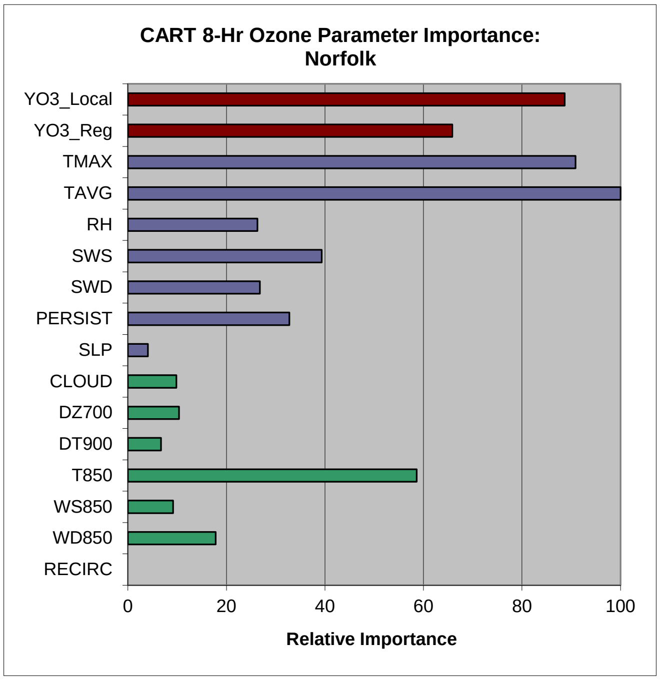


Figure 78g. Average parameter importance for the 8-hour ozone CART analysis: Norfolk.

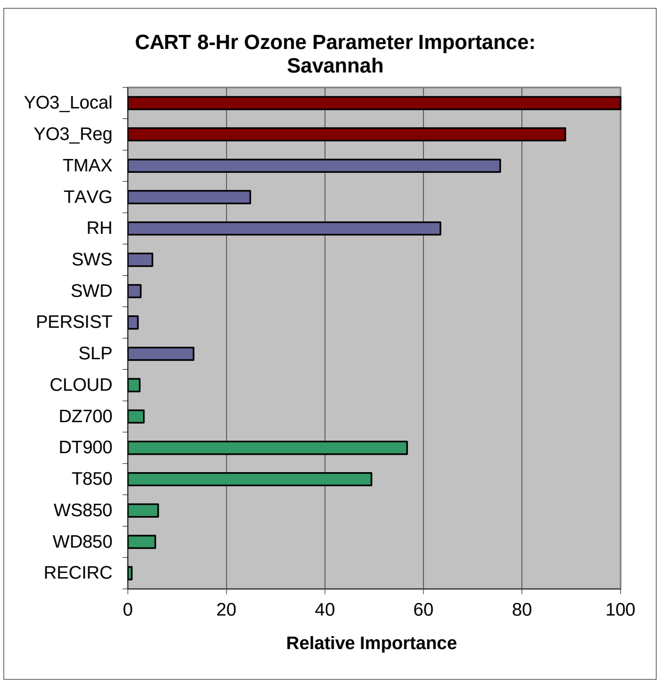


Figure 78h. Average parameter importance for the 8-hour ozone CART analysis: Savannah.

Parameter importance varies among the different areas, especially with regard to the local, surface meteorological parameters. For all areas, prior day ozone concentrations are an important factor in determining the ozone category for the current day ozone. The CART results indicate that both carryover (local parameter) and transport (regional parameters) play an important role in determining ozone concentration. Surface temperature and 850 mb temperature (which is an indicator of stability) are also important for all areas. Relative humidity is important for the more southern areas (Norfolk and Savannah). Surface wind speed and directions are of moderate importance for most areas and tend to be more important than upper-air wind speed and direction in determining ozone concentration.

To summarize the results, the average parameter importance for all areas is displayed in Figure 79.

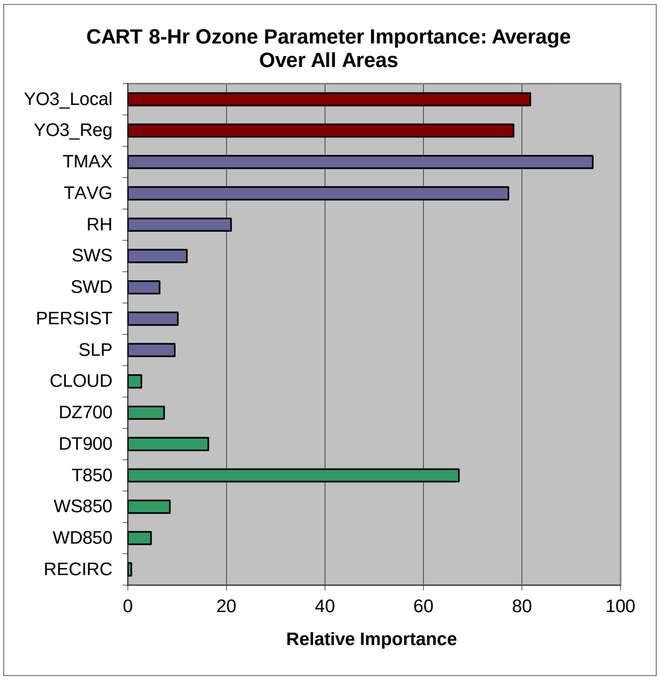


Figure 79. Average parameter importance for 8-hour ozone CART analysis: Average over all areas.

On average, the most important parameters include: prior day maximum 8-hour ozone concentration in the area of interest, prior day maximum 8-hour ozone concentration in potential upwind areas, surface temperature, 850 mb temperature, and relative humidity. Of secondary importance are stability (DT900), surface wind speed, and persistence.

4.4.3. Characteristics of High Ozone Bins

In the previous section, we identified certain parameters that are important to the classification of days with respect to 8-hour ozone concentration and concluded that these parameters have the potential to influence air quality at the monitoring sites. However, understanding the causes of high ozone concentrations also requires an understanding of the relationship between the parameters and the air quality metrics, as well as the specific combinations of parameters (conditions) that lead to impaired air quality. In this section, we further explore those relationships using the CART input data and results.

Each value of the classification parameter may be represented by more than one bin, allowing for the possibility that different combinations of the independent parameters can be associated with a single value of the classification parameter (i.e., that different sets of meteorological conditions can lead to high ozone). CART assumes that there is a relationship between the independent parameters and the classification parameter, and that this relationship can be extracted from the data.

Greater insight is gained by considering the characteristics of the key bins that represent the high ozone days for each area. Key bins were defined as those containing the greatest number of correctly classified days. One or two bins from each of the two highest categories for each area were identified and the characteristics of those bins were examined and compared. Figure 80 displays and compares selected parameters for the key high ozone bins for each area. The parameters are grouped as follows: air quality related parameters, relative humidity, temperature parameters, stability and persistence parameters, wind speed parameters and wind direction parameters. The bin category and number of days in each bin is also given. As a reminder, the concentration categories are defined as follows: Category 1 (< 60 ppb), Category 2(60 to 75 ppb), Category 3(75 to 95 ppb), and Category 4 (≥ 95 ppb). Category 4 was not needed for all areas.

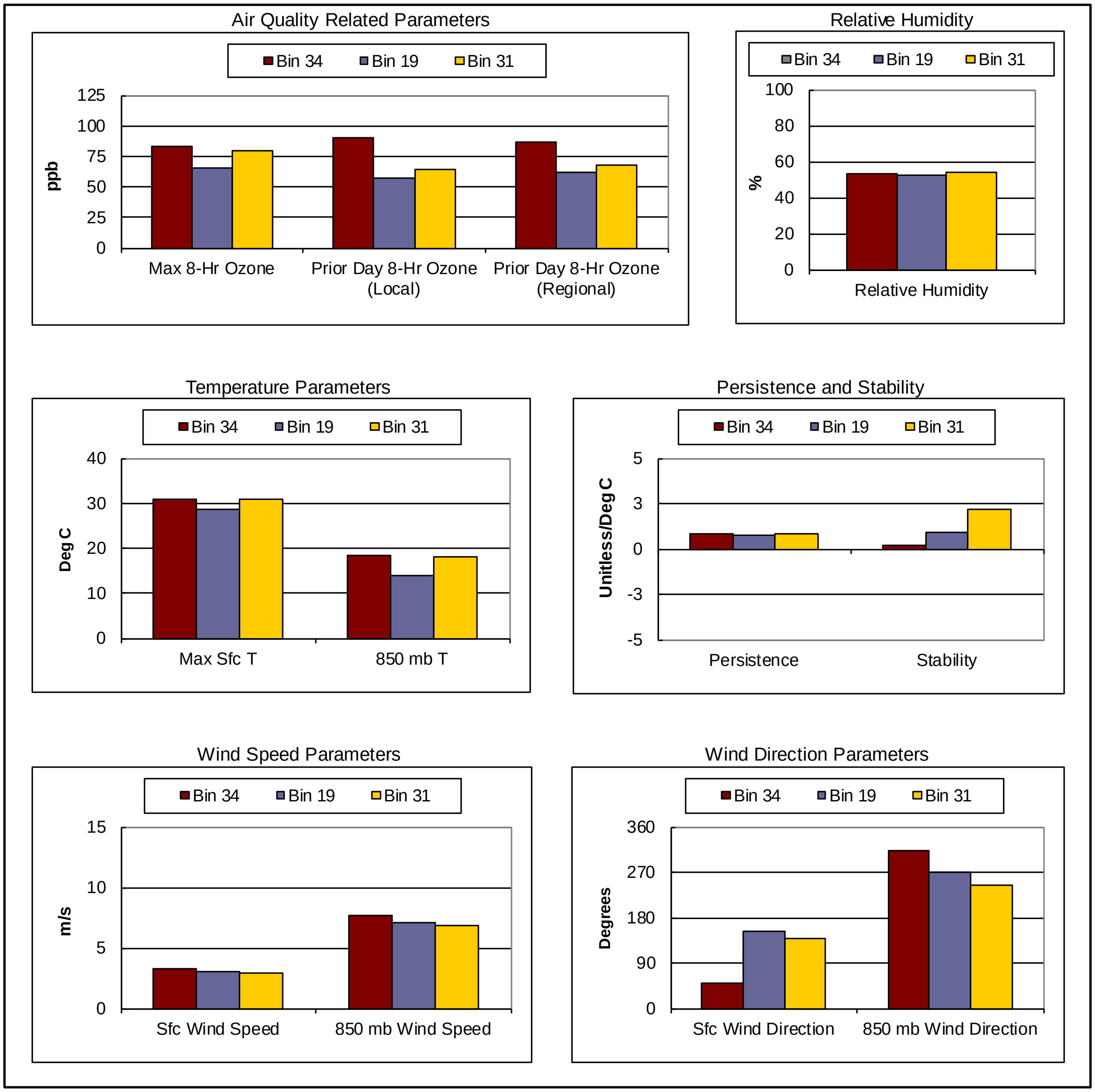


Figure 80a. Average values of selected parameters by bin for the key high ozone bins: Portland. The key bins are: Bin 34 = Category 4 (9 Days); Bin 19 = Category 4 (21 Days); Bin 31 = Category 3 (17 Days).

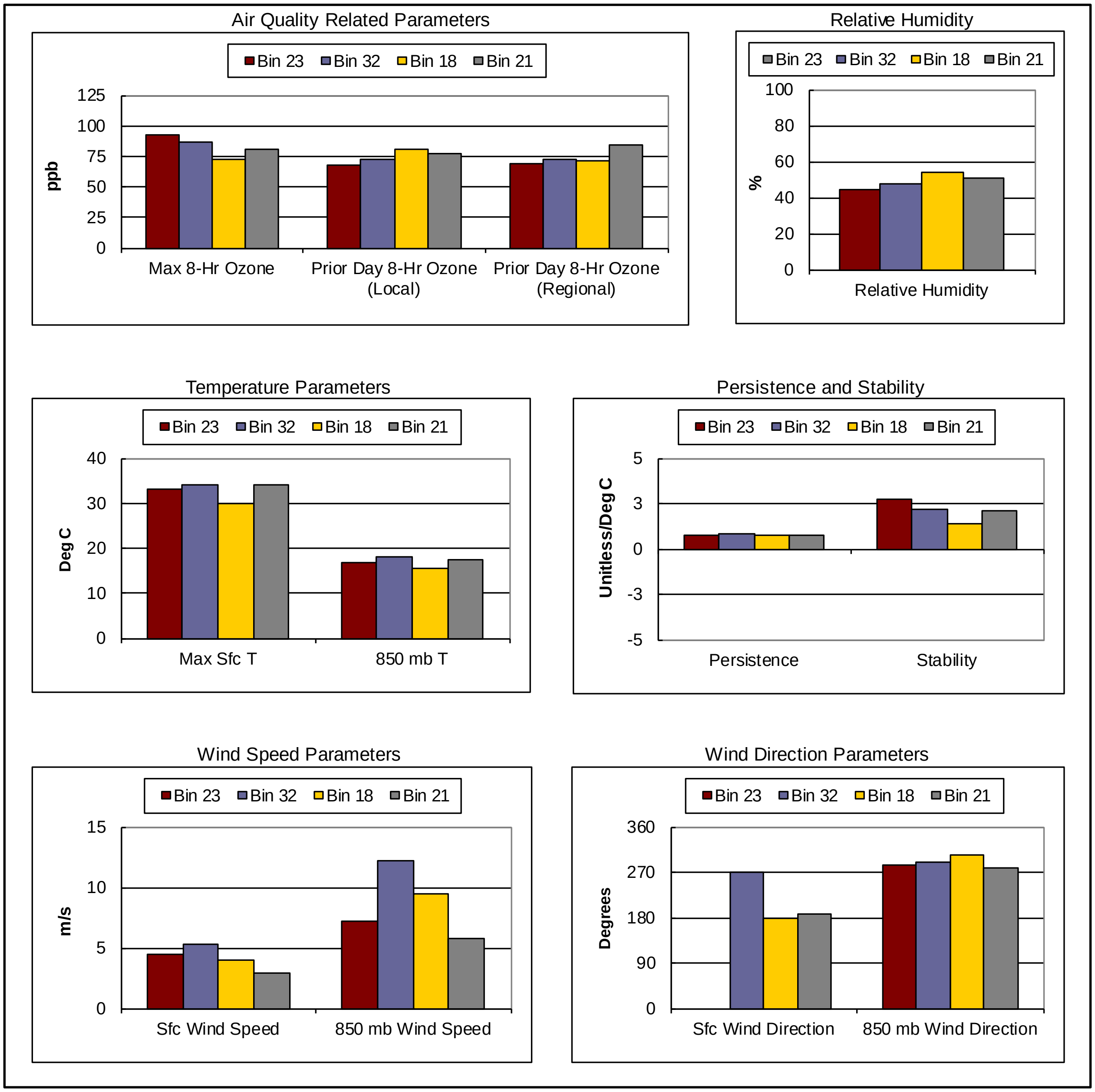


Figure 80b. Average values of selected parameters by bin for the key high ozone bins: Providence. The key bins are: Bin 23 = Category 4 (9 Days); Bin 34 = Category 4 (8 Days); Bin 18 = Category 3 (32 Days); Bin 21 = Category 3 (10 Days).

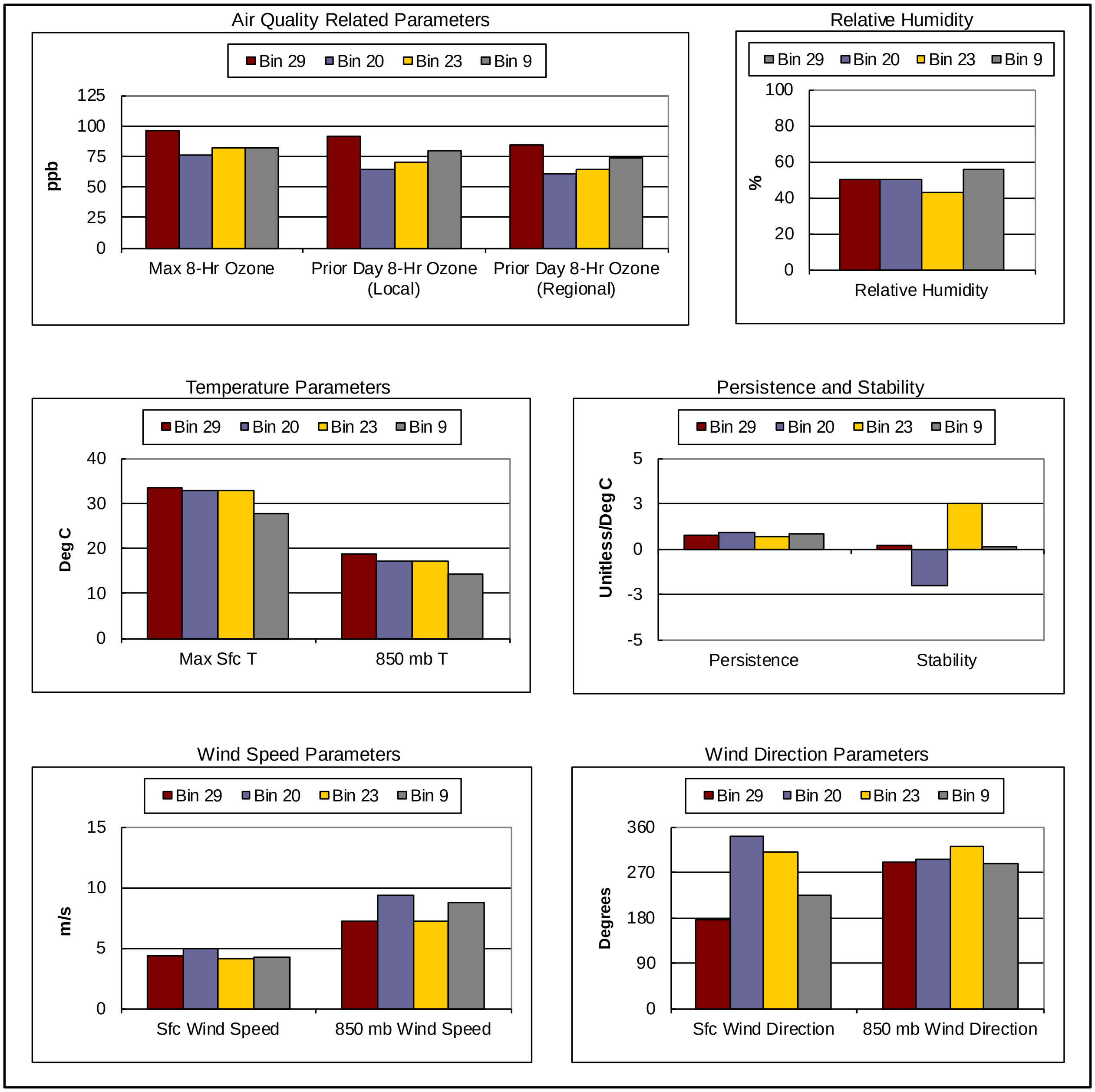


Figure 80c. Average values of selected parameters by bin for the key high ozone bins: New York. The key bins are: Bin 29 = Category 4 (16 Days); Bin 20 = Category 3 (24 Days); Bin 23 = Category 3 (22 Days); Bin 9 = Category 3 (7 Days).

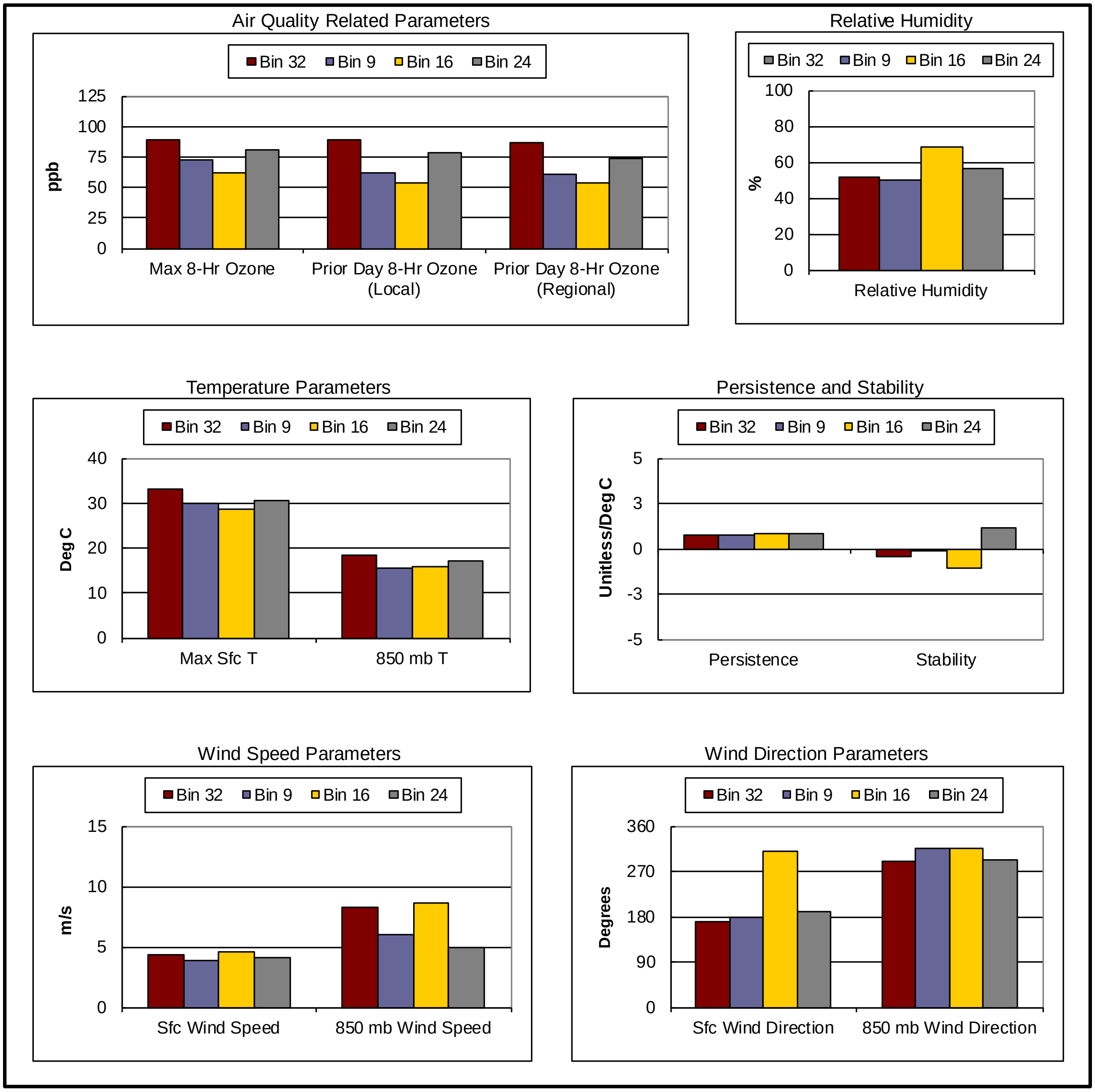


Figure 80d. Average values of selected parameters by bin for the key high ozone bins: Newark-Elizabeth. The key bins are: Bin 32 = Category 4 (12 Days); Bin 9 = Category 3 (22 Days); Bin 16 = Category 3 (18 Days); Bin 24 = Category 3 (11 Days).

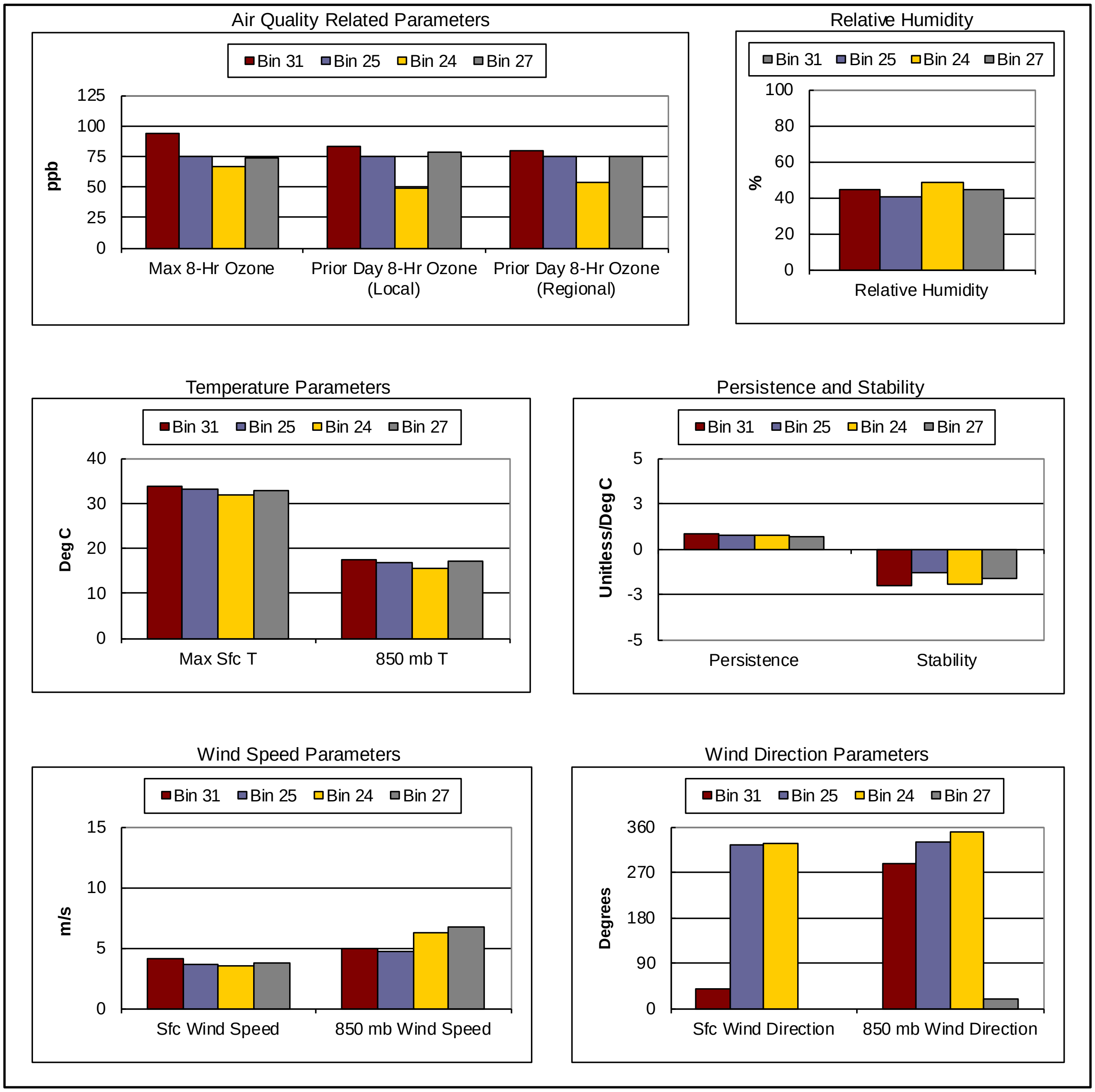


Figure 80e. Average values of selected parameters by bin for the key high ozone bins: Brigantine NWR. The key bins are: Bin 31 = Category 4 (11 Days); Bin 25 = Category 3 (38 Days); Bin 24 = Category 3 (35 Days); Bin 27 = Category 3 (23 Days).

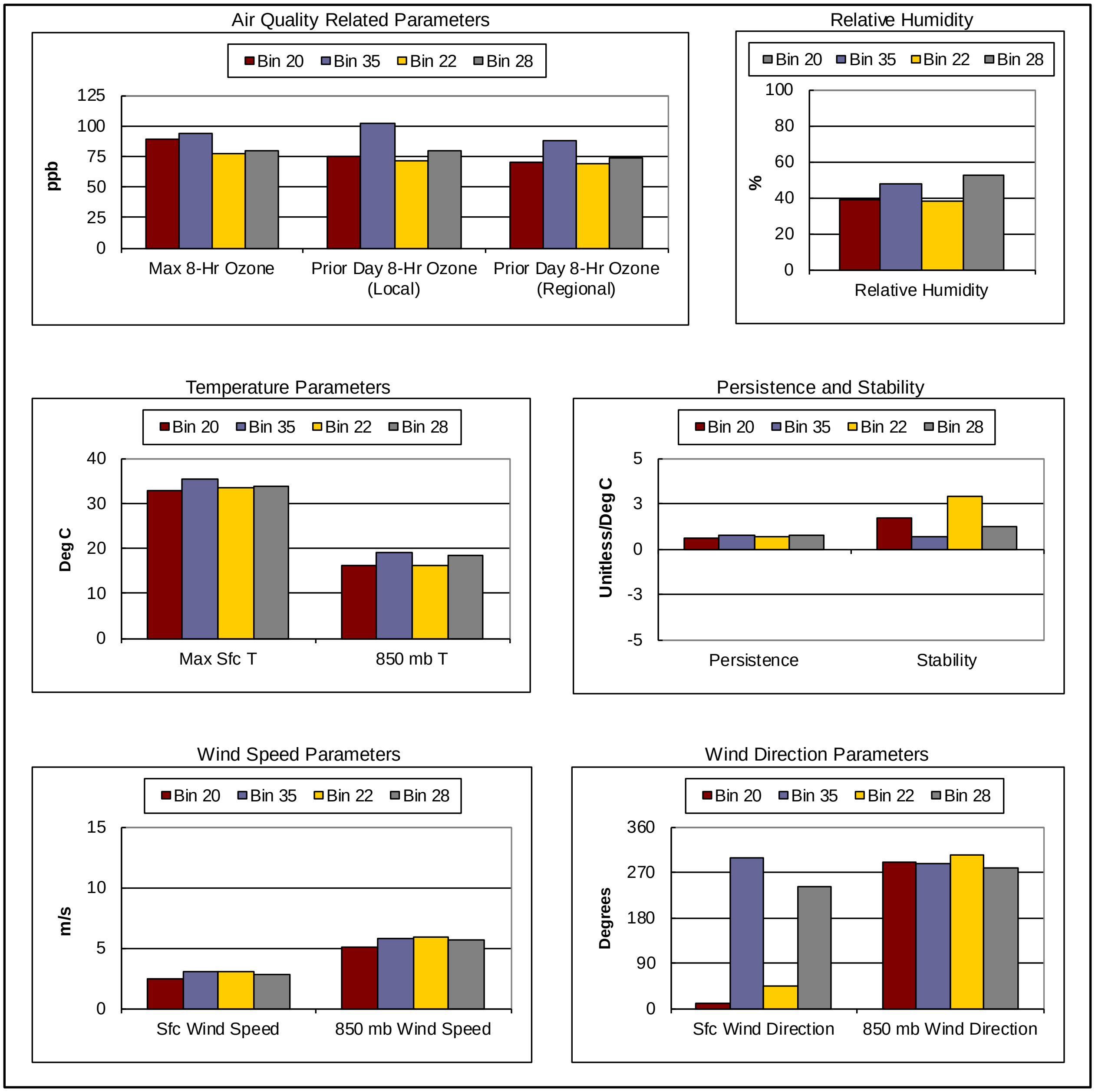


Figure 80f. Average values of selected parameters by bin for the key high ozone bins: Baltimore. The key bins are: Bin 20 = Category 4 (17 Days); Bin 35 = Category 4 (14 Days); Bin 22 = Category 3 (32 Days); Bin 28 = Category 3 (28 Days).

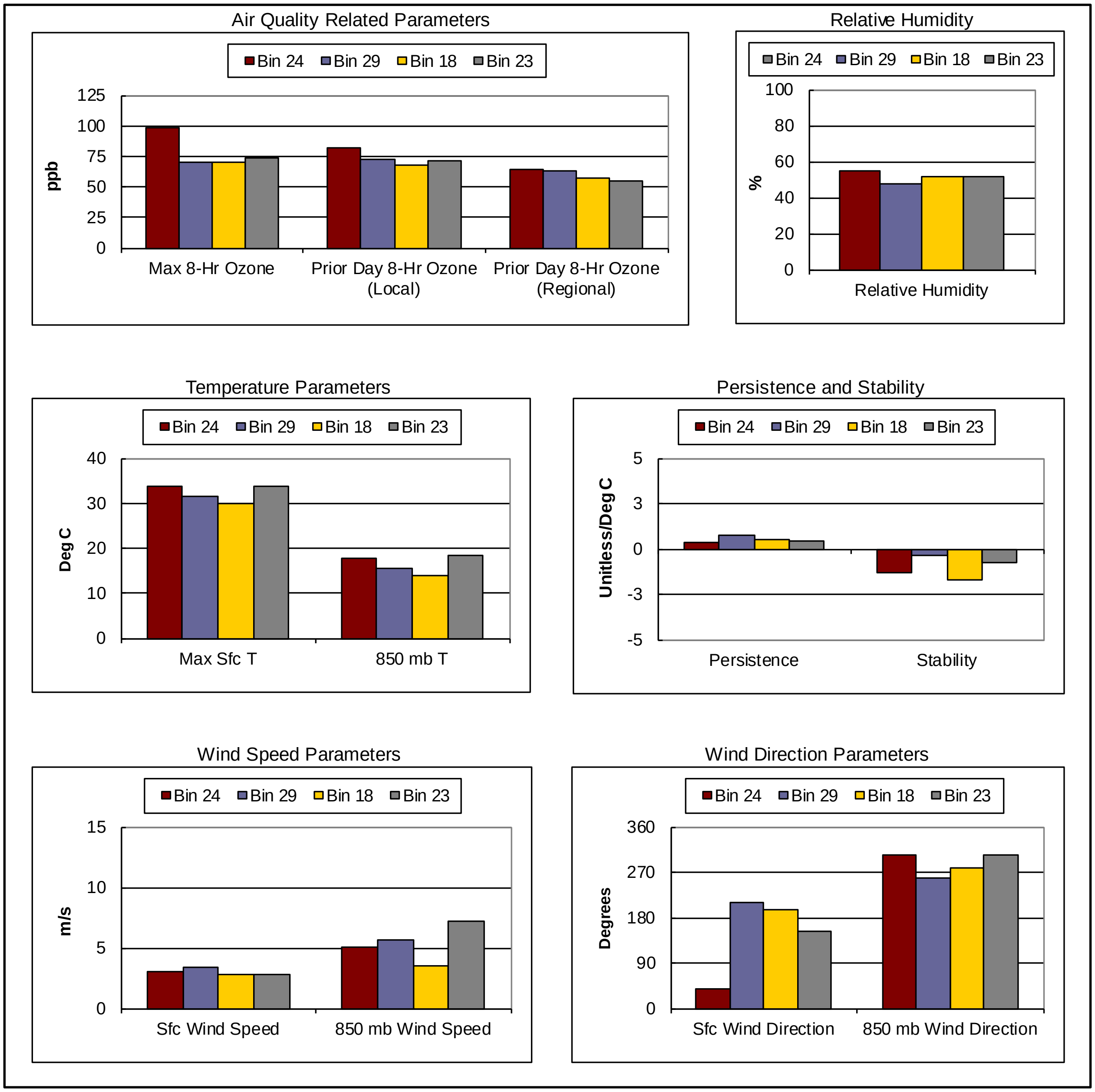


Figure 80g. Average values of selected parameters by bin for the key high ozone bins: Norfolk. The key bins are: Bin 24 = Category 4 (8 Days); Bin 29 = Category 3 (55 Days); Bin 18 = Category 3 (17 Days); Bin 23 = Category 3 (15 Days).

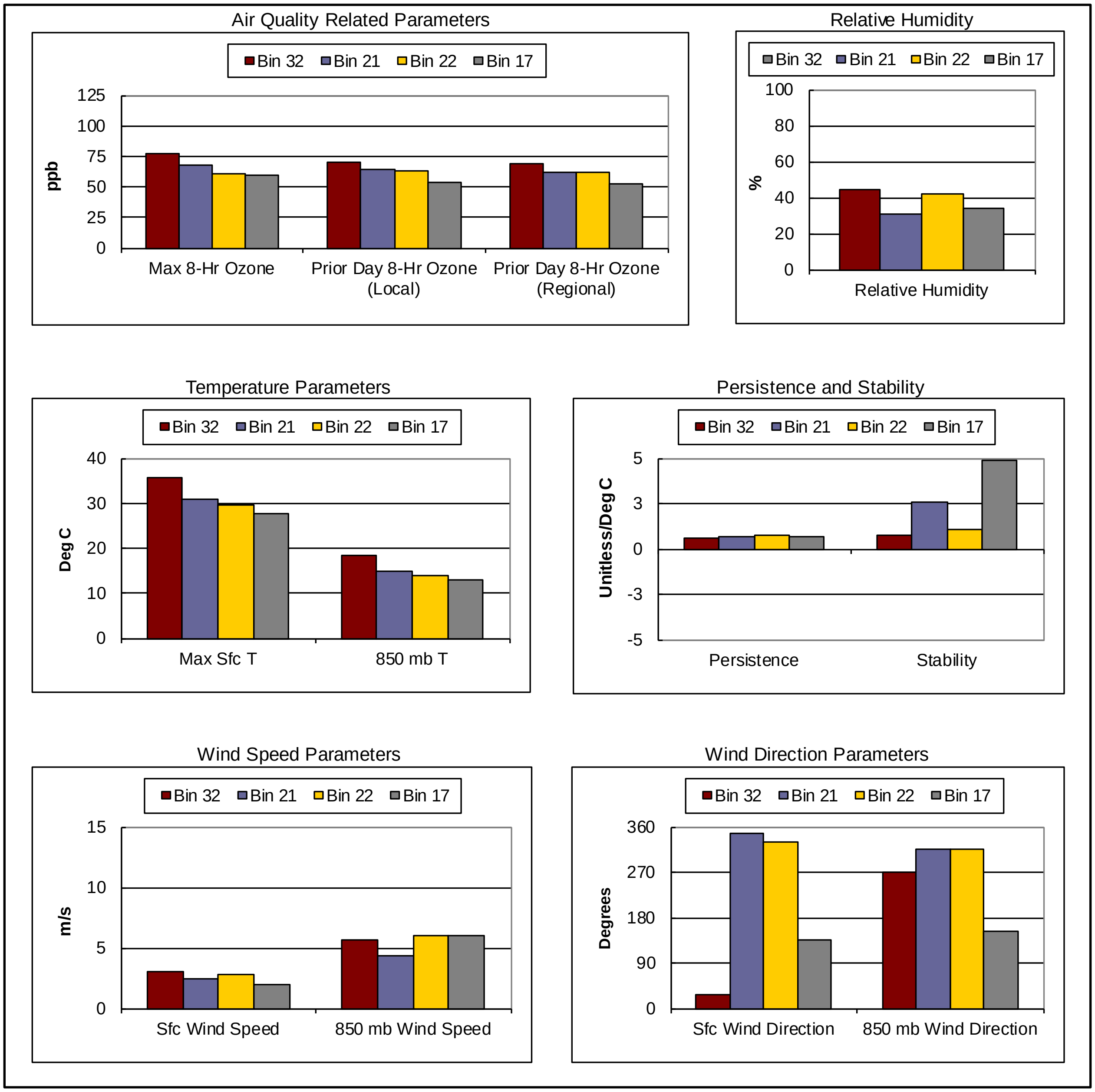


Figure 80h. Average values of selected parameters by bin for the key high ozone bins: Savannah. The key bins are: Bin 32 = Category 3 (13 Days); Bin 21 = Category 2 (7 Days); Bin 22 = Category 2 (78 Days); Bin 17= Category 2 (25 Days).

While there are many similarities in the conditions that describe the key bins, there are also some important differences. Many of these relate to prior day ozone concentration, stability, and wind direction (and, therefore, source-receptor relationships).

Using Baltimore as an example (Figure 69f), two Category 4 and two Category 3 bins are presented. Comparing the two Category 4 bins, days in Bin 35 are characterized by higher prior day ozone concentrations (locally and regionally) and higher relative humidity, temperature, and wind speed than days in Bin 20. Days within Bin 20 are more stable. Midday average surface wind directions are quite different for the two bins, and are northerly for Bin 20 but westerly for Bin 35. The Category 3 bins have lower ozone concentrations and a mix of conditions that are in some cases more conducive to ozone and in other cases less conducive to ozone than the Category 4 bins. Days placed in Bin 28 are characterized by slightly higher prior day ozone concentrations and higher humidity than days in Bin 22. Days in Bin 22 are more stable. Midday average surface wind directions are northeasterly for Bin 28 and southwesterly for Bin 35. The results indicate that different combinations of local parameters can result in high ozone concentrations and that prior day ozone concentration (both regional and local) is a key distinguishing feature between the two categories.

4.4.4. Summary of Findings

The CART analysis, together with the selected air quality and meteorological input parameters, correctly classifies, on average, approximately 88 percent of the ozone season days for 2000–2010 according to daily maximum 8-hour ozone concentration. CART classification accuracy for the eight study areas ranges from approximately 81 to 95 percent. When only meteorological data are used as input to the CART analysis, classification accuracy is slightly lower (for most sites) and this indicates that the selected meteorological data are reasonably good indicators of ozone concentration for areas along the Atlantic Coast.

The CART classification technique can provide information about the relative importance of the various independent parameters in distinguishing days with different ozone air quality characteristics. Parameter importance varies among the different areas. On average, the most important parameters include: prior day maximum 8-hour ozone concentration in the area of interest, prior day maximum 8-hour ozone concentration in potential upwind areas, surface temperature, 850 mb temperature, and relative humidity. Of secondary importance are stability, surface wind speed, and persistence.

Analysis of the variations in the input parameters across defined ozone concentration categories reveals that there are numerous similarities among the areas and that high ozone concentrations are associated with relatively higher temperatures, lower relative humidity, lower wind speeds, greater stability, less cloud cover, and less rainfall, compared to days with lower ozone concentrations. For most areas, wind directions also vary by category which indicates that wind direction also affects ozone concentration. High ozone days are also characterized by both local and regional buildup of ozone, as indicated by the prior-day average ozone concentrations, which increase for each higher ozone category.

High ozone days for each area are divided among several CART bins, and this indicates that different combinations of the input parameters can lead to high ozone in each area (i.e., that there are multiple pathways to high ozone). Analysis of the key high ozone bins (bins containing the most number of high ozone days) reveals that one of the key distinguishing factors among the high ozone bins is wind direction. Differences in the prior-day regional ozone concentrations among the bins suggests that regional transport can be a factor in determining the ozone level, but that it is not always a dominant factor. Local conditions can also be important and different combinations of local parameters can result in high ozone concentrations. For several of the areas, subtle differences in meteorology and prior-day ozone can mean the difference between exceedance days and non-exceedance days. This finding has implications for air quality forecasting and attainment strategy development as part of air quality planning and management.

5.0 CART ANALYSIS FOR SELECTED COASTAL AREAS: PM2.5

The Classification and Regression Tree (CART) analysis technique was also used to examine the relationships between onshore and offshore meteorological conditions and air quality relating to particulate matter in selected port/harbor areas along the Atlantic Coast. The focus of this analysis was daily (24-hour average) $PM_{2.5}$. CART was applied for Portland, Providence, New York, Newark-Elizabeth, Baltimore, Norfolk, Wilmington, and Savannah.

The objective of this analysis was to explore the relationships between the offshore meteorological conditions, onshore meteorological conditions, and $PM_{2.5}$ concentrations in each of the areas of interest. Also of interest is the role of wind direction (and specifically onshore-directed flow) in determining high $PM_{2.5}$ regimes. All of the data presented in this section are included in the ARAQDB.

5.1. CART Application Procedures

CART was applied for the period 2000–2010. Details of the CART application for $PM_{2.5}$ are presented in this section.

As part of this analysis, CART was applied using the full set of input data and then using only the meteorological input parameters. This was done to examine the relative importance of the meteorological versus air quality parameters in determining $PM_{2.5}$ concentration and whether the selected meteorological parameters (in the absence of prior-day air quality information) are good indicators of $PM_{2.5}$ concentration.

5.1.1. Identification of CART Input Parameters

A first step in the application of CART is the identification of the input parameters. The following list includes available meteorological and air quality parameters that are expected to influence $PM_{2.5}$ concentrations along the Atlantic Coast. The list of input parameters was adapted from the CART analysis conducted for the former Minerals Management Service (MMS) as part of a similar data synthesis study for the Gulf of Mexico region (Douglas et al., 2009).

Surface Meteorological Parameters

Surface meteorological parameters were used to characterize the local meteorological conditions. The surface meteorological inputs for CART are listed below.

- **Temperature**
  - Daily maximum temperature (ºC)
  - Daily average temperature (ºC)
- **Relative Humidity**
  - Daily average relative humidity (%)

- **Wind**
  - 24-hour average vector wind direction bin; value of 1 through 5, indicating the wind direction corresponding to the 24-hour vector average wind direction. Bin definitions (in degrees) are: [315, 45), [45, 135), [135, 225), [225, 315), or calm, respectively.
  - 24-hour average scalar wind speed (ms^{-1})
  - Persistence index (24-hour average vector wind speed/24-hour average scalar wind speed).
- **Pressure**
  - 24-hour average sea level pressure (mb)
- **Precipitation**
  - 24-hour total precipitation (in)

Upper-Air Meteorological Parameters

Upper-air meteorological parameters were used to characterize the regional-scale meteorological conditions. The upper-air parameters are as follows:

- **Temperature**

  900 mb

  - 900 mb to surface temperature gradient, defined here as the difference between the temperature at 900 mb and the surface using the morning (0500 LST) temperature sounding data (ºC)

  850 mb

  - Upper-air 850 mb temperature corresponding to the morning (0500 LST) sounding on the current day (ºC)
  - Upper-air 850 mb temperature corresponding to the evening (1700 LST) sounding on the current day (ºC)
- **Wind**

  700 mb

  The following two upper-air wind variables were computed using data from the prior day's evening sounding for 700 mb:

  - Wind speed (ms^{-1})
  - Wind direction bin; value of 1 through 5, indicating the wind direction: (in degrees) [315, 45), [45, 135), [135, 225), [225, 315), or calm, respectively

850 mb

The following two upper-air wind variables were computed using data from the prior day's evening sounding, and the current day's morning and evening soundings for 850 mb (for a total of six input variables for each upper-air monitoring site):

– Wind speed (ms^{-1})

– Wind direction bin; value of 1 through 5, indicating the wind direction: (in degrees) [315, 45), [45, 135), [135, 225), [225, 315), or calm, respectively

- **Recirculation**

850 mb

– Recirculation index (value of 0 or 1) that is based on the difference between the average wind direction yesterday and today and/or scalar wind speed.

- **Geopotential Height**

700 mb

– Difference in the daily average geopotential height above sea level of the 700 mb surface (m) using height for the current day minus height for the prior day.

- **Clouds**

700/850 mb

The cloud indicator variable combines data from both the 700 and 850 mb and was computed using data from the morning and evening soundings.

– Cloud index. Value based on relative humidity at the 850 mb (rh850) and 700 mb (rh700) levels. Ranges from 1 to 3 are based on the empirical analysis of observed data and are defined as follows:

  - if (rh850 < 80% and rh700 < 65%) then cloud = 1;
  - if (rh850 >= 80% and rh700 < 65%) then cloud = 2;
  - if (rh850 < 80% and rh700 >= 65%) then cloud = 2;
  - if (rh850 >= 80% and rh700 >= 65%) then cloud = 3

Air Quality Parameters

In addition to the meteorological input parameters, $PM_{2.5}$ concentrations for prior days locally, as well as for the region were also used in the CART analysis.

- **PM2.5**

– *Classification parameter for the application of CART for $PM_{2.5}$.* Assigned a value of 1 through 4, such that each value corresponds to a different range of 24-hour average $PM_{2.5}$ concentration. The concentration ranges are: less than 15 μgm^{-3}, 15 to 25 μgm^{-3}, 25 to 35 μgm^{-3} and greater than or equal 35 μgm^{-3}.

All of the $PM_{2.5}$ data used for this analysis are Federal Reference Method (FRM) data.

- **Local $PM_{2.5}$ Indicator Variables**
  - Prior-day 24-hour average $PM_{2.5}$ concentration at the site being analyzed (μgm^{-3}).

- **Regional $PM_{2.5}$ Indicator Variables**
  - Prior-day 24-hour average $PM_{2.5}$ concentrations averaged over nearby and thus potentially upwind sites (μgm^{-3}). The specific sites and number of potential upwind sites is different for each CART region.

5.1.2. Quality Assurance Steps

Following each application, the results were assessed using statistical measures of the goodness of the classification, and then checked for physical reasonableness. The procedures are the same as those used for the ozone analysis (refer to Section 4.2.2).

5.1.3. Assessment of CART Results

The CART results were displayed in a variety of ways, both as part of the quality assurance and to aid the analysis of the results.

CART trees with approximately 25-35 bins were selected to optimize classification accuracy and physical reasonableness. The high $PM_{2.5}$ days, however, were grouped into one to seven bins (all high $PM_{2.5}$ days in the Portland and Norfolk areas were placed into a single bin).

Tabular summaries of classification accuracy were prepared and classification accuracy, by category and overall, were calculated. Overall classification accuracy ranged from 70 to 97 percent.

The relative importance of the various input parameters to the CART classification tree was examined and plotted for each site.

5.2. CART DATA

The observed $PM_{2.5}$ and meteorological data used in the CART analysis are summarized in Tables 18 through 25 and provide information about the meteorological conditions associated with different levels of $PM_{2.5}$ concentration for the selected port/harbor areas.

To examine the variations in $PM_{2.5}$ versus meteorology, 24-hour average $PM_{2.5}$ concentrations were obtained for representative monitoring sites for the selected areas. Based on the observed value of the 24-hour average $PM_{2.5}$ concentration, each day was then assigned to one of the four concentration categories (less than 15 μgm^{-3}, 15 to 25 μgm^{-3}, 25 to 35 μgm^{-3}, and greater than or equal to 35 μgm^{-3}). Then average values of the meteorological parameters were calculated for all days within each of the $PM_{2.5}$ concentration categories. In addition to the meteorological parameters, the 24-hour average $PM_{2.5}$ concentration for each category is provided. Prior day $PM_{2.5}$ concentrations for the local area and potential upwind areas are also provided.

The combined $PM_{2.5}$ and meteorological summaries tables for each area are presented in the order listed above (north to south).

Table 18
Summary of $PM_{2.5}$ and Meteorological Data by $PM_{2.5}$ Concentration Category for 2000–2010: Portland.

$PM_{2.5}$ Data are for Portland; Surface Meteorological Data are for Portland International Airport. The Ranges in Ozone Concentration for Categories 1 through 4 are as follows: <15, 15-25, 25-35 and $\geq$ 35 μgm^{-3}.

	Category 1	Category 2	Category 3	Category 4
No. of Days	499	87	20	5
$PM_{2.5}$ Parameters				
$PM_{2.5}$ at Portland (μgm^{-3})	7.9	18.9	28.7	39.5
Yesterday's $PM_{2.5}$ Portland (μgm^{-3})	8.3	17.6	26.0	34.9
Yesterday's $PM_{2.5}$ North Atlantic Region (μgm^{-3})	8.6	15.0	19.8	28.7
Surface Meteorological Parameters				
Max. surface temperature (°C)	13.1	11.2	16.0	22.3
Min. surface temperature (°C)	4.3	0.3	4.6	12.8
Average relative humidity (%)	69	72	74	76
Surface wind speed (ms^{-1})	3.4	2.4	2.3	2.2
Surface wind direction (degrees)	279	215	225	180
Persistence	0.7	0.7	0.7	0.8
Sea level pressure (mb)	1019	1020	1018	1016
Rainfall (inches)	0.2	0.1	0.1	0.0
Upper-Air Meteorological Parameters				
Temperature AM 850 mb at Gray (°C)	2.1	1.0	5.0	14.4
Temperature PM 850 mb at Gray (°C)	2.8	2.9	6.7	13.8
Stability at Gray (°C)	-1.5	1.4	1.9	1.4
Geopotential hgt difference 700 mb at Gray (m)	-3.4	13.8	0.9	-25.5
Wind speed yesterday 700 mb at Gray (ms^{-1})	10.6	11.3	9.1	8.1
Wind dir. yesterday 700 mb at Gray (degrees)	276	287	270	284
Wind speed yesterday 850 mb at Gray (ms^{-1})	10.6	11.3	9.1	8.1
Wind speed AM 850 mb at Gray (ms^{-1})	10.4	9.6	9.3	8.2
Wind speed PM 850 mb at Gray (ms^{-1})	10.6	11.1	11.7	11.5
Wind dir. yesterday 850 mb at Gray (degrees)	288	291	273	270
Wind dir. AM 850 mb at Gray (degrees)	299	275	259	270
Wind dir. PM 850 mb at Gray (degrees)	291	272	273	284
Recirculation index at Gray	0.0	0.0	0.0	0.0
Cloud index at Gray	1.8	1.7	1.7	1.8

Table 19
Summary of $PM_{2.5}$ and Meteorological Data by $PM_{2.5}$ Concentration Category for 2000–2010: Providence.

$PM_{2.5}$ Data are for East Providence; Surface Meteorological Data are for Providence T F Green Airport. The Ranges in Ozone Concentration for Categories 1 through 4 are as follows: <15, 15-25, 25-35 and ≥ 35 μgm^{-3}.

	Category 1	Category 2	Category 3	Category 4
No. of Days	755	127	13	3
$PM_{2.5}$ Parameters				
$PM_{2.5}$ at East Providence (μgm^{-3})	7.4	18.8	28.8	41.6
Yesterday's $PM_{2.5}$ East Providence (μgm^{-3})	8.6	14.3	20.0	26.2
Yesterday's $PM_{2.5}$ Mid-North Atlantic Region (μgm^{-3})	10.5	16.6	22.3	29.5
Surface Meteorological Parameters				
Max. surface temperature (°C)	15.3	18.4	22.5	27.4
Min. surface temperature (°C)	6.6	8.3	11.8	16.3
Average relative humidity (%)	65	72	72	71
Surface wind speed (ms^{-1})	4.1	3.2	3.2	3.4
Surface wind direction (degrees)	282	227	223	255
Persistence	0.8	0.8	0.8	0.8
Sea level pressure (mb)	1020	1020	1019	1017
Rainfall (inches)	0.2	0.1	0.0	0.1
Upper-Air Meteorological Parameters				
Temperature AM 850 mb at Chatham (°C)	4.2	7.1	9.9	13.4
Temperature PM 850 mb at Chatham (°C)	4.6	8.5	11.2	14.8
Stability at Chatham (°C)	-2.7	-0.6	0.0	1.1
Geopotential hgt difference 700 mb at Chatham (m)	-1.9	5.1	10.5	1.1
Wind speed yesterday 700 mb at Chatham (ms^{-1})	14.6	13.3	12.2	10.8
Wind dir. yesterday 700 mb at Chatham (degrees)	274	281	285	291
Wind speed yesterday 850 mb at Chatham (ms^{-1})	11.4	10.3	9.2	8.3
Wind speed AM 850 mb at Chatham (ms^{-1})	11.1	10.2	8.9	10.5
Wind speed PM 850 mb at Chatham (ms^{-1})	11.3	10.8	10.3	10.3
Wind dir. yesterday 850 mb at Chatham (degrees)	284	282	278	286
Wind dir. AM 850 mb at Chatham (degrees)	282	275	275	270
Wind dir. PM 850 mb at Chatham (degrees)	289	271	260	259
Recirculation index at Chatham	0.0	0.0	0.0	0.0
Cloud index at Chatham	1.7	1.7	1.6	1.6

Table 20
Summary of $PM_{2.5}$ and Meteorological Data by $PM_{2.5}$ Concentration Category for 2000–2010: New York.

$PM_{2.5}$ Data are for Hempstead; Surface Meteorological Data are for JFK International Airport. The Ranges in Ozone Concentration for Categories 1 through 4 are as follows: <15, 15-25, 25-35 and ≥ 35 μgm^{-3}.

	Category 1	Category 2	Category 3	Category 4
No. of Days	960	229	54	18
$PM_{2.5}$ Parameters				
$PM_{2.5}$ at Hempstead (μgm^{-3})	8.0	18.6	28.6	41.9
Yesterday's $PM_{2.5}$ Hempstead (μgm^{-3})	8.8	16.6	23.9	33.8
Yesterday's $PM_{2.5}$ Mid-North Atlantic Region (μgm^{-3})	9.8	15.8	21.5	28.3
Surface Meteorological Parameters				
Max. surface temperature (°C)	15.2	17.8	22.5	29.1
Min. surface temperature (°C)	8.0	10.3	14.0	19.5
Average relative humidity (%)	64	72	73	70
Surface wind speed (ms^{-1})	5.4	4.2	3.9	4.1
Surface wind direction (degrees)	275	206	202	218
Persistence	0.8	0.8	0.8	0.8
Sea level pressure (mb)	1021	1020	1019	1017
Rainfall (inches)	0.1	0.1	0.1	0.1
Upper-Air Meteorological Parameters				
Temperature AM 850 mb at Brookhaven (°C)	3.8	7.0	11.1	15.0
Temperature PM 850 mb at Brookhaven (°C)	4.3	8.0	12.2	15.9
Stability at Brookhaven (°C)	-1.4	0.7	1.4	0.8
Geopotential hgt difference 700 mb at Brookhaven (m)	0.0	4.9	4.5	-4.8
Wind speed yesterday 700 mb at Brookhaven (ms^{-1})	14.7	13.3	11.4	10.0
Wind dir. yesterday 700 mb at Brookhaven (degrees)	279	283	284	294
Wind speed yesterday 850 mb at Brookhaven (ms^{-1})	11.1	10.1	8.6	8.7
Wind speed AM 850 mb at Brookhaven (ms^{-1})	11.3	10.3	8.7	7.6
Wind speed PM 850 mb at Brookhaven (ms^{-1})	11.6	10.9	9.5	8.9
Wind dir. yesterday 850 mb at Brookhaven (degrees)	294	287	279	286
Wind dir. AM 850 mb at Brookhaven (degrees)	294	284	272	278
Wind dir. PM 850 mb at Brookhaven (degrees)	297	281	278	274
Recirculation index at Brookhaven	0.0	0.0	0.0	0.0
Cloud index at Brookhaven	1.7	1.7	1.6	1.7

Table 21
Summary of $PM_{2.5}$ and Meteorological Data by $PM_{2.5}$ Concentration Category for 2000–2010: Newark-Elizabeth.

$PM_{2.5}$ Data are for Elizabeth Lab; Surface Meteorological Data are for Newark International Airport. The Ranges in Ozone Concentration for Categories 1 through 4 are as follows: <15, 15-25, 25-35 and $\geq 35\ \mu gm^{-3}$.

	Category 1	Category 2	Category 3	Category 4
No. of Days	755	127	13	3
$PM_{2.5}$ Parameters				
$PM_{2.5}$ at Elizabeth Lab (μgm^{-3})	8.9	19.1	28.8	41.8
Yesterday's $PM_{2.5}$ Elizabeth Lab (μgm^{-3})	11.5	16.7	20.4	29.5
Yesterday's $PM_{2.5}$ Mid-North Atlantic Region (μgm^{-3})	9.6	13.6	16.9	24.1
Surface Meteorological Parameters				
Max. surface temperature (°C)	15.8	19.5	21.7	24.3
Min. surface temperature (°C)	7.7	10.6	12.4	14.5
Average relative humidity (%)	57	64	67	67
Surface wind speed (ms^{-1})	4.8	3.7	3.5	3.4
Surface wind direction (degrees)	316	252	239	248
Persistence	0.8	0.7	0.7	0.7
Sea level pressure (mb)	1020	1020	1019	1020
Rainfall (inches)	0.1	0.1	0.1	0.1
Upper-Air Meteorological Parameters				
Temperature AM 850 mb at Brookhaven (°C)	3.2	7.4	9.1	11.2
Temperature PM 850 mb at Brookhaven (°C)	3.4	8.5	10.5	12.6
Stability at Brookhaven (°C)	-2.2	0.6	1.4	1.9
Geopotential hgt difference 700 mb at Brookhaven (m)	-1.1	3.9	2.9	7.5
Wind speed yesterday 700 mb at Brookhaven (ms^{-1})	15.2	13.8	12.7	11.4
Wind dir. yesterday 700 mb at Brookhaven (degrees)	280	281	284	299
Wind speed yesterday 850 mb at Brookhaven (ms^{-1})	11.8	10.0	9.6	8.9
Wind speed AM 850 mb at Brookhaven (ms^{-1})	11.4	10.2	9.6	8.3
Wind speed PM 850 mb at Brookhaven (ms^{-1})	11.2	10.9	10.9	9.6
Wind dir. yesterday 850 mb at Brookhaven (degrees)	298	284	283	293
Wind dir. AM 850 mb at Brookhaven (degrees)	302	275	276	272
Wind dir. PM 850 mb at Brookhaven (degrees)	308	273	273	270
Recirculation index at Brookhaven	0.0	0.0	0.0	0.0
Cloud index at Brookhaven	1.7	1.7	1.7	1.6

Table 22
Summary of $PM_{2.5}$ and Meteorological Data by $PM_{2.5}$ Concentration Category for 2000–2010: Baltimore.

$PM_{2.5}$ Data are for Essex; Surface Meteorological Data are for Baltimore Washington International Airport. The Ranges in Ozone Concentration for Categories 1 through 4 are as follows: <15, 15-25, 25-35 and ≥ 35 μgm^{-3}.

	Category 1	Category 2	Category 3	Category 4
No. of Days	2143	911	271	89
$PM_{2.5}$ Parameters				
$PM_{2.5}$ at Essex (μgm^{-3})	9.2	19.0	28.8	41.0
Yesterday's $PM_{2.5}$ Essex (μgm^{-3})	11.4	16.4	23.8	30.6
Yesterday's $PM_{2.5}$ Mid-South Atlantic Region (μgm^{-3})	11.2	15.3	20.4	25.2
Surface Meteorological Parameters				
Max. surface temperature (°C)	16.7	20.7	22.9	26.5
Min. surface temperature (°C)	7.3	9.6	11.7	14.6
Average relative humidity (%)	64	68	71	67
Surface wind speed (ms^{-1})	3.3	2.2	2.0	2.1
Surface wind direction (degrees)	287	208	210	231
Persistence	0.8	0.8	0.8	0.7
Sea level pressure (mb)	1021	1020	1020	1019
Rainfall (inches)	0.2	0.1	0.1	0.1
Upper-Air Meteorological Parameters				
Temperature AM 850 mb at Dulles (°C)	4.7	8.6	10.8	13.5
Temperature PM 850 mb at Dulles (°C)	5.3	9.7	11.9	14.4
Stability at Dulles (°C)	-1.4	1.7	2.6	3.0
Geopotential hgt difference 700 mb at Dulles (m)	-1.2	2.6	0.2	-0.8
Wind speed yesterday 700 mb at Dulles (ms^{-1})	15.1	12.6	11.1	9.4
Wind dir. yesterday 700 mb at Dulles (degrees)	279	282	280	296
Wind speed yesterday 850 mb at Dulles (ms^{-1})	11.0	8.5	7.6	6.8
Wind speed AM 850 mb at Dulles (ms^{-1})	11.4	8.9	8.3	6.6
Wind speed PM 850 mb at Dulles (ms^{-1})	10.6	9.2	8.6	7.4
Wind dir. yesterday 850 mb at Dulles (degrees)	278	274	270	285
Wind dir. AM 850 mb at Dulles (degrees)	294	275	275	287
Wind dir. PM 850 mb at Dulles (degrees)	283	266	267	272
Recirculation index at Dulles	0.0	0.0	0.0	0.1
Cloud index at Dulles	1.8	1.7	1.7	1.6

Table 23
Summary of $PM_{2.5}$ and Meteorological Data by $PM_{2.5}$ Concentration Category for 2000–2010: Norfolk.

$PM_{2.5}$ Data are for Norfolk; Surface Meteorological Data are for Norfolk International Airport. The Ranges in Ozone Concentration for Categories 1 through 4 are as follows: <15, 15-25, 25-35 and ≥ 35 μgm^{-3}.

	Category 1	Category 2	Category 3	Category 4
No. of Days	957	273	53	15
$PM_{2.5}$ Parameters				
$PM_{2.5}$ at Norfolk (μgm^{-3})	9.1	18.6	28.9	48.7
Yesterday's $PM_{2.5}$ Norfolk (μgm^{-3})	10.0	16.9	24.4	41.8
Yesterday's $PM_{2.5}$ Mid-South Atlantic Region (μgm^{-3})	11.0	17.6	23.9	34.5
Surface Meteorological Parameters				
Max. surface temperature (°C)	18.8	23.5	27.9	30.6
Min. surface temperature (°C)	10.6	14.7	18.7	20.5
Average relative humidity (%)	68	73	73	66
Surface wind speed (ms^{-1})	4.3	3.4	3.0	3.3
Surface wind direction (degrees)	338	276	228	230
Persistence	0.8	0.7	0.7	0.6
Sea level pressure (mb)	1021	1019	1018	1017
Rainfall (inches)	0.1	0.1	0.1	0.1
Upper-Air Meteorological Parameters				
Temperature AM 850 mb at Wallops Island (°C)	6.1	10.7	13.8	15.7
Temperature PM 850 mb at Wallops Island (°C)	6.8	11.2	15.1	16.6
Stability at Wallops Island (°C)	-2.0	-1.1	-0.8	-1.5
Geopotential hgt difference 700 mb at Wallops Island (m)	-3.2	2.5	-1.4	2.2
Wind speed yesterday 700 mb at Wallops Island (ms^{-1})	14.7	12.5	9.5	10.4
Wind dir. yesterday 700 mb at Wallops Island (degrees)	275	280	290	311
Wind speed yesterday 850 mb at Wallops Island (ms^{-1})	11.0	9.4	7.4	7.9
Wind speed AM 850 mb at Wallops Island (ms^{-1})	11.0	9.0	7.1	7.3
Wind speed PM 850 mb at Wallops Island (ms^{-1})	11.5	9.0	8.1	7.8
Wind dir. yesterday 850 mb at Wallops Island (degrees)	279	281	294	280
Wind dir. AM 850 mb at Wallops Island (degrees)	282	287	289	284
Wind dir. PM 850 mb at Wallops Island (degrees)	282	287	276	275
Recirculation index at Wallops Island	0.0	0.0	0.0	0.0
Cloud index at Wallops Island	1.7	1.7	1.8	1.7

Table 24
Summary of $PM_{2.5}$ and Meteorological Data by $PM_{2.5}$ Concentration Category for 2000–2010: Wilmington.

$PM_{2.5}$ Data are for Castle Hayne; Surface Meteorological Data are for Wilmington International Airport. The Ranges in Ozone Concentration for Categories 1 through 4 are as follows: <15, 15-25, 25-35 and $\geq$ 35 μgm^{-3}.

	Category 1	**Category 2**	**Category 3**	**Category 4**
No. of Days	755	127	13	3
$PM_{2.5}$ Parameters				
$PM_{2.5}$ at Castle Hayne (μgm^{-3})	8.5	18.1	26.4	38.9
Yesterday's $PM_{2.5}$ Castle Hayne (μgm^{-3})	9.0	15.5	22.1	32.8
Yesterday's $PM_{2.5}$ South Atlantic Region (μgm^{-3})	10.5	14.8	21.0	22.1
Surface Meteorological Parameters				
Max. surface temperature (°C)	22.1	27.9	30.7	29.0
Min. surface temperature (°C)	11.7	17.5	20.6	19.4
Average relative humidity (%)	71	72	69	76
Surface wind speed (ms^{-1})	3.3	2.9	3.0	3.2
Surface wind direction (degrees)	218	228	194	117
Persistence	0.8	0.8	0.8	0.6
Sea level pressure (mb)	1020	1018	1017	1021
Rainfall (inches)	0.2	0.1	0.1	0.1
Upper-Air Meteorological Parameters`				
Temperature AM 850 mb at Moorhead City (°C)	9.5	14.0	15.8	14.4
Temperature PM 850 mb at Moorhead City (°C)	9.9	14.5	16.3	15.7
Stability at Moorhead City (°C)	-0.6	-0.1	-0.7	-3.1
Geopotential hgt difference 700 mb at Moorhead City (m)	-0.5	1.4	-1.8	14.7
Wind speed yesterday 700 mb at Moorhead City (ms^{-1})	9.3	7.7	5.2	8.9
Wind dir. yesterday 700 mb at Moorhead City (degrees)	276	296	315	333
Wind speed yesterday 850 mb at Moorhead City (ms^{-1})	9.3	7.7	5.2	8.9
Wind speed AM 850 mb at Moorhead City (ms^{-1})	9.2	7.9	7.4	5.5
Wind speed PM 850 mb at Moorhead City (ms^{-1})	9.3	7.5	5.3	6.0
Wind dir. yesterday 850 mb at Moorhead City (degrees)	276	291	270	270
Wind dir. AM 850 mb at Moorhead City (degrees)	281	291	276	0
Wind dir. PM 850 mb at Moorhead City (degrees)	275	290	294	180
Recirculation index at Moorhead City	0.0	0.0	0.0	0.0
Cloud index at Moorhead City	1.7	1.7	1.8	1.7

Table 25
Summary of $PM_{2.5}$ and Meteorological Data by $PM_{2.5}$ Concentration Category for 2000–2010: Savannah.

$PM_{2.5}$ Data are for Savannah; Surface Meteorological Data are for Savannah International Airport. The Ranges in Ozone Concentration for Categories 1 through 4 are as follows: <15, 15-25, 25-35 and $\geq$ 35 μgm^{-3}.

	Category 1	Category 2	Category 3	Category 4
No. of Days	833	309	41	12
$PM_{2.5}$ Parameters				
$PM_{2.5}$ at Savannah (μgm^{-3})	9.8	18.6	27.9	44.0
Yesterday's $PM_{2.5}$ Savannah (μgm^{-3})	10.6	17.2	24.7	34.3
Yesterday's $PM_{2.5}$ South Atlantic Region (μgm^{-3})	9.7	14.8	19.7	23.2
Surface Meteorological Parameters				
Max. surface temperature (°C)	24.3	26.3	26.7	27.7
Min. surface temperature (°C)	13.8	13.7	14.4	13.9
Average relative humidity (%)	72	71	71	70
Surface wind speed (ms-1)	3.0	2.2	2.0	2.0
Surface wind direction (degrees)	192	211	153	180
Persistence	0.8	0.7	0.7	0.8
Sea level pressure (mb)	1020	1020	1020	1020
Rainfall (inches)	0.1	0.1	0.0	0.1
Upper-Air Meteorological Parameters				
Temperature AM 850 mb at Jacksonville (°C)	12.7	13.3	13.4	14.0
Temperature PM 850 mb at Jacksonville (°C)	12.8	13.6	14.0	15.1
Stability at Jacksonville (°C)	-0.7	0.7	1.2	3.0
Geopotential hgt difference 700 mb at Jacksonville (m)	-1.8	2.9	-2.1	10.5
Wind speed yesterday 700 mb at Jacksonville (ms-1)	10.7	8.8	8.3	8.4
Wind dir. yesterday 700 mb at Jacksonville (degrees)	263	295	315	330
Wind speed yesterday 850 mb at Jacksonville (ms-1)	8.5	6.3	5.6	5.2
Wind speed AM 850 mb at Jacksonville (ms-1)	8.9	6.4	6.0	5.0
Wind speed PM 850 mb at Jacksonville (ms-1)	8.6	6.8	6.6	5.9
Wind dir. yesterday 850 mb at Jacksonville (degrees)	248	293	315	304
Wind dir. AM 850 mb at Jacksonville (degrees)	245	277	275	45
Wind dir. PM 850 mb at Jacksonville (degrees)	262	284	275	293

The tabular summaries indicate that, for all areas, previous day $PM_{2.5}$ concentrations are higher for days with the highest $PM_{2.5}$ concentrations. For all but two areas, high $PM_{2.5}$ concentrations are also associated with relatively higher temperatures. For Wilmington and Savannah, days within Category 3 bins have slightly higher temperatures than those for Category 4, but higher than for the lower category bins. Wind speeds at the surface and aloft are often similar for days within Categories 2 through 4, but wind speeds for high $PM_{2.5}$ days are always lower than for the bins containing the days with the lowest concentrations. For most areas, wind directions also vary by category which indicates that wind direction also affects $PM_{2.5}$ concentration. The specific wind directions and variations across the categories are different for each area.

5.3. CART RESULTS

The CART results for $PM_{2.5}$ are presented in the remainder of this section. As noted earlier, the CART results can provide information about the relative importance of the various independent parameters in distinguishing days with different $PM_{2.5}$ air quality characteristics as well as the combinations of parameters that lead to high $PM_{2.5}$. This information has been extracted from the CART analysis results for $PM_{2.5}$ and is discussed in this section.

5.3.1. Classification Accuracy

CART classification accuracy ranges from 70 to 97 percent for full CART analyses, which include both meteorological data and prior-day air quality data, and from 66 to 89 percent for the meteorological data only analyses. The results for both applications are summarized in Table 26.

Table 26
Summary of CART Classification Accuracy for 24-hour $PM_{2.5}$

CART Area	Classification Accuracy (%)	
	Meteorological & Air Quality Data	Meteorological Data Only
Portland	97	89
Providence	82	83
New York	94	82
Newark-Elizabeth	70	68
Baltimore	72	66
Norfolk	94	75
Wilmington	95	88
Savannah	92	72

Classification accuracy for the meteorological data only CART runs is lower by 2 to 20 percentage points compared to the full CART run. For one area (Providence) it is 1 percentage point higher. This range in reduction in classification accuracy indicates that the selected meteorological data are better indicators of $PM_{2.5}$ concentration for some areas than others. For those areas with a large difference in classification accuracy, regional-scale buildup and transport of $PM_{2.5}$ is likely an important factor in determining $PM_{2.5}$ concentration.

Our goal for the full data CART application for $PM_{2.5}$ for this study was 70 percent classification accuracy and this goal was met for six of the eight sites. Classification accuracies for Newark-Elizabeth and Baltimore were slightly below our target at 68 and 66 percent, respectively.

5.3.2. Classification Parameter Importance

As described in section 4.4.2 for ozone, parameter importance is calculated by CART based on the number of times each parameter is used, either as a split parameter or as a surrogate parameter, to construct the final classification tree. We use parameter importance in this analysis to identify those parameters that are statistically relevant to the classification and assume that these same parameters are also physically relevant to 24-hour average $PM_{2.5}$ concentrations. That is, we assume that the parameters that are most important in determining the structure of the CART tree are also most important in determining $PM_{2.5}$ air quality.

Parameter importance for each area is displayed in Figure 81. In each plot, the relative importance assigned to several of the surface and upper-air meteorology categories is the maximum over the parameters that comprise the grouping (e.g., the morning and evening 850 mb temperatures comprise the upper-air temperature group). The category abbreviations are defined as follows and represent one or more of the CART input parameters:

YPM_Local = Yesterday's 24-hour average $PM_{2.5}$ concentration for the area of interest

YPM_Regional = Yesterday's 24-hour average $PM_{2.5}$ concentration for neighboring and upwind areas (average for the group)

TMAX = Daily maximum temperature

TAVG = Daily average temperature

RH = Relative humidity

WS (Sfc) = Surface wind speed (maximum for the surface wind speed parameter group)

WD (Sfc) = Surface wind direction (maximum for the surface wind speed parameter group)

PERSIST = Persistence or sea-breeze index

SLP = Sea level pressure

PRECIP = Total rainfall (same as the RAIN parameter used in the ozone analyses)

CLOUD = Cloud cover index

DZ700 = Daily change in geopotential height at the 700 mb level

DT900 = 900 mb to surface temperature difference

T850 = 850 mb temperature (maximum for the upper-air temperature parameter group)

WS (Upper) = Wind speed aloft (maximum for the upper-air wind speed parameter group)

WD (Upper) = Wind direction aloft (maximum over the upper-air wind speed parameter group)

In this and subsequent plots of parameter importance, red is used for air quality parameters, blue is used for surface meteorological parameters, and green is used for upper-air parameters.

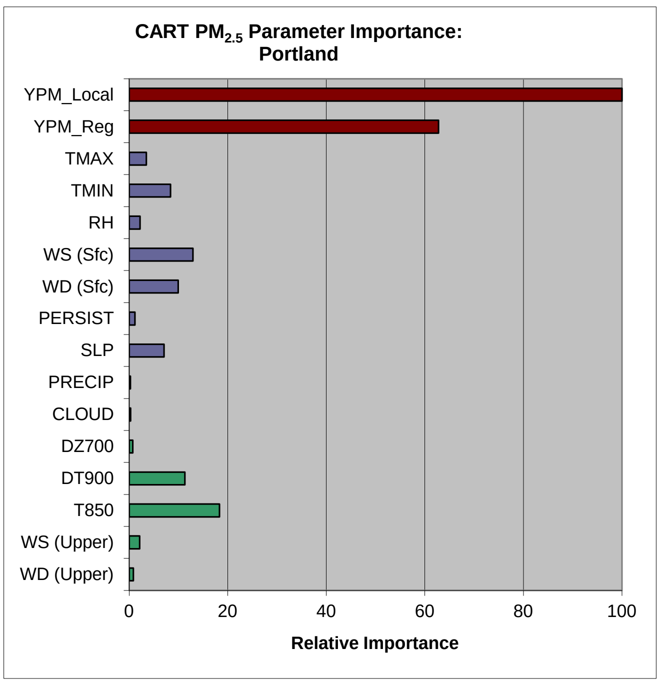


Figure 81a. Average parameter importance for the 24-hour $PM_{2.5}$ CART analysis: Portland.

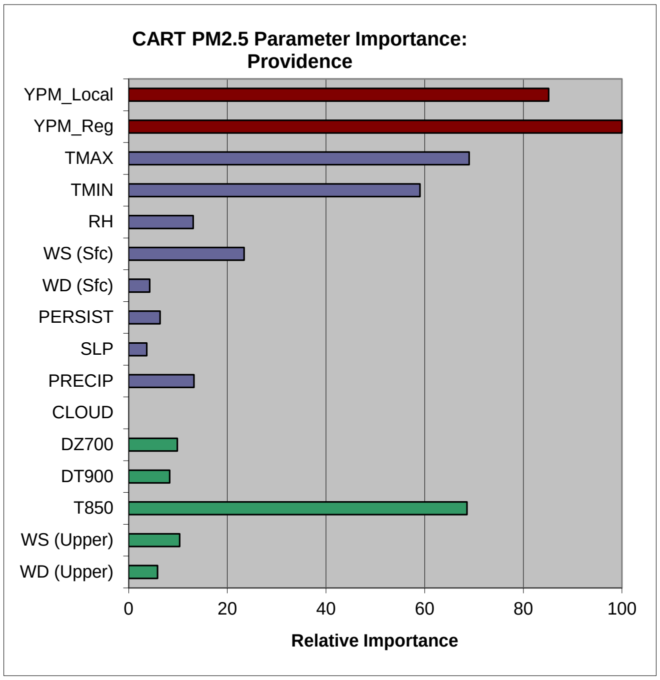


Figure 81b. Average parameter importance for the 24-hour $PM_{2.5}$ CART analysis: Providence.

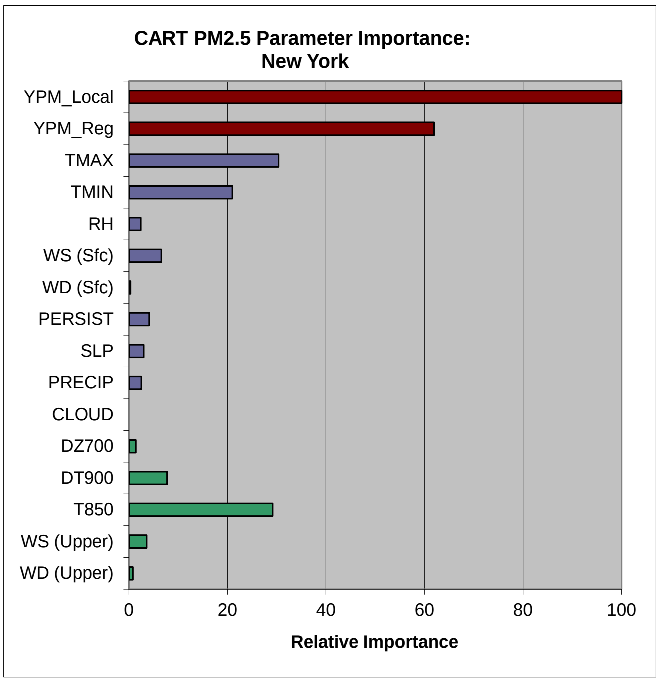


Figure 81c. Average parameter importance for the 24-hour $PM_{2.5}$ CART analysis: New York.

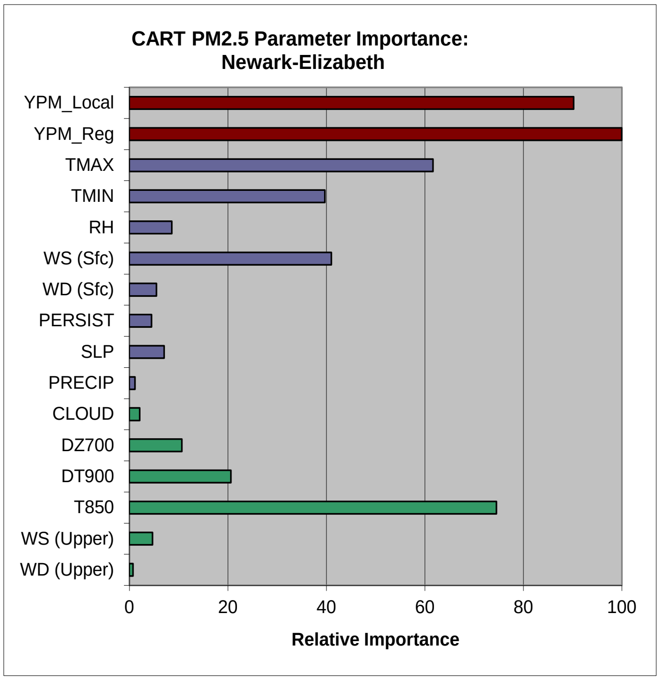


Figure 81d. Average parameter importance for the 24-hour $PM_{2.5}$ CART analysis: Newark-Elizabeth.

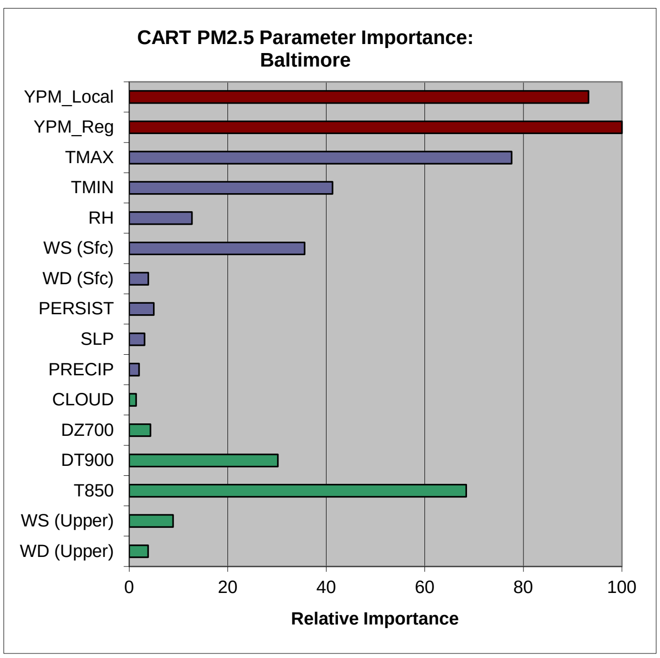


Figure 81e. Average parameter importance for the 24-hour $PM_{2.5}$ CART analysis: Baltimore.

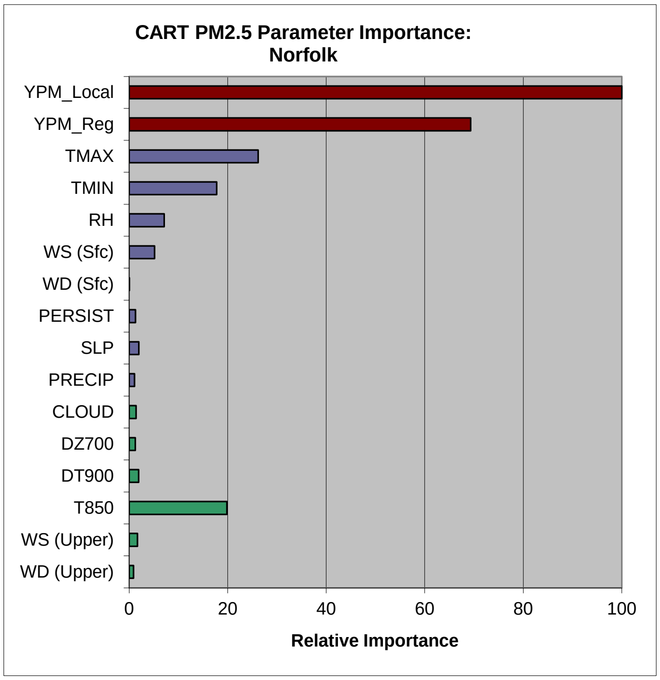


Figure 81f. Average parameter importance for the 24-hour PM.5 CART analysis: Norfolk.

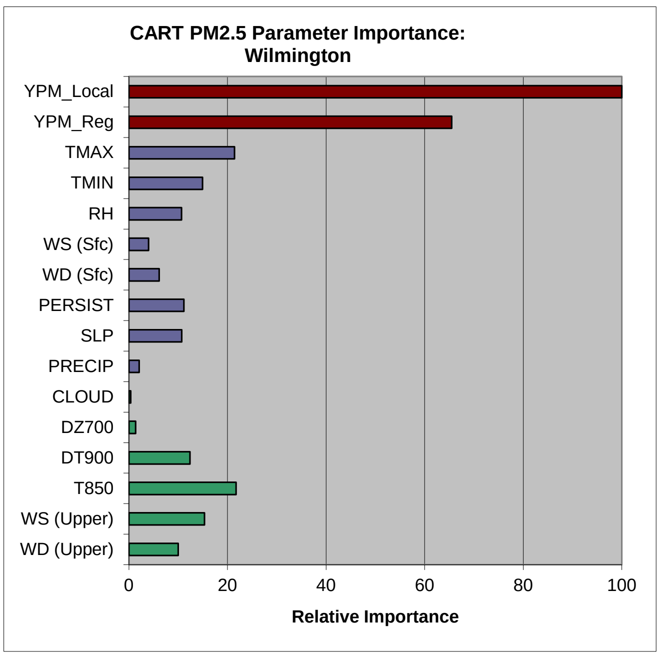


Figure 81g. Average parameter importance for the 24-hour $PM_{2.5}$ CART analysis: Wilmington.

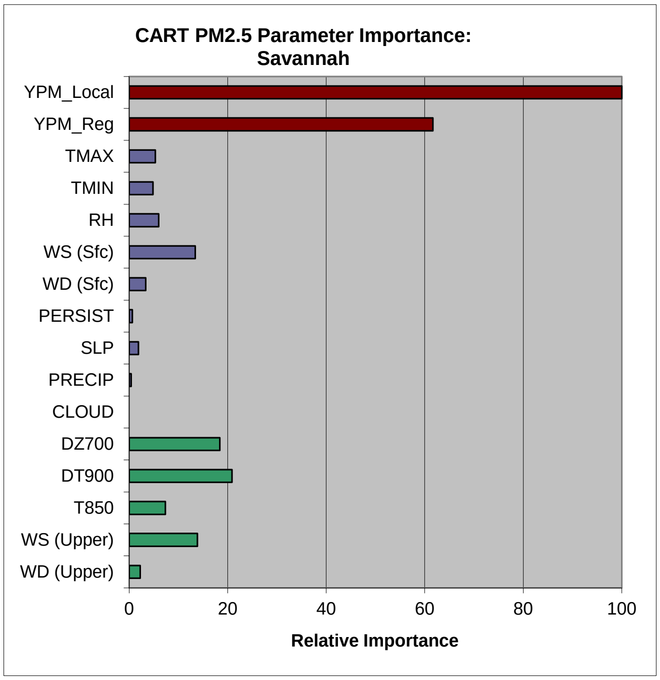


Figure 81h. Average parameter importance for the 24-hour $PM_{2.5}$ CART analysis: Savannah.

Parameter importance varies among the different areas, especially with regard to the local, surface meteorological parameters. For all areas, prior day $PM_{2.5}$ concentrations are an important factor in determining the $PM_{2.5}$ category for the current day. The CART results indicate that both carryover (local parameter) and transport (regional parameters) play an important role in determining $PM_{2.5}$ concentration. Whereas for ozone, surface temperature and 850 mb temperature (which is an indicator of stability) were important for all areas, for $PM_{2.5}$ they were important for only six of the eight areas of interest. Temperature is less important in the northernmost (Portland) and southernmost (Savannah) areas. Surface wind speed is of moderate importance for Newark-Elizabeth and Baltimore, and of some importance in the other areas.

To summarize the results, the average parameter importance for all areas is displayed in Figure 82.

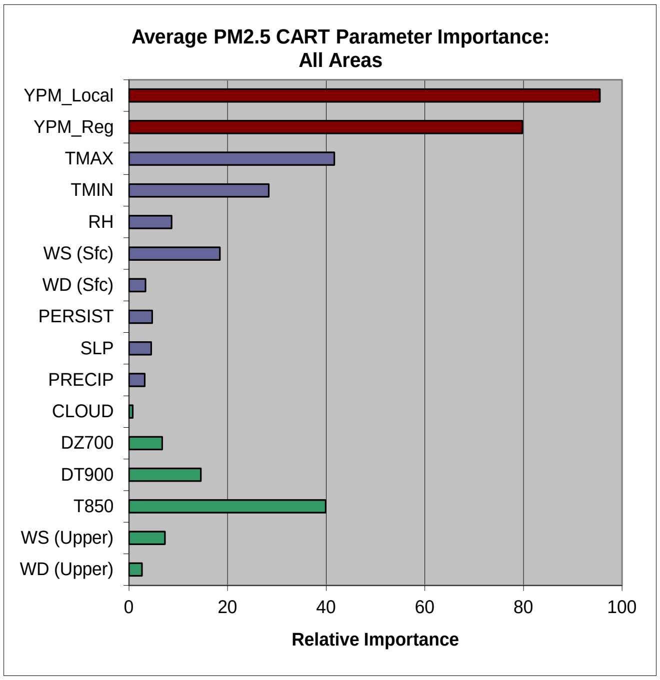


Figure 82. Average parameter importance for 8-hour ozone CART analysis: Average over all areas.

On average, the most important parameters include: prior day 24-hour $PM_{2.5}$ concentration in the area of interest, prior day maximum 24-hour $PM_{2.5}$ concentration in potential upwind areas, surface temperature, and 850 mb temperature. Of secondary importance are surface wind speed, and stability (DT900).

5.3.3. Characteristics of High PM2.5 Bins

In the previous section, we identified certain parameters that are important to the classification of days with respect to 24-hour average $PM_{2.5}$ concentration and concluded that these parameters have the potential to influence air quality at the monitoring sites. However, understanding the causes of high $PM_{2.5}$ concentrations (as was the case with high ozone concentrations) also requires an understanding of the relationship between the parameters and the air quality metrics, as well as the specific combinations of parameters (conditions) that lead to impaired air quality.

Each value of the classification parameter may be represented by more than one bin, allowing for the possibility that different combinations of the independent parameters can be associated with a single value of the classification parameter (i.e., that different sets of meteorological conditions can lead to high $PM_{2.5}$). CART assumes that there is a relationship between the independent parameters and the classification parameter, and that this relationship can be extracted from the data.

In this section we further explore the characteristics of the key bins that represent the high $PM_{2.5}$ days for each area. Key bins were defined as those containing the greatest number of correctly classified days. One or two bins from each of the two highest categories for each area were identified and the characteristics of those bins were examined and compared. Figure 83 displays and compares selected parameters for the key high $PM_{2.5}$ bins for each area. The parameters are grouped as follows: air quality related parameters, relative humidity, temperature parameters, stability and persistence parameters, wind speed parameters and wind direction parameters. For ease of comparison, figure scales are consistent for each parameter for all but two areas. Scales for the figures depicting stability for Newark-Elizabeth and Baltimore were increased to accommodate the relatively large values of that parameter, for those two areas. The bin category and number of days in each bin is also given. As a reminder, the concentration categories are defined as follows: Category 1 (< 15 μgm^{-3}), Category 2 (15 to 25 μgm^{-3}), Category 3 (25 to 35 μgm^{-3}), and Category 4 ($\geq$ 35 μgm^{-3}).

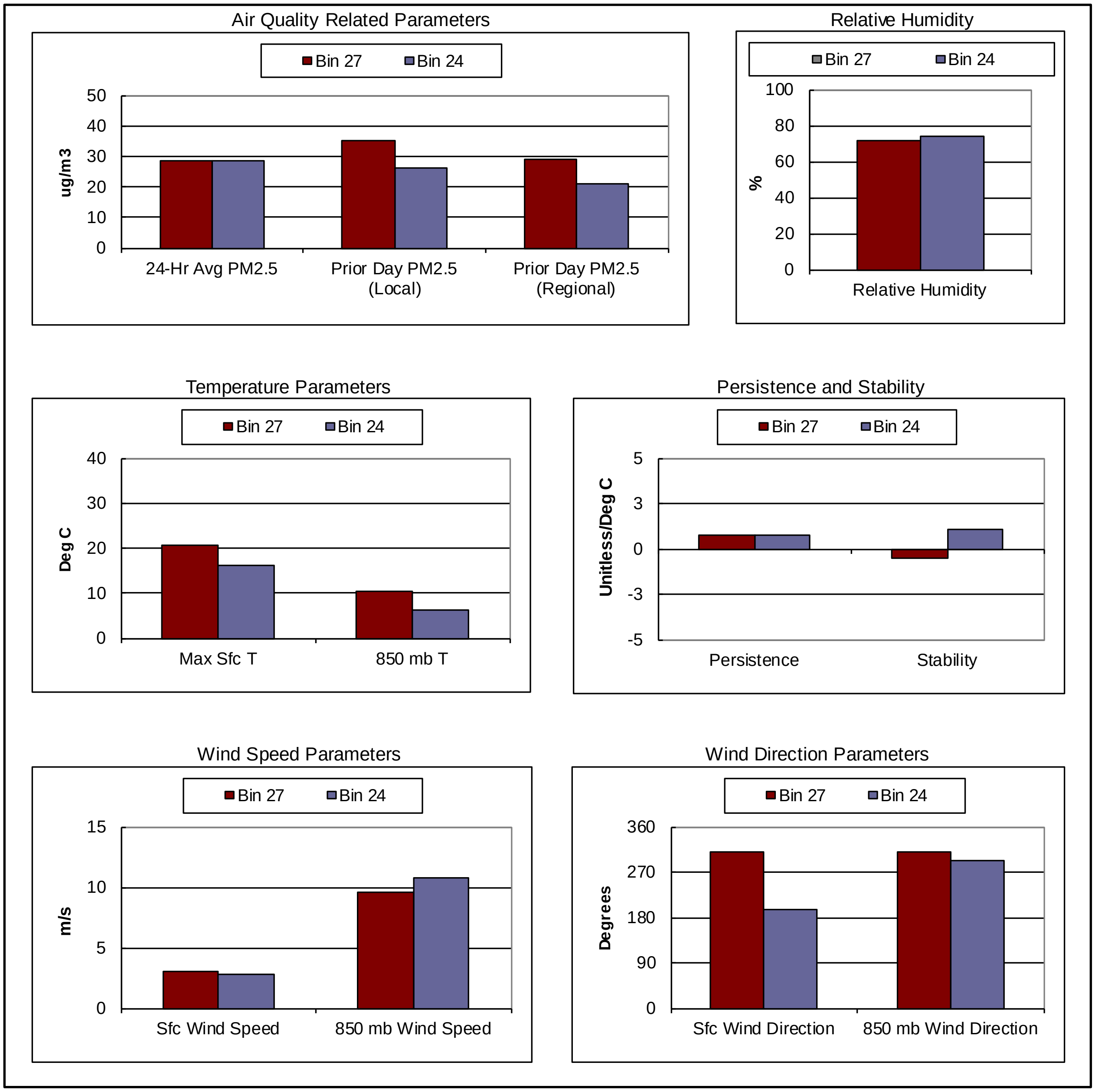


Figure 83a. Average values of selected parameters by bin for the key high $PM_{2.5}$ bins: Portland. The key bins are: Bin 27 = Category 4 (9 Days); Bin 24 = Category 3 (19 Days).

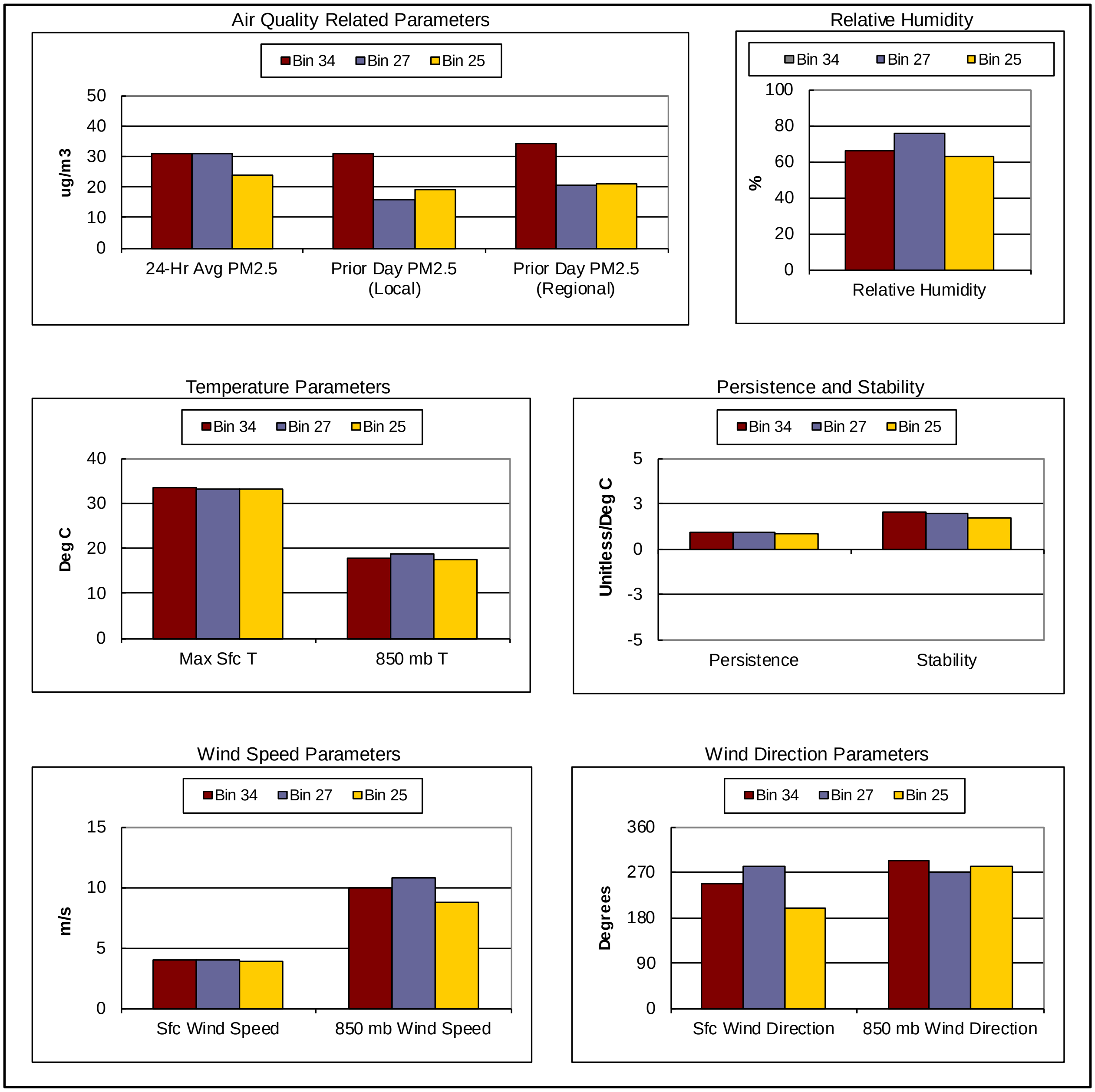


Figure 83b. Average values of selected parameters by bin for the key high $PM_{2.5}$ bins: Providence. The key bins are: Bin 34 = Category 4 (25 Days); Bin 27 = Category 4 (6 Days); Bin 25 = Category 3 (43 Days).

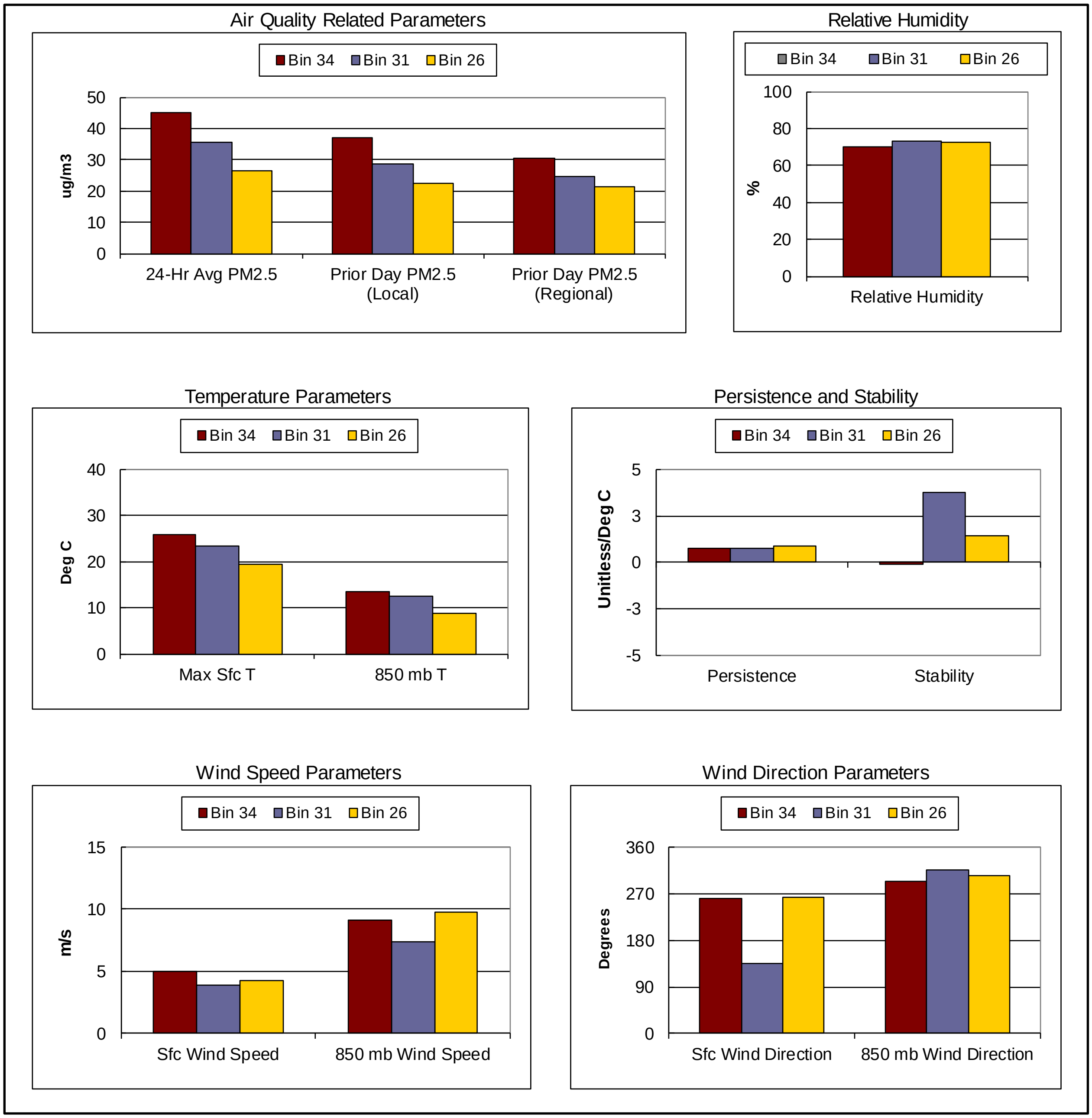


Figure 83c. Average values of selected parameters by bin for the key high $PM_{2.5}$ bins: New York. The key bins are: Bin 34 = Category 4 (11 Days); Bin 31 = Category 4 (8 Days); Bin 26 = Category 3 (35 Days).

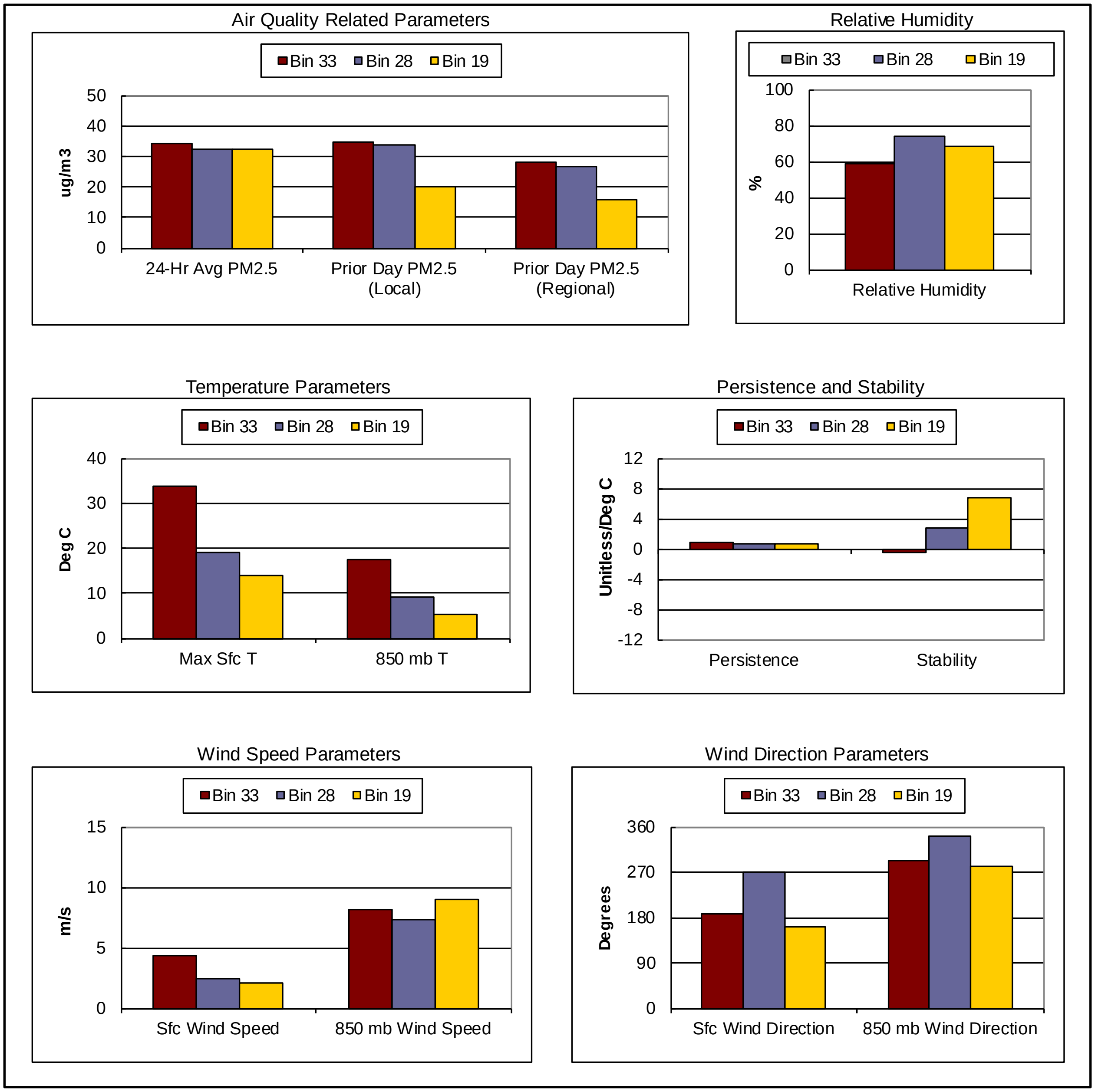


Figure 83d. Average values of selected parameters by bin for the key high $PM_{2.5}$ bins: Newark-Elizabeth. The key bins are: Bin 33 = Category 4 (55 Days); Bin 28 = Category 4 (34 Days); Bin 19 = Category 4 (23 Days).

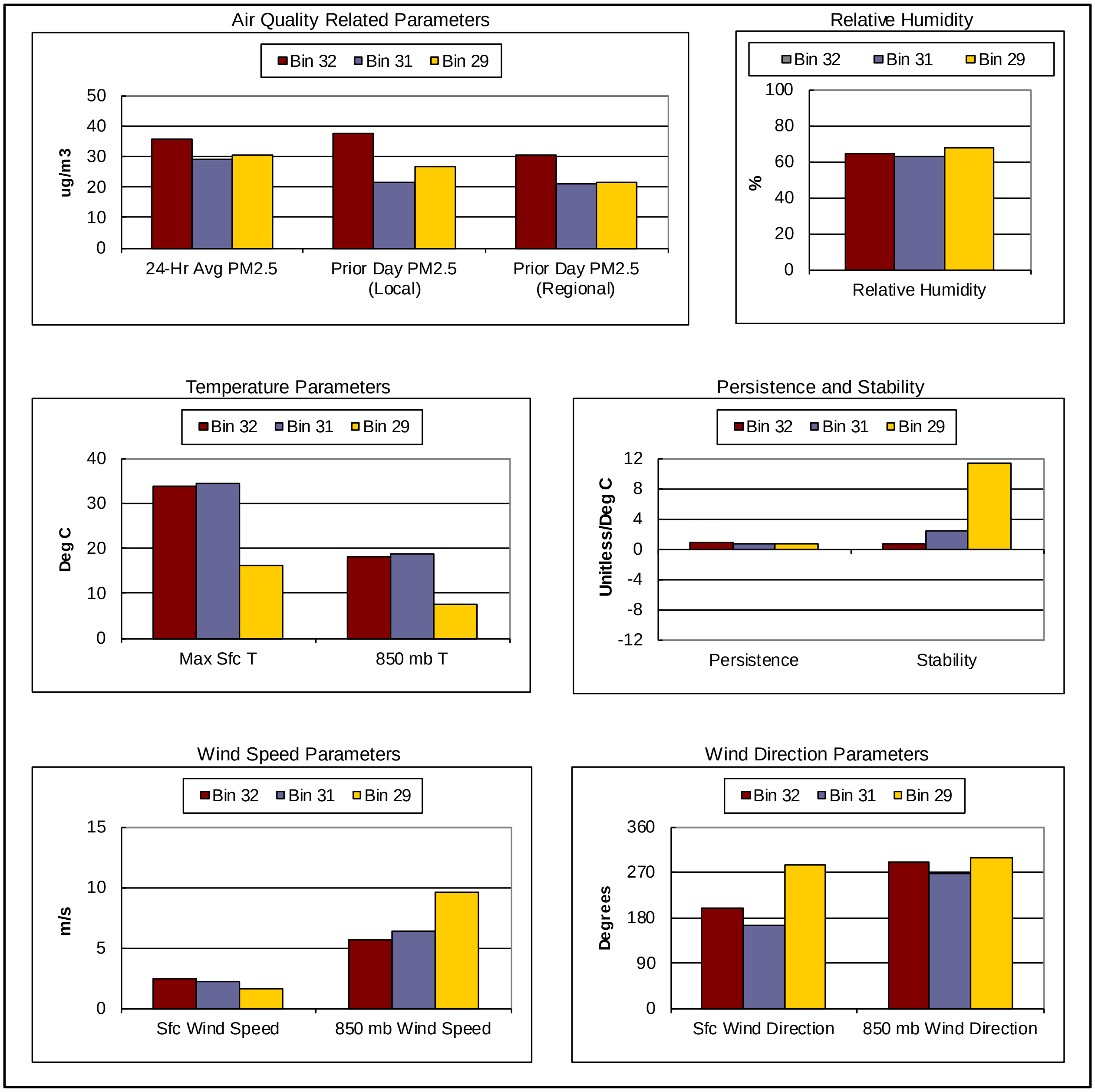


Figure 83e. Average values of selected parameters by bin for the key high $PM_{2.5}$ bins: Baltimore. The key bins are: Bin 32 = Category 4 (69 Days); Bin 29 = Category 4 (27 Days); Bin 31 = Category 4 (32 Days).

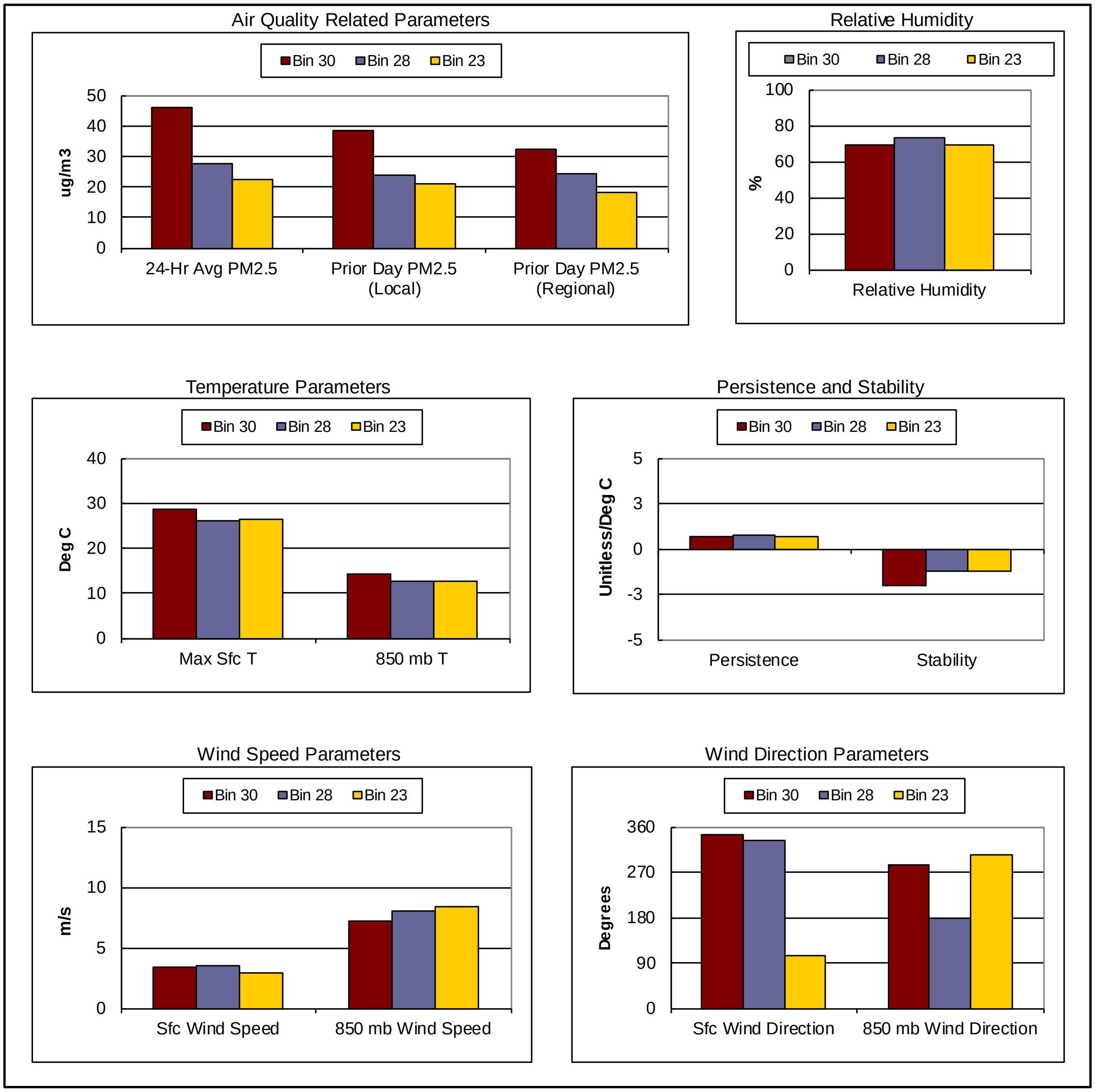


Figure 83f. Average values of selected parameters by bin for the key high $PM_{2.5}$ bins: Norfolk. The key bins are: Bin 30 = Category 4 (18 Days); Bin 28 = Category 3 (39 Days); Bin 23 = Category 3 (8 Days).

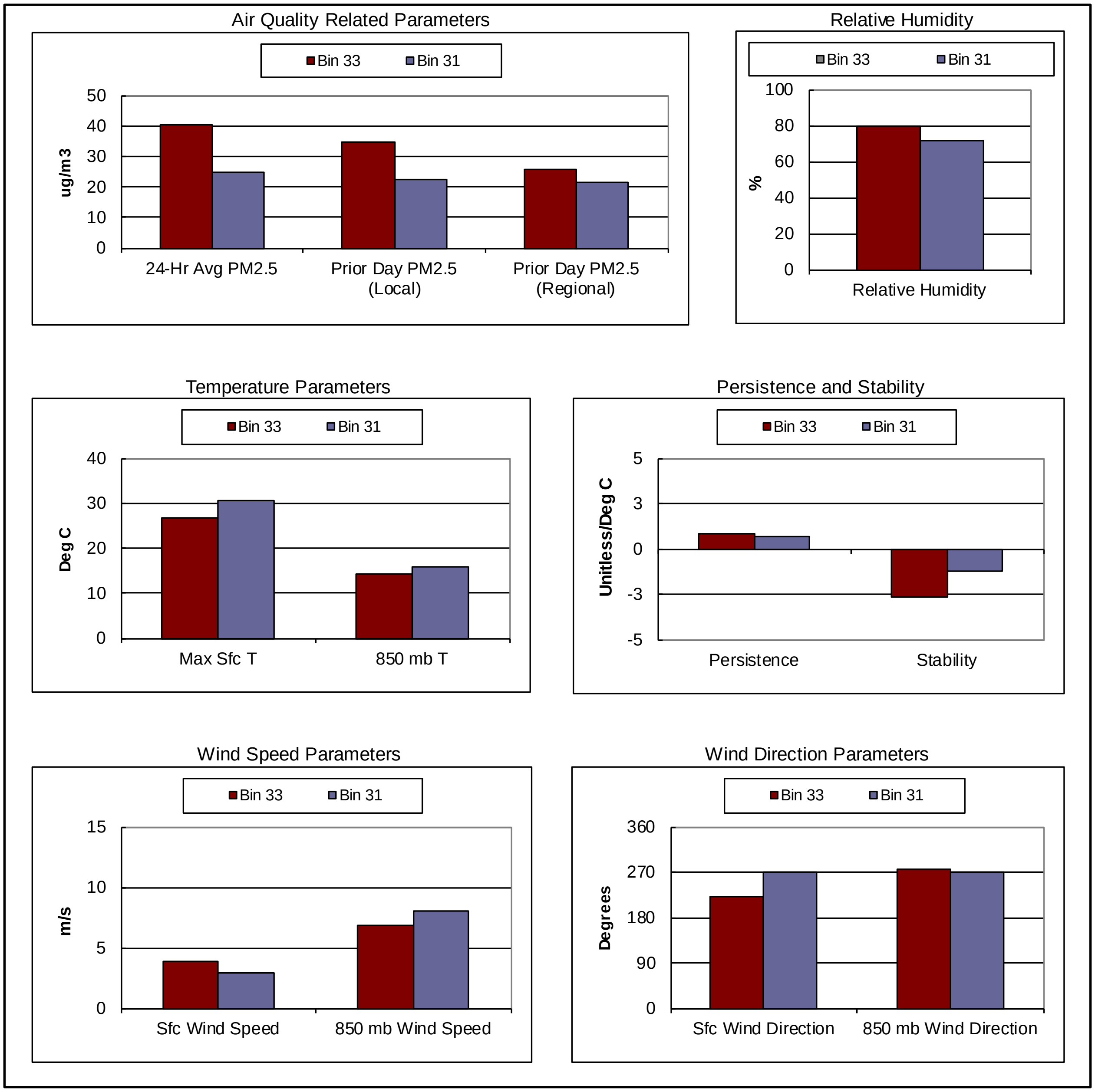


Figure 83g. Average values of selected parameters by bin for the key high $PM_{2.5}$ bins: Wilmington. The key bins are: Bin 33 = Category 4 (2 Days); Bin 31 = Category 3 (17 Days).

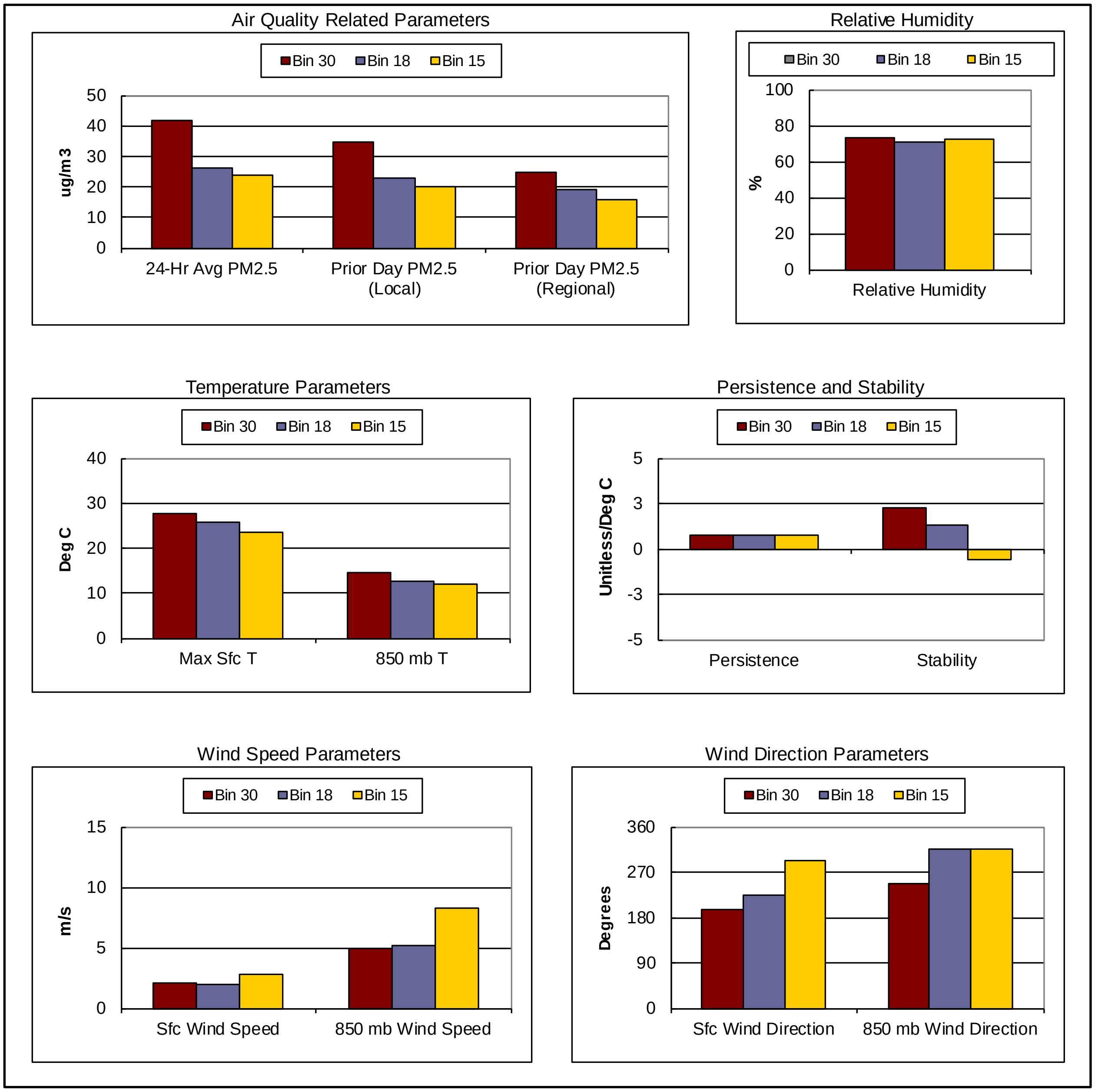


Figure 83h. Average values of selected parameters by bin for the key high $PM_{2.5}$ bins: Savannah. The key bins are: Bin 30 = Category 4 (12 Days); Bin 18 = Category 3 (25 Days); Bin 15 = Category 3 (9 Days).

While there are many similarities in the conditions that describe the key bins, there are also some important differences. Many of these relate to prior day $PM_{2.5}$ concentration, temperature, stability, and wind direction (and, therefore, source-receptor relationships).

Using Newark-Elizabeth as an example (Figure 72d), three Category 4 bins are presented. All three bins have similar 24-hour average $PM_{2.5}$ concentrations. Bin 33 contains days that, on average, have slightly higher 24-hour average $PM_{2.5}$ concentrations than do Bin 28 and Bin 19. A comparison of Bin 33 and Bin 28 indicates that prior day $PM_{2.5}$ concentrations are similar for both bins, but days in Bin 33 have much warmer temperatures and higher wind speeds both at the surface and are much less stable (are actually unstable) than those in Bin 28. Days within Bin 28 and Bin 19 on average have very similar 24-hour average $PM_{2.5}$ concentrations yet prior day's $PM_{2.5}$ concentrations are much higher for days in Bin 28. Days in Bin 28 have somewhat warmer temperatures at the surface and aloft, nearly identical surface wind speeds and slightly lower wind speeds aloft than do days in Bin 19. Wind directions vary as well. The results indicate that different combinations of local parameters can result in high $PM_{2.5}$ concentrations and that prior day $PM_{2.5}$ concentration (both regional and local) is not necessarily the sole distinguishing feature between days in the bins.

5.3.4. Summary of Findings

The CART analysis, together with the selected air quality and meteorological input parameters, correctly classifies, on average, approximately 87 percent of the days for 2000–2010 according to 24-hour average $PM_{2.5}$ concentration. CART classification accuracy for the eight study areas ranges from approximately 70 to 97 percent. When only meteorological data are used as input to the CART analysis, classification accuracy is only somewhat lower (for most sites) and this indicates that the selected meteorological data are reasonably good indicators of $PM_{2.5}$ concentration for areas along the Atlantic Coast.

The CART classification technique can provide information about the relative importance of the various independent parameters in distinguishing days with different $PM_{2.5}$ air quality characteristics. Parameter importance varies among the different areas. On average, the most important parameters include: prior day 24-hour average $PM_{2.5}$ concentration in the area of interest, prior day 24-hour average $PM_{2.5}$ concentration in potential upwind areas, surface temperature, and 850 mb temperature. Of secondary importance are surface wind speed and stability (DT900).

Analysis of the variations in the input parameters across defined $PM_{2.5}$ concentration categories reveals that there are some similarities among the areas and that for all areas, previous day $PM_{2.5}$ concentrations are higher for days with the highest $PM_{2.5}$ concentrations. For all but two areas, high $PM_{2.5}$ concentrations are also associated with relatively higher temperatures. For Wilmington and Savannah, days within Category 3 bins have slightly higher temperatures than those for Category 4, but higher than for the lower category bins. Wind speeds at the surface and aloft are often similar for days within Categories 2 through 4, but wind speeds for high $PM_{2.5}$ days are always lower than for the days within bins containing the days with the lowest concentrations. For most areas, wind directions also vary by category which indicates that wind direction also affects $PM_{2.5}$ concentration. The specific wind directions and variations across the categories are different for each area.

Except for Portland and Norfolk, the high $PM_{2.5}$ days for each area are divided among several CART bins, and this indicates that different combinations of the input parameters can lead to high $PM_{2.5}$ concentrations in each area (i.e., that there are multiple pathways to high $PM_{2.5}$). Analysis of the key high $PM_{2.5}$ bins (bins containing the most number of high $PM_{2.5}$ days) reveals that in addition to differences in prior day local $PM_{2.5}$ concentration, differences in the prior day regional $PM_{2.5}$ concentrations as well as wind direction suggests that regional transport can be a factor in determining the $PM_{2.5}$ concentrations. For several of the areas, subtle differences in meteorology and prior-day $PM_{2.5}$ can mean the difference between exceedance days and non-exceedance days. This finding has implications for air quality forecasting and attainment strategy development as part of air quality planning and management.

6.0 CART ANALYSIS SELECTED COASTAL AREAS: VISIBILITY

The Classification and Regression Tree (CART) analysis technique was used to examine the relationships between onshore and offshore meteorological conditions and air quality relating to visibility in six selected port/harbor areas along the Atlantic Coast, including three Class I areas: Brigantine NWR, Swanquarter NWR and Okefenokee NWR. Three additional areas, Casco Bay, Martha's Vineyard and New York City, were also included in this analysis. The focus of this analysis was visibility, quantified by extinction coefficient (the attenuation of light per unit distance due to scattering and absorption by particles and gases in the atmosphere).

The objective of this analysis was to explore the relationships between meteorological conditions and visibility in each of the areas of interest. All of the data presented in this section are included in the ARAQDB.

6.1. CART Application Procedures

CART was applied for the period 2000–2010. Details of the CART application for visibility are presented in this section.

As part of this analysis, CART was applied using the full set of input data and then using only the meteorological input parameters. This was done to examine the relative importance of the meteorological versus air quality parameters in determining visibility conditions and whether the selected meteorological parameters (in the absence of prior-day air quality information) are good indicators of visibility regimes.

6.1.1. Identification of CART Input Parameters

A first step in the application of CART is the identification of the input parameters. The following list includes available meteorological and air quality parameters that are expected to influence visibility along the Atlantic Coast. The list of input parameters was adapted from the CART analysis conducted for the former Minerals Management Service (MMS) as part of a similar data synthesis study for the Gulf of Mexico region (Douglas et al., 2009).

Surface Meteorological Parameters

Surface meteorological parameters were used to characterize the local meteorological conditions. The surface meteorological inputs for CART are listed below.

- **Temperature**
  - Daily maximum temperature (ºC)
  - Daily average temperature (ºC)
- **Relative Humidity**
  - Average relative humidity (%)

- **Wind**
  - 24-hour average vector wind direction bin; value of 1 through 5, indicating the wind direction corresponding to the 24-hour vector average wind direction. Bin definitions (in degrees) are: [315, 45), [45, 135), [135, 225), [225, 315), or calm, respectively.
  - 24-hour average vector wind speed (ms^{-1})
  - Persistence index (24-hour average vector wind speed/24-hour average scalar wind speed).
- **Pressure**
  - 24-hour average sea level pressure (mb)
- **Precipitation**
  - 24-hour total precipitation (in)
  - Number of hours of measurable precipitation

Upper-Air Meteorological Parameters

Upper-air meteorological parameters were used to characterize the regional-scale meteorological conditions. The upper-air parameters are as follows:

- **Temperature**

  900 mb

  - 900 mb to surface temperature gradient, defined here as the difference between the temperature at 900 mb and the surface using the morning (0500 LST) temperature sounding data (ºC)

  850 mb

  - Upper-air 850 mb temperature corresponding to the morning (0500 LST) sounding on the current day (ºC)
  - Upper-air 850 mb temperature corresponding to the evening (1700 LST) sounding on the current day (ºC)
- **Wind**

  700 mb

  The following two upper-air wind variables were computed using data from the prior day's evening sounding for 700 mb:

  - Wind speed (ms^{-1})
  - Wind direction bin; value of 1 through 5, indicating the wind direction: (in degrees) [315, 45), [45, 135), [135, 225), [225, 315), or calm, respectively

850 mb

The following two upper-air wind variables were computed using data from the prior day's evening sounding, and the current day's morning and evening soundings for 850 mb (for a total of six input variables for each upper-air monitoring site):

- Wind speed (ms^{-1})
- Wind direction bin; value of 1 through 5, indicating the wind direction: (in degrees) [315, 45), [45, 135), [135, 225), [225, 315), or calm, respectively

- **Recirculation**

850 mb

- Recirculation index (value of 0 or 1) that is based on the difference between the average wind direction yesterday and today and/or scalar wind speed.

- **Geopotential Height**

700 mb

- Difference in the daily average geopotential height above sea level of the 700 mb surface (m) using height for the current day minus height for the prior day.

- **Clouds**

700/850 mb

The cloud indicator variable combines data from both the 700 and 850 mb and was computed using data from the morning and evening soundings.

- Cloud index. Value based on relative humidity at the 850 mb (rh850) and 700 mb (rh700) levels. Ranges from 1 to 3 are based on the empirical analysis of observed data and are defined as follows:
    - if (rh850 < 80% and rh700 < 65%) then cloud = 1;
    - if (rh850 >= 80% and rh700 < 65%) then cloud = 2;
    - if (rh850 < 80% and rh700 >= 65%) then cloud = 2;
    - if (rh850 >= 80% and rh700 >= 65%) then cloud = 3

Air Quality Parameters

In addition to the meteorological input parameters, $PM_{2.5}$ concentrations for prior days locally as well as for the region were also used in the CART analysis.

- **Extinction Coefficient**
    - *Classification parameter for the application of CART for visibility.* Assigned a value of 1 through 5, such that each value corresponds to a different range of extinction coefficient. These correspond to the ranges defined by the 20, 50, 80, and 95 percentile values of calculated extinction coefficient for each site.

- **Local $PM_{2.5}$ Indicator Variables**
  - Prior-day 24-hour average $PM_{2.5}$ concentration at the site being analyzed (μgm^{-3}).
- **Regional $PM_{2.5}$ Indicator Variables**
  - Prior-day 24-hour average $PM_{2.5}$ concentrations averaged over nearby and thus potentially upwind sites (μgm^{-3}). The specific sites and number of potential upwind sites is different for each CART region.

6.1.2. Quality Assurance Steps

Following each application, the results were assessed using statistical measures of the goodness of the classification, and then checked for physical reasonableness. The procedures are the same as those used for the ozone analysis (refer to Section 4.2.2).

6.1.3. Assessment of CART Results

The CART results were displayed in a variety of ways, both as part of the quality assurance and to aid the analysis of the results.

CART trees with approximately 32-36 bins were selected to optimize classification accuracy and physical reasonableness. The high extinction coefficients days, however, were grouped into three to five bins.

Tabular summaries of classification accuracy were prepared and classification accuracy, by category and overall, were calculated. Overall classification accuracy ranged from 64 to 97 percent.

The relative importance of the various input parameters to the CART classification tree was examined and plotted for each site.

6.2. CART DATA

The visibility data (extinction coefficients), observed $PM_{2.5}$ and meteorological data used in the CART analysis are summarized in Tables 27 through 32 and provide information about the meteorological and air quality ($PM_{2.5}$) conditions associated with different visibility levels for the selected port/harbor areas.

To examine the variations in visibility versus meteorology and air quality, (calculated) daily average extinction coefficients were obtained for representative monitoring sites for the selected areas. Based on the ranking of the value of the extinction coefficient, each day was then assigned to one of the five categories (less than the 20^{th} percentile, 20^{th} to 50^{th} percentile, 50^{th} to 80^{th} percentile, 80^{th} to 95^{th} percentile, and greater than or equal to the 95^{th} percentile). Actual extinction coefficient "cut-off" values varied between areas. Average values of the meteorological and air quality parameters were then calculated for all days within each of the visibility categories. In addition to the meteorological parameters, the average extinction coefficient for each category is provided. Prior day $PM_{2.5}$ concentrations for the local area and potential upwind areas are also provided.

The combined visibility, $PM_{2.5}$ and meteorological summary tables for each area are ordered north to south.

Table 27
Summary of Extinction Coefficient, $PM_{2.5}$ and Meteorological Data by Extinction Coefficient Category for 2000–2010: Casco Bay.

Extinction Coefficient and $PM_{2.5}$ Data are for Casco Bay;
Surface Meteorological Data are for Portland International Airport.
The Ranges in Extinction Coefficient for Categories 1 through 5 are as follows:
<30, 30-40, 40-70, 70-115 and $\geq$ 115Mm $^{-1}$.

	Category 1	Category 2	Category 3	Category 4	Category 5
No. of Days	219	294	412	160	52
Visibility and Air Quality Related Parameters					
Extinction Coefficient at Casco Bay (Mm^{-1})	24.5	34.5	51.7	88.4	160.5
Yesterday's $PM_{2.5}$ at Casco Bay (μgm^{-3})	3.1	4.3	6.1	9.9	17.8
Yesterday's $PM_{2.5}$ at North Atlantic Region (μgm^{-3})	6.7	8.3	10.0	13.5	18.1
Surface Meteorological Parameters					
Max. surface temperature (°C)	10.2	11.4	13.0	17.2	25.2
Min. surface temperature (°C)	2.5	2.7	3.5	6.4	15.2
Avg. relative humidity (%)	65	67	71	75	76
Avg. vector surface wind speed (ms^{-1})	3.6	2.6	2.2	2.0	2.1
Avg. surface wind direction (degrees)	331	296	224	200	191
Persistence	0.8	0.7	0.7	0.7	0.8
Sea level pressure (mb)	1017	1021	1020	1019	1017
Rainfall (inches)	0.2	0.2	0.1	0.1	0.1
Upper-Air Meteorological Parameters					
Temperature AM 850 mb at Gray (°C)	-1.0	0.3	2.5	7.0	14.1
Temperature PM 850 mb at Gray (°C)	-0.8	1.2	3.4	8.1	14.6
Stability at Gray (°C)	-2.8	-1.8	-0.3	1.5	1.3
Geopotential hgt difference 700 mb at Gray (m)	0.4	1.9	0.2	0.4	-9.7
Wind speed yesterday 700 mb at Gray (ms^{-1})	14.6	14.6	14.0	13.8	10.8
Wind dir. yesterday 700 mb at Gray (degrees)	280	280	277	274	277
Wind speed yesterday 850 mb at Gray (ms^{-1})	13.2	10.4	9.9	9.7	8.1
Wind speed AM 850 mb at Gray (ms^{-1})	13.0	10.4	9.3	9.7	8.7
Wind speed PM 850 mb at Gray (ms^{-1})	11.6	10.7	10.2	11.4	8.7
Wind dir. yesterday 850 mb at Gray (degrees)	315	295	284	274	273
Wind dir. AM 850 mb at Gray (degrees)	333	315	276	273	265
Wind dir. PM 850 mb at Gray (degrees)	327	297	278	270	267
Recirculation index at Gray	0.1	0.0	0.0	0.0	0.0
Cloud index at Gray	1.9	1.7	1.8	1.7	1.8

Table 28
Summary of Extinction Coefficient, $PM_{2.5}$ and Meteorological Data by Extinction Coefficient Category for 2000–2010: Martha's Vineyard.

Extinction Coefficient and PM2.5 Data are for Martha's Vineyard; Surface Meteorological Data are for Vineyard Haven Airport. The Ranges in Extinction Coefficient for Categories 1 through 5 are as follows: <35, 35-50, 50-110, 110-135 and ≥ 135 Mm^{-1}.

	Category 1	Category 2	Category 3	Category 4	Category 5
No. of Days	183	275	352	46	46
Visibility and Air Quality Related Parameters					
Extinction Coefficient at Martha's Vineyard (Mm^{-1})	29.7	41.6	70.9	119.6	187.9
Yesterday's $PM_{2.5}$ at Martha's Vineyard (μgm^{-3})	3.8	5.1	7.7	11.8	17.8
Yesterday's $PM_{2.5}$ at Mid-North Atlantic Region (μgm^{-3})	7.2	9.4	12.3	17.2	21.3
Surface Meteorological Parameters					
Max. surface temperature (°C)	10.7	12.3	16.1	21.0	24.6
Min. surface temperature (°C)	2.1	3.3	7.3	11.6	16.6
Avg. relative humidity (%)	66	70	77	83	83
Avg. vector surface wind speed (ms^{-1})	4.1	4.1	3.7	3.6	3.7
Avg. surface wind direction (degrees)	340	318	236	212	222
Persistence	0.8	0.8	0.8	0.8	0.9
Sea level pressure (mb)	1020	1021	1019	1018	1016
Rainfall (inches)	0.1	0.1	0.1	0.1	0.0
Upper-Air Meteorological Parameters					
Temperature AM 850 mb at Chatham (°C)	0.2	1.7	6.4	12.6	14.7
Temperature PM 850 mb at Chatham (°C)	1.2	2.6	7.2	13.2	15.2
Stability at Chatham (°C)	-3.7	-3.2	-1.5	0.9	0.2
Geopotential hgt difference 700 mb at Chatham (m)	10.0	2.7	-6.4	-1.4	-1.8
Wind speed yesterday 700 mb at Chatham (ms^{-1})	14.7	14.5	14.8	12.8	10.7
Wind dir. yesterday 700 mb at Chatham (degrees)	280	279	270	273	275
Wind speed yesterday 850 mb at Chatham (ms^{-1})	11.9	10.8	11.0	12.2	9.3
Wind speed AM 850 mb at Chatham (ms^{-1})	10.3	10.0	11.5	11.7	10.3
Wind speed PM 850 mb at Chatham (ms^{-1})	10.3	11.2	11.8	12.8	10.7
Wind dir. yesterday 850 mb at Chatham (degrees)	301	303	270	277	267
Wind dir. AM 850 mb at Chatham (degrees)	318	297	265	274	318
Wind dir. PM 850 mb at Chatham (degrees)	311	298	269	274	311
Recirculation index at Chatham	0.1	0.0	0.0	0.0	0.0
Cloud index at Chatham	1.7	1.7	1.7	1.8	1.7

Table 29
Summary of Extinction Coefficient, $PM_{2.5}$ and Meteorological Data by Extinction Coefficient Category for 2000–2010: New York City.

Extinction Coefficient and $PM_{2.5}$ Data are for New York City;
Surface Meteorological Data are for LaGuardia International Airport.
The Ranges in Extinction Coefficient for Categories 1 through 5 are as follows:
<60, 60-85, 85-140, 140-225 and ≥ 225 Mm^{-1}.

	Category 1	Category 2	Category 3	Category 4	Category 5
No. of Days	183	275	352	46	46
Visibility-and Air Quality Related Parameters					
Extinction Coefficient at New York City (Mm^{-1})	47.3	70.5	107.4	172.0	283.3
Yesterday's $PM_{2.5}$ at New York City (μgm^{-3})	6.8	9.0	12.2	18.1	24.9
Yesterday's $PM_{2.5}$ at Mid-North Atlantic Region (μgm^{-3})	7.3	9.0	11.1	14.5	19.7
Surface Meteorological Parameters					
Max. surface temperature (°C)	16.0	15.3	16.2	19.6	25.4
Min. surface temperature (°C)	9.5	9.1	9.2	11.8	17.1
Avg. relative humidity (%)	53	59	61	61	65
Avg. vector surface wind speed (ms^{-1})	5.2	4.1	3.3	3.0	2.4
Avg. surface wind direction (degrees)	3	297	242	198	185
Persistence	0.8	0.8	0.7	0.7	0.7
Sea level pressure (mb)	1020	1020	1020	1020	1017
Rainfall (inches)	0.1	0.2	0.2	0.1	0.2
Upper-Air Meteorological Parameters					
Temperature AM 850 mb at Brookhaven (°C)	3.0	3.6	4.7	7.2	12.8
Temperature PM 850 mb at Brookhaven (°C)	3.1	4.1	5.5	8.8	13.9
Stability at Brookhaven (°C)	-3.2	-1.6	0.3	1.1	1.7
Geopotential hgt diff. 700 mb at Brookhaven (m)	2.5	0.1	3.3	9.0	-1.8
Wind speed yesterday 700 mb Brookhaven (ms^{-1})	14.9	14.9	14.3	13.7	10.7
Wind dir. yesterday 700 mb Brookhaven (degrees)	283	276	288	280	295
Wind speed yesterday 850 mb Brookhaven (ms^{-1})	12.0	11.0	10.5	10.2	8.0
Wind speed AM 850 mb at Brookhaven (ms^{-1})	11.8	11.5	10.3	10.3	8.0
Wind speed PM 850 mb at Brookhaven (ms^{-1})	10.8	11.4	12.0	11.8	9.7
Wind dir. yesterday 850 mb at Brookhaven (degrees)	311	313	291	280	275
Wind dir. AM 850 mb at Brookhaven (degrees)	343	299	283	277	273
Wind dir. PM 850 mb at Brookhaven (degrees)	335	301	280	267	277
Recirculation index at Brookhaven	0.1	0.0	0.0	0.0	0.0
Cloud index at Brookhaven	1.7	1.7	1.8	1.7	1.7

Table 30
Summary of Extinction Coefficient, $PM_{2.5}$ and Meteorological Data by Extinction Coefficient Category for 2000–2010: Brigantine NWR.

Extinction Coefficient and $PM_{2.5}$ Data are for Brigantine NWR;
Surface Meteorological Data are for Atlantic City International Airport.
The Ranges in Extinction Coefficient for Categories 1 through 5 are as follows:
<50, 50-70, 70-115, 115-180 and $\geq$ 180 Mm^{-1}.

	Category 1	Category 2	Category 3	Category 4	Category 5
No. of Days	265	300	176	50	63
Visibility-and Air Quality Related Parameters					
Extinction Coefficient at Brigantine (Mm^{-1})	40.6	59.4	89.4	138.8	224.5
Yesterday's $PM_{2.5}$ at Brigantine (μgm^{-3})	5.5	7.0	9.6	13.7	20.9
Yesterday's $PM_{2.5}$ at Mid-South Atlantic Region (μgm^{-3})	9.1	10.8	13.9	17.6	22.9
Surface Meteorological Parameters					
Max. surface temperature (°C)	15.3	15.5	17.9	21.3	29.0
Min. surface temperature (°C)	6.2	5.8	7.4	11.0	18.0
Avg. relative humidity (%)	69	69	69	72	70
Avg. vector surface wind speed (ms^{-1})	3.7	3.4	2.9	2.5	2.4
Avg. surface wind direction (degrees)	353	252	223	218	212
Persistence	0.8	0.8	0.8	0.8	0.8
Sea level pressure (mb)	1022	1021	1020	1019	1018
Rainfall (inches)	0.2	0.2	0.1	0.1	0.0
Upper-Air Meteorological Parameters					
Temperature AM 850 mb at Wallops Island (°C)	5.8	5.6	7.6	10.1	14.8
Temperature PM 850 mb at Wallops Island (°C)	6.0	6.4	8.5	11.2	15.9
Stability at Wallops Island (°C)	-2.7	-2.3	-1.2	-0.9	-1.2
Geopotential hgt diff. 700 mb at Wallops Is. (m)	-11.7	-1.8	4.4	-0.8	1.3
Wind speed yesterday 700 mb Wallops Is. (ms-1)	14.3	15.2	14.2	12.0	8.2
Wind dir. yesterday 700 mb Wallops Is. (degrees)	276	273	277	283	295
Wind speed yesterday 850 mb Wallops Is. (ms-1)	10.9	11.8	10.3	9.2	6.8
Wind speed AM 850 mb at Wallops Island (ms^{-1})	11.2	11.4	10.1	8.8	7.3
Wind speed PM 850 mb at Wallops Island (ms^{-1})	11.2	11.3	10.6	9.6	7.5
Wind dir. yesterday 850 mb at Wallops Island (degrees)	289	282	279	277	288
Wind dir. AM 850 mb at Wallops Island (degrees)	315	283	279	277	281
Wind dir. PM 850 mb at Wallops Island (degrees)	315	291	274	276	279
Recirculation index at Wallops Island	0.1	0.0	0.0	0.0	0.0
Cloud index at Wallops Island	1.8	1.7	1.7	1.8	1.6

Table 31
Summary of Extinction Coefficient, $PM_{2.5}$ and Meteorological Data by Extinction Coefficient Category for 2000–2010: Swanquarter NWR.

Extinction Coefficient and $PM_{2.5}$ Data are for Swanquarter NWR;
Surface Meteorological Data are for Cape Hatteras Airport.
The Ranges in Extinction Coefficient for Categories 1 through 5 are as follows:
<40, 40-60, 60-95, 95-140 and ≥140 Mm^{-1}.

	Category 1	Category 2	Category 3	Category 4	Category 5
No. of Days	138	330	316	134	52
Visibility-and Air Quality Related Parameters					
Extinction Coefficient at Swanquarter (Mm^{-1})	34.1	49.4	74.0	111.0	181.1
Yesterday's $PM_{2.5}$ at Swanquarter (μgm^{-3})	4.3	5.8	8.2	12.0	16.3
Yesterday's $PM_{2.5}$ at South Atlantic Region (μgm^{-3})	8.8	9.8	12.0	14.2	17.2
Surface Meteorological Parameters					
Max. surface temperature (°C)	20.1	19.2	20.0	24.5	27.9
Min. surface temperature (°C)	14.4	12.6	13.6	18.1	22.2
Avg. relative humidity (%)	78	74	77	80	81
Avg. vector surface wind speed (ms^{-1})	3.7	3.6	3.7	2.9	3.0
Avg. surface wind direction (degrees)	66	313	286	265	219
Persistence	0.8	0.8	0.8	0.8	0.8
Sea level pressure (mb)	1021	1021	1020	1018	1016
Rainfall (inches)	0.4	0.1	0.1	0.1	0.0
Upper-Air Meteorological Parameters					
Temperature AM 850 mb at Moorhead City (°C)	9.4	8.6	9.9	13.8	16.6
Temperature PM 850 mb at Moorhead City (°C)	9.9	9.4	10.2	14.4	17.3
Stability at Moorhead City (°C)	-2.0	-0.7	-0.7	0.0	-0.8
Geopotential hgt difference 700 mb Moorhead (m)	-8.8	5.0	-2.5	2.7	3.4
Wind speed yesterday 700 mb at Moorhead (ms-1)	11.7	13.3	13.3	10.0	8.8
Wind dir. yesterday 700 mb at Moorhead (degrees)	259	273	277	293	311
Wind speed yesterday 850 mb at Moorhead (ms-1)	9.3	9.2	9.7	7.4	6.6
Wind speed AM 850 mb at Moorhead City (ms^{-1})	9.1	9.5	9.4	7.7	7.0
Wind speed PM 850 mb at Moorhead City (ms^{-1})	9.6	9.5	10.2	7.0	7.1
Wind dir. yesterday 850 mb at Moorhead (degrees)	217	274	273	284	293
Wind dir. AM 850 mb at Moorhead City (degrees)	234	275	284	290	284
Wind dir. PM 850 mb at Moorhead City (degrees)	252	277	276	290	272
Recirculation index at Moorhead City	0.1	0.1	0.0	0.1	0.1
Cloud index at Moorhead City	1.8	1.7	1.7	1.6	1.7

Table 32

Summary of Extinction Coefficient, $PM_{2.5}$ and Meteorological Data by Extinction Coefficient Category for 2000–2010: Okefenokee NWR.

Extinction Coefficient and $PM_{2.5}$ Data are for Okefenokee;
Surface Meteorological Data are for Jacksonville International Airport.
The Ranges in Extinction Coefficient for Categories 1 through 5 are as follows:
<50, 50-70, 70-95, 95-160 and ≥160 Mm^{-1}.

	Category 1	Category 2	Category 3	Category 4	Category 5
No. of Days	211	427	360	219	61
Visibility-and Air Quality Related Parameters					
Extinction Coefficient at Okefenokee (Mm^{-1})	41.7	59.9	80.8	115.4	219.1
Yesterday's $PM_{2.5}$ at Okefenokee (μgm^{-3})	5.4	6.9	9.0	12.0	19.8
Yesterday's $PM_{2.5}$ at South Atlantic Region (μgm^{-3})	8.5	9.8	11.6	15.1	19.6
Surface Meteorological Parameters					
Max. surface temperature (°C)	23.9	24.9	25.7	27.5	30.0
Min. surface temperature (°C)	13.7	13.5	14.1	16.1	18.6
Avg. relative humidity (%)	75	73	74	74	74
Avg. vector surface wind speed (ms^{-1})	2.5	2.4	2.2	2.3	1.8
Avg. surface wind direction (degrees)	249	180	83	7	119
Persistence	0.8	0.8	0.8	0.8	0.7
Sea level pressure (mb)	1020	1021	1020	1019	1018
Rainfall (inches)	0.2	0.1	0.1	0.1	0.0
Upper-Air Meteorological Parameters					
Temperature AM 850 mb at Jacksonville (°C)	12.1	12.2	12.6	13.7	15.4
Temperature PM 850 mb at Jacksonville (°C)	12.2	12.4	12.9	14.1	15.9
Stability at Jacksonville (°C)	-0.9	-0.2	0.1	-0.1	0.2
Geopotential hgt diff. 700 mb at Jacksonville (m)	-10.4	1.2	3.8	0.6	-0.5
Wind speed yesterday 700 mb Jacksonville (ms^{-1})	12.5	10.8	9.7	8.8	6.9
Wind dir. yesterday 700 mb Jacksonville (degrees)	246	266	279	299	321
Wind speed yesterday 850 mb Jacksonville (ms^{-1})	10.0	8.3	7.4	6.4	5.5
Wind speed AM 850 mb at Jacksonville (ms^{-1})	10.6	8.6	7.7	6.7	5.0
Wind speed PM 850 mb at Jacksonville (ms^{-1})	9.8	8.6	7.5	7.0	6.0
Wind dir. yesterday 850 mb Jacksonville (degrees)	222	258	267	299	308
Wind dir. AM 850 mb at Jacksonville (degrees)	248	250	262	277	336
Wind dir. PM 850 mb at Jacksonville (degrees)	264	257	269	278	297
Recirculation index at Jacksonville	0.0	0.1	0.1	0.1	0.1
Cloud index at Jacksonville	1.8	1.7	1.7	1.6	1.6

The tabular summaries indicate that, for all areas, average previous day $PM_{2.5}$ concentrations (local and regional) increase with increasing extinction coefficient (decreasing visibility). Maximum surface temperatures for all areas and minimum surface temperatures for nearly all areas show similar trends, i.e. temperatures increase with increasing extinction coefficient. Except for Martha's Vineyard, wind speeds aloft are the lowest for days with the highest extinction coefficients. High extinction coefficient days are most often associated with more stable atmospheric conditions as well. For most areas, wind directions also vary by category and the specific wind directions and variations across the categories are different for each area.

The CART results for visibility are presented in the remainder of this section. As noted earlier, the CART results can provide information about the relative importance of the various independent parameters in distinguishing days with different visibility characteristics as well as the combinations of parameters that lead to high extinction coefficients (poor visibility) or low extinction coefficients (good visibility). This information has been extracted from the CART analysis results and is discussed in this section.

6.2.1. Classification Accuracy

CART classification accuracy ranges from 64 to 97 percent for the full CART analyses, which include both meteorological data and prior-day air quality data, and from 66 to 89 percent for the meteorological data only analyses. In general, the classification accuracies for the full CART analyses are lower than for ozone and $PM_{2.5}$. This indicates that the relationships between the input parameters and the classification parameter are less well defined for extinction coefficient. This is possibly due to the complex role of moisture in determining light extinction—affecting both particle formation and the contribution of sulfate and nitrate particle species to light extinction. The results for both applications are summarized in Table 33.

Table 33
Summary of CART Classification Accuracy for Visibility

CART Area	Classification Accuracy (%)	
	Meteorological & Air Quality Data	Meteorological Data Only
Casco Bay	72	87
Martha's Vineyard	75	80
New York City	97	55
Brigantine NWR	69	47
Swanquarter NWR	94	89
Okefenokee NWR	64	66

Classification accuracy for the meteorological data only CART runs is considerably lower compared to the full CART run for New York and Brigantine NWR and only slightly lower for Swanquarter NWR. For the two most northern areas, Casco Bay and Martha's Vineyard, and the southernmost area, Okefenokee NWR, the classification accuracy for the meteorological data only CART runs are 15, 6 and 2 percentage points, respectively, better than the full CART runs.

Our goal for the full data CART application for extinction coefficient for this study was 70 percent classification accuracy and this goal was met for four of the six sites. Classification accuracy for Brigantine NWR was just below target classification accuracy (at 69 percent) and that for Okefenokee was 6 percentage points below target.

6.2.2. Classification Parameter Importance

As described in section 4.4.2 for ozone, parameter importance is calculated by CART based on the number of times each parameter is used, either as a split parameter or as a surrogate parameter, to construct the final classification tree. We use parameter importance in this analysis to identify those parameters that are statistically relevant to the classification and assume that these same parameters are also physically relevant to the extinction coefficient and therefore, visibility. That is, we assume that the parameters that are most important in determining the structure of the CART tree are also most important in determining good or poor visibility.

Parameter importance for each area is displayed in Figure 84. In each plot, the relative importance assigned to several of the surface and upper-air meteorology categories is the maximum over the parameters that comprise the grouping (e.g., the morning and evening 850 mb temperatures comprise the upper-air temperature group). The category abbreviations are defined as follows and represent one or more of the CART input parameters:

YPM_Local = Yesterday's 24-hour average $PM_{2.5}$ concentration for the area of interest

YPM_Regional = Yesterday's 24-hour average $PM_{2.5}$ concentration for neighboring and upwind areas (average for the group)

TMAX = Daily maximum temperature

TAVG = Daily average temperature

RH = Relative humidity

WS (Sfc) = Surface wind speed (maximum for the surface wind speed parameter group)

WD (Sfc) = Surface wind direction (maximum for the surface wind speed parameter group)

PERSIST = Persistence or sea-breeze index

SLP = Sea level pressure

PRECIP = Total rainfall (same as the RAIN parameter used in the ozone analyses)

CLOUD = Cloud cover index

DZ700 = Daily change in geopotential height at the 700 mb level

DT900 = 900 mb to surface temperature difference

T850 = 850 mb temperature (maximum for the upper-air temperature parameter group)

WS (Upper) = Wind speed aloft (maximum for the upper-air wind speed parameter group)

WD (Upper) = Wind direction aloft (maximum over the upper-air wind speed parameter group)

In this and subsequent plots of parameter importance, red is used for air quality parameters, blue is used for surface meteorological parameters, and green is used for upper-air parameters.

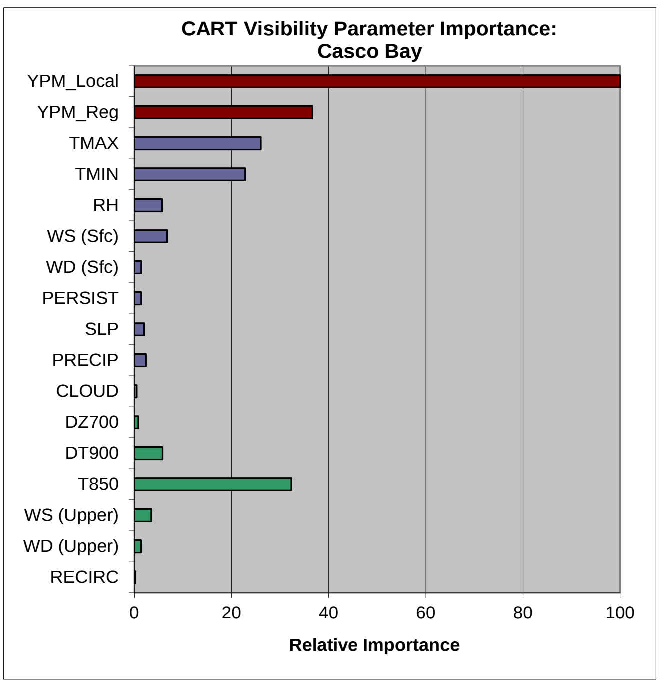


Figure 84a. Average parameter importance for the visibility CART analysis: Casco Bay.

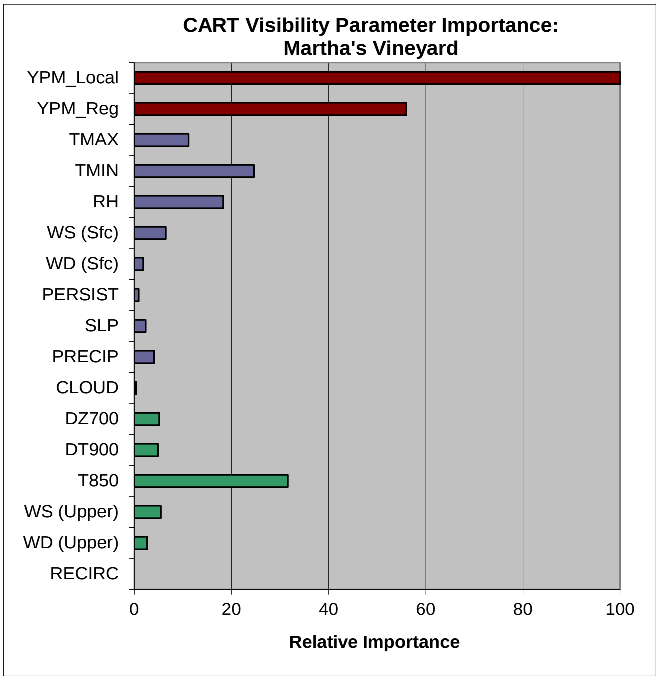


Figure 84b. Average parameter importance for the visibility CART analysis: Martha's Vineyard.

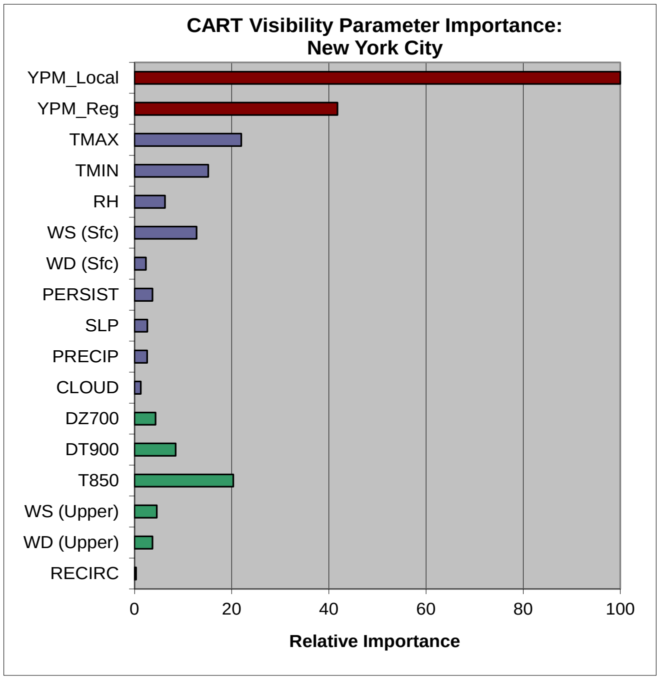


Figure 84c. Average parameter importance for the visibility CART analysis: New York City.

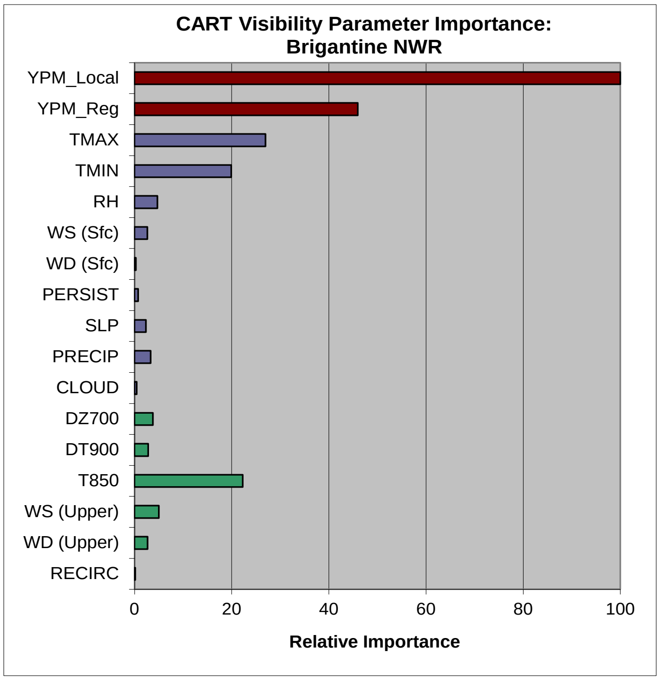


Figure 84d. Average parameter importance for the visibility CART analysis: Brigantine NWR.

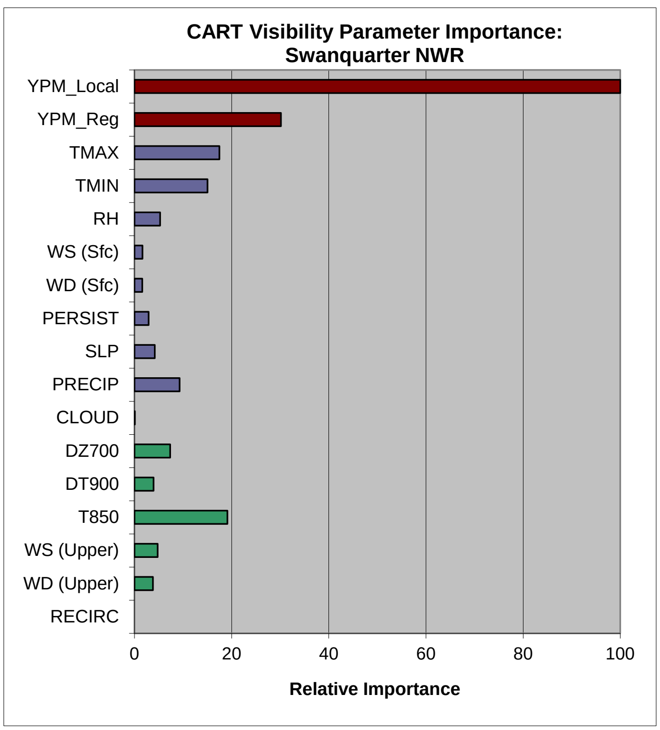


Figure 84e. Average parameter importance for the visibility CART analysis: Swanquarter NWR.

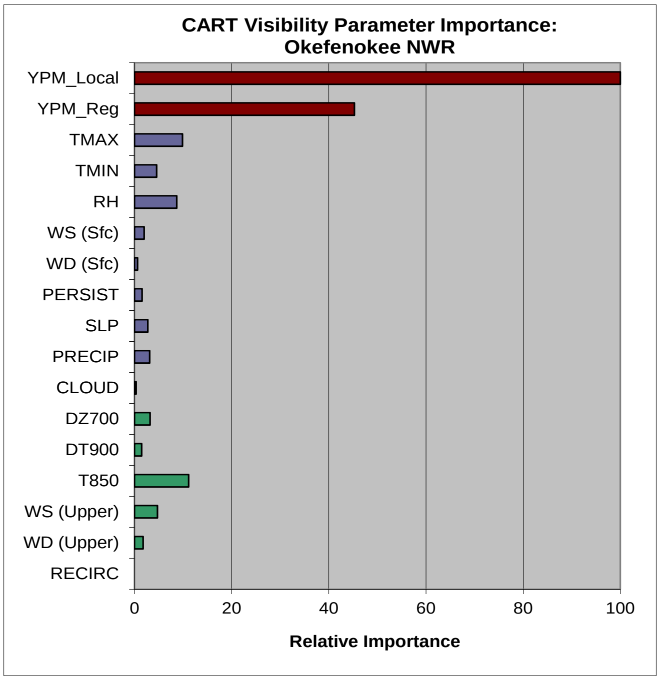


Figure 84f. Average parameter importance for the visibility CART analysis: Okefenokee NWR.

Parameter importance varies among the different areas, especially with regard to the local, surface meteorological parameters. For all areas, prior day $PM_{2.5}$ concentrations are an important factor in determining the quality of visibility for the current day. The CART results indicate that both carryover (local parameter) and transport (regional parameters) play an important role in determining whether visibility will be good or poor. Temperatures at the surface and aloft are important for five of the areas and to a lesser extent at Okefenokee NWR. Relative humidity and surface wind speed are somewhat important in most areas as well. To summarize the results, the average parameter importance for all areas is displayed in Figure 85.

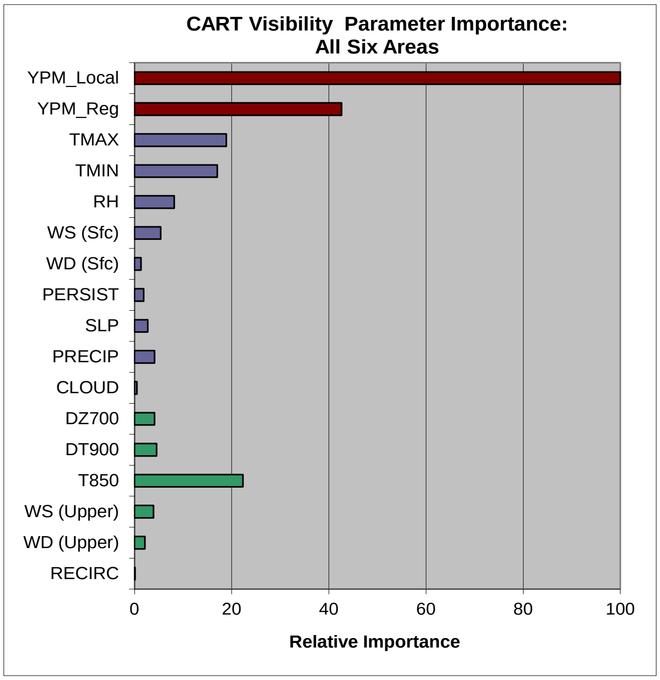


Figure 85. Average parameter importance for 8-hour ozone CART analysis: Average over all areas.

On average, the most important parameters include: prior day 24-hour $PM_{2.5}$ concentration in the area of interest, prior day maximum 24-hour $PM_{2.5}$ concentration in potential upwind areas, surface temperature, and 850 mb temperature. Of secondary importance are relative humidity, surface wind speed, and stability (DT900).

6.2.3. Characteristics of Poor Visibility Bins

In the previous section, we identified certain parameters that are important to the classification of days with respect to poor visibility and concluded that these parameters have the potential to influence visibility at the monitoring sites. However, understanding the causes of poor visibility (as was the case with high ozone and $PM_{2.5}$ concentrations) also requires an understanding of the relationship between the parameters and the air quality metrics, as well as the specific combinations of parameters (conditions) that lead to impaired air quality.

Each value of the classification parameter may be represented by more than one bin, allowing for the possibility that different combinations of the independent parameters can be associated with a single value of the classification parameter (i.e., that different sets of meteorological conditions can lead to poor visibility). CART assumes that there is a relationship between the independent parameters and the classification parameter, and that this can be extracted from the data.

In this section we further explore the characteristics of the key bins that represent the high extinction coefficient (and therefore poor visibility) days for each area. Key bins were defined as those containing the greatest number of correctly classified days. One or two bins from each of the two highest categories for each area were identified and the characteristics of those bins were examined and compared. Figure 86 compares selected parameters for the key high extinction coefficient bins for each area. The parameters are grouped as follows: air quality related parameters, relative humidity, temperature parameters, stability and persistence parameters, wind speed parameters and wind direction parameters. For ease of comparison, figure scales are consistent for each parameter for each area. The bin category and number of days in each bin is also given. As a reminder, the categories are defined based on the 20, 50, 80 and 95 percentile values of extinction coefficient for each site.

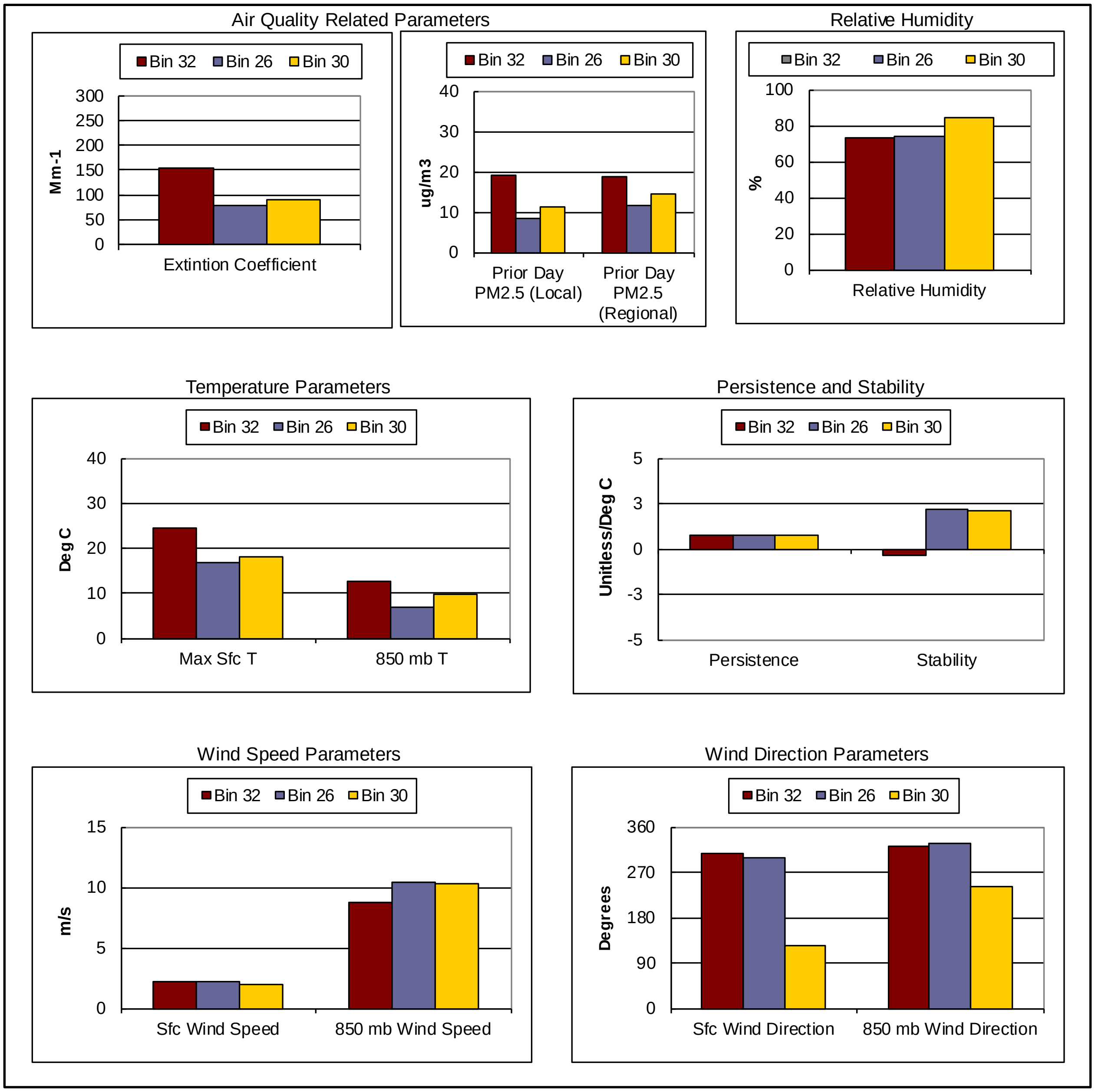


Figure 86a. Average values of selected parameters by bin for the key high extinction coefficient bins: Casco Bay. The key bins are: Bin 32 = Category 5 (52 Days); Bin 26 = Category 4 (65 Days); Bin 30 = Category 4 (42 Days).

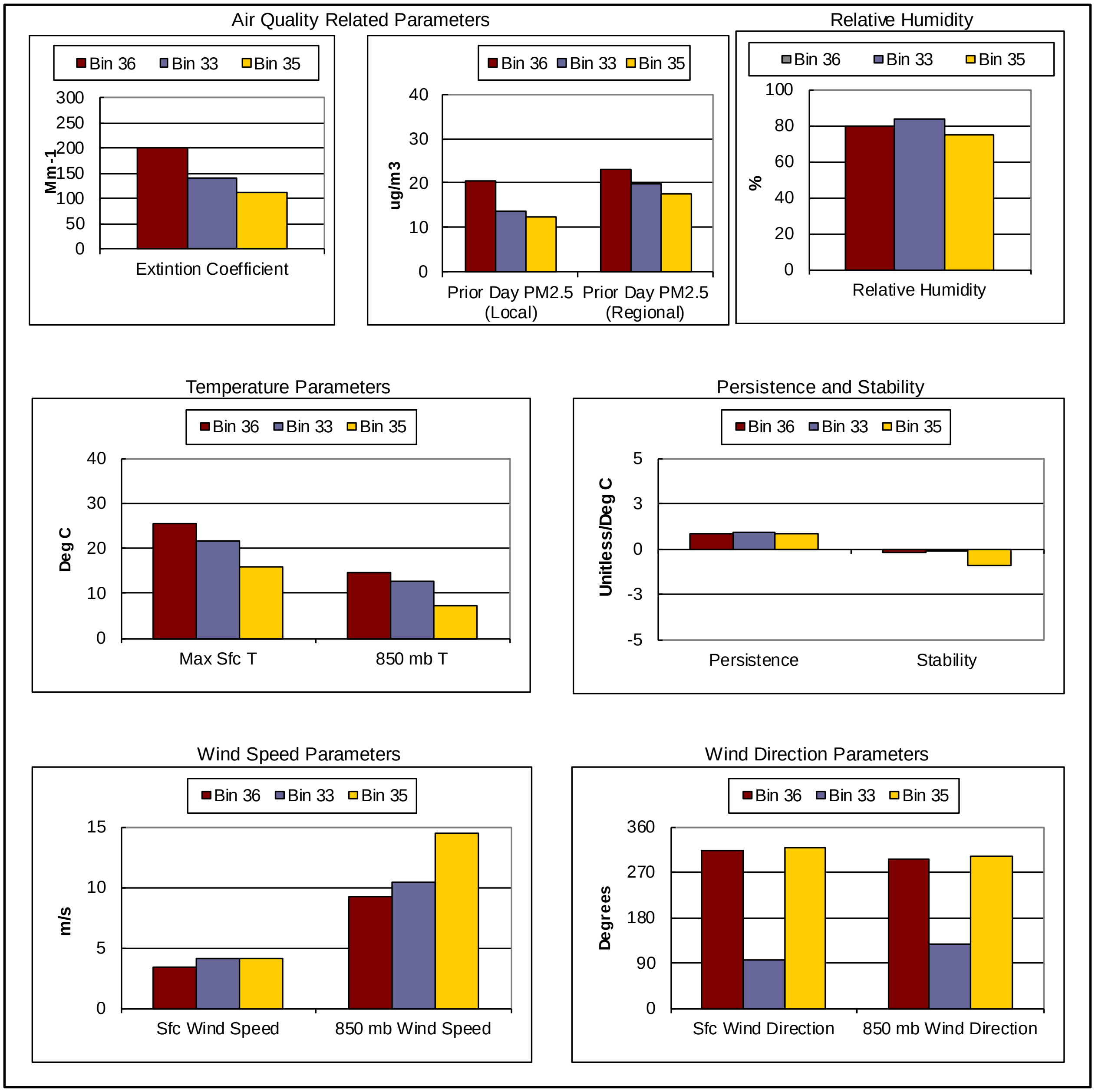


Figure 86b. Average values of selected parameters by bin for the key high extinction coefficient bins: Martha's Vineyard. The key bins are: Bin 36 = Category 5 (31 Days); Bin 33 = Category 5 (21 Days); Bin 35 = Category 4 (14 Days).

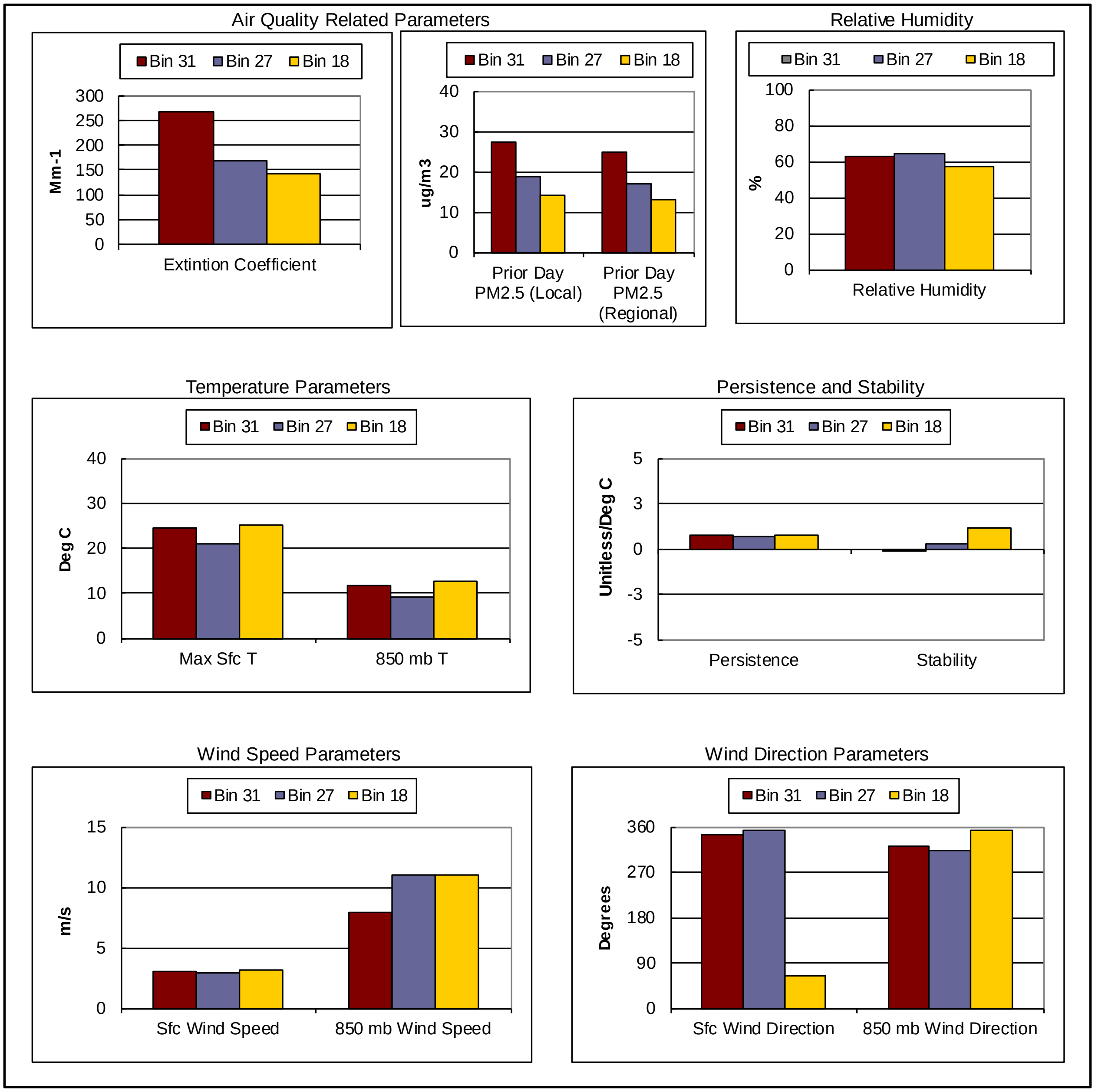


Figure 86c. Average values of selected parameters by bin for the key high extinction coefficient bins: New York City. The key bins are: Bin 31 = Category 5 (31 Days); Bin 27 = Category 4 (48 Days); Bin 18 = Category 4 (19 Days).

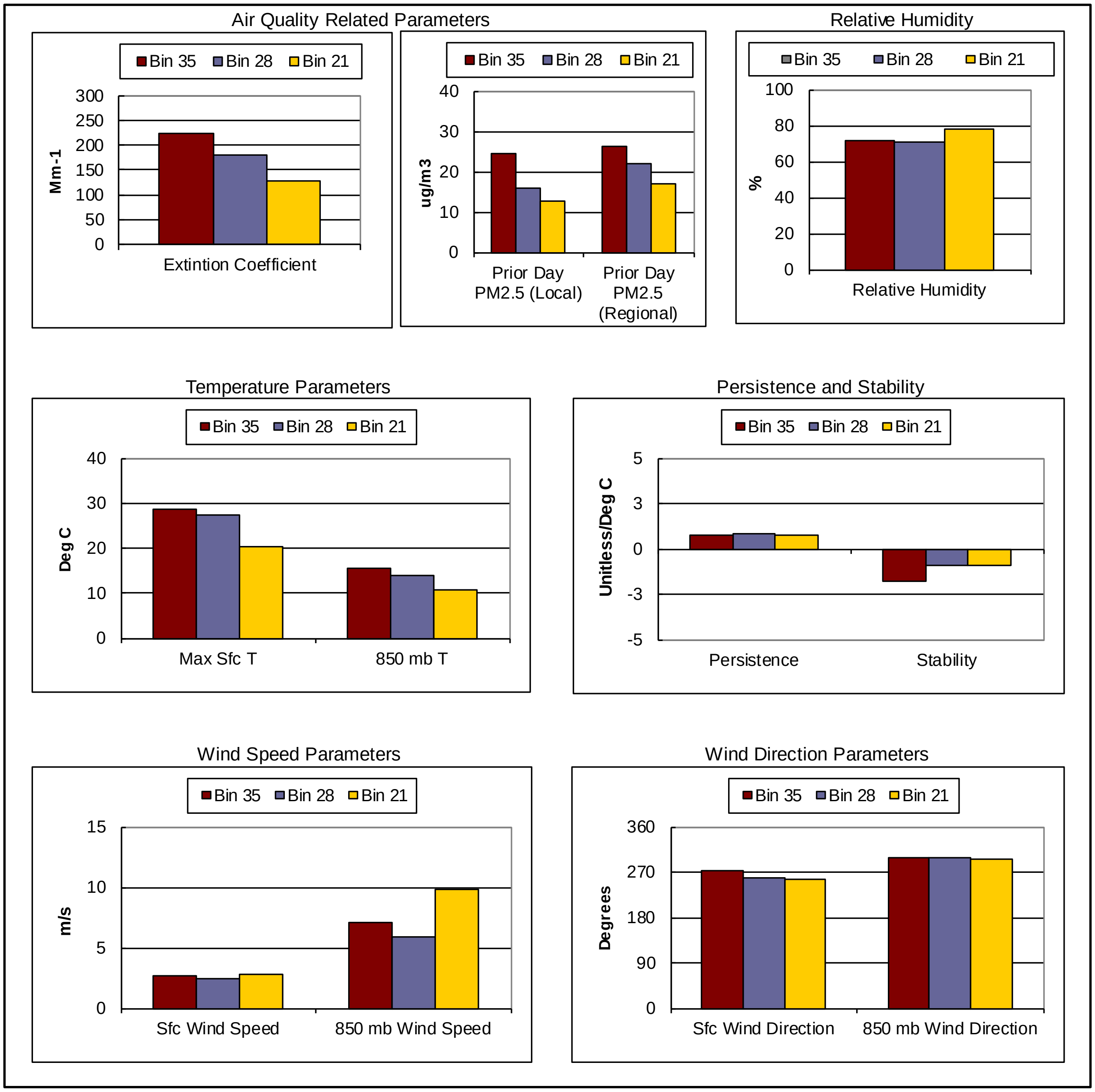


Figure 86d. Average values of selected parameters by bin for the key high extinction coefficient bins: Brigantine NWR. The key bins are: Bin 35 = Category 5 (42 Days); Bin 28 = Category 5 (16 Days); Bin 21= Category 4 (65 Days).

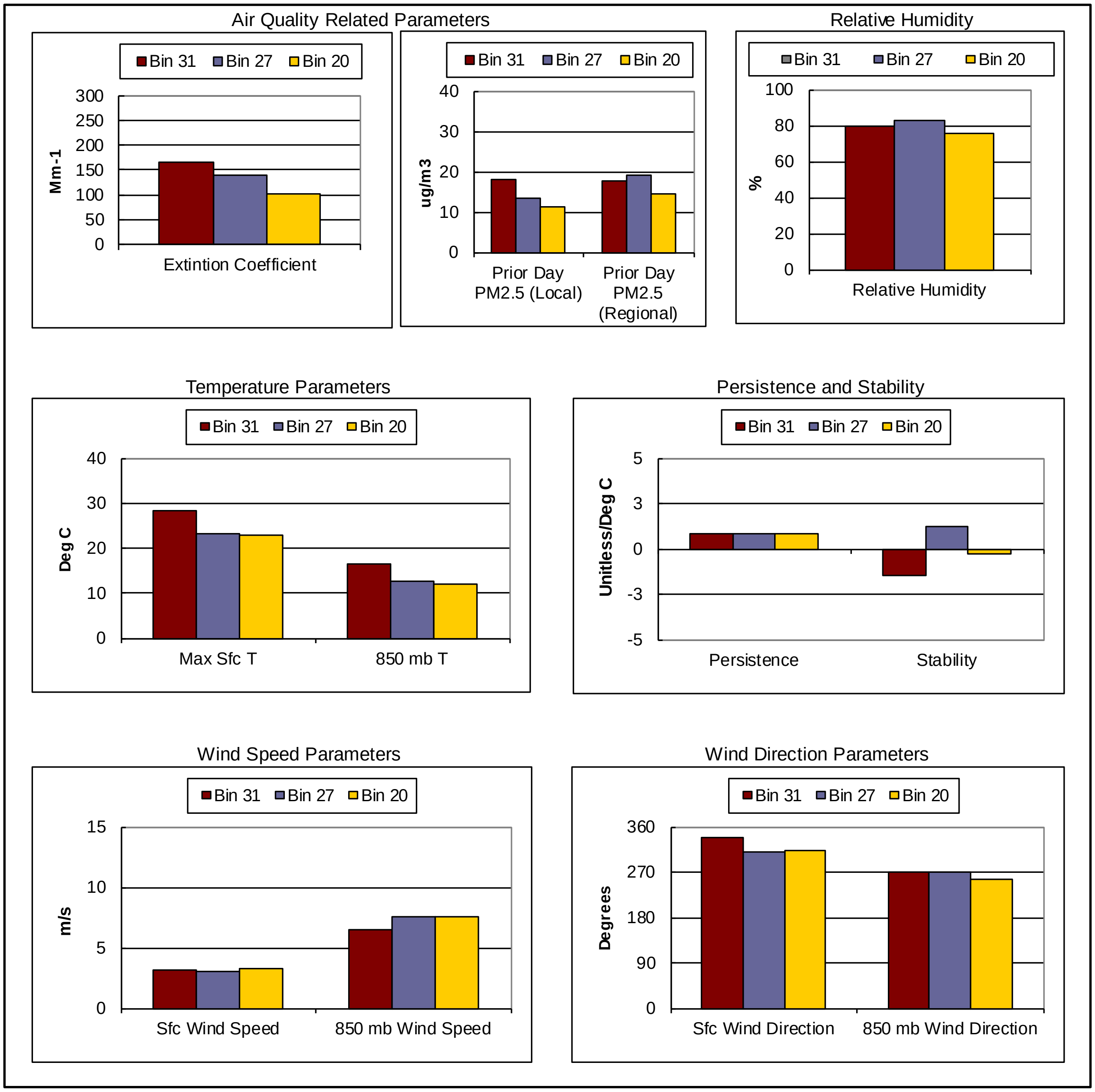


Figure 86e. Average values of selected parameters by bin for the key high extinction coefficient bins: Swanquarter NWR. The key bins are: Bin 31 = Category 5 (52 Days); Bin 27 = Category 5 (16 Days); Bin 20 = Category 4 (73Days).

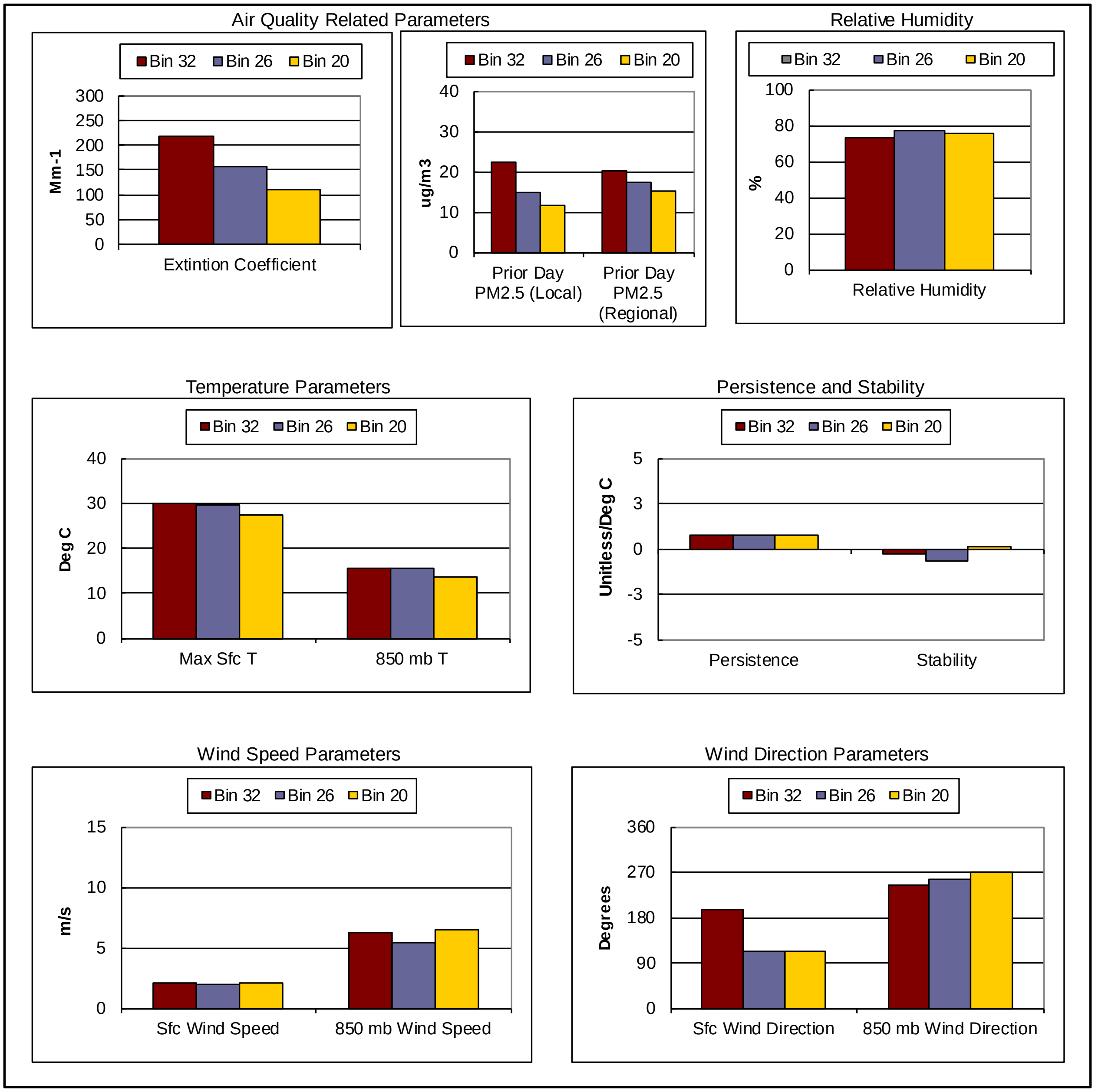


Figure 86f. Average values of selected parameters by bin for the key high extinction coefficient bins: Okefenokee NWR. The key bins are: Bin 32 = Category 4 (46 Days); Bin 26 = Category 3 (36 Days); Bin 20 = Category 3 (109 Days).

While there are many similarities in the conditions that describe the key bins, there are also some important differences. Many of these relate to prior day $PM_{2.5}$ concentration, temperature, stability, and wind direction (and, therefore, source-receptor relationships).

Using New York City (because it had the best classification accuracy of the three areas) as an example (Figure 75d), two Category 5 bins and one Category 4 bins are presented. For this area, because of the excellent classification accuracy, it appears that the selection of 'predictor' variables was good. Comparing the two Category 5 bins, days in Bin 35 are characterized by higher prior day $PM_{2.5}$ concentrations (locally and regionally), slightly higher temperature at the surface and aloft, higher surface wind speeds, and are more unstable than days in Bin 28.

The Category 4 bin has lower prior day $PM_{2.5}$ concentrations (locally and regionally) as well as lower temperatures at the surface and aloft than the Category 5 bins. Days placed in Bin 21 have higher wind speeds aloft and slightly higher humidity than do the days in the Category 5 bins. In general though, the range of the extinction coefficient in the bins appears to be affected the most by the prior day $PM_{2.5}$ concentrations (locally and regionally) and temperatures.

A further example of differences between classification bins is illustrated by the results for Martha's Vineyard. Three key bins are presented (Figure 75b), two Category 5 bins and one Category 4 bin. Comparing the two Category 5 bins, days in Bin 36 are characterized by higher prior day $PM_{2.5}$ concentrations (locally and regionally) and higher temperature at the surface and aloft than days in Bin 28. These differences are slight compared to the differences in wind direction that categorize the days in Bin 36 and Bin 28. Days in Bin 36 are categorized by winds (surface and aloft) from the east-northeast whereas those in Bin 28 are from the west or west-northwest, i.e. winds that are essentially from the opposite direction.

The Category 4 bin has lower prior day $PM_{2.5}$ concentrations (locally and regionally) as well as lower temperatures at the surface and aloft than the Category 5 bins. Days placed in Bin 35 have higher wind speeds aloft and either comparable or slightly higher wind speeds at the surface. Days in Bin 35 are also more unstable than the in the Category 5 bins

The results indicate that different combinations of local parameters can result in high extinction coefficients (poor visibility) and that although prior day $PM_{2.5}$ concentration (both regional and local) is a key distinguishing feature between the two categories, differences in meteorology affect play a role as well.

6.2.4. Summary of Findings

The CART analysis, together with the selected air quality and meteorological input parameters, correctly classifies, on average, approximately 78 percent of the days for 2000–2010 according to extinction coefficient. CART classification accuracy for the six study areas ranges from approximately 64 to 97 percent. Classification accuracy for the meteorological data only CART runs is considerably lower compared to the full CART run for New York and Brigantine NWR and only slightly lower for Swanquarter NWR. For the two most northern areas, Casco Bay and Martha's Vineyard, and the southernmost area, Okefenokee NWR, the classification accuracy for the meteorological data only CART runs are 15, 6 and 2 percentage points, respectively, better than the full CART runs. The mixed results might indicate the selected meteorological data are reasonably good indicators of extinction coefficients for areas along the Atlantic Coast, but that the use of prior day $PM_{2.5}$ concentrations is not as clear cut.

The CART classification technique can provide information about the relative importance of the various independent parameters in distinguishing days with different visibility characteristics. Parameter importance varies among the different areas. On average, the most important parameters include: prior day 24-hour $PM_{2.5}$ concentration in the area of interest, prior day maximum 24-hour $PM_{2.5}$ concentration in potential upwind areas, surface temperature, and 850 mb temperature. Of secondary importance are relative humidity, surface wind speed, and stability.

Analysis of the variations in the input parameters across defined extinction coefficient categories reveals that there are some similarities among the areas and that for all areas, average previous day $PM_{2.5}$ concentrations (local and regional) increase with increasing extinction coefficient (decreasing visibility). Maximum surface temperatures for all areas and minimum surface temperatures for nearly all areas show similar trends, i.e. temperature increase with increasing extinction coefficient. Except for Martha's Vineyard, wind speeds aloft are the lowest for days with the highest extinction coefficients. For most areas, wind directions also vary by category which indicates that wind direction also affects extinction coefficients and hence visibility. The specific wind directions and variations across the categories are different for each area.

High extinction coefficient days for each area are divided among several CART bins, and this indicates that different combinations of the input parameters can lead to poor visibility in each area (i.e., that there are multiple pathways to extinction coefficients). Analysis of the key high extinction coefficient bins (bins containing the most poor visibility days) reveals that there are numerous distinguishing factors among the high extinction coefficient days. Prior-day regional and local $PM_{2.5}$ concentrations vary among the bins as do temperatures and, in some cases wind direction. In most cases, high extinction coefficient days are associated with the more stable atmospheric conditions and have the lowest wind speeds aloft. For several of the areas, subtle differences in meteorology and prior-day $PM_{2.5}$ concentrations can mean the difference between good or poor visibility days. This finding has implications for air quality forecasting and attainment strategy development as part of air quality planning and management.

7.0 AIR QUALITY TRENDS ANALYSIS

This section further examines the role of meteorology in determining the air quality characteristics of selected areas along the Atlantic Coast.

7.1. BACKGROUND AND OBJECTIVES

There are several reasons for further developing this information. One reason is that the analysis of air quality trends requires an understanding of the relationships between air quality and meteorology, and, in particular, how the variations in meteorology during a given period influence the ambient air quality. Another reason is that, as discussed earlier in this report, certain air quality metrics (design values) are used to characterize the air quality of an area and determine whether or not air quality standards are met. These metrics can be influenced by year-to-year variations in meteorology and this can reduce the stability of the standards. Year-to-year variations in meteorology and especially unusually persistent meteorological conditions during one or more of the years comprising a design-value cycle can lead to a design value that is not representative of typical, longer-term average conditions. All of the data presented in this section are included in the ARAQDB.

7.2. METHODOLOGY FOR ESTIMATING METEOROLOGICALLY ADJUSTED AIR QUALITY TRENDS

This section summarizes the development of meteorologically adjusted 8-hour ozone, $PM_{2.5}$ and visibility metrics for selected areas along the Atlantic Coast. The approach relies on results of the CART analysis, presented in Sections 4, 5 and 6 of this report. CART was applied separately for ozone, $PM_{2.5}$ and visibility for the period 2000–2010. Each day was placed into a classification bin that corresponds to a certain range of concentration (ozone and $PM_{2.5}$) or extinction coefficient (visibility) and a specific set of meteorological conditions. While the category of a bin reflects the value of the air quality metric (i.e., concentration or severity) associated with the bin's meteorological conditions, the number of days in a bin represents the frequency with which those conditions occur. Since the bins are determined using a multi-year period, individual years may be normalized such that the different sets of meteorological conditions are represented no more or less than they are on average over all years in the period. This is the basis for the meteorologically adjusted design values presented in this section. Meteorologically adjusted air quality values were calculated for each CART application following the steps outlined below:

Step 1. Determine the number of days to include from each bin.

- Use the average number of days per year.

Step 2. For each year, add days to underrepresented bins.

- Use the average value of days within that bin, for that year, if available.
- Otherwise, use the average value of days within that bin for the following year, if available.
- Otherwise, use the average value of days within that bin for the ten-year span.

Step 3. For each year, eliminate excess days from overrepresented bins.

- Assign random numbers to each day and eliminate excess days based on the random numbers

Step 4. Use resulting values from the normalized years to calculated meteorologically-adjusted air quality metrics.

This approach retains the day-specific information needed to calculate certain metrics like the fourth highest 8-hour average ozone concentration and the 98th percentile 24-hour average $PM_{2.5}$ concentrations.

7.3. RESULTS

Meteorologically-adjusted ozone, $PM_{2.5}$ and visibility values are presented in this section.

7.3.1. Ozone

Meteorologically adjusted 8-hour ozone concentrations were calculated for the following port/harbor areas: Portland, Providence, New York, Newark-Elizabeth, Brigantine NWR, Baltimore, Norfolk, and Savannah. The CART analysis results presented in Section 4 provide the basis for the meteorological adjustment. The analysis period is 2000–2010, April through October only.

The daily 8-hour ozone concentrations for each normalized year were used to calculate several ozone air quality metrics. These include: number of 8-hour ozone exceedance days per year, 4th highest daily maximum 8-hour average ozone concentration for each year, annual average daily maximum 8-hour average ozone concentration (average over the ozone season), and the 8-hour ozone design value (three-year average of the annual 4th highest daily maximum 8-hour average ozone concentration). The actual and meteorologically adjusted values for each of these metrics for each of the areas of interest are provided in Figure 87. Note that the design values for 2000 and 2001 are based on one and two years of data, respectively.

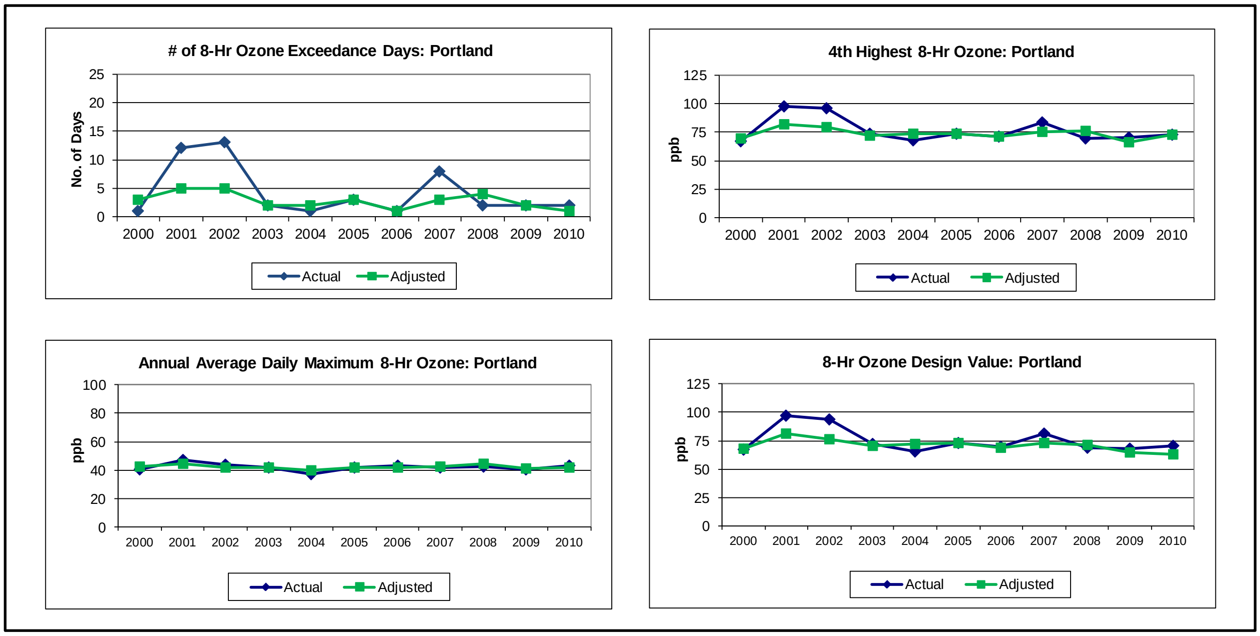


Figure 87a. Meteorologically adjusted ozone concentrations and metrics based on the CART analysis results: Portland.

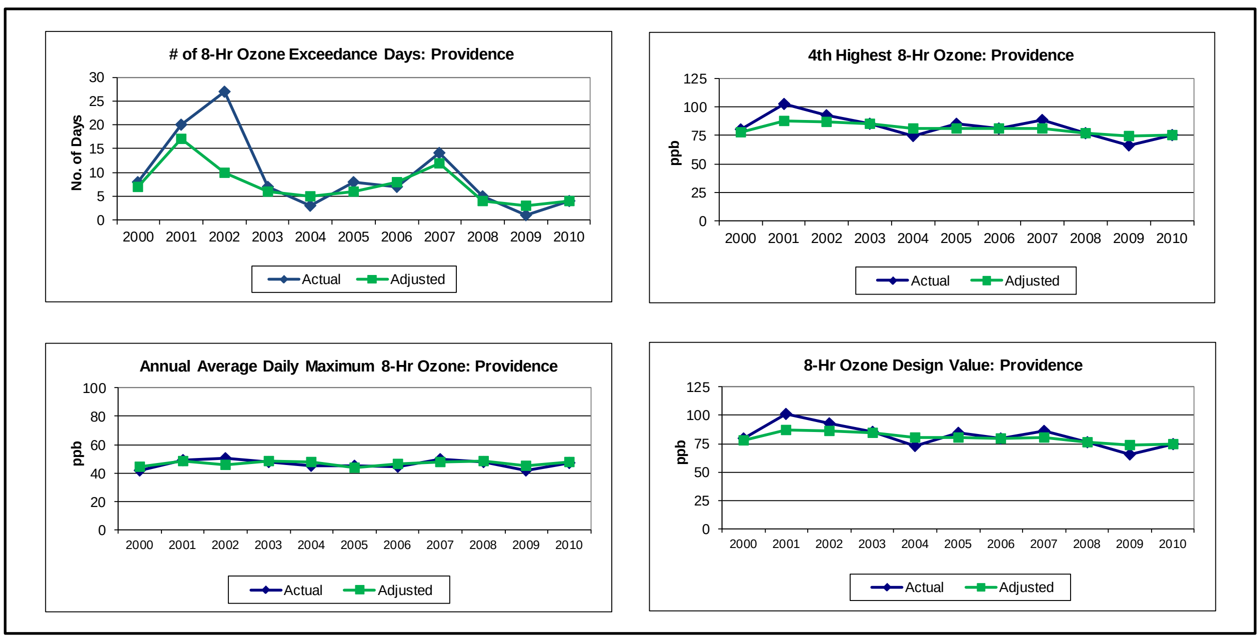


Figure 87b. Meteorologically adjusted ozone concentrations and metrics based on the CART analysis results: Providence.

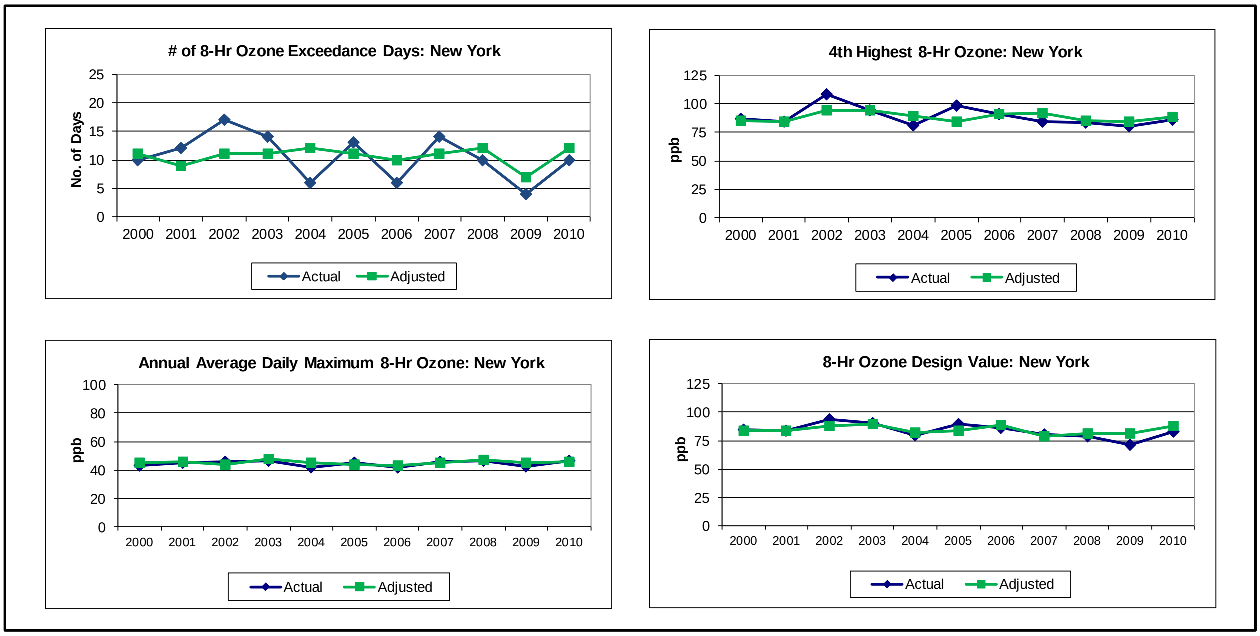


Figure 87c. Meteorologically adjusted ozone concentrations and metrics based on the CART analysis results: New York.

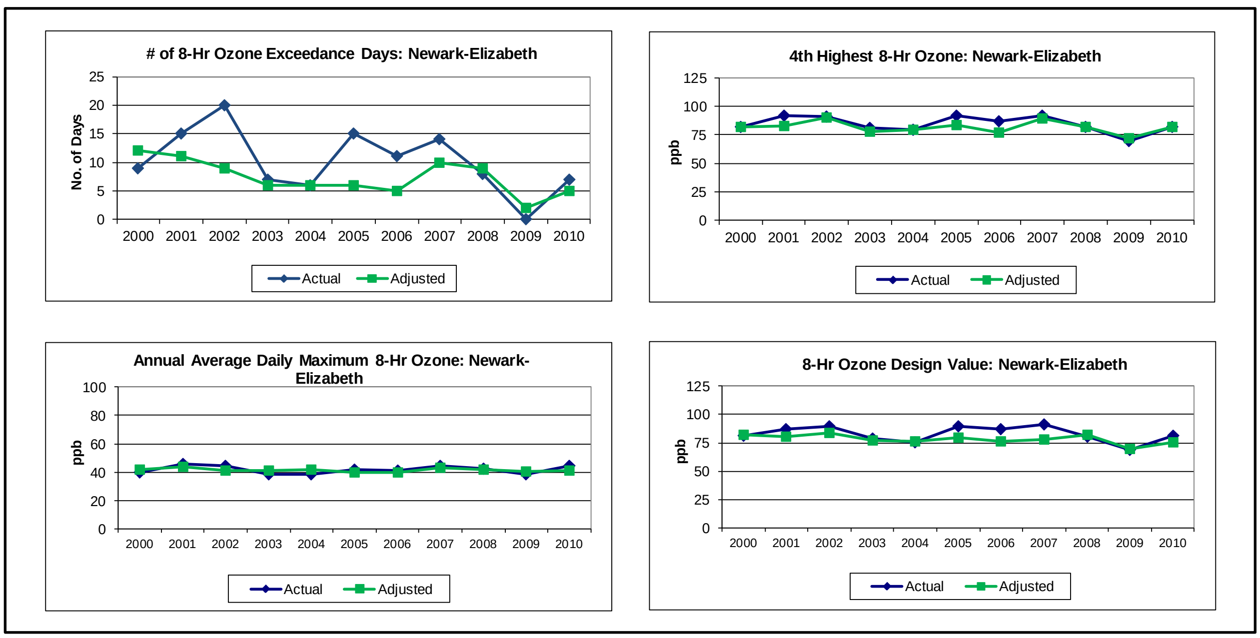


Figure 87d. Meteorologically adjusted ozone concentrations and metrics based on the CART analysis results: Newark-Elizabeth.

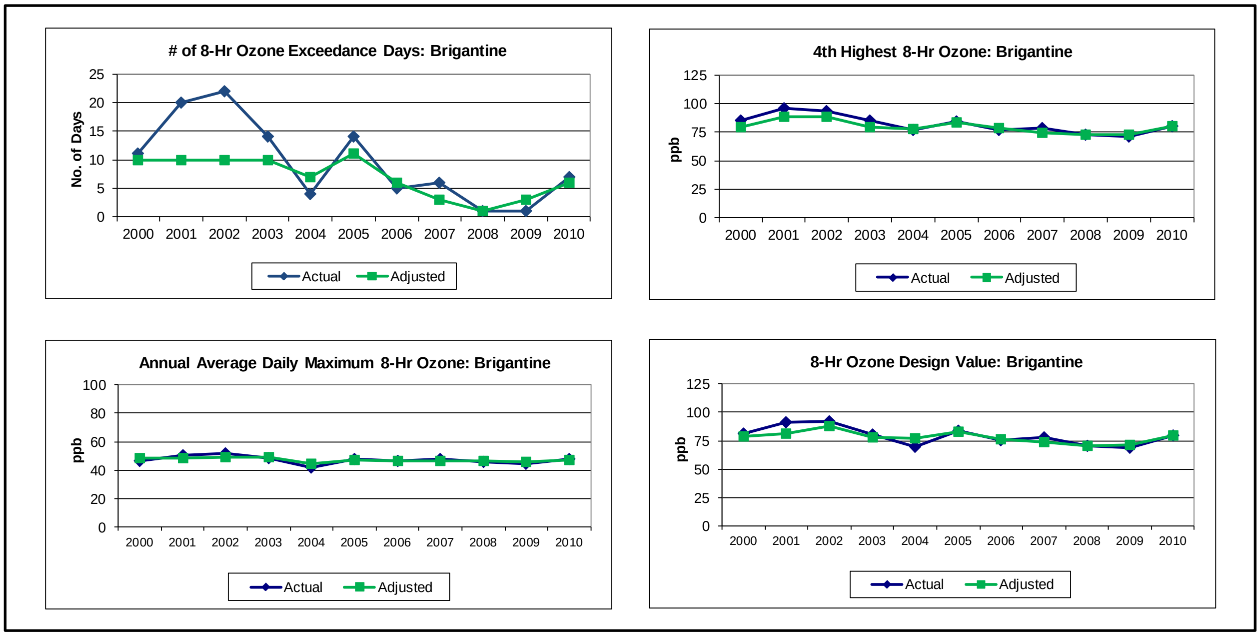


Figure 87e. Meteorologically adjusted ozone concentrations and metrics based on the CART analysis results: Brigantine NWR.

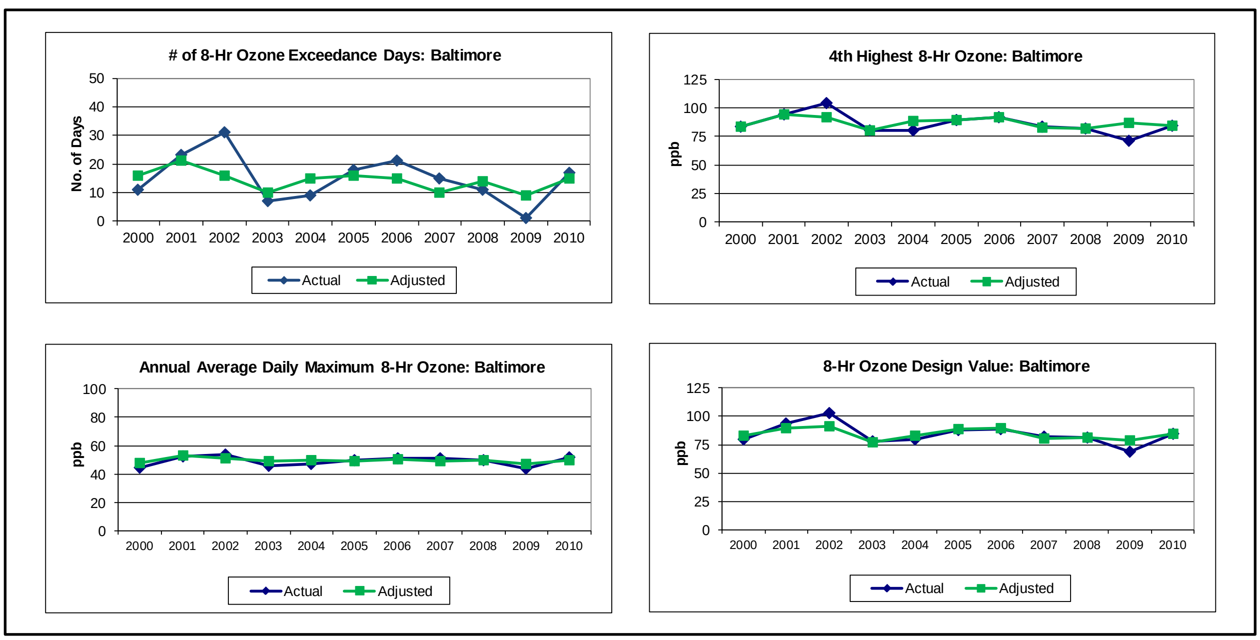


Figure 87f. Meteorologically adjusted ozone concentrations and metrics based on the CART analysis results: Baltimore.

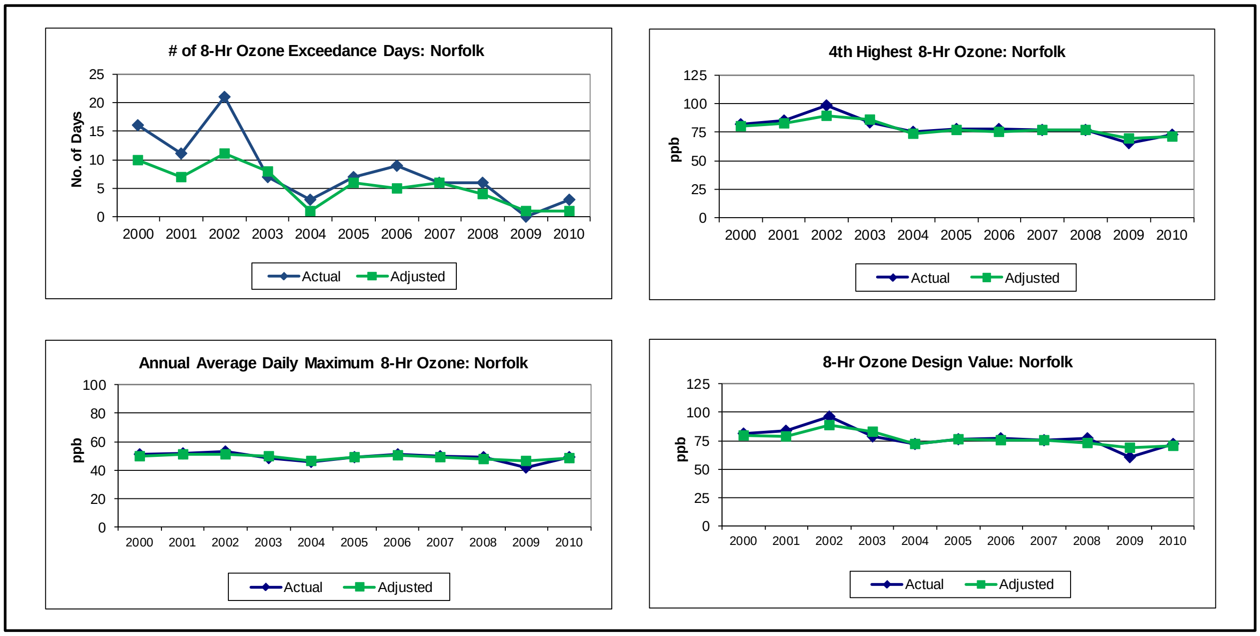


Figure 87g. Meteorologically adjusted ozone concentrations and metrics based on the CART analysis results: Norfolk.

Figure 87h. Meteorologically adjusted ozone concentrations and metrics based on the CART analysis results: Savannah.

The meteorological adjusted values show less variation from year to year. The results indicate that for most areas ozone concentrations were highest during the early part of the period and that this is, in part, due to the effects of meteorology. Both the actual and adjusted values indicate that the year-to-year trend in ozone is relatively flat or slightly downward between 2000 and 2010.

7.3.2. PM2.5

Meteorologically adjusted $PM_{2.5}$ concentrations were calculated for the following port/harbor areas: Portland, Providence, New York, Newark-Elizabeth, Baltimore, Norfolk, Wilmington (NC), and Savannah. The CART analysis results presented in Section 5 provide the basis for the meteorological adjustment. The analysis period is 2000–2010.

The daily 24-hour $PM_{2.5}$ concentrations for each normalized year were used to calculate several air quality metrics. These include: number of days per year with 24-hour average $PM_{2.5}$ concentrations greater than 12 μgm^{-3}, number of days per year with 24-hour average $PM_{2.5}$ concentrations greater than 35 μgm^{-3}, 98th percentile 24-hour average $PM_{2.5}$ concentration, and annual average $PM_{2.5}$ concentration. The actual and meteorologically adjusted values for each of these metrics for each of the areas of interest are provided in Figure 88.

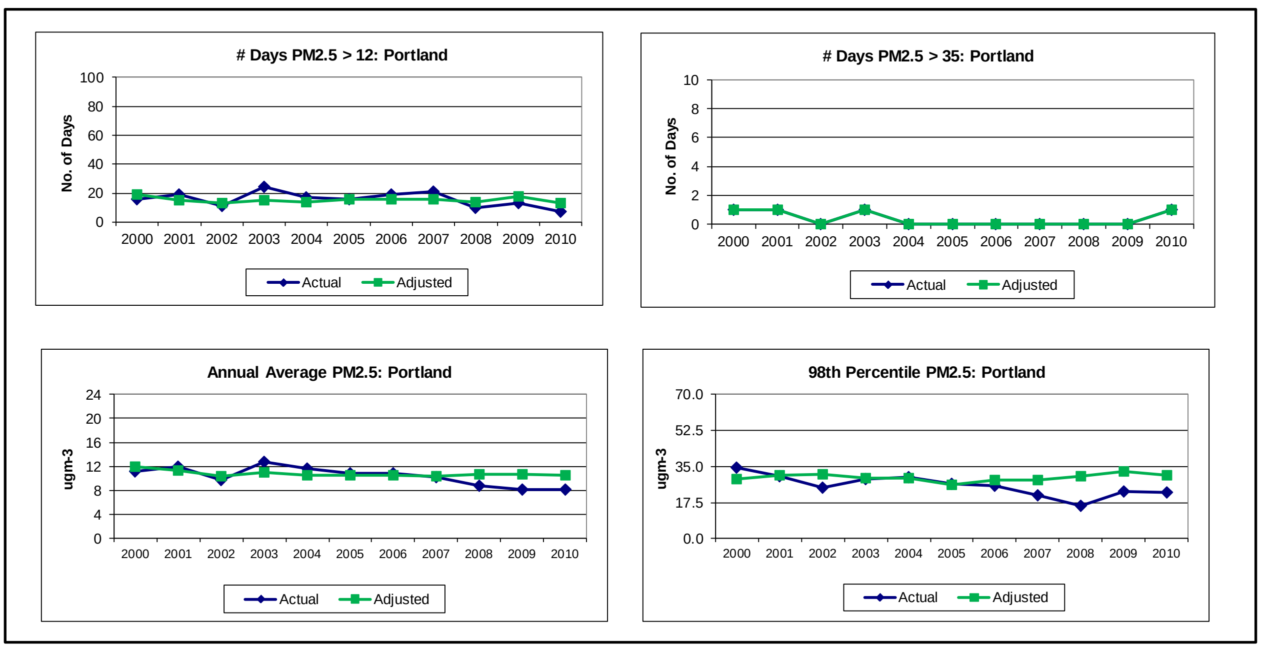


Figure 88a. Meteorologically adjusted $PM_{2.5}$ concentrations and metrics based on the CART analysis results: Portland.

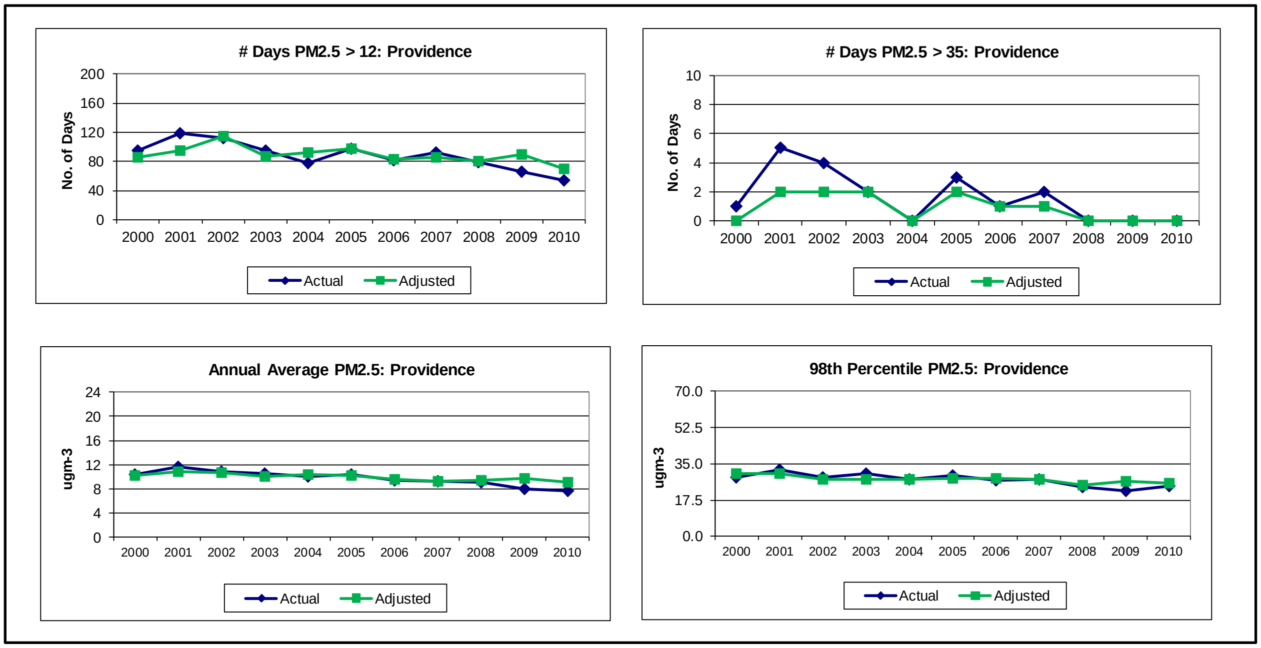


Figure 88b. Meteorologically adjusted $PM_{2.5}$ concentrations and metrics based on the CART analysis results: Providence.

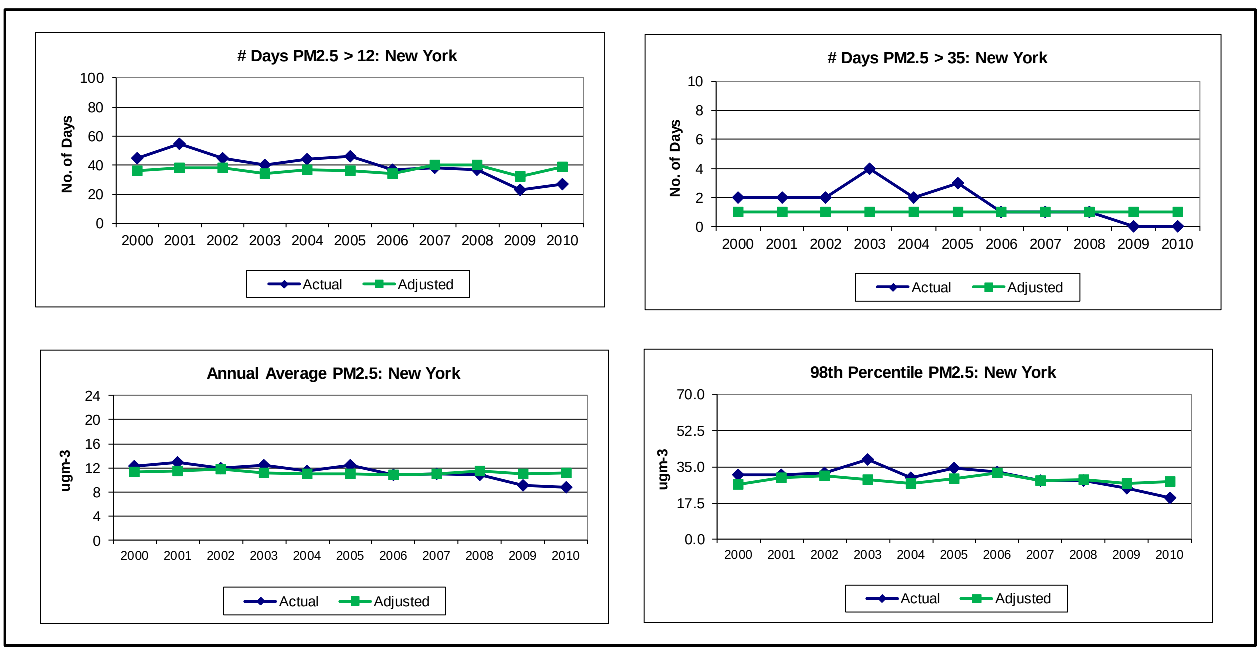


Figure 88c. Meteorologically adjusted $PM_{2.5}$ concentrations and metrics based on the CART analysis results: New York.

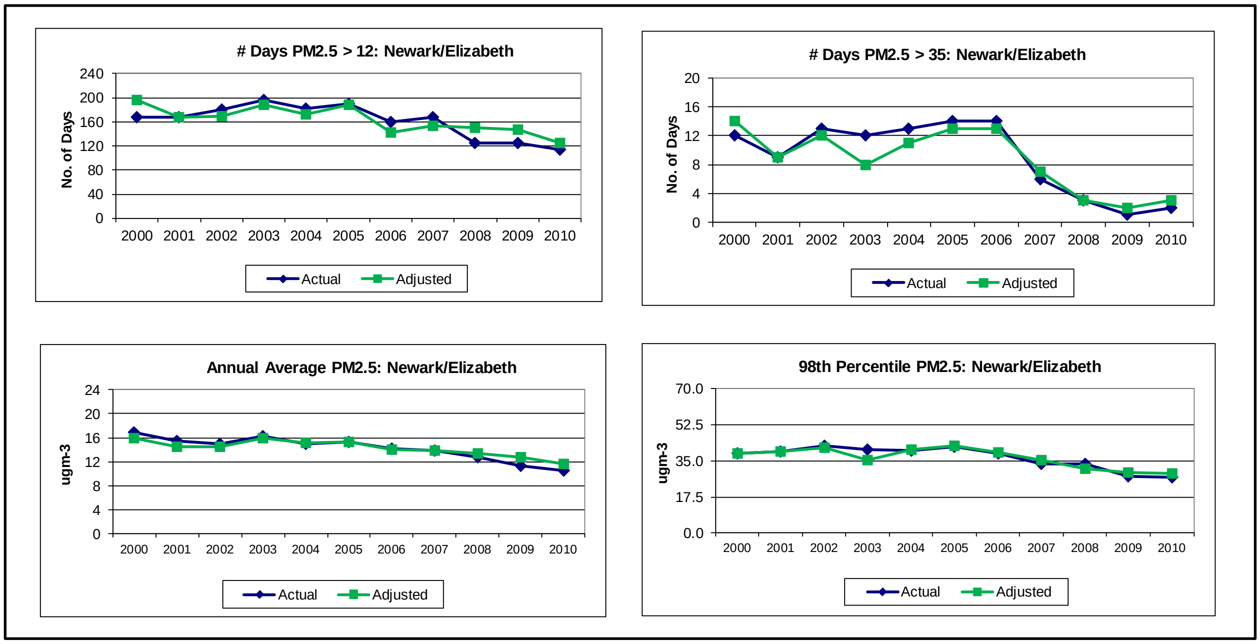


Figure 88d. Meteorologically adjusted $PM_{2.5}$ concentrations and metrics based on the CART analysis results: Newark-Elizabeth.

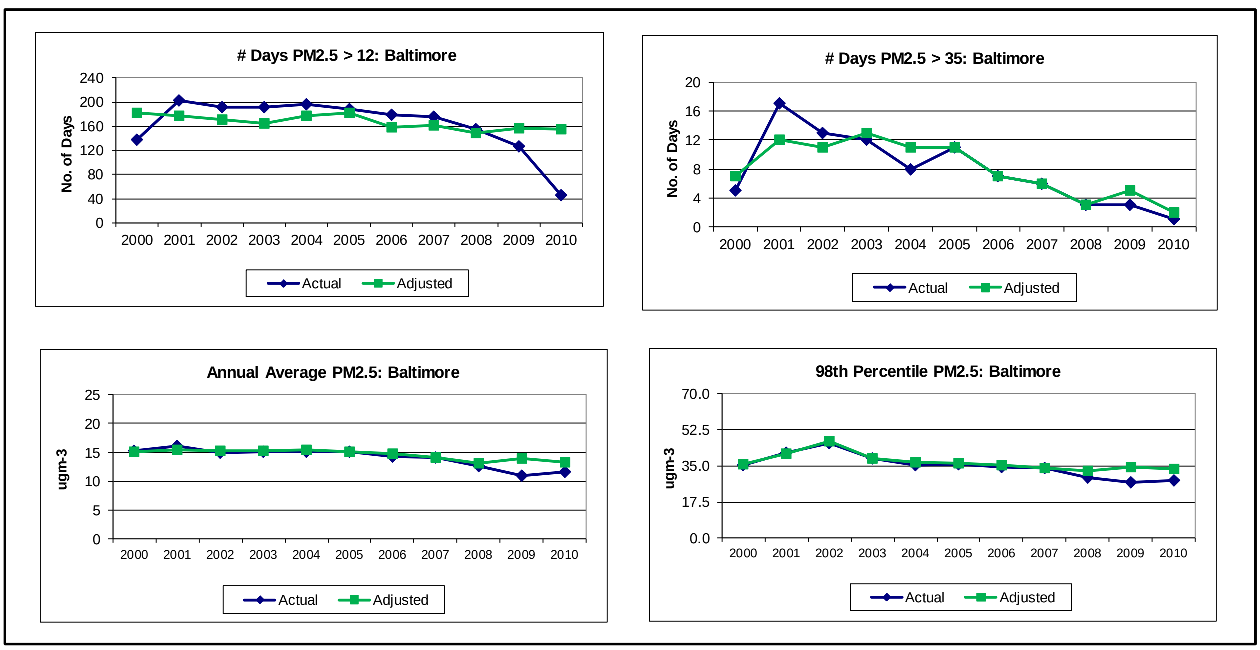


Figure 88e. Meteorologically adjusted $PM_{2.5}$ concentrations and metrics based on the CART analysis results: Baltimore.

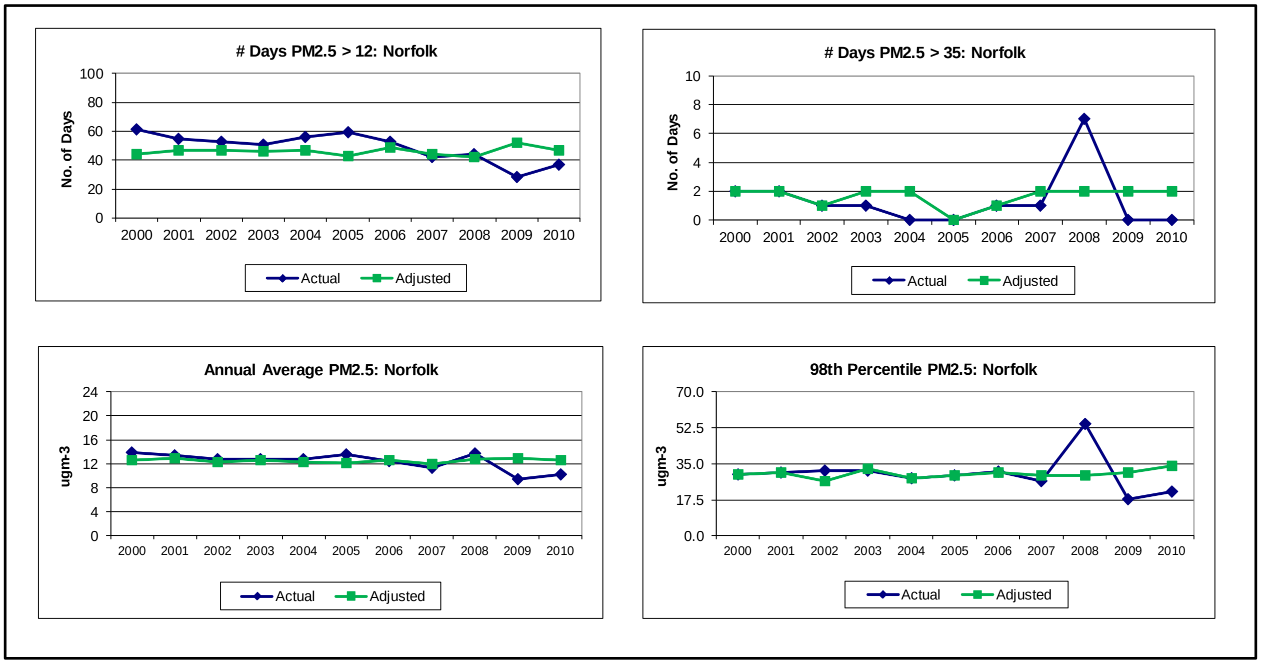


Figure 88f. Meteorologically adjusted $PM_{2.5}$ concentrations and metrics based on the CART analysis results: Norfolk.

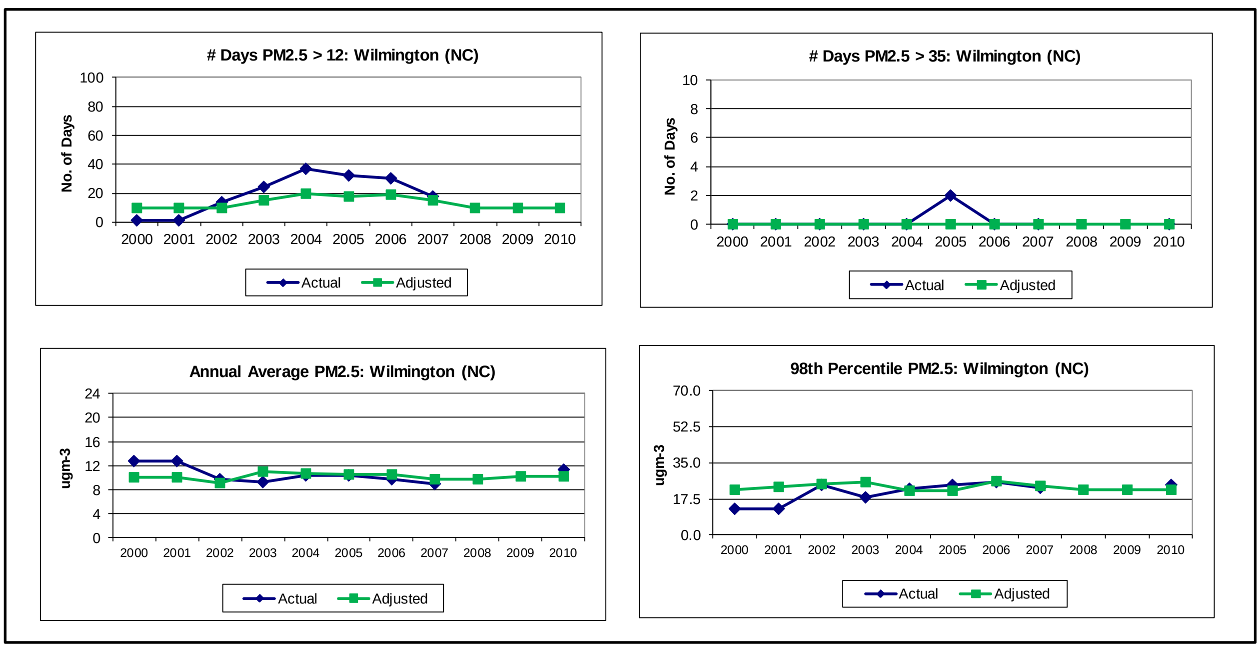


Figure 88g. Meteorologically adjusted $PM_{2.5}$ concentrations and metrics based on the CART analysis results: Wilmington (NC).

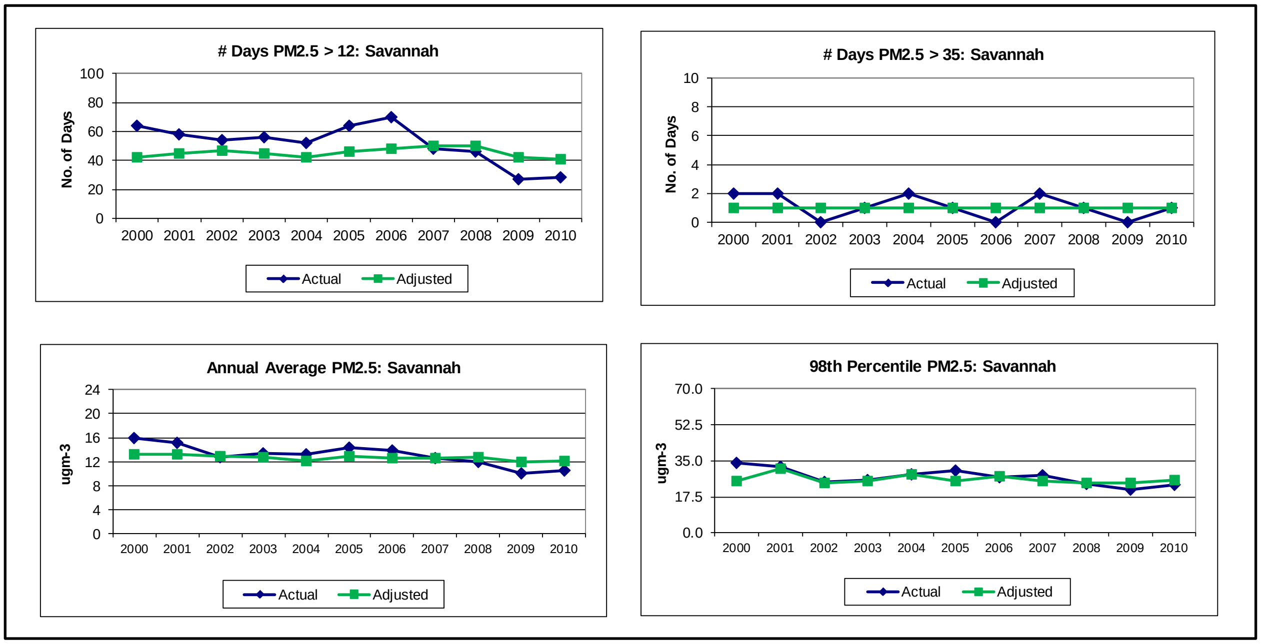


Figure 88h. Meteorologically adjusted $PM_{2.5}$ concentrations and metrics based on the CART analysis results: Savannah.

The meteorological adjusted values show less variation from year to year. The results indicate that for several areas (for example, Portland, Baltimore, Norfolk, and Savannah), the apparent downward trend in $PM_{2.5}$ is in part attributable to meteorology (conditions conducive to higher $PM_{2.5}$ in 2000–2001 and lower $PM_{2.5}$ in 2008–2010). The adjusted data indicate a flatter trend.

7.3.3. Visibility

Meteorologically adjusted extinction coefficients were calculated visibility in six selected port/harbor areas along the Atlantic Coast, including three Class I areas: Casco Bay, Martha's Vineyard, New York City, Brigantine NWR, Swanquarter NWR and Okefenokee NWR. Each is represented by an IMPROVE site. The CART analysis results presented in Section 6 provide the basis for the meteorological adjustment. The analysis period is 2000–2010.

The daily extinction values for each normalized year were used to calculate 98th percentile extinction coefficient and annual average extinction coefficient. The actual and meteorologically adjusted values for these metrics for each of the areas of interest are provided in Figure 89.

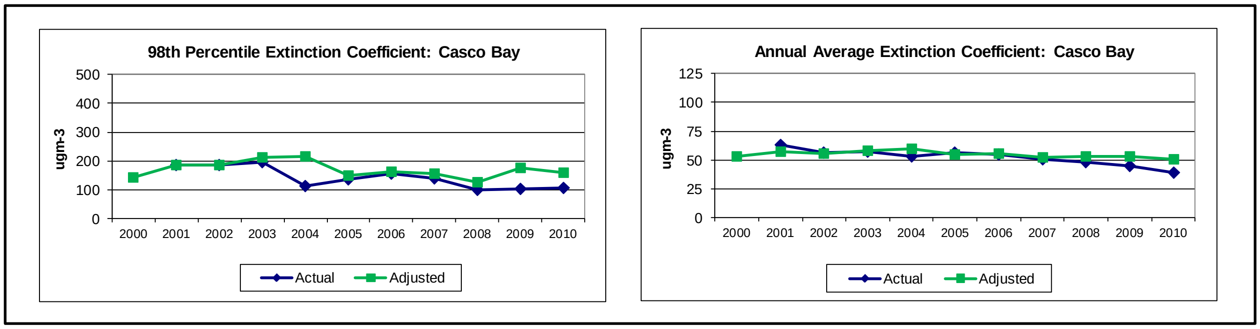


Figure 89a. Meteorologically adjusted extinction coefficient and visibility metrics based on the CART analysis results: Casco Bay.

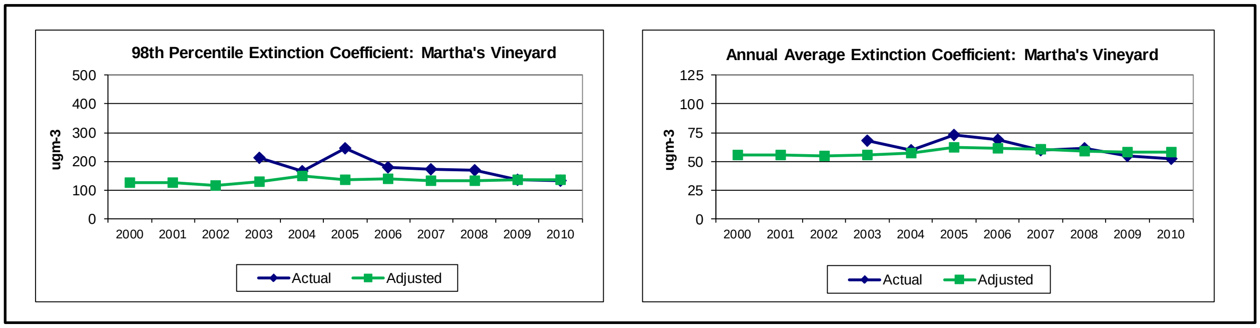


Figure 89b. Meteorologically adjusted extinction coefficient and visibility metrics based on the CART analysis results: Martha's Vineyard.

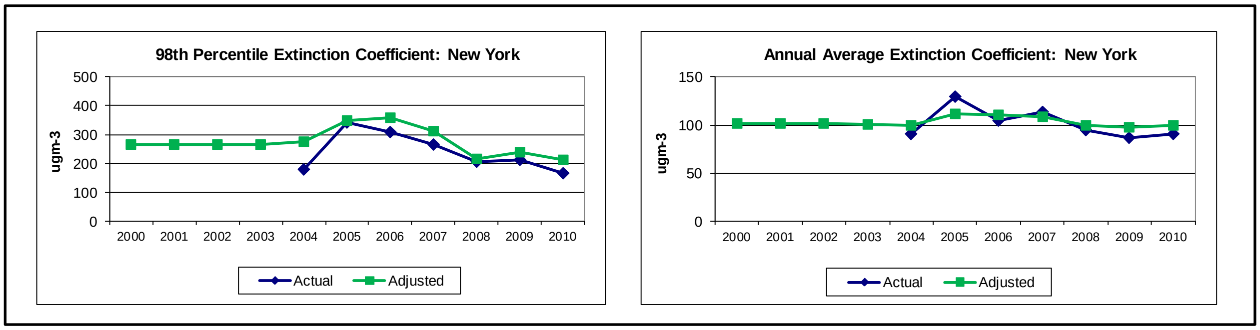


Figure 89c. Meteorologically adjusted extinction coefficient and visibility metrics based on the CART analysis results: New York City.

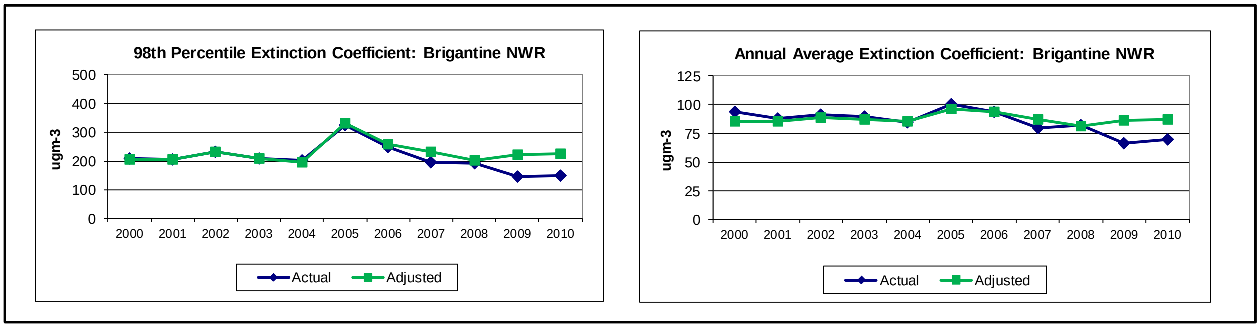


Figure 89d. Meteorologically adjusted extinction coefficient and visibility metrics based on the CART analysis results: Brigantine NWR.

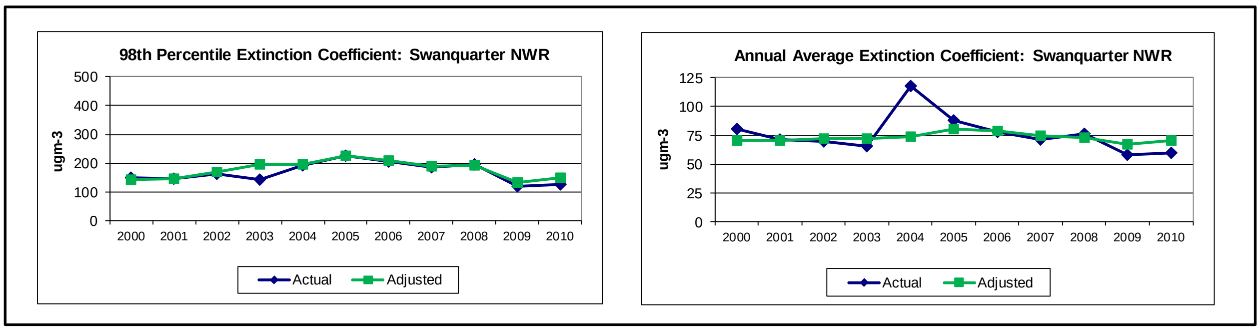


Figure 89e. Meteorologically adjusted extinction coefficient and visibility metrics based on the CART analysis results: Swanquarter NWR.

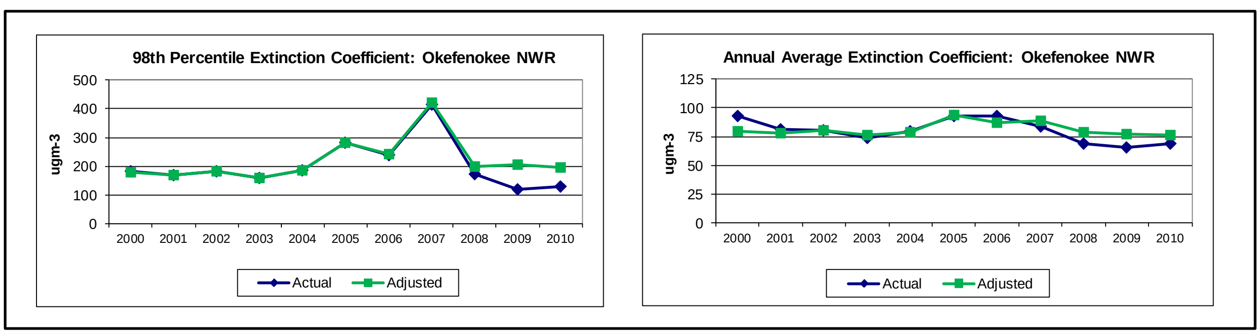


Figure 89f. Meteorologically adjusted extinction coefficient and visibility metrics based on the CART analysis results: Okefenokee NWR.

Both the actual and meteorologically adjusted values indicate a relative flat trend in annual average extinction coefficient. The actual data show a slight downward trend after about 2005 and in some cases (for example, Martha's Vineyard, New York, and Okefenokee) this is also supported by the meteorologically adjusted values.

8.0 OVER-LAND AND OVER-WATER DATASETS FOR USE WITH OCD5

The offshore and Coastal Dispersion model (Hanna et al., 1985; DiCristofaro and Hanna, 1989; Chang and Hahn, 1997) is a Gaussian dispersion model that was designed to simulate the effects of offshore emissions on onshore/coastal air quality. The meteorological inputs are used to characterize the over-water boundary layer including over-water transport and dispersion, as well as the transition to over-land dispersion conditions in connection with onshore flow.

As part of this study, meteorological datasets for use with version 5 of the OCD modeling system (OCD5) were prepared, following the guidelines on input preparation for OCD5 presented in the user's guide by Chang and Hahn (1997). The OCD5 input files were prepared for all years for the period 2005–2009. The OCD5 model requires meteorological input files for selected over-land (onshore) and over-water (offshore) locations. The offshore sites are paired with onshore sites for the purpose of filling in missing offshore data. These files were prepared using onshore surface and upper-air data from the NWS, mixing height estimates obtained from the National Climatic Data Center (NCDC), and offshore buoy data from the NDBC.

8.1. SURFACE, UPPER-AIR, AND BUOY SITE GROUPINGS

Onshore surface data include wind speed, wind direction, temperature, cloud cover, and ceiling height. Upper-air data are the twice-daily mixing heights. The surface and upper-air parameters were processed using the meteorological processor program PCRAMMET (USEPA, 1999). In addition to reformatting the data and identifying missing data points, PCRAMMET also calculates various stability parameters for the onshore locations. The resulting onshore meteorological data file is referred to as the "lmet" file. Information from the lmet file is then used along with the buoy data to generate the "wmet" file. In this study, we used the program BUOY_WME to reformat the buoy data and then applied OCDPRO to fill in the missing required elements in the wmet files. The BUOY_WME reformatting program was developed and provided by BOEM.

OCD5 meteorological input data files were prepared for the following groupings of buoy, onshore surface, and onshore upper-air sites. Each grouping is intended to represent a section of the Atlantic region as indicated in parentheses.

- **OCD Group 1**: Portland, ME
  Buoy: 44007 (Portland, ME)
  Surface data: Portland International Jetport
  Upper-air data: Gray, ME
- **OCD Group 2:** (Boston, MA)
  Buoy: 44013 (Boston, MA)
  Surface data: Boston Logan International Airport
  Upper-air data: Chatham, MA

- **OCD Group 3**: (Martha's Vineyard, MA)
  C-MAN: BUZM3 (Buzzard's Bay, MA) and NTKM3 (Nantucket Island, MA for 2009 only)
  Surface data: Vineyard Haven Airport
  Upper-air data: Chatham, MA
- **OCD Group 4:** (Nantucket, MA)
  C-MAN: BUZM3 (Buzzard's Bay, MA) and NTKM3 (Nantucket Island, MA for 2009 only)
  Surface data: Nantucket Memorial Airport
  Upper-air data: Chatham, MA
- **OCD Group 5:** (Providence, RI)
  C-MAN: BUZM3 (Buzzard's Bay, MA) and NTKM3 (Nantucket Island, MA for 2009 only)
  Surface data: Providence T. F. Green Airport
  Upper-air data: Chatham, MA
- **OCD Group 6:** (Newark-Elizabeth, NJ)
  C-MAN: ALSN6 (Ambrose Light for 2005–2008)
  Buoy: 44065 (New York Harbor Entrance for part of 2008 and all of 2009)
  Surface data: Newark International Airport
  Upper-air data: Brookhaven, NY
- **OCD Group 7**: (Atlantic City, NJ)
  Buoy: 44009 (Delaware Bay)
  Surface data: Atlantic City International Airport
  Upper-air data: Wallops Island, VA
- **OCD Group 8**: (Ocean City, MD)
  Buoy: 44009 (Delaware Bay)
  Surface data: Ocean City Municipal Airport
  Upper-air data: Wallops Island, VA
- **OCD Group 9**: (Norfolk, VA)
  Buoy: 44014 (Virginia Beach, VA)
  Surface data: Norfolk International Airport
  Upper-air data: Wallops Island, VA
- **OCD Group 10**: (Cape Hatteras, NC)
  Buoy: 41025 (Diamond Shoals, NC)
  Surface data: Cape Hatteras Airport
  Upper-air data: Morehead City, NC
- **OCD Group 11:**
  Buoy: 41004 (Edisto, SC)
  Surface data: Charleston International Airport
  Upper-air data: Charleston

- **OCD Group 12**:
  C-MAN: FWYFI (Fowey Rocks, FL)
  Surface data: Miami-Dade International Airport
  Upper-air data: Miami, FL

8.2. OVER-LAND DATA FILES

Over-land meteorological data are primarily used by OCD5 to estimate the temperature, stability, and turbulence characteristics of the atmosphere. In the OCD5 model, over-water observations of wind direction and wind speed are assumed to apply to both over-water and over-land areas. However, if on-site meteorological observations of these parameters over the water are not available, then hourly over-land values are used. The corresponding over-water data are contained in the wmet data files, which are discussed in Section 4.3.

8.2.1. Data Processing Procedures

Preparation of the over-land (lmet) data included several steps:

- Surface data for the sites listed above were obtained from NCDC (ftp://ftp3.ncdc.noaa.gov/pub/data/noaa/) in Integrated Surface Hourly (ISH) format. The data were then converted to abbreviated-ISH using the program ishapp2, also available from NCDC at (ftp://ftp.ncdc.noaa.gov/pub/software/). The abbreviated-ISH formatted files were then converted to the SAMSON format using the program NCDC_CNV, written by Russell Lee, and available at (http://www.rflee.com/RFL_Pages/Meteor.html). SAMSON stands for Solar and Meteorological Surface Observational Network and contains hourly solar radiation data along with selected meteorological elements.

- Twice-daily mixing height estimates for the upper-air sites were also obtained from NCDC. These were specifically prepared by NCDC for this project, using the standard Holzworth (1972) technique, in accordance with the guidelines for using PCRAMMET. Daily values of the nocturnal (minimum) and afternoon (maximum) mixing heights were provided in the format required by PCRAMMET. Files were re-formatted slightly because the field position of the afternoon mixing height in the files produced by NCDC is not the same as the position required by PCRAMMET.

- For each surface and upper-air site, missing data were identified and replaced with estimated values that were based on persistence (for less than 6 hours) or interpolation or substitution (by hand) for all other cases.

- PCRAMMET was then run for each surface/upper-air site pair. Standard PCRAMMET ASCII output files were generated.

- Quality assurance checks tailored to the lmet files were performed to ensure that all available data were incorporated into the lmet data files, that selected processed data values matched those in the raw data files, that no meaningful error messages were generated by PCRAMMET, and that the format of the lmet files is correct.

8.2.2. File Naming Convention

Each lmet file contains data for one surface/upper-air site pair for one year. The file names are:

lmet_group#_yyyy.dat

where group# is the OCD group number listed above (this indicates the surface/upper-air site pair) and yyyy is the four-digit year. In a few cases, the surface and upper-air sites are the same for different groups. In keeping with the group# naming convention, duplicate files were made and named according to the OCD group number.

8.2.3. Content and Format of LMET Datafiles

The content and format of the lmet meteorological data files is described in detail by Chang and Hahn (1997). Specifically, Section 3.2.2 of this document describes the file and Table 3-13 of the document list the contents and the formats.

8.3. Over-Water Data Files

Over-water meteorological data are used by OCD5 to estimate the temperature and stability characteristics of the atmosphere over the water. In addition, over-water observations of wind direction and wind speed are used by the OCD model, as available. Buoy data can be much more sporadic than data from land-based stations, so there are several options for filling in missing data using persistence, over-land data, and/or default values.

8.3.1. Data Processing Procedures

Preparation of the over-water (wmet) data included several steps:

- Buoy data for the sites listed above (in Section 4.1) were obtained from NDBC, primarily via download from the web-based NCDC data archive. The web site address is http://www.ndbc.noaa.gov.
- The buoy data were reformatted using the program BUOY-WME, which was provided by BOEM.
- The program OCDPRO (Chang and Hahn, 1997) was then applied using the reformatted buoy data and the lmet data for the corresponding surface/upper-air site pair. OCDPRO was iteratively applied to replace all missing data with estimated values. OCDPRO applies persistence for missing data for periods of less than 12 hours and replaces the missing values with default values for periods of greater than 12 hours. The following default values were applied:

Relative humidity 80%
Air temperature ....Over-land air temperature
Air minus water temperature ....0°C
Mixing height.....................................500 m

- Quality assurance checks tailored to the wmet files were performed to ensure that all available data were incorporated into the wmet data files, that selected processed data values matched those in the raw data files, that the data substitution was done in a consistent manner, that the lmet and wmet files were paired correctly for application of OCDPRO, and that the format of the wmet files is correct.

8.3.2. File Naming Convention

Each lmet file contains data for one buoy/surface/upper-air site group for one year. The file names are:

wmet_group#_yyyy.dat

where group# is the OCD group number listed above (this indicates the buoy/surface/upper-air site group) and yyyy is the four-digit year.

8.3.3. Content and Format of WMET Datafiles

The content and format of the wmet meteorological data files is described in detail by Chang and Hahn (1997). Specifically, Section 3.2.3 of this document describes the file and Table 3-15 of the document list the contents and the formats.

8.4. Summary of QA/QC Procedures

In preparing these datasets, it was assumed that the meteorological and air quality data had already received some level of data validation. Consequently, the QA/QC procedures focused on data handling and processing procedures, observance of data flags, and ensuring the accuracy, completeness, and consistency of the processed datasets.

To ensure the reliability of the meteorological and air quality data as well as the extraction, processing and reformatting steps, the following quality assurance checks were conducted:

- All programs/codes used to process and reformat the data were reviewed and checked before each application.
- All data flags were reviewed and used appropriately to guide the data processing (e.g., to exclude erroneous or questionable data).
- The site locations and IDs were checked and confirmed.
- The units for all data elements were checked and confirmed.
- The temporal resolution for each data type was checked and confirmed.

- The range of time over which the data are available and the date/time stamp for each data element was reviewed.
- For each type of data file prepared, multiple random dates and times were selected and the values of the processed/reformatted data elements were spot-checked against the original data files.
- This same check was also done for the derived quantities, such as mixing heights.
- The values of the each parameter for each site were sorted according to magnitude, to check that all values are within an acceptable range.
- The data files for each site and year were checked for completeness.
- Finally, the format, content and name of each file was verified.

8.5. Notes on Possible Data Quality Issues and Limitations

Most of the data quality issues for the OCD files pertain to missing data. In a few cases, mixing heights were missing for either the morning or afternoon period or for the entire day (both periods). This is the result of missing upper-air sounding data. To fill in the missing data, the values from the same time period from the prior day were substituted. The occurrence of missing upper-air sounding data/mixing heights was roughly the same for all years.

Similarly, hourly surface meteorological data for the land-based monitoring sites were missing for some sites and periods used in preparing the OCD dataset. In this case, persistence was applied on an hourly basis, for up to approximately 6 hours. For longer periods, interpolation was used or the missing values were replaced with data from a prior day - based on the time of day and an analysis of the overall meteorological conditions and tendencies revealed in the available data. Persistence was applied automatically using a simple program. The interpolation/replacement was done by hand. A majority of the substitutions were for wind directions reported as variable and, for the most part, these were assigned the wind direction from the hour before.

Buoy data were also missing for some sites and periods used in preparing the OCD dataset. As discussed earlier in this section the OCDPRO tool was used to fill in the missing buoy data. One key assumption in the buoy files is the use of default values for several of the parameters including over-water mixing heights. Periods where data were missing for a large number of consecutive days are noted below.

OCD Group 1:

Buoy: 44007

- 2005: Days 27-137
- 2007: Days 106-157

OCD Group 3:

C-MAN: BUZM3

- 2005: Days 1-50 (water temperature only), 50-130, 130-193 (water temperature only)
- 2006: Days 193 – 229

OCD Group 4:

C-MAN: BUZM3

- 2005: Days 1-50 (water temperature only), 50-130, 130-193 (water temperature only)
- 2006: Days 193 – 229

OCD Group 5:

C-MAN: BUZM3

- 2005: Days 1-50, 50-193
- 2006: Days 193 – 229

OCD Group 6:

C-MAN: ALSN6

- 2005: Days 1-197 (water temperature only), 197-365.
- 2006: Days 1-59, 59-166 (water temperature only)
- 2008: Days 130-210 (water temperature only),

OCD Group 9:

Buoy: 44014

- 2006: Days 1-75, 90-151

OCD Group 10:

Buoy: 41025

- 2005: Days 1-78

OCD Group 11:

Buoy: 41004

- 2007: Days 202-298.
- 2009: Days 265-328

OCD Group 12:

C-MAN: FWYFI

- 2005: Days 206-230

Finally, the user of this dataset should note that the buoy, surface, and upper-air sites were grouped based on location and each group is intended to represent over-water and over-land conditions for a certain portion of the Atlantic Coastal area. The representativeness of the sites may vary by region and by year.

The OCD5 files prepared for this study have not been used for any OCD5 modeling, so the integrity of the files has not been fully tested. Application of the OCD5 model may be version and platform dependent and minor formatting and other issues may arise in using these files, especially in response to changes in model or the computer system on which it is run.

9.0 SUMMARY OF KEY FINDINGS AND RECOMMENDATIONS FOR FURTHER STUDIES

The ARAQDB can be used to support a variety of air quality studies for the Atlantic region. Air quality for key port/harbor areas and Class I areas along the Atlantic Coast is affected by local geographical, meteorological and emissions characteristics. Due to the predominance of westerly winds, air quality for most areas along the Atlantic coast is also influenced by pollutant transport from other areas in the continental U.S.

Based on a review of recent data, key air quality issues include attainment of the 8-hour ozone standard for a number of port/harbor areas and visibility at Class I and other areas along the coast. The New York, Newark-Elizabeth, Wilmington (DE), and Baltimore areas are currently designated non-attainment areas for ozone. A review of recent 8-hour ozone design values for key port/harbor areas along the Atlantic Coast indicates that for most areas the design values either decrease with time or stay about the same for the most recent five years with available data. Design values above the 8-hour ozone standard were reported for Martha's Vineyard/Nantucket, New York, Newark-Elizabeth, Wilmington (DE), and Baltimore during this period.

For most sites, the annual and 24-hour $PM_{2.5}$ design values are below the standard. However, the New York, Newark-Elizabeth, and Wilmington (DE) areas are currently designated non-attainment areas for 24-hour $PM_{2.5}$. Designations for the annual $PM_{2.5}$ standard are expected to be issued in 2014. A review of recent data shows that for most areas, the design values either decrease with time or stay about the same for the most recent five years with available data. For Portland, Newport News/Norfolk, Wilmington (NC), Charleston, and Savannah, the 24-hour design values increase with time, especially between 2008 and 2010. Although $PM_{2.5}$ concentrations are generally lower than the standards, improvements in visibility are needed to achieve the 2018 and natural conditions goals for Class I and other areas along the coast.

9.1. DATA SUMMARIES

Data summaries provide an overview of the meteorological, air quality and emissions data and highlight key features/components of the integrated database. A number of routine and region-specific meteorological parameters were examined to assess the meteorological characteristics of selected port/harbor areas in the Atlantic region, and to examine how meteorological conditions vary throughout the region and throughout the year.

9.1.1. Meteorological Data

Based on the surface meteorological data, temperatures for all sites exhibit the expected seasonal characteristics and monthly average temperatures increase from north to south. Precipitation amounts and the month-to-month variations are different among the sites. The more southern sites are characterized by greater precipitation amounts and greater month-to-month variation compared to the more northern sites. For all sites, average wind speeds are lower during the summer months and higher during the winter months. Average wind directions have a westerly component during the winter months and a southerly component during the summer months – except for Miami which has southeasterly winds year round.

For many sites, 2005 and 2009 are characterized by relatively higher precipitation compared to other years in the 2000–2010 analysis period, but the year-to-year variations in precipitation are different among the sites. With a few exceptions, the average persistence index does not vary much from year to year, indicating that no years stand out as having a much greater frequency of sea-breeze-conducive conditions compared to other years.

At the buoy sites, sea surface temperature exhibits the expected seasonal variations, with the lowest average temperatures in March and the highest in August. The persistence index shows more month-to-month variability than for the onshore locations and indicates that sea breeze circulation is most frequent in spring (March, April and May) and late summer/early fall (September and October). Wind speeds are lower and daytime winds (on average) exhibit a westerly component during the winter months, a southerly component during the summer months, and, for two of the buoys (Delaware Bay and Diamond Shoals), an easterly component in September. Both the sea-surface temperature and persistence parameters exhibit some year-to-year variation and this varies among the sites.

Based on the upper-air data, the 850 mb temperatures, dew-point temperatures, wind speeds, and wind directions exhibit strong regional and seasonal variations. For all locations, wind speeds aloft are lowest during the summer months and the stability index indicates greater stability during the winter months.

9.1.2. Air Quality Data

As noted earlier, ozone is one of the key air quality issues affecting the coastal port/harbor areas of the Atlantic Coast. Ozone concentrations are influenced by numerous factors including geography, local emissions, and pollutant transport and thus vary considerably by region and by site. Peak ozone concentrations for the selected port/harbor areas occur at different times of the year and different times of the day. On average, the highest ozone concentrations occur in August for the Portland and Martha’s Vineyard areas, in June and July for the Newark-Elizabeth area, and in July for Norfolk and Savannah. The diurnal profile for the Newark-Elizabeth area site is typical of urban areas and shows a peak at approximately 1400 LST. The flatter, broader diurnal profile for the remaining sites is more typical of sites for which the ozone concentrations are influence by a sea-breeze circulation. For all sites, the number of exceedance days and the 8-hour ozone design values decrease with time throughout the eleven-year period. The combined analysis of ozone and wind data reveals that, overall, there are a wide range of patterns among the different locations. One general finding is that moving along the coast from north to south, there is a shift from southerly to northerly wind components on higher ozone days. The lowest concentrations tend to occur with easterly winds, although this varies slightly from area to area.

For most sites, the annual and 24-hour $PM_{2.5}$ design values for selected port/harbor areas along the Atlantic Coast are below the NAAQS throughout the analysis period. However, for the Newark, Norfolk and Savannah area sites, the annual average $PM_{2.5}$ concentrations are greater than 12 μgm^{-3} for several design value periods, especially during the early part of the analysis period. Similarly 24-hour $PM_{2.5}$ design values are less than 35 μgm^{-3} for all sites and design value periods, with the exception of Newark through 2008. For most of the selected area, the average maximum concentrations tend to be highest during the summer months. For the Portland, Martha's Vineyard, Newark and Norfolk areas, there are also high values during the winter months of January, February, November and December. For Savannah, the peak values do not vary much throughout the year. Without fully accounting for year-to-year differences in meteorology, a downward trend in both the annual and 24-hour design values is apparent for most sites. The combined analysis of $PM_{2.5}$ and wind data indicates that, for most sites, higher $PM_{2.5}$ concentrations occur under conditions of low surface wind speeds and a wide range of conditions aloft.

Analysis of visibility data for selected coastal areas indicates that sulfate is the greatest contributor to poor visibility. Nitrate, organic carbon, and elemental carbon also contribute to visibility degradation in New York City and organic carbon contributes substantially at the Okefenokee NWR site. The data for most sites indicate a slight downward trend (improved visibility) during the analysis period, especially for the worst visibility days. The combined analysis of visibility and wind data indicates that higher extinction coefficients occur under a range of wind speeds and wind directions and that recirculation leads to poorer visibility along the middle and southern portions of the Atlantic Coast.

9.1.3. Emissions Data

Observed air quality along the Atlantic coast is influenced by a multitude of anthropogenic and biogenic sources emitting criteria pollutants, with the highest density of anthropogenic emissions occurring in the highly populated urban areas or at the major ports. Based on emission estimates from the latest available national inventory for 2008, the highest levels of emissions are in counties with the highest population centers or at the major port facilities, including Miami, New York, and Boston. The major contributors to NO_x and CO emissions along the Atlantic coast are on-road mobile sources, while the major contributors to anthropogenic VOC, PM_{10}, $PM_{2.5}$ and NH_3 emissions are area sources (including home heating units, solvent utilization, petroleum storage and transport, solid waste and wastewater treatment facilities, landfills, small boilers, restaurants, outdoor grills, road dust, agricultural operations, and open burning). For SO_2, the major contributors are elevated point sources, such as power plants.

9.2. CART Analyses

The Classification and Regression Tree (CART) analysis technique was used to examine the relationships between onshore and offshore meteorological conditions and air quality in selected port/harbor areas along the Atlantic Coast. CART was applied separately for ozone, $PM_{2.5}$, and visibility.

9.2.1. Ozone CART Analysis

- The CART analysis correctly classifies, on average, approximately 88 percent of the ozone season days for 2000–2010 according to daily maximum 8-hour ozone concentration. When only meteorological data are used as input to the CART analysis, classification accuracy is slightly lower (for most sites) and this indicates that the selected meteorological data are reasonably good indicators of ozone concentration for areas along the Atlantic Coast.

The CART classification technique can provide information about the relative importance of the various independent parameters in distinguishing days with different ozone air quality characteristics. On average, the most important parameters include: prior day maximum 8-hour ozone concentration in the area of interest, prior day maximum 8-hour ozone concentration in potential upwind areas, surface temperature, 850 mb temperature, and relative humidity. Of secondary importance are stability, surface wind speed, and persistence.

Analysis of the variations in the input parameters across defined ozone concentration categories reveals that high ozone concentrations are associated with relatively higher temperatures, lower relative humidity, lower wind speeds, greater stability, less cloud cover, and less rainfall, compared to days with lower ozone concentrations. For most areas, wind directions also vary by category which indicates that wind direction also affects ozone concentration. High ozone days are also characterized by both local and regional buildup of ozone, as indicated by the prior-day average ozone concentrations, which increase for each higher ozone category.

High ozone days for each area are divided among several CART bins, and this indicates that different combinations of the input parameters can lead to high ozone in each area (i.e., that there are multiple pathways to high ozone). Analysis of the key high ozone bins (bins containing the most number of high ozone days) reveals that one of the key distinguishing factors among the high ozone bins is wind direction. Differences in the prior-day regional ozone concentrations among the bins suggests that regional transport can be a factor in determining the ozone level, but that it is not always a dominant factor.

9.2.2. PM2.5 CART Analysis

The CART analysis, together with the selected air quality and meteorological input parameters, correctly classifies, on average, approximately 87 percent of the days for 2000–2010 according to 24-hour average $PM_{2.5}$ concentration. When only meteorological data are used as input to the CART analysis, classification accuracy is lower indicating that the selected meteorological data are reasonably good indicators of $PM_{2.5}$ concentration (but not as good as for ozone).

On average, the most important parameters include: prior day 24-hour average $PM_{2.5}$ concentration in the area of interest, prior day 24-hour average $PM_{2.5}$ concentration in potential upwind areas, surface temperature, and 850 mb temperature. Of secondary importance are surface wind speed, and stability.

The highest $PM_{2.5}$ concentrations are associated with prior day buildup of $PM_{2.5}$. For all but two areas, high $PM_{2.5}$ concentrations are also associated with relatively higher temperatures, and lower wind speeds. For most areas, wind directions also vary by category.

Based on the analysis of the key high $PM_{2.5}$ bins, differences in the prior day regional $PM_{2.5}$ concentrations as well as wind direction suggest that regional transport can be a factor in determining the $PM_{2.5}$ concentrations.

9.2.3. Visibility CART Analysis

- The CART analysis, together with the selected air quality and meteorological input parameters, correctly classifies, on average, approximately 78 percent of the days for 2000–2010 according to extinction coefficient. Classification accuracy for the meteorological data only CART runs is lower compared to the full CART run and the reduction in accuracy varies by area.

On average, the most important parameters include: prior day 24-hour $PM_{2.5}$ concentration in the area of interest, prior day maximum 24-hour $PM_{2.5}$ concentration in potential upwind areas, surface temperature, and 850 mb temperature. Of secondary importance are relative humidity, surface wind speed, and stability.

Previous day $PM_{2.5}$ concentrations (local and regional) increase with increasing extinction coefficient (decreasing visibility). Maximum surface temperatures for all areas and minimum surface temperatures for nearly all areas also increase with increasing extinction coefficient. For most areas, wind speeds aloft are the lowest for days with the highest extinction coefficients and wind directions also vary by category.

Analysis of the key high extinction coefficient bins reveals that there are numerous distinguishing factors among the high extinction coefficient days. Prior-day regional and local $PM_{2.5}$ concentrations vary among the bins as do temperatures and, in some cases wind direction. In most cases, high extinction coefficient days are associated with the more stable atmospheric conditions and have the lowest wind speeds aloft.

9.3. AIR QUALITY TRENDS

The CART results were also used as the basis for the development of meteorologically adjusted 8-hour ozone, $PM_{2.5}$ and visibility for selected areas along the Atlantic Coast. Specifically, the frequency of occurrence of the conditions within each of the classification bins was used to define a typical year and the individual years were normalized such that the different sets of meteorological conditions are represented no more or less than they are for this typical year.

Overall, the meteorological adjusted values show less variation from year to year.

The results for ozone indicate that for most areas ozone concentrations were highest during the early part of the period and that this is, in part, due to the effects of meteorology. Both the actual and adjusted values indicate that the year-to-year trend in ozone is relatively flat or slightly downward between 2000 and 2010.

The results for $PM_{2.5}$ indicate that for several areas (for example, Portland, Baltimore, Norfolk, and Savannah), the apparent downward trend in $PM_{2.5}$ is in part attributable to meteorology (conditions conducive to higher $PM_{2.5}$ in 2000–2001 and lower $PM_{2.5}$ in 2008–2010). The adjusted data indicate a flatter trend.

For visibility, both the actual and meteorologically adjusted values indicate a relative flat trend in annual average extinction coefficient. The actual data show a slight downward trend after about

2005 and in some cases (for example, Martha's Vineyard, New York, and Okefenokee) this is also supported by the meteorologically adjusted values.

9.4. RECOMMENDATIONS

In addition to the analyses presented in this report, the ARAQDB could be used support:

- Detailed analysis of meteorological and/or air quality data for selected onshore or offshore locations.
- Meteorological and/or air quality modeling studies of the entire area or selected subdomains.
- Analysis of whether observed changes in air quality are correlated among the different areas of interest and assessment of whether the air quality changes are primarily regional, local, or a combination.
- Identification of possible climate change indicators, such as trends in ambient temperature, wave heights, wind speeds, and sea surface temperature.

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The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

The Bureau of Ocean Energy Management Mission

The Department of the Interior's Bureau of Ocean Energy Management (BOEM) manages the exploration and development of the nation's offshore resources. It seeks to appropriately balance economic development, energy independence, and environmental protection through oil and gas leases, renewable energy development and environmental reviews and studies. The Office of Renewable Energy Programs (OREP) is responsible for the renewable energy activities and alternate energy-related programs on the OCS. The OREP oversees the development and implementation of renewable energy leases and provides policy direction, coordination, and oversight. The OREP embraces a “cradle to grave” approach for managing renewable energy projects to ensure orderly, safe, and environmentally responsible renewable energy development on the OCS. The OREP and BOEM together strive to fulfill its responsibilities through the general guiding principles of: (1) being responsive to the public's concerns and interests by maintaining a dialogue with all potentially affected parties and (2) carrying out its programs with an emphasis on working to enhance the quality of life for all Americans by lending BOEM assistance and expertise to economic development and environmental protection.