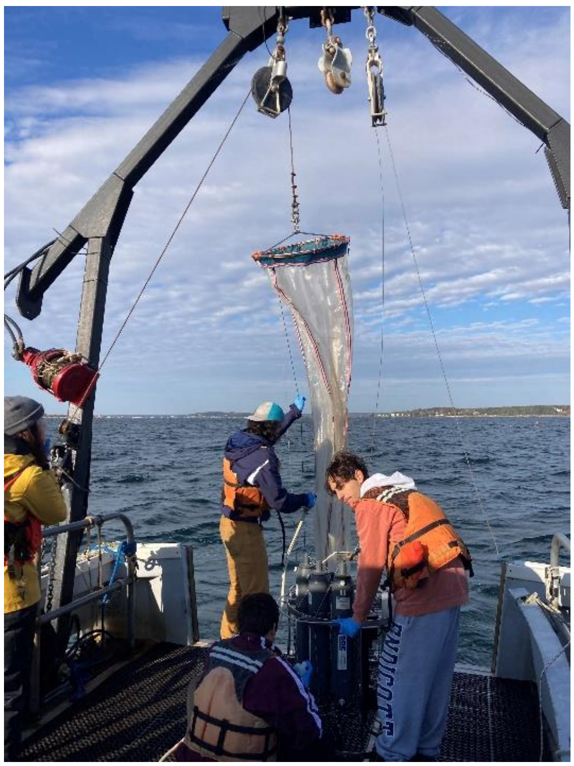
OCS Study
BOEM 2023-015

Sustained monitoring of zooplankton populations at the Coastal Maine Time Series (CMTS) and Wilkinson Basin Time Series (WBTS) stations in the western Gulf of Maine: Results from 2005-2022



U.S. Department of the Interior
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Sustained monitoring of zooplankton populations at the Coastal Maine Time Series (CMTS) and Wilkinson Basin Time Series (WBTS) stations in the western Gulf of Maine: Results from 2005-2022

February 2021

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DISCLAIMER

Study collaboration and funding were provided by the U.S. Department of the Interior, Bureau of Ocean Energy Management (BOEM), Environmental Studies Program, Washington, DC, under Agreement Number M19AC00022. This report has been technically reviewed by BOEM, and it has been approved for publication. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of BOEM, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

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CITATION

Runge J, Karp Boss L, Dullaert E, Ji, R, Motyka J, Young-Morse R, Pugh, D, Shellito S, Vandemark D. (University of Maine, Orono, ME). 2023. Sustained monitoring of zooplankton populations at the Coastal Maine Time Series (CMTS) and Wilkinson Basin Time Series (WBTS) stations in the western Gulf of Maine: Results from 2005-2022. Sterling (VA): U.S. Department of the Interior, Bureau of Ocean Energy Management. 40 p. Report No.: OCS Study BOEM 2023-015. Contract No.: CA M19AC00022.

ABOUT THE COVER

University of Maine students assisting with vertical net tow and CTD Rosette sample collection at the Coastal Maine Time Series (CMTS) station off the coast of the Damariscotta Estuary, mid-coast Maine. Photo credit: J. Runge

ACKNOWLEDGMENTS

The authors wish to thank Robbie Downs, captain of the University of Maine research vessel, *Ira C*, and Bryan Soares, captain of the University of New Hampshire research vessel, *Gulf Challenger*, for their service in assuring that the sample collection was conducted competently and safely. Cameron Thompson and Rebecca Jones are acknowledged for their effort and technical skill in sample and data collection and analysis conducted prior to 2020. We thank Sean O'Neill, Camille Ross, Tom Kiffney and countless undergraduate students enrolled in the University of Maine Semester by the Sea program at the Darling Marine Center for their assistance with sample collection and analysis over the course of the present project.

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List of Abbreviations and Acronyms

AMOC	Atlantic Meridional Overturning Circulation
BLOS	Bigelow Laboratory for Ocean Sciences
BOEM	Bureau of Ocean Energy Management
CI	Western Gulf of Maine *Calanus* Index
CMTS	Coastal Maine Time Series (previously also known as DMC-2)
EcoMon	NOAA Ecosystem Monitoring Surveys (1988-present)
ERDAPP	Environmental Research Division Data Access Program: a data server that provides consistent file formats for downloading scientific datasets
ISMN	Integrated Sentinel Monitoring Network
GoM	Gulf of Maine
MARMAP	NOAA Marine Resources Monitoring, Assessment, & Prediction program (1977-1987)
MLD	Mixed Layer Depth
MBON	Marine Biodiversity Observation Network
NARW	North Atlantic right whale
NERACOOS	Northeastern Regional Association of Coastal Ocean Observing Systems
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
OBIS	Ocean Biodiversity Information System
SST	Sea Surface Temperature
TGB	Tail of the Grand Banks
WBTS	Wilkinson Basin Time Series (previously also known as WB-7)

1 Summary

BOEM Cooperative Agreement M19AC00022 supported collection and analysis of samples from the Wilkinson Basin Time Series (WBTS) and Coastal Maine Time Series (CMTS) stations as part of the NERACOOS Integrated Sentinel Monitoring Network (ISMN) Gulf of Maine MBON project. The WBTS and CMTS stations are strategically located in the western Gulf of Maine to monitor planktonic ecosystem characteristics in the Maine Coastal Current, a regional production driver, and in Wilkinson Basin, the primary overwintering habitat for the energy-rich foundation species, the planktonic copepod *Calanus finmarchicus*, that supports the Gulf of Maine subarctic food web and its ecosystem services.

This report presents results and interpretation of data collected at the time series stations between 2020 and 2022. The focus of the BOEM support was the assessment of zooplankton abundance and diversity in the context of change in oceanographic conditions in the Gulf of Maine. This focus is the primary subject of this report. Analysis of ancillary MBON data, including bacterial, phytoplankton and microzooplankton composition as well as a full hydrographic analysis will be provided at the end of the broader ISMN MBON award in fall, 2023.

Over the past decade, mean water column temperatures in the Gulf of Maine have been rising rapidly, on the order of 0.12°C/yr. The temperature rise is driven by air-sea thermal interaction causing increased heating at the surface as well as a shift in the dynamic balance between cold Labrador Current and warm Atlantic slope water regulating deep layer temperature. There is evidence for a marked shift in oceanographic conditions around 2010, associated with a landward shift in the position of the Gulf Stream forcing warmer, saltier slope water onto the NW Atlantic shelf and into the Gulf of Maine. This shift appears to have constricted the southward flow of the coastal Nova Scotia Current and shelf-break Labrador Current, sources of supply of the lipid-rich planktonic copepod, *Calanus finmarchicus*, a foundation species of the historic Gulf of Maine subarctic food web. A dramatic ecosystem effect of this shift has been the displacement of summer foraging habitat for North Atlantic right whales from the eastern Gulf of Maine to the Gulf of St. Lawrence due to a substantial reduction in the abundance of *C. finmarchicus*, their primary prey.

To observe changes in the abundance of *C. finmarchicus* and planktonic biodiversity in the western Gulf of Maine, with particular interest in the periods before and after 2010, ISMN-MBON has developed the Calanus Index (CI), showing the seasonal and interannual trend in abundance of late-stage (CIII to CVI) *C. finmarchicus*, which are the energy-rich stages of particular importance to right whales as well as forage fish like herring and sand lance that support Gulf of Maine fisheries. The CI is based on abundance at the WBTS station, for which there is evidence that the CI accurately reflects abundance across the basin, based on comparison with NOAA MARMAP/EcoMon survey data. The CI indicates a decline in abundance of *C. finmarchicus* in late summer through winter that in 2020-2021 was 15-40% of levels observed between 2005-2010, prior to the oceanographic shift. The abundance of *C. finmarchicus* in spring, however, has remained robust since 2010. These seasonal results reflect differences in primary drivers controlling *C. finmarchicus* population dynamics in the Gulf of Maine. Spring abundance results from local reproduction responding to a favorable timing of availability of phytoplankton food. The reduced summer abundance is hypothesized to be under the control of the balance between downstream

advective loss and upstream supply of *C. finmarchicus* from the Maine Coastal Current and adjacent deep waters, associated with the reduction of external supply from slope water sources. Observations of summer abundance of *C. finmarchicus* late stages at the CMTS station show approximately a 30% decline from 2008 to 2021, consistent with the WBTS CI. Data collected in 2022 at both the CMTS and WBTS stations, however, indicate a rebound in *Calanus* abundance. This rebound suggest a recent change in oceanographic conditions affecting supply of *Calanus* into the Gulf of Maine; whether this is a singular annual event or the start of a longer-term increase in *Calanus* abundance awaits future observations.

Observations of the diversity of planktonic copepods, which constitute most of the zooplankton in the catch from the vertically integrated plankton net tows, also indicate a shifting pattern of planktonic diversity since 2010. Species richness in Wilkinson Basin has increased from 12-15 to 16-18 common species, depending on season, between the periods 2005-2010 and 2011-2017. While late summer-fall *C. finmarchicus* abundance has declined, the abundance of smaller copepod species has increased, in some cases by a factor of 2-5. This increase in abundance of smaller species, however, is not sufficient to offset a decline in total zooplankton biomass in late summer through winter, reflecting the decline of the much larger and biomass dominant *Calanus finmarchicus*.

Analysis of chlorophyll *a* profiles at Wilkinson Basin are consistent with these observations of change in zooplankton biodiversity. Not only is the phytoplankton bloom more intense in in the period 2011-2017 compared to 2005-2010, but also phytoplankton biomass is higher in fall and winter, supporting increased reproduction of *C. finmarchicus* in late winter-spring and higher numbers of smaller copepod species.

Continued observing of planktonic biodiversity at the WBTS and CMTS time series stations will provide timely indicators and up-to-date assessment of ecosystem change at the base of the food web, needed to understand and respond to changes in Gulf of Maine ecosystem services.

Bas Kohler/ICES Jour. Mar. Sci.

2 Introduction

This BOEM CA sustains seasonal and long-term observing time series stations in the Maine Coastal Current and in Wilkinson Basin that have been identified by the NERACOOS- Integrated Sentinel Monitoring Network (ISMN) as essential components of an observing strategy for monitoring pelagic ecosystem change in the Gulf of Maine. The Wilkinson Basin Time Series Station (WBTS: 260 m depth), located in the northwest corner of Wilkinson Basin, was initiated in 2005. The Coastal Maine Time Series Station (CMTS: 110 m depth), located in mid-coast Maine at the western margin of the Maine Coastal Current, was initiated in 2008. In 2019, the two time series were integrated into the Gulf of Maine Marine Biodiversity Observation Network (GoM MBON), administered by ISMN. This BOEM CA contributes support for time series sample collection and analysis for the period between 2020 and 2023.

The specific objectives of the research supported by this BOEM CA are:

1. Collect hydrographic and chlorophyll data and zooplankton samples at monthly intervals (WBTS) and during the summer months (CMTS)
2. Enumerate zooplankton samples for *Calanus finmarchicus* abundance and measures of zooplankton biodiversity
3. Prepare and archive data in the ISMN and MBON data portals
4. Analyze, interpret and disseminate through reports, publications and meeting presentations the hydrographic, chlorophyll and zooplankton data with respect to observing change in the Gulf of Maine ecosystem. This is done in conjunction with other components of the ISMN Gulf of Maine MBON receiving support from other federal partners supporting MBON

2.1 NERACOOS, ISMN and MBON: a brief history

2.1.1 The formation of the ISMN

Recognizing significant gaps in observing capability and underachievement in synthesis of overall ecosystem status, The Northeast Regional Association of Coastal Ocean Observing Systems (NERACOOS) and the Northeast Regional Ocean Council (NROC) through their respective Ocean and Coastal Ecosystem Health Committees, initiated in 2012 a joint project to address gaps in the Northeast Region's capability to observe key biotic and abiotic ecosystem variables that are likely impacted by climate forcing (Runge et al. 2012). A series of open regional workshops between 2013-2016 led to the creation of a Science and Implementation Plan for the Integrated Sentinel Monitoring Network (ISMN: www.sentinelmonitoring.org).

Administered by NERACOOS, the ISMN serves as a coordinating regional infrastructure. Its goals are to collect observing data where there are gaps for key ecosystem variables, facilitate cost-efficient regional measurement and integrated interpretation of ecosystem change, and serve as a portal for access to the multiple regional observing datasets. Observational goals include broad monitoring for biodiversity change in ways that may or may not be predictable, but also monitoring of sentinels: key ecosystem variables for which there is mechanistic understanding of ecosystem function and impact from environmental change.

2.1.2 The ISMN fixed time series stations WBTS and CMTS

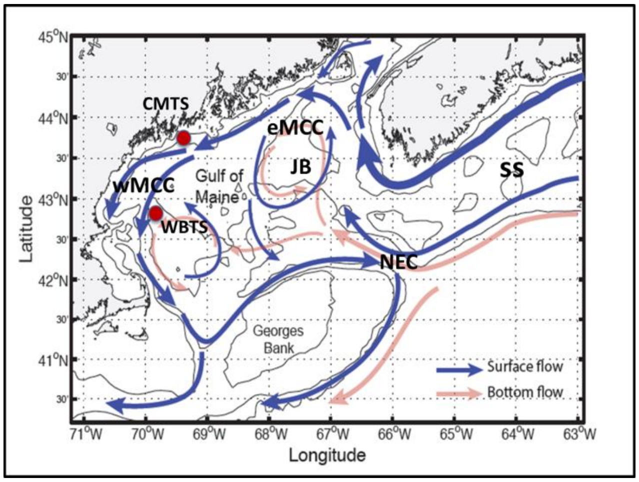

Figure 1. The GoM Time Series Stations
Blue and red arrows: surface and deep currents. eMCC and wMCC: eastern and western branches of the Maine Coastal Current. JB: Jordan Basin; NEC: Northeast Channel. Approximate locations of Coastal Maine Time Series station (CMTS: diamond) and Wilkinson Basin Time Series station (star). Figure redrawn from Beardsley et al. (1997), courtesy of R.Ji and C. Chen.

The ISMN identified monthly, time series observations of plankton biodiversity as a crucial gap for recording change in the GoM marine ecosystem, not only for understanding phenological shifts (Ji et al. 2010) but also for expanded observation of long-term diversity changes across trophic levels in the plankton. Two established time series stations, the Coastal Maine Time Series (CMTS) station (established 2008) located in mid-coast Maine at the western edge of the Maine Coastal Current and the Wilkinson Basin Time Series (WBTS) station (established 2005) located in the deep western GoM basin (Figure 1) were favored because of the existing time series data, the proximity to coastal ports allowing single-day missions to collect samples and the strategic importance of the two locations for understanding the population dynamics of the planktonic copepod, *Calanus finmarchicus*, a key sentinel ecosystem variable. The Maine Coastal Current (Figure 1) is the primary supply route of production to the western and southern Gulf of Maine, including the Stellwagen National Marine Sanctuary, Cape Cod Bay, and Georges Bank (Runge et al. 2015). Wilkinson Basin is the main overwintering habitat of *C. finmarchicus* in the western GoM and the major source and key node for the western GoM lipidscape.

These stations were maintained by PIs at the University of Maine and University of New Hampshire with sampling (nominally monthly, but with gaps due to funding instability) for hydrography and mesozooplankton (including ichthyoplankton at CMTS) and hydrography until all funding sources expired in 2017.

2.1.3 The Marine Biodiversity Observation Network in the Gulf of Maine

In Fall, 2019, the ISMN was awarded funding from this BOEM CA and from other federal sources to establish the Marine Biodiversity Observation Network (MBON) in the Gulf of Maine. This BOEM CA supported plankton and hydrographic sample collection at CMTS and WBTS through 2022. The MBON sampling protocol includes not only mesozooplankton diversity and abundance and standard hydrographic measurements (supported directly by BOEM), but also bacteria, microzooplankton and phytoplankton abundance and diversity, the analysis of which is funded by other federal sources supporting the National MBON. The suite of monthly observations at CMTS and WBTS combines traditional with new approaches to biodiversity assessment, with the goal of observing seasonal and long-term changes in planktonic community structure across planktonic trophic levels from bacteria to the mesozooplankton.

As part of the GoM MBON award, the BOEM CA has also supported engagement of regional experts to integrate the time series observations at CMTS and WBTS with NOAA plankton data and visual and acoustic sightings into statistical and dynamic models predicting the foraging patterns of the North Atlantic right whale (e.g. Ross et al. 2023). This predictive tool can be used in management decisions related to regulation of shipping lanes and entanglement in fishing gear. Documentation of shifting planktonic biodiversity and the role of *Calanus* will also have applications for understanding the future GoM ecosystem structure and function.

2.2 Background: The Gulf of Maine pelagic ecosystem

2.2.1 Changing oceanographic conditions in the Gulf of Maine

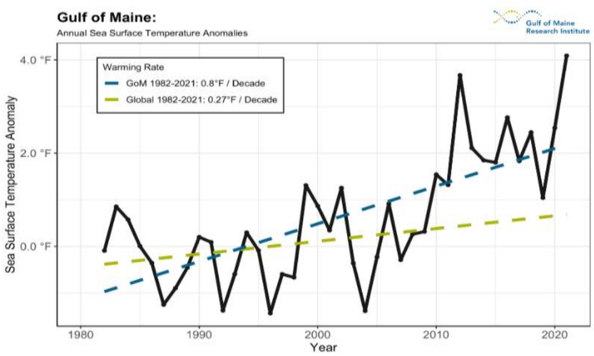

Figure 2. Annual sea surface temperature anomalies (°F) for the Gulf of Maine between 1982-2021. Dashed lines show trends for the GoM and for the global ocean. GMRI (2022)

The Gulf of Maine (GoM) lies at the epicenter of the most rapid warming trend in U.S. coastal waters. Over the past four decades, surface temperatures have been warming at approximately 0.04°C/yr, more than four times the century-long average for the region (Shearman and Lenz 2010), considerably faster than other U.S. coastal regions (Pershing et al. 2015) and the global average (Fig. 2). The temperature rise since about 2005 has been even faster, 0.12°C/yr, about 10 times faster than the century average and occurring at all depths (Seidov et al. 2021). Analysis of SST anomalies by month and year indicate a clear pattern of increased temperatures since 2010, especially in summer through winter (Fig. 3).

The physical oceanographic drivers of the recent decadal warming trend in the Gulf of Maine are complex, involving thermal air-sea interactions in the surface layer, incursion of warm slope water, particularly near the Tail of the Grand Banks (TGB), squeezing the Slope Water area and hindering cold Labrador Current flow to the Gulf of Maine (Fig. 4), and generation of warm eddies at the TGB that propagate from east to west along the Canadian Northeast Shelf Break (Seidov et al. 2021; Neto et al. 2021; Brickman et al. 2018; Thibodeau et al. 2018). Hydrographic observations indicate that the primary driver is a northward shift in the position of the Gulf Stream, migrating closer to the TGB and reducing westward Labrador Current transport since about 2008 (Neto et al. 2021; Seidov et al. 2021). These observations are consistent with observations of a recent weakening of the Atlantic Meridional Overturning Circulation (AMOC: Caesar et al. 2021) and high-resolution climate ocean modeling suggesting that CO_2 increase driving warmer Arctic winters reducing deep convective flow in the Labrador Sea and the subpolar Northeast Atlantic (Saba et al. 2016; Thornalley et al. 2018). The recent warming in the Gulf of Maine since 2010 has been characterized as a climate-driven regime shift in the Gulf of Maine/western Scotian Shelf (Meyer-Gutbrod et al. 2021), although it is still not clear whether the present Labrador Sea-Gulf Stream interaction will continue over the longer

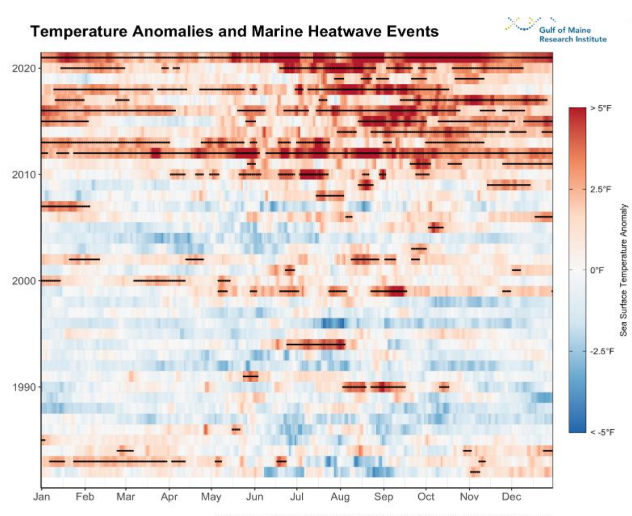

Figure 3. Mean GoM SST anomalies (in °F) by month for the years 1982-2021
Color shows magnitude of the anomaly, from negative (blue) to positive (red). Black lines show marine heatwaves. Figure from the Gulf of Maine Research Institute (2022): https://gmri.org/stories/warming-21

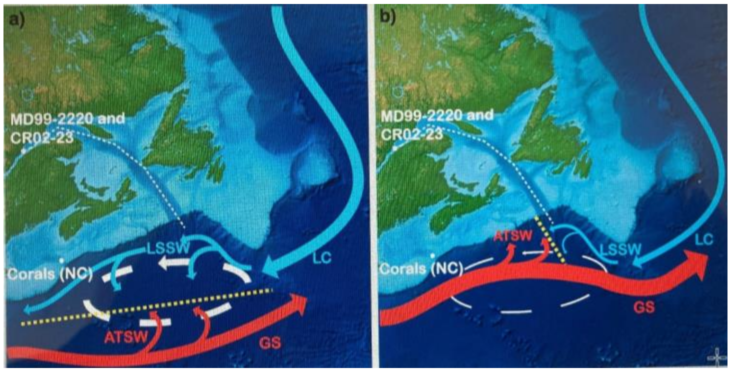

Figure 4. Schematic of circulation pattern off the Northwest Atlantic Canadian Shelf east of the Gulf of Maine.
Left panel: Historically, the westward flowing Gulf Stream (GS) is separated from the eastward-flowing subsurface Labrador Current (LSSW) by a slope water gyre (white arrows). Right panel: Observations indicate that recently, a northward shift in the Gulf Stream has intruded closer to the shelf break, squeezing off flow from the subsurface LSSW resulting in transport of warmer and saltier water into the Gulf of Maine via the Gulf's deep Northeast Channel. (From Thibodeau et al. 2018)

term (Seidov et al. 2021). This uncertainty underscores the value of timely assessment of the Gulf of Maine planktonic ecosystem afforded by routine monitoring at the CMTS and WBTS ISMN-MBON stations.

2.2.2 The Gulf of Maine food web and the ecosystem role of the planktonic copepod, *Calanus finmarchicus*

The GoM ecosystem supports the most valuable U.S. fishery (lobster, with a landed value of > $669 million in 2016: NOAA fisheries statistics) and one of the most valuable U.S. fishing seaports (New Bedford: $327 million in 2016: Bonner 2017). Evidence is mounting that the recent warming trend is affecting ecosystem structure and services, for example, the closure of the northern shrimp fishery (Sharp 2018), the slow recovery of Atlantic cod (Pershing et al. 2015) and the highly publicized decline in recovery of the population of endangered North Atlantic right whales (Kraus et al.2016; Record et al 2019; Meyer-Gutbrod et al. 2021).

The GoM is presently situated at the southern margin of the North Atlantic Subarctic Biome (Fig. 5). This cold-water ecosystem is characterized by seasonal periods of high phytoplankton productivity, an abundance of large-bodied, diapausing calanoid copepods, forage fish (herring, sandlance, capelin in the north and crustacean euphausids) that feed on the lipid-rich calanoid copepods. Higher trophic levels (cod and other groundfish, tuna, seabirds, marine mammals) prey on the forage fish or, in the case of the North Atlantic right whale, the lipid-rich copepods directly (Pershing and Stamieskin 2020).

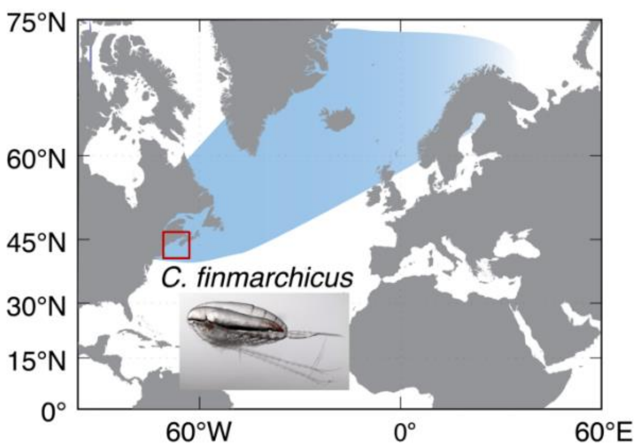

Figure 5. The subarctic range of the planktonic copepod, *Calanus finmarchicus*
Red square shows the Gulf of Maine. Inset: *C. finmarchicus* stage CV, showing lipid rich oil sac.

The large-bodied diapausing copepods are represented in the GoM almost entirely by *Calanus finmarchicus*. This one species has historically been remarkably successful in this region, constituting 75-90% of the mesozooplankton biomass (Fig. 6). Energy-rich storage lipids typically constitute more than half of the body weight of the preadult stage CV that is abundant in early summer through fall. As the predominant food source, principally through its energy-rich lipids, for planktivorous forage fish, including coastal herring, sandlance and mackerel, the carnivorous euphausid, *Meganyctiphanes norvegica*, (another important food source for forage fish) and the endangered North Atlantic right whale, *C. finmarchicus* serves as a foundation species in the GoM pelagic food web (Johnson et al. 2011) (Fig. 7). This role for the species in the western Gulf of Maine has been recognized since the earliest oceanographic surveys (Bigelow 1924).

Statistical habitat models (Reygondeau and Beaugrand 2011; Grieve et al. 2017) predict dramatic declines of *C. finmarchicus* in the next few decades. Recent individual-based life cycle and coupled physical biological modeling of *C. finmarchicus* (Maps et al. 2012; Runge et al. 2015; Ji et al. 2017; Record et al. 2019) has revealed advective pathways supplying *Calanus* to the western and eastern Gulf of Maine. The diapausing stock in the western GoM, including Stellwagen and Georges Banks, is supplied in summer through October by *Calanus* that reproduce and grow in the relatively nutrient and phytoplankton rich Maine Coastal Current, a mechanism known as the CAST (Coastal Amplification of Supply and Transport) hypothesis (Ji et al. 2017). Because of the amplification (due in part by the high fecundity potential of *C. finmarchicus* females) in the relatively cool Maine Coastal Current, effects of warming on the western Gulf of Maine abundance have been mitigated (Runge et al. 2015). Moreover, the recent early availability of phytoplankton (measured as chlorophyll a) in late winter/early spring in the western GoM has provided a favorable match with emergence of *Calanus* from diapause, resulting in high egg production and a strong spring cohort that supplies the southern GoM in spring and early summer (Record et al. 2019; results updated here in this report). The strong spring cohort and abundance of other copepod species, also responding to the early primary production, are consistent with the high number of foraging NARW present in Cape Cod Bay during winter and spring.

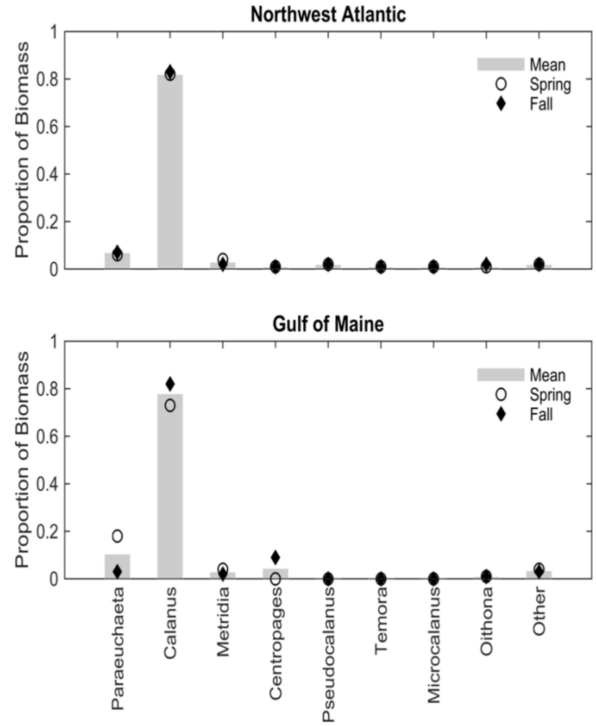

Figure 6. Proportion of total biomass of planktonic copepods, organized by decreasing body size.
Data for Northwest Atlantic from Canadian Atlantic Zone Monitoring Program (Courtesy of C. Johnson, BIO). Data for the GoM from analysis of WBTS samples (2005-2012). In the GoM, *C. finmarchicus* represents >90% of the total *Calanus* species' biomass. Planktonic copepods constitute >94% of the estimated total mesozooplankton biomass in the GoM basin.

In the eastern Gulf of Maine, a different oceanographic pathway prevails. Since about 2010, deep water temperatures and salinity have increased, reflecting a shift in the main advective pathway into the eastern Gulf of Maine, from the cold, *Calanus* rich Nova Scotia Shelf current to warm, *Calanus*-poor transport of Atlantic Temperate Slope Water into the eastern Gulf through the deep Northeast Channel. The result has been a substantial, order of magnitude decrease in *C. finmarchicus* abundance, starting in about 2010.

A consequence in the reduction of *C. finmarchicus* abundance has been a dramatic decline in presence of NARW in the eastern Gulf of Maine and Bay of Fundy, their traditional late summer/fall feeding grounds (Record et al. 2019). Instead, NARW's have been bypassing the Gulf of Maine in substantial numbers to feed in the Gulf of St. Lawrence, where a large number have been found injured or dead due to fishing gear entanglements and ship strikes. The evidence points to large scale circulation changes driving the recent warming trend linking climate-driven shifts in the AMOC and Gulf Stream position to the decline of *Calanus* and NARW's in the eastern Gulf of Maine. This shift in foraging habitat was not anticipated and poses a management challenge to conserve the remaining NARW's from mortality due to entanglement and ship strikes where they are not expected.

Based on this mechanistic understanding of the oceanographic and production pathways maintaining *C. finmarchicus* in the GoM, the future sustainability of the species in the region is in question. The CAST mechanism may not be capable of mitigating the reduction of supply of *Calanus* from the eastern GoM. Moreover, a favorable timing of winter phytoplankton availability in relation to emergence from diapause in the deep parts of the western GoM is not assured. Observations at the ISMN-MBON time series stations serve to provide up-to-date information about changes occurring in the planktonic ecosystem.

2.2.3 The value of ISMN MBON time series observing

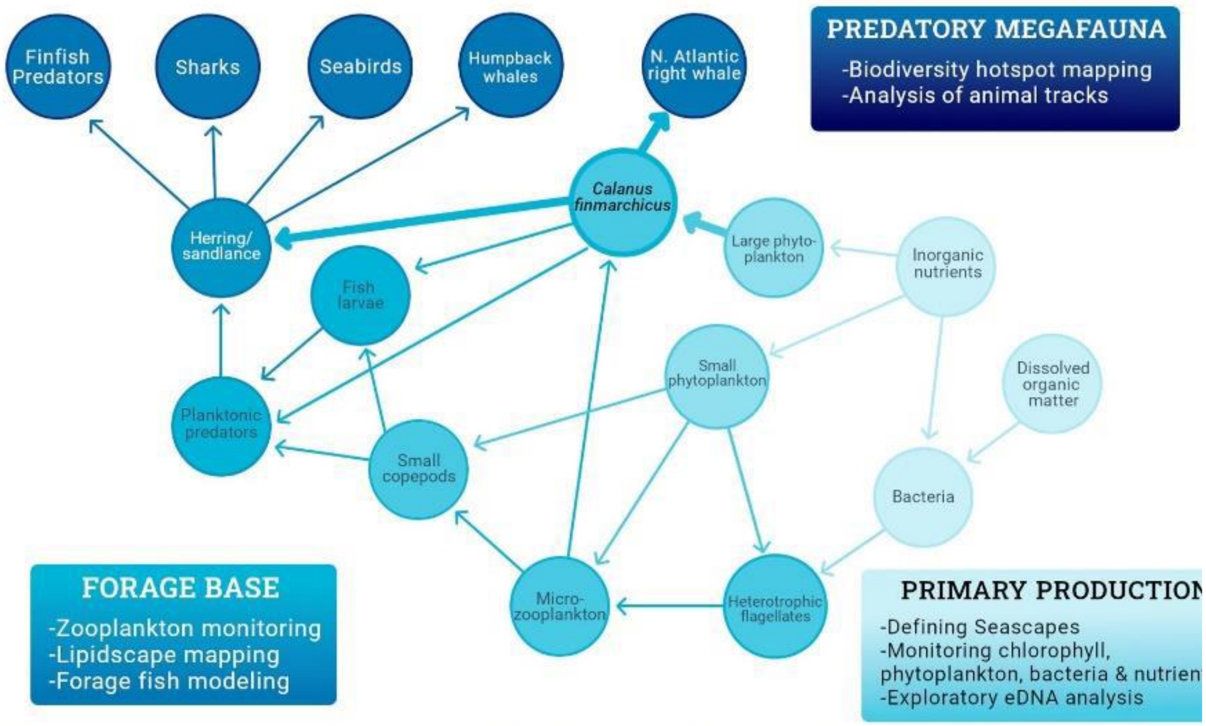

Figure 7. Key components of the Gulf of Maine pelagic food web.
Heavy arrows illustrate the primary lipid pathway.

The ISMN-MBON project identifies *C. finmarchicus* as a sentinel variable indicating the health of the Gulf of Maine as we know it historically. The sampling program at WBTS and CMTS are designed to provide information on the seasonal and longer-term status of the species. In addition to measurements of abundance of *C. finmarchicus*, the ISMN-MBON project collects data to assess whether and how the planktonic ecosystem as a whole is changing. Oceanographic conditions and planktonic biodiversity variables are measured to assess status of the microplankton community supporting *C. finmarchicus* and other zooplankton and the diversity of the mesozooplankton assemblage is followed, with particular focus on how diversity change would affect ecosystem function. This continued observation of the western Gulf of Maine plankton diversity provides timely indicators and ecosystem change needed to understand and respond to changes in the Gulf of Maine’s ecosystem services.

3 Methods

Sampling at the WBTS and CMTS stations follow as a guideline the protocols established by the Atlantic Zone Monitoring Program (AZMP) established by Fisheries and Oceans Canada (Mitchell et al. 2002). All samples were taken during daytime hours, typically mid-morning to mid-afternoon.

3.1 Environmental data

3.1.1 Wilkinson Basin Time Series (WBTS) Station

Location: Gulf of Maine: Wilkinson Basin. Latitude: 42°51.7′; Longitude: -69°51.8′. Average station depth: 257 m

Start and duration of sampling: 6 December, 2004-present. There were 106 one-day cruises during which CTD casts were conducted between 6 December, 2004 and 19 July, 2017. Net tow sample were also collected on 80 of those days. Sampling recommenced at the station in January, 2020 as part of the NERACOOS ISMN-MBON Gulf of Maine project.

Funding Support: Portions of the time series collection and analysis were supported by NSF awards OCE-1041081, OCE-1235920 and OCE-1459087, an award from the Maine Department of Marine Resources (2010-2012) and State Wildlife Grant # ME F14AP00073 from the U.S. Fish and Wildlife Service (2013-2016). ISMN-MBON sampling through 2023 has been supported by BOEM Cooperative Agreement M19AC00022 to the University of Maine and MBON award NA19NOS0120197 to NERACOOS.

Wilkinson Basin is one of the three major basins where depths exceed 200 meters in the Gulf of Maine. The Wilkinson Basin Time Series station (WBTS, also known as WB-7) is located approximately 38 nautical miles from New Castle, NH, home port of the University of New Hampshire research vessel, R/V Gulf Challenger.

The R/V Gulf Challenger water sampling system comprises a Sea-Bird Electronics (SBE) 25Plus CTD, an SBE-55 Sampling Rosette with six four-liter Niskin bottles, a dedicated Hawboldt Industries SPR 1424/S Science winch, and a SBE-33 real-time monitoring and sampling deck unit. The system provides high resolution vertical profiling of hydrographic properties (e.g. conductivity, salinity, temperature), physiochemical properties (e.g. Photosynthetically Active Radiation (PAR)), and surrogates for biological and geological processes (e.g. dissolved oxygen, chlorophyll-a fluorescence and beam transmittance). The raw CTD data and bottle trips are acquired by SBE Seasave on a Windows 7 workstation and are processed from hex files to cnv files. Post cruise data processing has been completed on a Windows 7 machine running SEABIRD SBE DATA Processing version 7.22.5 At most stations, Niskin bottles are used to capture water samples at depths of 2, 10, 20 and 40 meters or, since 2020, 0 and 50 meters as well as the depth of the chlorophyll maximum, determined by inspection of the fluorescence profile at the time of the cruise. To measure chlorophyll a concentration, duplicate, 100 mL or 500-550 mL subsamples are collected from Nisken bottles at each depth. Water is filtered immediately on the vessel using glass fiber filters (GF/F) and polycarbonate membrane filters with pore sizes of 0.7 µm and 0.1µm. Chlorophyll-a concentrations are calculated were using equations in Strickland and Parsons (1972). Prior to 2014, IOP profilers calibrated annually were used to measure water column stimulated fluorescence. After 2014, the nominal chlorophyll-a readings from stimulated fluorescence measured with a Wetlabs Wetstar Chorophyll Fluorometer S/N WSS-164 are corrected with chlorophyll concentrations measured from bottle samples.

3.1.2 Coastal Maine Series (CMTS) Station

Location: Mid-coast Gulf of Maine, 8km offshore of Damariscotta Estuary at the western margin of the Maine Coastal Current. Lat.: 43°44.8′ N; Lon: 69° 30.1′ W. Station depth: 105-110 m.

Start and duration of sampling: 15 April, 2008– present. The mesozooplankton time series and associated environmental data commenced on 15 April, 2008. Between 15 April, 2008 and 12 July, 2017 there were 124 one-day cruises. Sampling was sparse between 2017-2019 due to lack of funding. Sampling recommenced at the station in 2020 as part of the NERACOOS ISMN-MBON Gulf of Maine project.

Funding Support. Portions of the time series collection and analysis were supported by NSF awards OCE-1041081, OCE-1235920 and OCE-1459087, an award from the Maine Department of Marine Resources (2010-2012) and State Wildlife Grant # ME F14AP00073 from the U.S. Fish and Wildlife Service (2013-2016). ISMN-MBON sampling through 2023 has been supported by BOEM Cooperative Agreement M19AC00022 to the University of Maine and MBON award NA19NOS0120197 to NERACOOS.

The Coastal Maine Time Series Station (CMTS, also known as DMC-2) is located approximately five nautical miles offshore of the mouth of the Damariscotta Estuary in mid-coast Maine (Fig. 1). Visits to the station were conducted at a semi-monthly to monthly frequency between April and October and less frequently between November and March. The collection, enumeration and data processing of samples collected was performed by Rebecca J Jones between 2008-2013 and by Cameron R.S. Thompson between 2013-2017. Since 2020, sampling has been conducted between mid-May and September by Jeffrey Runge and Sean O'Neill and *Calanus* stage-specific abundance enumerated by J. Runge.

Between 2008-2012, a SeaBird 19Plus conductivity-temperature-depth meter (CTD) was usually deployed at every station. Starting in 2013, the R/V Ira C SBE25plus Sealogger has been deployed. CTD data were processed with the SeaBird Data Processing software and then binned to 1-m increments. Calibration dates were 27 Jan 2006 and 23 May 2010 for the Seabird 19Plus and in March or April of 2012, 2015 and 2017 for the SBE25plus.

3.2 Mesozooplankton

To measure zooplankton abundance and biomass, two plankton net tows are made using a 0.75 meter diameter single ring (at CMTS) or a SEA-GEAR Model 9600 twin-ring 200µm mesh net (at WBTS). The nets are towed vertically at approx. 40m/min starting at 5 meters from the bottom. The samples are preserved in 4% buffered formaldehyde. For the dual ring casts, a third sample is sometimes preserved in 95%, denatured ethanol and on several occasions a fourth sample has been kept live, diluted with sea water and distributed into 3.7 L plastic containers, and placed in a cooler until transport back to the lab for live image analysis.

The zooplankton samples fixed in formaldehyde are further processed for identification and enumeration of species. The focus is on the planktonic copepod, *Calanus finmarchicus*, thus there are more samples processed for *Calanus finmarchicus* and their development stages are also determined. Samples are split in half with a Folsom Splitter. Half of the sample is designated for measurement of total zooplankton biomass. This sample split is filtered onto one or more pre-weighed glass fiber filters, each filter rinsed with 100 ml of tap water, dried in an oven 65°C for 24-48 h and then collectively weighed on a precision balance. The other half of the sample is drained of formaldehyde solution on a fine mesh screen, the contents of which are then placed in a 4l beaker containing a known quantity of filtered seawater (typically 2500-3000 ml). Subsamples with either a Hensen-Stempel pipette or a turkey baster emptied into graduated cylinder are taken while stirring the plankton with flat paddle. Multiple subsamples were taken to ensure at least 200 copepods and at least 50 *Calanus* copepodid stages are enumerated. Biomass (g dry weight m^{-2}) and abundance (number of individuals m^{-2}) are calculated by dividing the sample measurement (taking into account split and aliquot of subsamples) by the volume filtered by the vertically integrated net (net depth * 0.4418), then multiplying by the water column depth sampled by the net (i.e. the net depth). Net volume filtered was also determined by a General Oceanics flowmeter installed in the mouth of the net, but the geometrically determined volumes were chosen as the standard because flowmeter data was not available for every cast.

4 Results

This section presents results from environmental (temperature and salinity) and zooplankton measurements collected at the WBTS and CMTS stations. Samples for microheterotrophs, phytoplankton and bacteria abundance and composition were also taken during the time series cruises as part of the MBON award but not part of this BOEM CA. These data will be reported elsewhere.

The zooplankton, hydrographic and chlorophyll-a time series started in 2005 at WBTS and in 2008 (without chlorophyll a) at CMTS. The presentation of results at WBTS divides the data into the period prior to 2010, the generally acknowledged year of a hydrographic regime shift in the Gulf of Maine (Meyer-Gutbrod et al. 2021) and after 2010. The WBTS station was only visited once, in July, in 2010, so data from this year contributes little to the climatology of the 2004-2010 period. The cumulative number of WBTS sampling dates in each month of the two periods is shown in Figure 8.

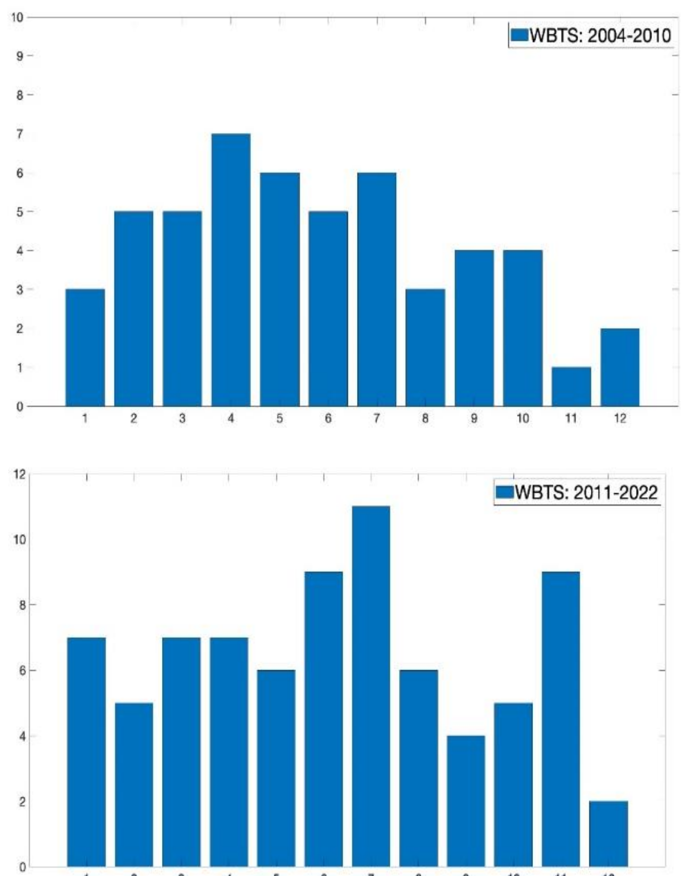

Figure 8. Cumulative number of samples collected each month at WBTS (hydrography, zooplankton and chlorophyll) Top panel: 2004-2010. Bottom panel: 2011-2022

4.1 Environmental variables: Temperature and Salinity

Temperature and salinity profile at WBTS have been processed at the University of New Hampshire for the entire time series. Analysis of the differences in temperature and salinity before (2004-2010) and in the decade after (2011-2021) is shown in Fig. 9. Consistent with observations of SST and water column mean GoM temperature trends (Seidov et al. 2021; GMRI 2022), water column temperatures at the WBTS station in the period since 2010 have been generally higher, by 1-3°C, particularly in the surface 75m in summer. The temperature rise in deep waters (>100m) has been more modest, on the order of 1°C. The temperature anomaly for the month of January rises to about 2°C, but the low number of

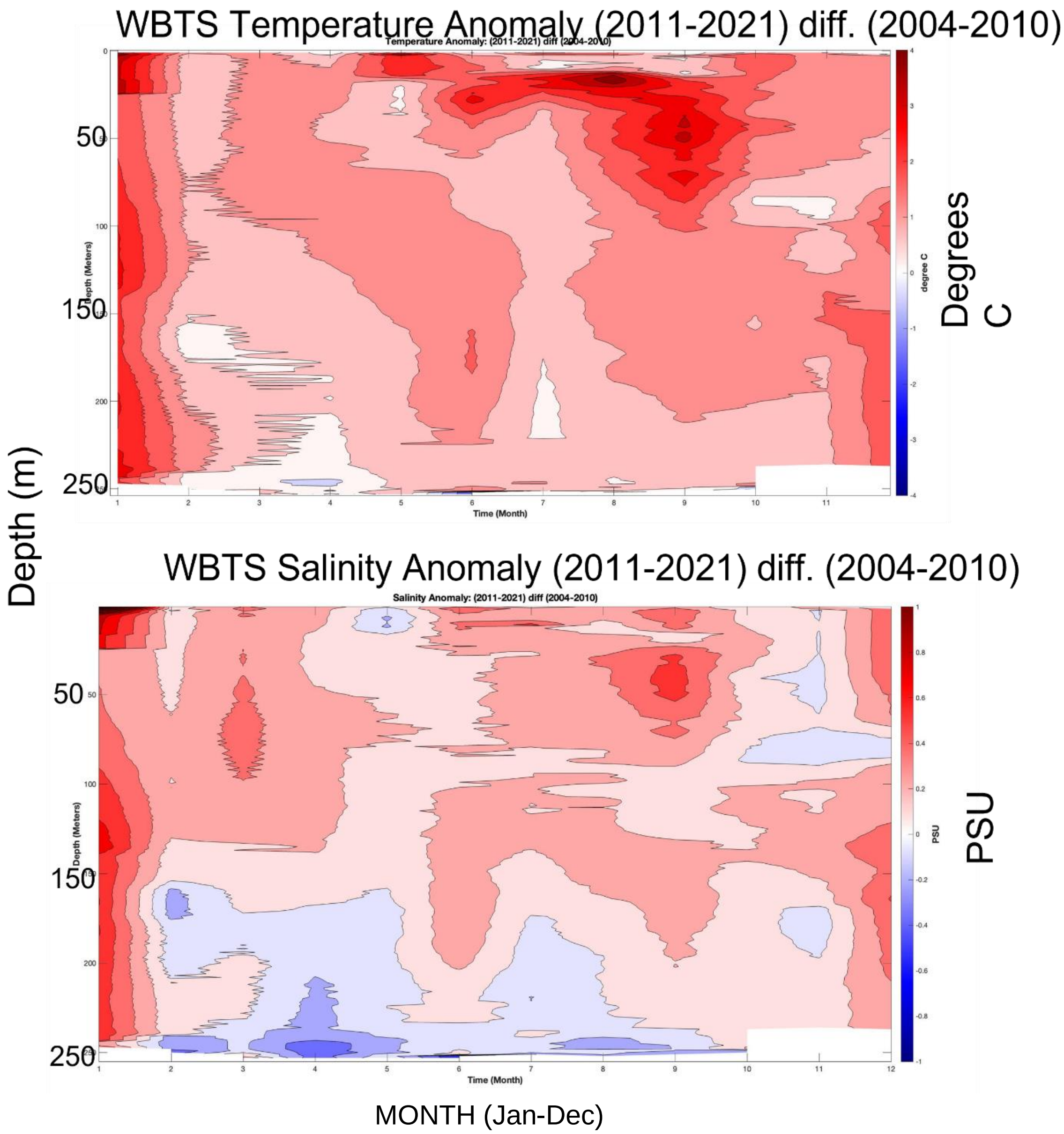

Figure 9. Monthly temperature (top panel) and salinity (bottom panel) anomalies
The difference between the 2011-2021 and 2004-2010 periods at WBTS. Temperature color scale from -4 to 4 °C; Salinity color scale from -1 to 1.

observations prior, especially prior to 2010, does not lend certainty that January is different from other months. Analysis of seasonal Wilkinson Basin bottom water temperature anomalies (Fig. 10) using NOAA MARMAP/EcoMon data shows warmer water by up to 2°C in 2011-14, but a weak or non-existent signal between 2015-2017 (more recent data not yet available). Salinity in Wilkinson Basin was also generally higher, by 0.2 to 0.8 units, but for bottom water >200m, which was generally lower by 0.1-0.4 units (Figs. 9 and 10) for the period 2011-2021.

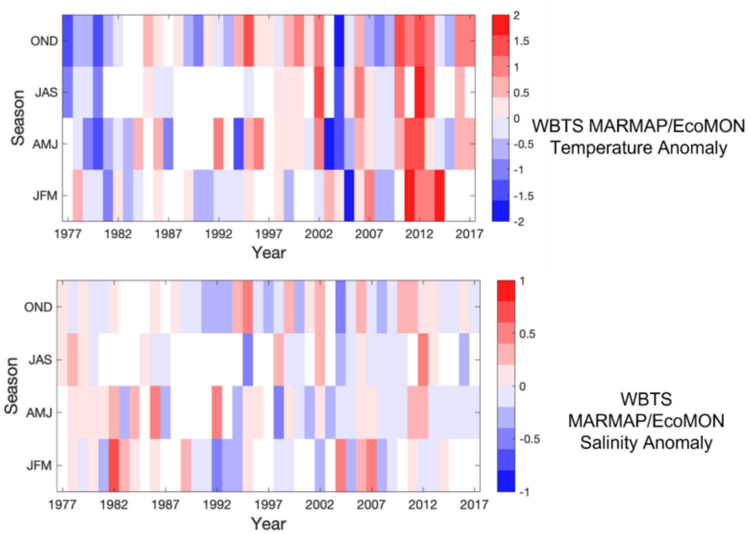

Figure 10. Monthly temperature (top panel) and salinity (bottom panel) anomalies in NOAA data
The difference between the 2011-2021 and 2004-2010 periods at WBTS. Temperature color scale from -4 to 4 °C; Salinity color scale from -1 to 1.

Insight into the interannual variation in subsurface temperature and years is presented in Figs 11-14. Mid depth (60-80 m) temperatures in the period between January and March (Fig. 11) were highest in 2011-13, then declined to temperatures closer to 2004-2010 values in 2014-15 and 2019, rising again in 2020-22. During the period between July and September, mid-depth temperatures (Fig. 12) were highest in 2012, then declined to temperatures closer to 2004-2010 values, rising again in 2020-22. January to March bottom water (180-220 m) temperatures rose by about 1.5°C in 2011-13, then declined to values somewhat lower than 2004-2010, rising again in 2017. July to September bottom water temperatures were higher by about 1-1.5°C in 2010 and 2012, then declined, rising again in 2017 to 2010-2012 levels in 2020-2022.

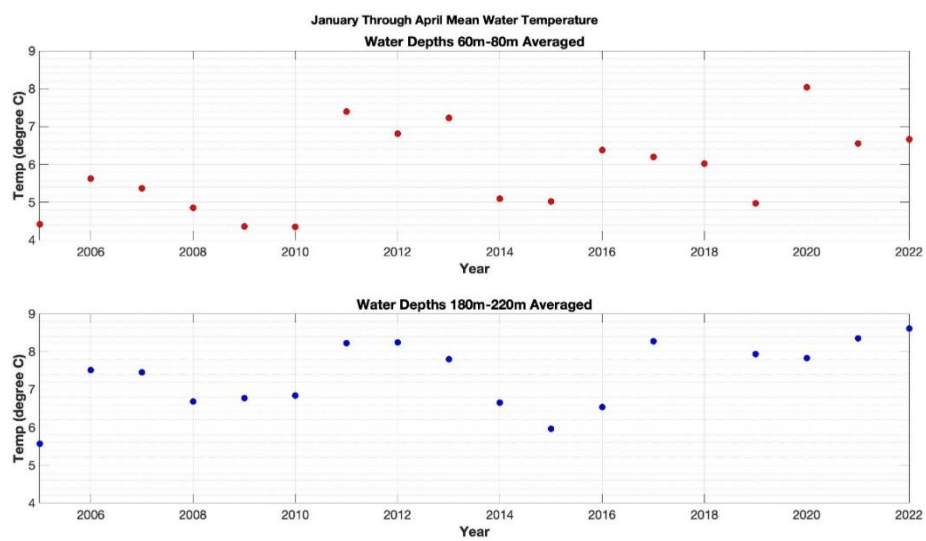

Figure 11. Mean water temperature (°C) in Jan.-Mar at the WBTS station
2005 – 2022. Top panel: 60-80 m. Bottom panel: 180-220 m .

Mid-depth and bottom layer salinities (Figs. 13-14) showed less of a trend through the time series, as reflected by the anomaly plot in Fig. 9. Bottom water salinities were high in 2011-13, but then declined between 2014-17 to slightly lower salinities than the 2004-2010 period.

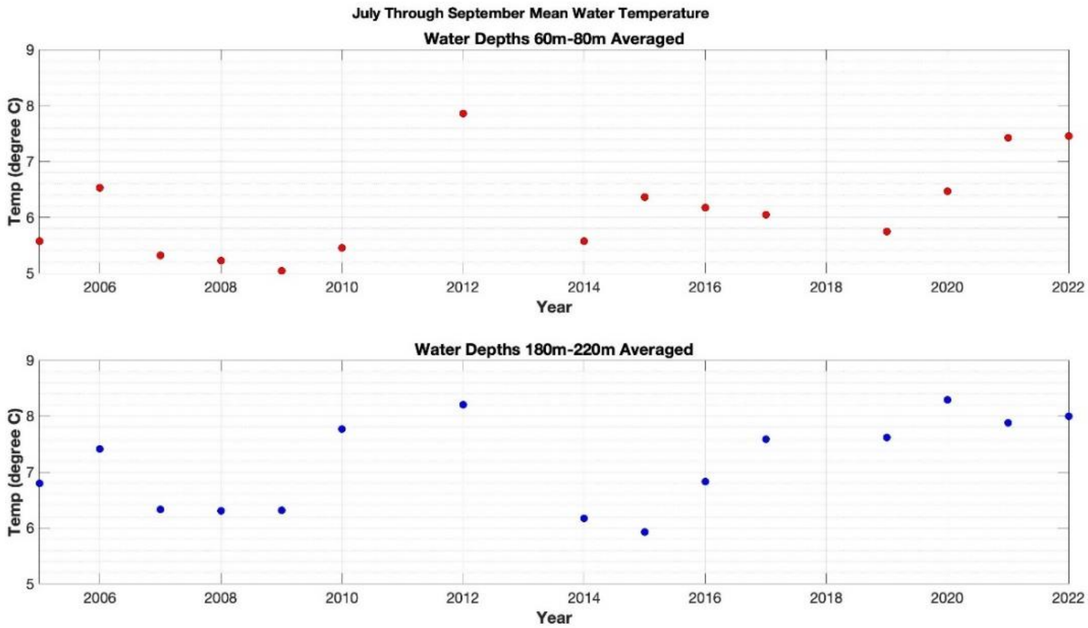

Figure 12. Mean water temperature (°C) in Jul-Sep at the WBTS station
2005- 2022 Top panel: 60-80 m. Bottom panel: 180-220 m

The dynamics controlling water column temperature and salinity in Wilkinson Basin are complex, involving transport and mixing of warm slope water, Labrador slope water and Scotian Shelf water. The analysis of the oceanographic influences on Wilkinson Basin is ongoing.

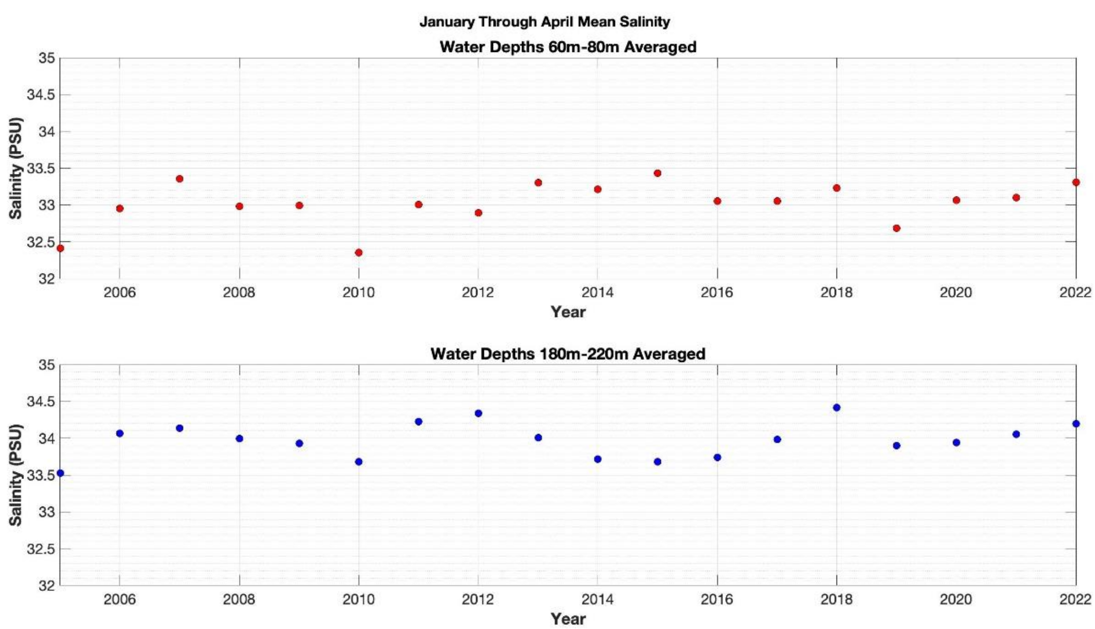

Figure 13. Mean salinity for January-March at the WBTS station
2005- 2022: Top panel: 60-80 m. Bottom panel: 180-220 m

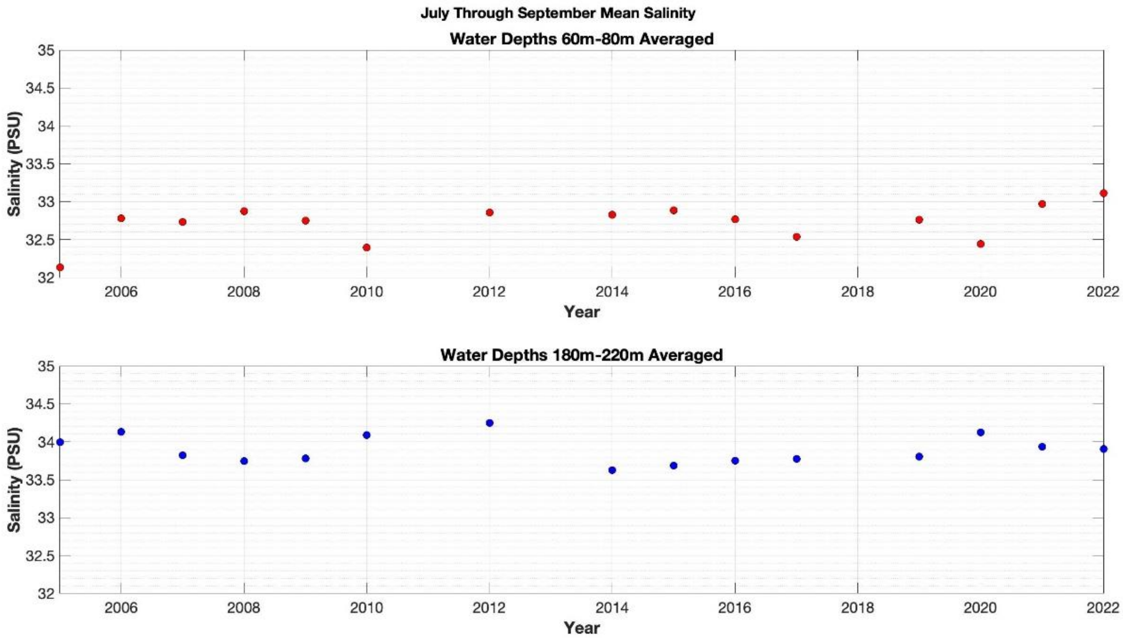

Figure 14. Mean salinity for July-September at the WBTS station
2005- 2022 Top panel: 60-80 m. Bottom panel: 180-220 m

4.2 Zooplankton

The primary focus of this BOEM Cooperative Agreement is assessment of the status of the zooplankton community in the western Gulf of Maine, in particular the status of the planktonic copepod, *Calanus finmarchicus,* the primary prey for summer foraging North Atlantic right whales and a sentinel indicator of health of the subarctic Gulf of Maine pelagic ecosystems and its associated ecosystem services.

In the results section here, we present the most updated Calanus Index for the western Gulf of Maine, compiling data collected at the WBTS and CMTS stations. The WBTS assessment is supported by results from CMTS, showing a similar reduction of summer abundance in the Maine Coastal Current. Observations of seasonal total zooplankton biomass captured in the vertically integrated net tows are consistent with this trend. Observations of spring and fall copepod biodiversity indicate a shifting community structure since 2010, with several smaller species increasing markedly in abundance relative to 2004-2010.

4.2.1 Seasonality in the status of *Calanus finmarchicus* in the western GoM

In Fig. 15, the seasonal pattern of *Calanus* abundance measured at the WBTS station over the entire time series is presented in comparison with the seasonal climatology of abundance in Wilkinson Basin from the NOAA EcoMon-MARMAP program between 1977-2019. To standardize with the NOAA data, which were obtained from 333-µm mesh bongo nets towed from 200-0m, the fixed-station abundances, obtained from 200-µm vertical tows from near bottom to the surface, are expressed as number m-3 and comprise stages CIII-CVI, which are considered to be the stages reliably captured with the larger mesh size of the bongo net.

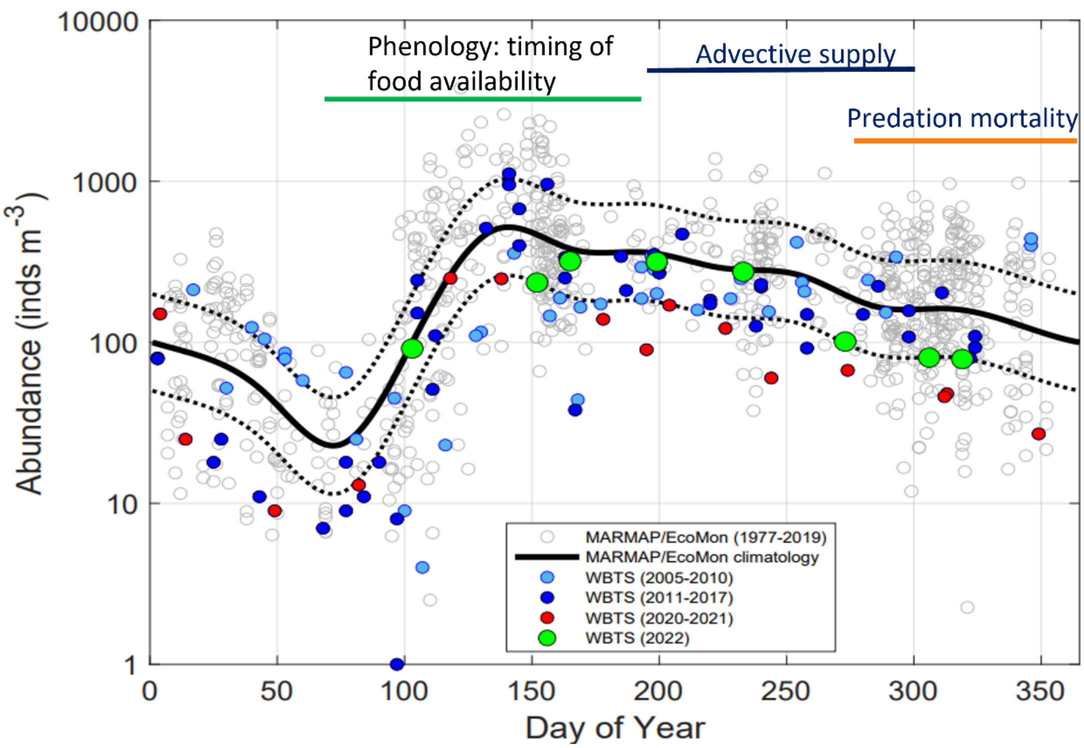

Figure 15. Calanus Index Phenology

Pattern of seasonal abundance (number m^{-3}: note log scale) of *C. finmarchicus* copepodid stages CIII-CVI at the WBTS station. X-axis represents time of year, from 1 January (yearday 0) to 31 December (yearday 365). Background gray circles show MARMAP/EcoMon abundance data in Wilkinson Basin between 1977-2017. Solid black line shows the seasonal pattern in mean abundance from the MARMAP/EcoMon data; dotted lines show 2x (top) and ½ (bottom) of the mean abundance. Light blue points: WBTS station data collected between 2005-2010. Dark blue points: WBTS station data collected between 2011-2017. Red points: WBTS data collected in 2020 and 2021. Green points: WBTS station data collected in 2022. WBTS was not sampled between 2017-2019 (funding hiatus). Colored horizontal lines show conceptual model of seasonally variable predominant drivers. Predominant drivers in winter (Jan-Mar: days 1-100) suggested to be a combination of predation mortality and advective loss.

The results from both observational programs show a seasonal low abundance of *C. finmarchicus* (mostly stage CV and adult females) in January-March, a vernal increase in March-mid-July (mostly younger stages arising from winter-spring reproduction) and a declining abundance (mostly stage CV) in later summer through winter. The WBTS station data correspond well to the seasonal pattern and magnitude of abundance found by the NOAA MARMAP/EcoMon program, giving credence to the fixed station data as an indicator of abundance across Wilkinson Basin, also supported by a study of *Calanus* abundance in Wilkinson Basin reported by Runge et al. (2015).

In their investigation of the temporal and spatial coherence of *C. finmarchicus* abundance in the NOAA MARMAP/EcoMon Gulf of Maine dataset, Ji et al. (2021) concluded that the population dynamics of *C. finmarchicus* in the Gulf of Maine are controlled by seasonally variable drivers. Their analysis showed little direct connection between spring abundance and either the preceding or subsequent abundance of the fall-winter stock. An assessment of the status of *C. finmarchicus* in the western Gulf of Maine must therefore consider the seasonality of drivers, and is best divided into spring-early summer, late summer-early fall, and late fall-winter periods, corresponding to the predominant roles of their associated drivers. A conceptual depiction of the prominent driver for each of these seasonal periods is shown in Figure 15.

The spring increase in *C. finmarchicus* abundance is primarily a function of local reproduction and growth supported by variable timing of the spring bloom and phytoplankton food availability prior to the bloom in late winter. The functional response of *C. finmarchicus* egg production rate, a proxy for birth rate, to phytoplankton biomass (as estimated by chlorophyll a concentration) is such that increases in phytoplankton standing stock between 25-100 mg chl a m-3 in the upper 50 m of the water column, can result in up to an order of magnitude increase in the daily output of *Calanus* eggs (Durbin et al. 2003; Runge et al. 2006). If the timing of phytoplankton food availability is favorable in winter through spring, increased *Calanus* egg production can mitigate or overcome a decline in the overwintering stock.

In late summer through early fall, the abundance of *C. finmarchicus* older stages in Wilkinson Basin, the main overwintering habitat in the western Gulf of Maine, is primarily driven by the advective balance between external supply and loss. The proximate external supply of *Calanus* to Wilkinson Basin comes primarily from the western and eastern branches of the Maine Coastal Current (Ji et al. 2017). The original source of *Calanus* in the Maine Coastal Current is the external supply to the eastern Gulf of Maine, either from the Nova Scotia/Labrador Current (*Calanus* rich) or temperate slope water west of the Gulf Stream (*Calanus*-poor). Summer, fall and winter abundances, when the *Calanus* population in Wilkinson Basin is primarily in Stage CV, are also affected by mortality from vertebrate and invertebrate predators, likely variable among years and perhaps increasing with increasing water temperatures (Ji et al. 2021; Wiebe et al. 2022).

The ISMN-MBON Calanus Index (CI) indicates trends in abundance of *C. finmarchicus* in the western Gulf of Maine based on data at the WBTS for each of these three seasonal periods. It also includes trends in the abundance of *C. finmarchicus* in summer at the CMTS station, which was chosen as a logistically feasible representative of the proximate supply of *C. finmarchicus* in the Maine Coastal Current to Wilkinson Basin. Trends in the abundance of stages CIII-CVI over the duration of the time series at each station are presented below and the Calanus Index is summarized in Table 1, updated through December, 2022.

Table 1. Calanus Index

Comparison of *Calanus finmarchicus* stage CIII-CVI abundance at the CMTS and WBTS stations in 2008 (prior to the 2010 oceanographic shift) with abundance in 2021 and 2022, as percent of 2008 levels. Abundances in 2008 and 2021 determined from regression analysis of late summer-early fall and late fall- winter time series shown in Fig 16. Abundance in 2022 represents the mean abundance in that year during the months covered by the respective time series. Spring index shows mean of AMJ abundances 2005-2009, 2020-2021 and 2022. NS: not a significant change. Note that Spring Index for period 2012-2017 was significantly higher than Spring Index in 2005-2009 by 353%.

Time series	Abundance 2008	Abundance 2021	Percent 2021/2008	Abundance 2022	Percent 2022/2008
CMTS Summer	37588	11423	30	30224	80
WBTS Late Summer	51598	19806	38	47192	91
WBTS Fall-Winter	27810	4085	15	17664	64
WBTS Spring	28018	45721	NS	53984	NS

4.2.1.1 The Summer -Winter Calanus Index

The long-term change in *C. finmarchicus* abundance in summer through winter is most clearly seen in Fig. 16, showing interannual change in abundance of stages CIII-CVI at the CMTS station in summer (JJAS) and at the WBTS station in the late summer-early fall (ASO) and late fall-winter periods (NDJFM). Following the conceptual model that the CMTS station is representative of the proximate upstream source of supply of *Calanus* to Wilkinson Basin after the local spring production, we have focused on a summer period (JJAS) at CMTS that is 1-2 months earlier than the WBTS late summer-fall period.

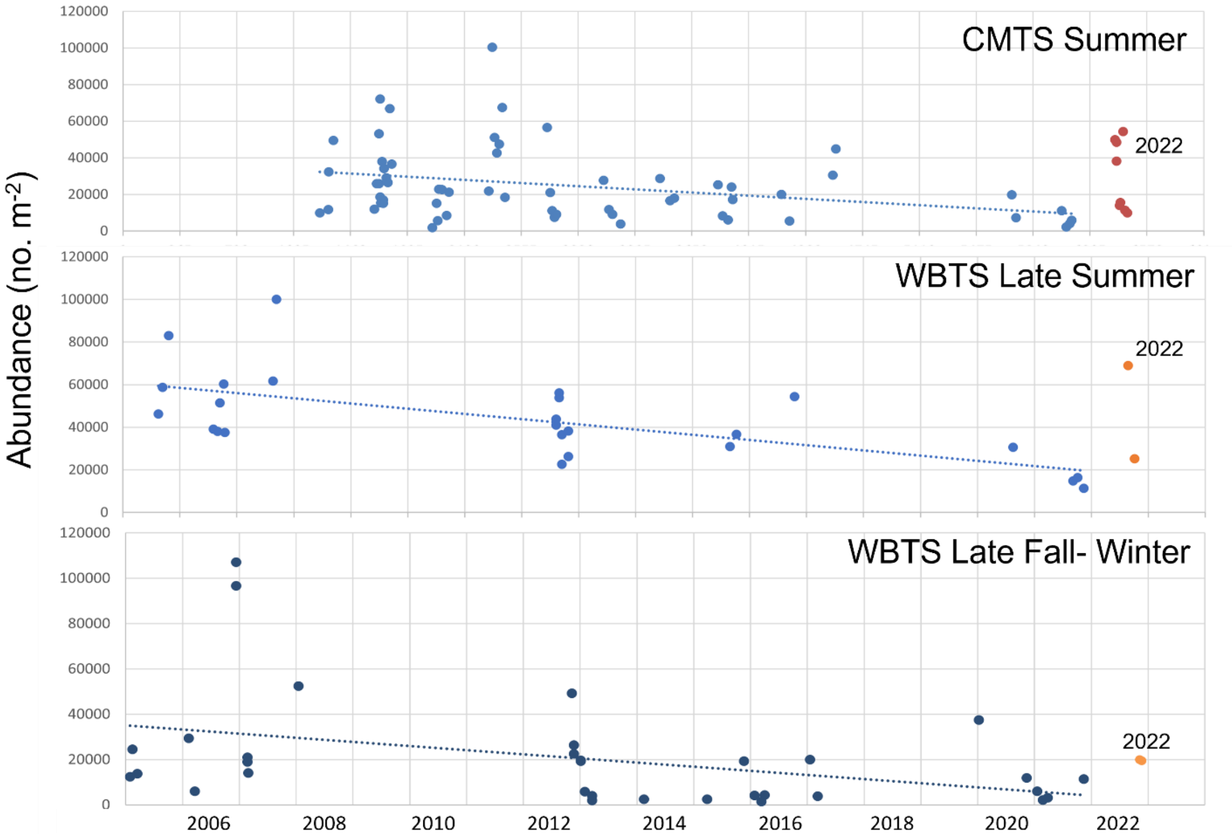

Figure 16. Calanus Index Time Series: Summer-Winter.
Abundance (no. m-2) of late stage *Calanus finmarchicus* (Stages CIII-CVI). Top panel: Summer (JJAS) abundance at the CMTS station. Regression line (2008-2021): Y= 38,222 – 4.70X where X is yearday from January 1, 2008 (r^2=0.11; p=0.006). Middle Panel: Late summer (ASO) abundance at the WBTS station. Regression line (2008-2021): Y= 60,663-6.70X, where X is yearday from January 1, 2005 (r^2=0.43; p=0.0001). Bottom Panel: Late Fall-Winter (NDJFM) abundance at the WBTS Station. Regression line (2008-2021): Y= 35,110 -5.00X, where X is yearday from January 1, 2005 (r^2=0.16; p=0.01). Data from 2022 (orange points) not included in regression, as this year appears to break from trend.

At all stations and seasonal periods, mean abundance of late-stage (CIII-CVI) *C. finmarchicus* has declined over the course of the time series. Summer abundance at the CMTS station declined from 37,599 m^{-2} (from regression analysis) between 2008 (the start of sampling) to 11,423 m^{-2} in 2021, which is 30% of the abundance in 2008 (Table 1). Late summer through winter abundances in Wilkinson Basin show corresponding declines: abundances in 2021 were 38% of 2008 levels in late summer-early fall and 15% of 2008 levels in late fall through winter. These observations are consistent with a decline in *C. finmarchicus* in upstream waters (represented by the CMTS) supplying Wilkinson Basin.

The summer through winter Calanus Index at the CMTS and WBTS stations shows a rebound in abundance in 2022 (Fig 16 and Table 1), to abundances that are 60-90% of 2008 levels. These most recent results highlight the potential for strong interannual variability in the interplay between the primary driving processes- local production, external supply and predation mortality. They raise the question whether a decadal-scale shift in oceanographic conditions subsequent to 2010 may be underway in the Gulf of Maine. Whether 2022 represents a blip in the downward abundance trend or signals a shift in oceanographic conditions awaits future data and further analysis.

4.2.1.2 The Spring Calanus Index

The spring Calanus Index (Fig. 17), presented as the time series of abundance of *C. finmarchicus* in spring and early summer (AMJJ) shows no change in abundance of stages CIII-CVI between 2005-2022 in Wilkinson Basin. The data indicate that the spring (AMJ) *Calanus* abundance actually increased in the 7-year period (2011-17) after the 2010 oceanographic shift (see zooplankton rank abundance comparisons below). The spring Calanus Index reflects robust local production of the first generation from the overwintering stock. Analysis of the time series of spring phytoplankton biomass presented below indicates an earlier timing of winter-early spring food availability for *Calanus* females emerging from diapause in late fall and winter, consistent with the conceptual model that a favorable match with food availability before the spring bloom will yield local production of offspring capable of offsetting the declining late fall-winter trend in *Calanus* stage CV abundance.

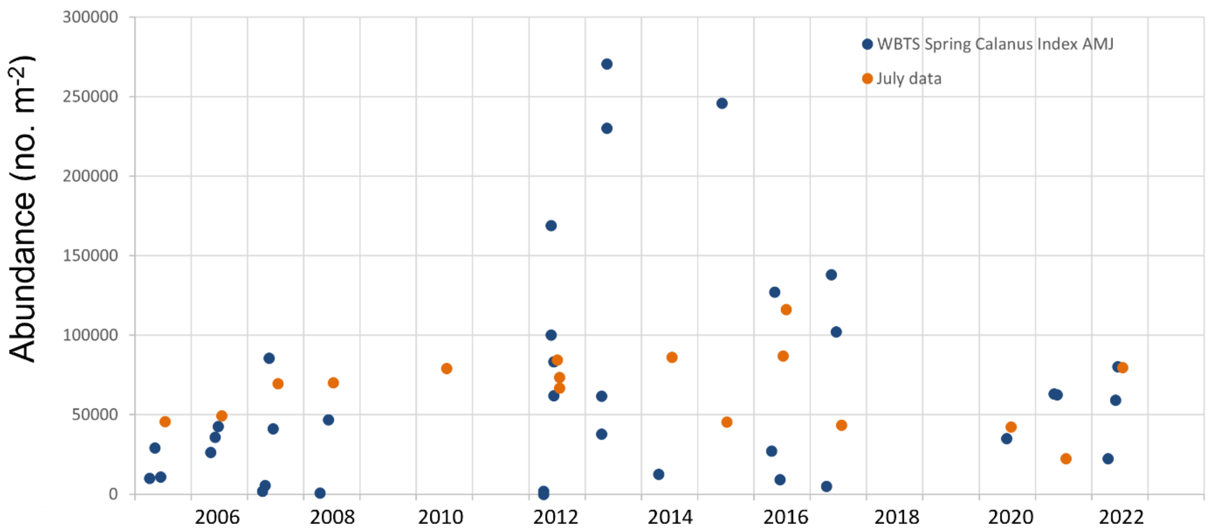

Figure 17. Calanus Index Time Series Index: Spring-Early Summer at WBTS
Abundance (no. m-2) of late stage *Calanus finmarchicus* (Stages CIII-CVI). Dark blue circles: April, May and June. Orange circles: July. No significant trend across all years (2005-2022). However, a significant increase between 2005-2017 (Y= 38,222 – 4.70X where X is yearday from January 1, 2005 (r^2=0.31; p=0.002), corresponding to the most recently available EcoMon data set.

4.2.1.3 The value of the Calanus Index

The Calanus Index based on the CMTS and WBTS station data provides a timely indicator of the status *Calanus finmarchicus* one to several years earlier than other surveys (e.g. the NOAA EcoMon survey or the Continuous Plankton Recorder survey), the analysis and dissemination of data for which typically lag collection by several years. Because the WBTS station is sampled monthly, it is shown to be sufficient to resolve (Ji et al. 2010) the seasonal differences in the primary drivers affecting abundance. The CI has the potential to become a forecast tool, for example in predicting abundance of sand lance, a key forage fish, at the Stellwagen Bank National Marine Sanctuary (Suca et al. 2021).

4.2.2 Zooplankton biomass

The biomass of zooplankton captured with the vertically integrating 200-µm mesh ring net tows (Fig. 18) has been monitored since the start of sampling at WBTS (2004) and CMTS (2007). Zooplankton biomass at an additional station in the Damariscotta Estuary (DMC-1 in Fig. 18) was also monitored between 2008-2017. At the CMTS and WBTS stations, zooplankton biomass is lowest in late winter and highest in summer. The predominance of *C. finmarchicus* in the deep Gulf of Maine is reflected in the higher biomass at WBTS (station depth: 260 m) compared to CMTS (110 m) and the Damariscotta Estuary (30 m), which is dominated by small, coastal and neretic copepods (*Acartia, Eurytemora* and *Temora* species).

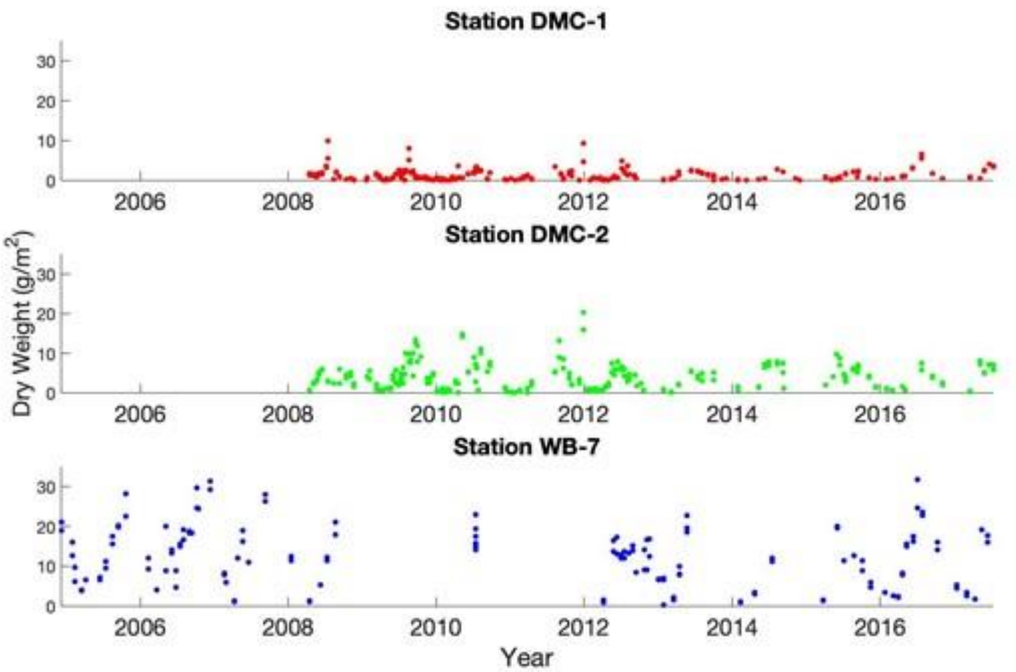

Figure 18 Spatial and temporal variation in GoM zooplankton dry mass (g m^{-2}): 2005-17
Top panel: a station in the Damariscotta Estuary (30 m depth). Middle panel: the CMTS station (also known as DMC-2: 110 m depth). Bottom panel: WBTS station (also known as WB-7: 260 m depth). Dry weight values represent the mass of zooplankton captured with a 200µm-mesh, 0.75 m diameter ring net towed from near bottom to the surface, normalized per m^2. Absence of points indicate gaps in the sampling record.

The interannual pattern by season of zooplankton dry weight at stations CMTS and WBTS reflect trends in the abundance of *C. finmarchicus*, which dominates the biomass of the zooplankton community (Fig. 19). Winter and summer biomass at WBTS shows a decline, consistent with a shift in external supply, whereas spring has been unchanged, consistent not only with strong winter-spring reproduction of *C. finmarchicus,* but also increases in abundance of smaller copepod species, as discussed in the next section. Summer biomass at CMTS shows a decline, whereas the winter and spring biomass remains unchanged.

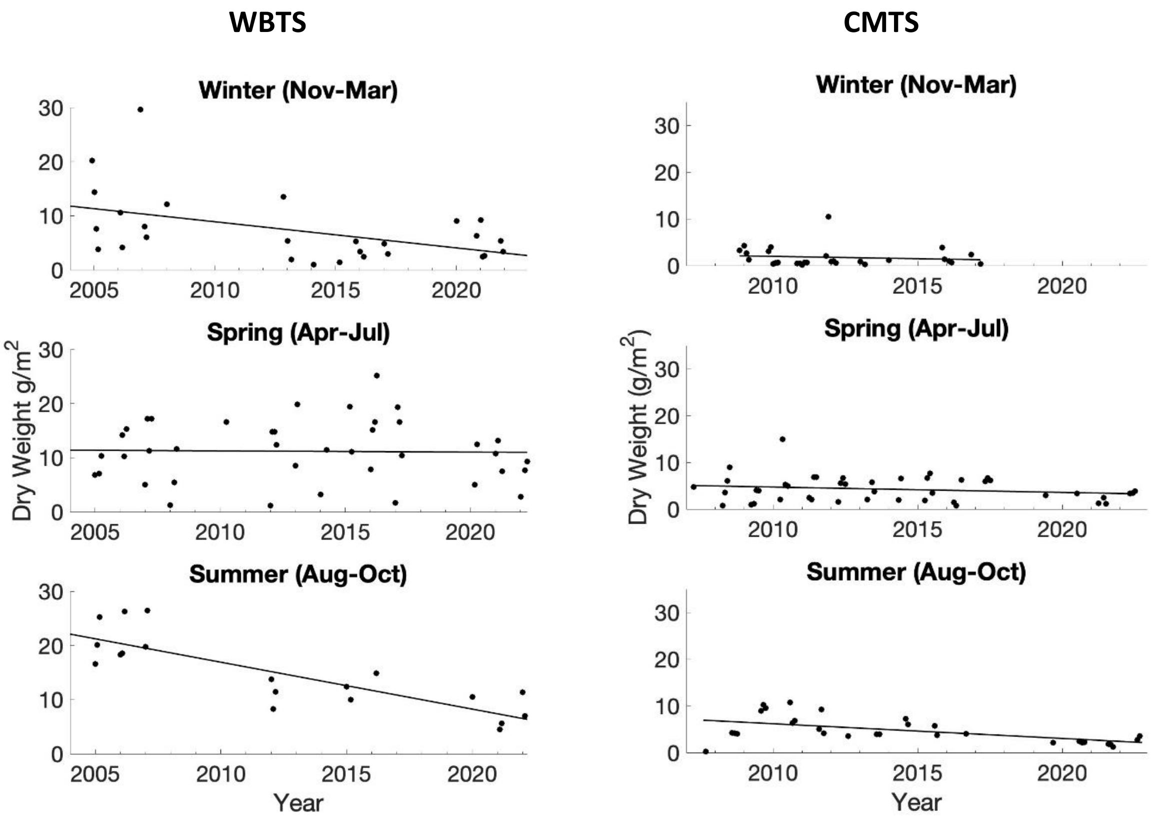

Figure 19. Zooplankton dry mass (g/m2) at the WBTS and CMTS stations

Left panel: WBTS; Right panel: CMTS). Values represent the dry weight of zooplankton captured with a 200um-mesh, 0.75m diameter ring net towed from near bottom to the surface, normalized per m^2. At WBTS, biomass significantly decreased in the winter (y = 0.001x + 11.790, p = 0.013, r2 = 0.221) and the summer (y = 0.002x + 22.098, p = 0.000, r2 = 0.695), but with no significant trend in the spring (y = 0.000x + 11.390, p = 0.894, r2 = 0.000). At CMTS, biomass significantly decreased in the summer (y = -0.001x + 6.960 , p = 0.001, r2 = 0.314), and did not show any significant trend in the winter (y = -0.000x + 2.264 , p = 0.536, r2 = 0.015) or spring (y = -0.000x + 5.038, p = 0.226, r2 = 0.035). In the regression analysis x = yearday since Jan 1st, 2004 at WBTS and Jan 1st, 2007 at CMTS.

4.2.3 Zooplankton biodiversity before and after the 2010 oceanographic shift

Copepods constitute the bulk of biomass of zooplankton captured with ring nets at the WBTS and CMTS stations. Analysis of rank abundance of copepod species in spring and fall (Figs. 20-23) shows the predominance of *C. finmarchicus*, the adult body size of which is considerably larger than adult sizes of most other species but for the carnivorous *Paraeuchaeta norvegica*, a common copepod predator in Wilkinson Basin. The rank abundance plots clearly show the low zooplankton biodiversity in the deep Gulf of Maine, reflecting a winnowing of zooplankton diversity in the North Atlantic Subarctic Biome by the Gulf of Maine’s particular oceanographic conditions. Since 2010, however, copepod species richness has increased, from about 12-15 species with detectable abundance in spring and fall between 2005-2010 to 16-18 species in spring and fall between 2011-2017. Preliminary analysis of biodiversity in 2020-2021 indicates the species richness has increased even further, with possibly new species introductions.

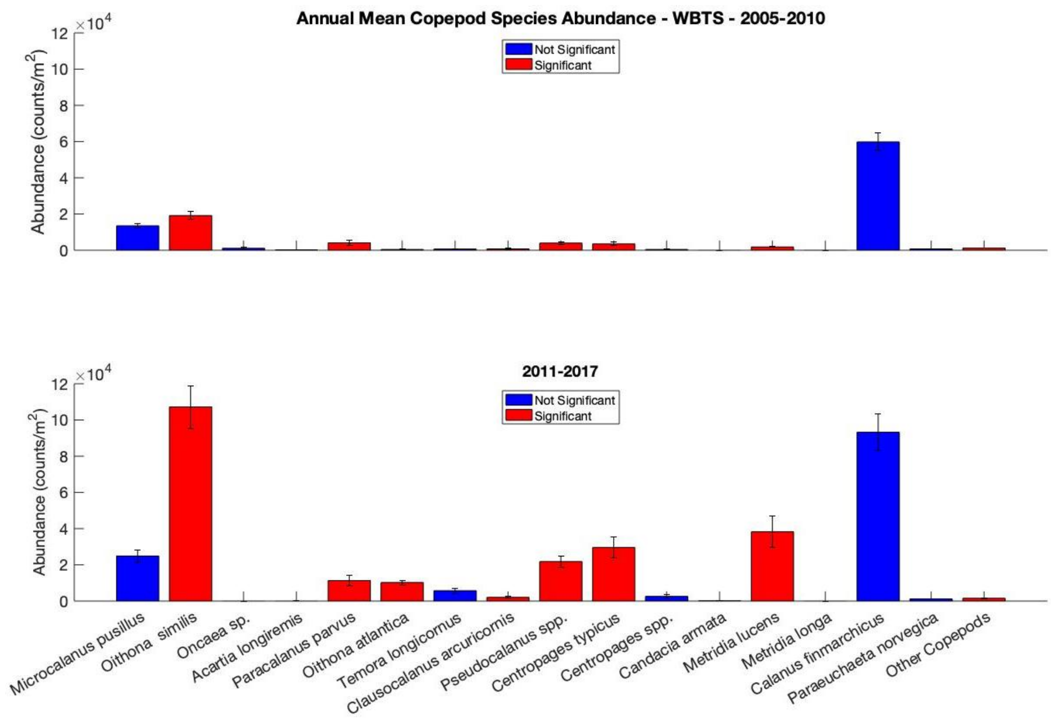

Figure 20. Mean annual rank abundance of copepod species at the WBTS station

Annual average abundance (mean number m^{-2}) of copepods in the 7 year period before (2004-2010) and after (2011-2017) the 2010 oceanographic shift.. Species are ordered by adult female prosome length, from smallest (left) to largest (right). Significance (P<0.05) determined by Mann-Whitney U test

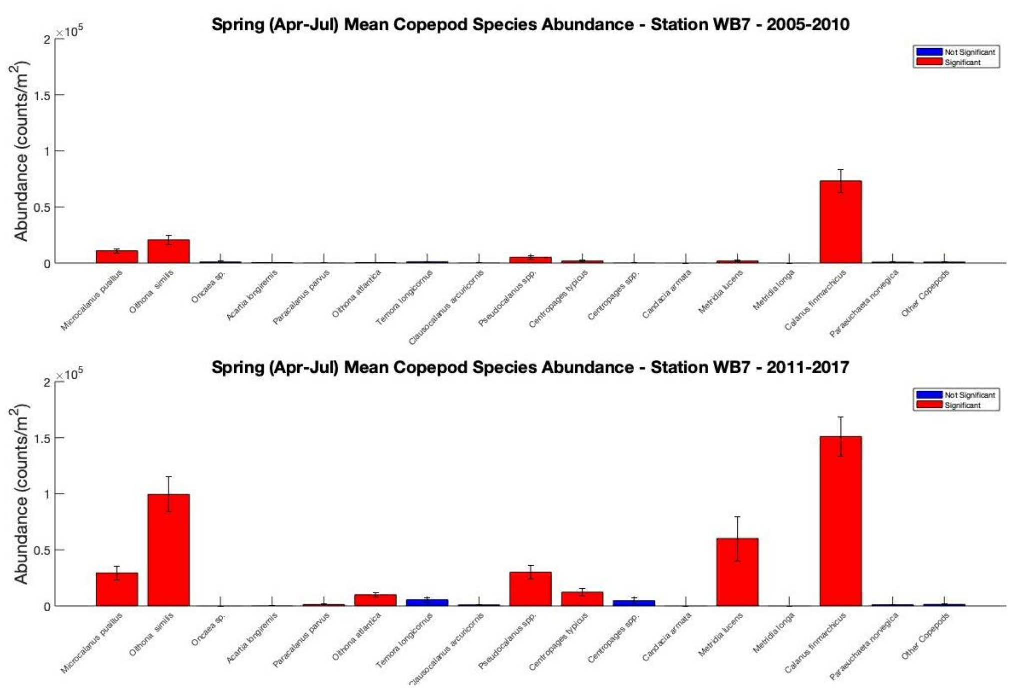

Figure 21. Mean spring rank abundance of copepod taxa at the WBTS station

Average abundance (mean number m^{-2}) of copepods in spring-early summer (Apr-Jul) in the 7 year period before (2004-2010) and after (2011-2017) the 2010 oceanographic shift.. Species are ordered by adult female prosome length, from smallest (left) to largest (right). Significance (P<0.05) determined by Mann-Whitney U test

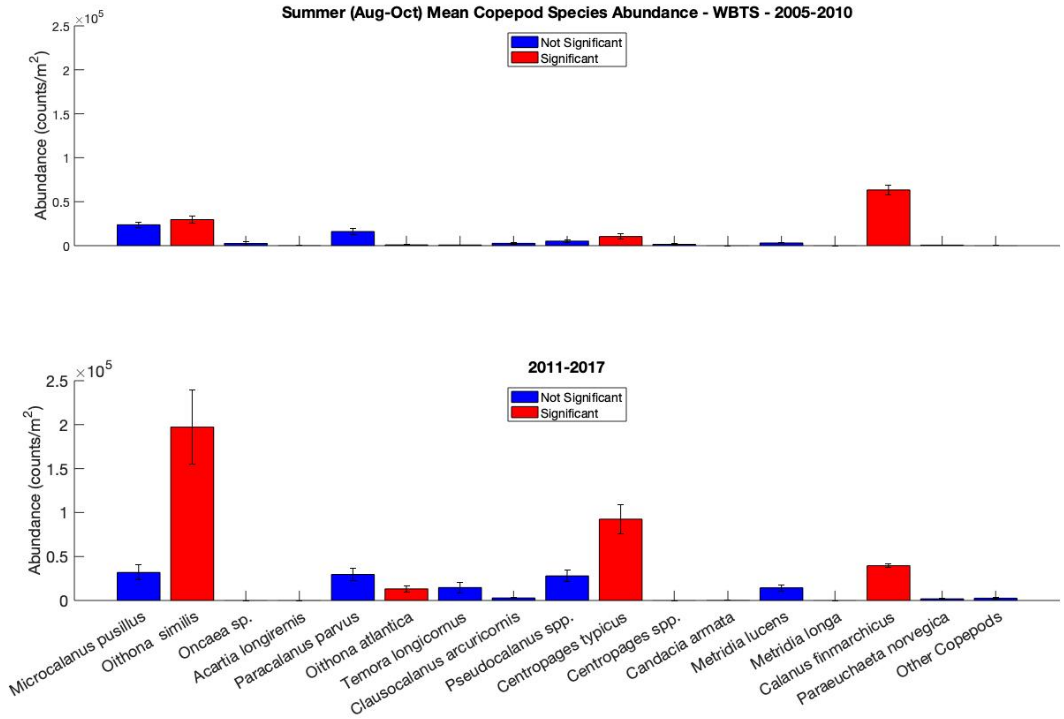

Figure 22. Mean late summer rank abundance of copepod taxa at the WBTS station
Average abundance (mean number m^{-2}) of copepods in late summer (Aug-Oct) in the 7-year period before (2004-2010) and after (2011-2017) the 2010 oceanographic shift. Species ordered by adult female prosome length, from smallest (left) to largest (right). Significance (P<0.05) determined by Mann-Whitney U test

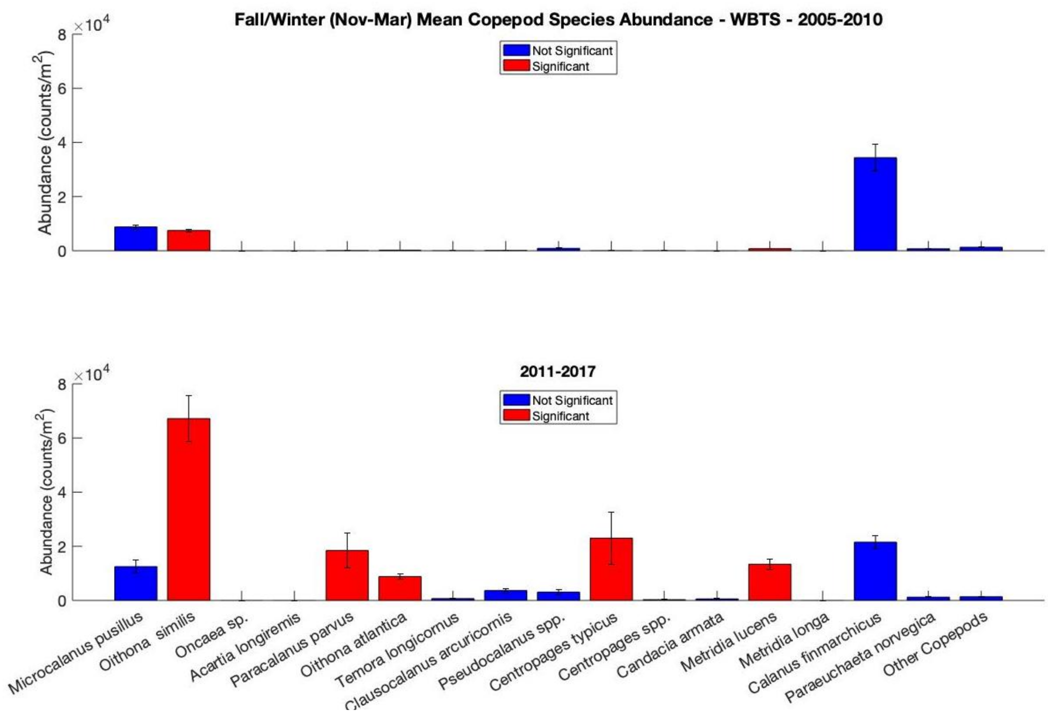

Figure 23. Mean winter rank abundance of copepod taxa at the WBTS station
Average abundance (mean number m^{-2}) of copepods in late summer (Aug-Oct) in the 7-year period before (2004-2010) and after (2011-2017) the 2010 oceanographic shift. Species ordered by adult female prosome length, from smallest (left) to largest (right). Significance (P<0.05) determined by Mann-Whitney U test

The rank abundance patterns show a shift in community structure between the two periods. Species of *Oithona Pseudocalanus*, *Metridia*, *Clausocalanus*, *Paracalanus*, and *Centropages* have increased by a factor of 2-5 or more in spring more recently. But for *Metridia* and *Centropages*, whose adult body sizes are, respectively, about 75% and 50% of *C. finmarchicus*, these copepod species are substantially smaller than *Calanus* and contribute little to the Gulf of Maine's planktonic lipidscape.

Species of *Oithona* and *Centropages* have seen significant increases over all seasons between the decades before and after 2010. *Oithona* has taken the place of *Calanus finmarchicus* as the most abundant species in the fall/winter and summer in the latter decade, driving a shift in size structure in the copepod community at WBTS.

4.3 Chlorophyll at WBTS

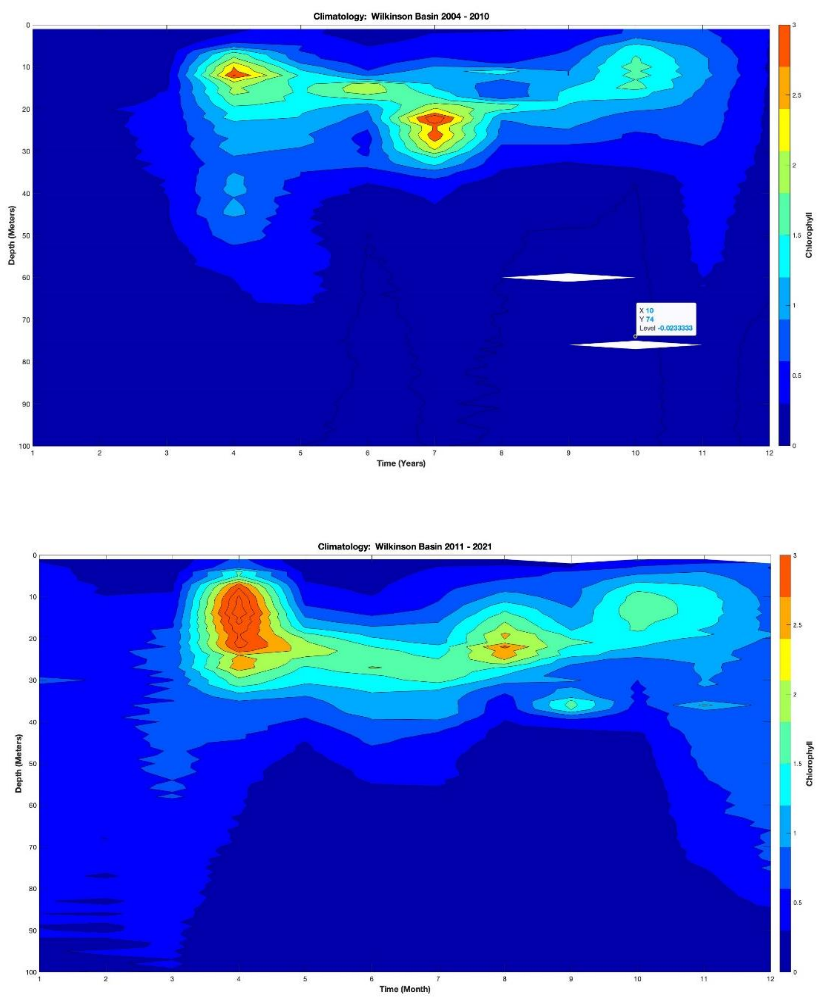

Figure 24. Mean monthly chlorophyll a concentration profiles at the WBTS station.
Chl. a estimated from the calibrated in-situ fluorometer installed on the R/V Gulf Challenger CTD rosette system (see methods). Climatology for the 2004-2010 (top panel) and 2011-2021 (bottom panel) periods.

The mean monthly chlorophyll profiles at station WBTS indicate a spring phytoplankton bloom in late March and April and a subsurface chlorophyll maximum at a depth of 20-35 m throughout the summer months (Fig. 24). The spring bloom has been more intense during the 2011-2021 period than earlier. Importantly, chlorophyll biomass in late fall through winter has been on the order of 0.3-0.9 µg chl. a liter -1, two to three times higher than during the previous period. Chlorophyll concentrations< 1-1.5 µg chl. a liter -1 are food limiting for *C. finmarchicus* and many other copepod species. Increases by a factor of two or more therefore have large impacts on growth and reproduction of copepods that are feeding during late fall and winter, including *C. finmarchicus* emerging from diapause. These more elevated concentrations allow reproduction during late winter and early spring. While not sufficient for maximum growth and reproduction, the elevated chlorophyll a concentration in late fall- early spring nevertheless are consistent with higher first generation abundances of later

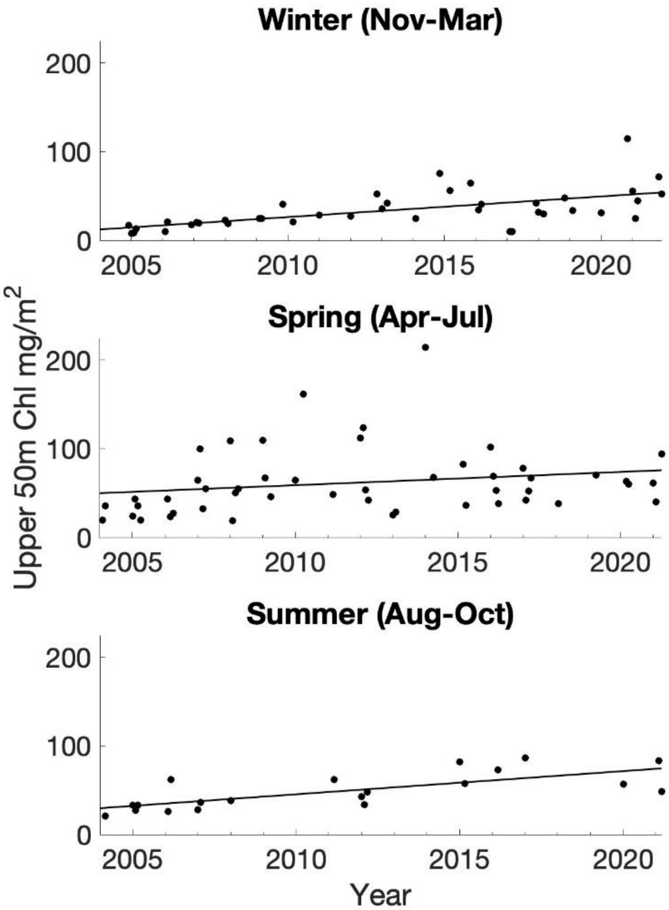

Figure 25. Time series of integrated chlorophyll *a* at the WBTS station
Chlorophyll standing stock (mg Chl a m^{-2}) in the upper 50m of the water column during the winter, spring and summer periods. Standing stock significantly increased in the winter (y = 0.007x + 11.767, p = 0.000, r^2 = 0.373) and summer (y = 0.007x + 28.981, p = 0.000, r^2 = 0.551) but no significant trend in spring (y = 0.004x + 48.774, p = 0.123, r^2 = 0.051). In the regression analysis x = yearday since Jan 1st, 2004.

stage *C. finmarchicus* in late spring, and increased abundances of smaller copepod species since 2010.

The interannual trend in seasonal phytoplankton food availability for herbivorous/ominorous zooplankton in Wilkinson Basin is shown by plotting over time the chlorophyll a standing stock integrated over the upper 50 m of the water column (Fig. 25). Chlorophyll *a* standing stocks increased significantly in the winter and summer, but not in the spring, corresponding to the spring bloom period. These results are consistent with the hypothesis that food availability during the summer through winter months, when food is most limiting, favored the population growth of smaller copepods as well as early reproduction of *Calanus finmarchicus* (seen in the rank abundance comparisons, Figs. 20-23) during the period after the oceanographic shift in 2010.

4.3.1 Mixed layer depth

Mixed layer depth (calculated from density profiles using the threshold method: Durbin et al. 2003) in the winter at WBTS provides an index of light conditions for phytoplankton growth before the spring phytoplankton bloom. On average the estimated MLD deepens from November (33.9m) through February (97.6m) and begins to shallow again in March (84.7m) but does not show a strong interannual trend (Fig. 26). However, the proportion of instances where the mixed layer depth is shallower than its monthly average increases from 46.7% in 2004-10 to 58.8% in 2011-17 and 63.6% in 2018-21 (Fig. 27). This trend is consistent with the increase in winter chlorophyll a standing stock (Fig. 25) and the hypothesis that, since 2010, an increase in winter periods of shallow MLD have provided favorable light conditions for phytoplankton growth.

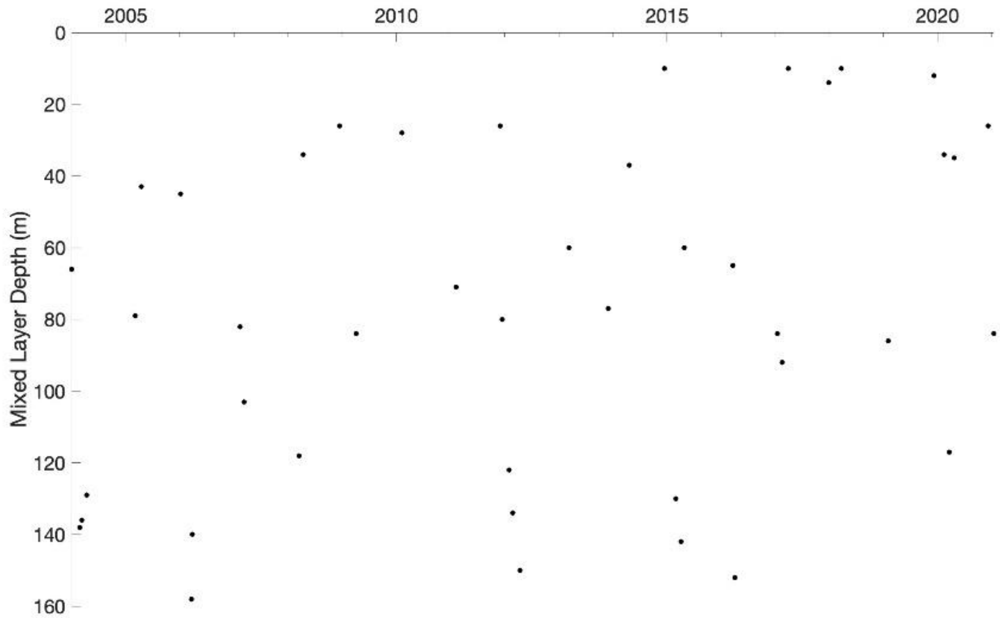

Figure 26. Estimated winter MLD at the WBTS station

Mixed Layer Depth values represent estimates obtained using the threshold method at a density difference of 0.04kg/m3 as compared to the density at 3m (representing the surface). This condition must be met over 5 consecutive depth measurements (1m) to account for any noise in the data.

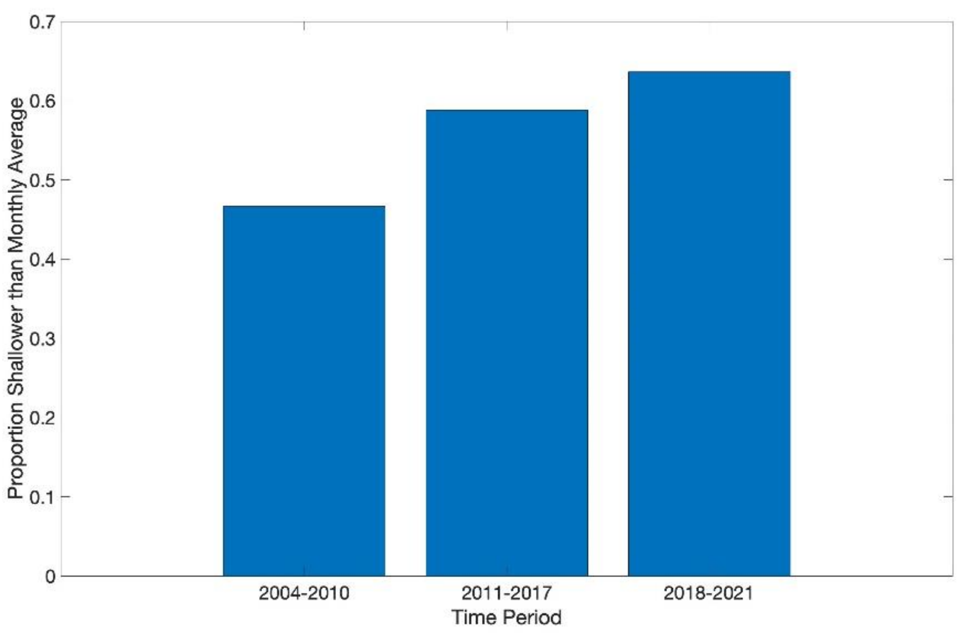

Figure 27. Proportion of shallow MLD in winter at the WBTS station

Proportion of instances when the Mixed Layer Depth was shallower than the average during the winter months (Nov-Mar) at WBTS. Mixed layer depth estimates were obtained as described in Fig.26, then an average was taken over the whole time period for each month in the winter period. These averages were subtracted from each MLD value in the corresponding month to calculate anomalies. Finally, the number of negative anomalies was divided by the total number of estimates for three time periods; 2004-2010 (n = 15), 2011-2017 (n = 17), 2018-2021 (n = 11). Note that there is no data available from November before 2012.

4.4 Data management

Data processing and administration has progressed along several fronts: 1) making data accessible via the ISMN ERDDAP server and 2) making data accessible via the OBIS portal, 3) PI submission to the MBON Data Portal and 4) development of the ISMN website as a means to access data and interpretation. This is an ongoing process that will continue through the end of the MBON award, which is funding the data management component of the study.

4.4.1 Making data accessible via ERDDAP

A DMAC working group was established at the outset of the project to develop processes and methodologies for integration of priority datasets into a common access portal. A dedicated ERDDAP instance was deployed for the initial development and processing of preliminary datasets. The team is developing a standard process for structuring data and metadata, which will allow us to bring future datasets into ERDDAP more quickly.
The datasets currently in development are available on the ISMN ERDDAP server: http://ismn.erddap.neracoos.org/erddap/info/index.html?page=1&itemsPerPage=1000, including the Gulf of Maine WBTS *Calanus* Abundance Observations.

This dataset is also available on the publicly accessible NERACOOS ERDDAP server (http://www.neracoos.org/erddap/tabledap/WBTS_CFIN_2005_2017.html).

Working in consultation with the NOAA NEFSC, the team has been processing phytoplankton and zooplankton data from the Continuous Plankton Recorder (CPR) Survey in the Gulf of Maine (1961-present). At this time, five datasets have been added, segmented by plankton type and methodology (phytoplankton/zooplankton and NOAA and SAHFOS). The datasets are undergoing revisions and review from NEFSC and key users of the data to maximize utility and usability. Because of differences in sampling and processing methodologies over the years, efforts are being made to develop robust metadata for these datasets that describes differences in sampling and counting methodologies, and to provide documentation of methodologies for data transformation steps used to get the data into its most usable form (will be available via GitHub upon completion).

4.4.2 Making data accessible via the OBIS portal

A major focus of this effort has been bringing data into compliance with the Darwin Core Standard, which is a requirement for submission to the Ocean Biodiversity Information System (OBIS) portal. Members of the DMAC team attended the Marine Biological Data Mobilization Workshop which allowed them to solicit feedback directly from OBIS node managers. As a result of this work, a series of Python scripts were developed to convert the WBTS Calanus Abundance data into a compliant state. The conversion process for the WBTS Calanus data is complete, and the dataset has been submitted to OBIS & GBIF (Global Biodiversity Information Facility). The submission process was handled collaboratively with OBIS node manager Abby Benson and was tracked on GitHub: https://github.com/ioos/bio_data_guide/issues/102.

The dataset can be viewed in the OBIS Portal here: https://obis.org/dataset/5ef55cd8-05a1-4569-8e17-ceb224e40f59,

and the GBIF Portal here: https://www.gbif.org/dataset/29651377-23c8-4f45-b439-693a1a23cee1.

The conversion scripts developed during this process will also be capable of converting additional MBON datasets and should only require slight modification to accommodate different use cases.

4.4.3 PI submission to the MBON Data Portal

The team has had initial meetings with members of the IOOS MBON DMAC working group to understand the process and requirements for submitting datasets from the Northeast MBON to the portal (https://mbon.ioos.us/). As datasets are finalized in ERDDAP, they will be submitted to the MBON Data Portal for integration.

4.4.4 Development of the ISMN website as a means to access data and interpretation

An important milestone is the launching of the ISMN website, www.sentinelmonitoring.org. The website provides a centralized location for users to learn about the ISMN collaborative, as well as access GoM MBON project data and results. The website will act as a centralized clearinghouse for regional data on key ecosystem indicators. Currently, efforts are focusing on the pelagic indicator *Calanus finmarchicus*. In addition to GoM MBON data, data from the Continuous Plankton Recorder will also soon be made available on the ISMN website. This leveraged effort from IOOS and NEFSC will improve data discovery to the website, as well as start to create a centralized clearinghouse for *Calanus* data. Later phases plan inclusion of data integration products that pull together planktonic data sets from throughout the region to help synthesize available information.

5 Discussion: The status of the Gulf of Maine pelagic ecosystem

A prominent result of the ISMN-MBON time series is continued confirmation of substantial reduction in abundance of the energy-rich stages of the planktonic copepod, *Calanus finmarchicus*, in the Gulf of Maine. Both the Calanus Index for Wilkinson Basin (WBTS) and late-stage abundance of *C. finmarchicus* at the western margin of the Maine Coastal Current (CMTS) were, in 2020-21, at about 30% of the recent historical mean level. Mean surface layer temperatures in the Gulf of Maine were at a record high in 2021, and inspection of phytoplankton and zooplankton samples from WBTS and CMTS (quantitative analysis of composition in 2020-22 plankton samples is ongoing) indicates continuation of a shift in biodiversity away from the *Calanus*-dominated subarctic food web that has been the historic foundation for Gulf of Maine ecosystem services.

The primary drivers of *C. finmarchicus* abundance in the Gulf of Maine, analyzed by Ji et al. (2022), are local production in spring and early summer, external supply from the surface layer Nova Scotia Current and deep water through the Northeast Channel, and predation from both visual (e.g. herring, sandlance) and non-visual (e.g. euphausids, chaetognaths, jellyfish and other invertebrates) predators. The WBTS time series data here indicate a shifting phenology toward higher phytoplankton biomass available in fall, winter and early spring, supporting local production in spring and early summer not only for C. finmarchicus, but also for other, smaller mesozooplankton species (e.g. copepods in the genera *Oithona*, *Pseudocalanus*, *Centropages* and *Metridia*). This shifting phenology, allowing local late winter-early spring copepod reproduction, is consistent with observations of sustained *C. finmarchicus* abundance in spring. However, a combination of summer-fall predation and reduced external supply, associated with a shift in transport away from cold, *Calanus*-rich subarctic water to warm, *Calanus*-poor Atlantic slope water is likely responsible for the substantial reduction in the energy-rich stock of *C. finmarchicus* in the western Gulf of Maine in summer and fall, the period during which forage fish (e.g. herring and sand lance) as well as North Atlantic right whales, accumulate lipids to sustain their growth and reproduction.

The value of the NERACOOS ISMN fixed stations is the timely provision of plankton indicators at seasonal scales. For example, data from summer 2022 indicate a rebound in *Calanus* abundance which has implications for the present condition of North Atlantic right whale foraging habitat as well as for forage fish recruitment and condition in the Gulf of Maine. Further monitoring and analysis of hydrographic and other data is needed to understand whether 2022 conditions represent a longer term shift or whether external supply continues to constrain *C. finmarchicus* abundance in the Gulf of Maine. While time series samples will indicate the abundance trends of some invertebrate predators (e.g. carnivorous copepods and chaetognaths), supplemental data are needed to understand trends in euphausids, jellyfish, and visual predators. In the meantime, continued sampling at the ISMN-MBON time series stations assures documentation of trends in *C. finmarchicus* and planktonic biodiversity, providing timely data for predictions and informed decisions related to management of Gulf of Maine ecosystem services.

6 Products

Research articles with all or partial support from the BOEM CA

Helenius, L, Head E, Jekielek P, Orphanides C. Pepin P, Perrin G, Plourde S, Ringuette M, Runge J, Walsh H. Johnson C. In preparation. Spatial variability in size and lipid content of the marine copepod Calanus finmarchicus across the Northwest Atlantic continental shelves: implications for North Atlantic right whale prey quality

Ross CH, Runge JA, Roberts JJ, Brady DC, Tupper B, Record NR. 2023. Estimating North Atlantic right whale prey based on *Calanus finmarchicus* thresholds. Mar. Ecol. Prog. Ser. 703: 1–16.

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Ji R, Runge JA, Davis CS, Wiebe P. 2022. Drivers of variability of *Calanus finmarchicus* in the Gulf of Maine: roles of internal production and external exchange. ICES Journal of Marine Science. 79 (3): 775–784. https://doi.org/10.1093/icesjms/fsab147.

Muller-Karger F, Kavanaugh M, Iken K, Montes E, Chavez F, Ruhl H, Miller R, Runge J, Grebmeier J, Cooper L, Helmuth B, Escobar-Biones E, Hammerschlag N, Estes M, Pearlman J, Hestir E, Duffy E, Sarri KJ, Hudson C, Landrum J, Canonico G, Jewitt L, Newton J, Kirkpatrick B, Anderson C, Bates A, Sousa-Pinto I, Nakaoka M, Soares J. 2021. Marine Life 2030: Forecasting Changes to Ocean Biodiversity to Inform Decision-Making: A Critical Role for the Marine Biodiversity Observation Network. Mar. Tech. Soc. Journal. 55(3): 84-85.

Manuscripts are in preparation to report on results of this study in research journals.

Presentations with all or partial support from the BOEM CA

Runge JA. Integrated Sentinel Monitoring Network. Northeast Regional Ocean Council (NROC) Annual Meeting. Coastal Resilience Networking Session. Nov. 20, 2020.

Runge JA. MBON activities in the Gulf of Maine support prediction of North Atlantic right whale foraging patterns. GeoBon Open Science Conference & All Hands Meeting 2020. Virtual. 6-10 July, 2020.

Ross C, Record N, Roberts J, Runge J, Tupper B. 2021. The dynamics of high-density *Calanus finmarchicus* patches on the US continental shelf. ASLO Aquatic Sciences Meeting. June 22-27, 2021.

Runge JA. 2021. Arctic climate, copepods and North Atlantic right whales: is big change coming to the Gulf of Maine ecosystem? UMaine Arctic Seminar Series, 19 October, 2021.

Ross C, Record N, Roberts J, Runge J, Tupper B. 2022. Modeled prey fields improve predicted distributions of endangered North Atlantic right whales. AGU-ASLO Ocean Sciences Meeting, 27 Feb-3 Mar, 2022 (Virtual).

Runge JA, Ji R, Record N, Pendleton D, Motyka J. 2022. Shifting biodiversity and effects on ecosystem services in the Gulf of Maine: The role of *Calanus finmarchicus*. AGU-ASLO Ocean Sciences Meeting, 27 Feb-3 Mar, 2022 (Virtual).

Runge J, Estes M, Muller-Karger F, Canonico G (Co-conveners). 2022. Marine Life 2030: Advancing Earth Observations and the Marine Biodiversity Observation Network (MBON) to measure and interpret marine biodiversity for global sustainability. Ocean Science Meeting. 27 Feb.-4 Mar. (Virtual)

Ross C, Roberts J, Runge J, Brady D, Pendleton D, Record N. 2022. Incorporating prey information into the Duke right whale density surface model. North Atlantic Right Whale Consortium Annual Meeting, Oct 25-26. New Bedford, MA.

Applications

Application of the Calanus Index as an indicator of condition of the Stellwagen Bank National Marine Sanctuary. NERACOOS, in collaboration with staff at the Stellwagen Bank National Marine Sanctuary (SBNMS) has been awarded a research grant from the NOAA Climate Program Office (CPO) to use the WBTS Calanus Index in conjunction with an index of Atlantic herring abundance and the proportion of warm slope water in the Gulf of Maine to predict recruitment of northern sand lance in the SBNMS, based on a relationship between these variables (Suca et al. 2021). The work will develop an interactive tool providing zooplankton and sand lance forecasts that can be used by SBNMS managers and stakeholders to inform the SBNMS Climate Vulnerability Assessment.

We envision other uses of the Calanus Index to provide real time and future forecasts of the state of the ecosystem in the western Gulf of Maine, including the NOAA State of the Ecosystem on the NE U.S. Shelf assessments and possible applications to prediction of lobster recruitment (e.g. Carloni et al. 2018) and NARW foraging habitat (e.g. Ross et al. 2023). We are interested in exploring other applications that would be useful to BOEM in resource management decisions.

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