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High-Resolution Regional Ocean Climatologies with the Northwest Atlantic as an Example: A Review

Mishonov A V[1,4*], Seidov D[1], Baranova O K[1], Bouchard C[2], Boyer T P[1], Cross S L[3], Larsen K[2], Nyadjro E S[2,5], Parsons, A R[2] and Weathers K[2]

[1]*NOAA National Centers for Environmental Information (NCEI), Silver Spring, MD*

[2]*NOAA National Centers for Environmental Information (NCEI), Stennis Space Center, MS*

[3]*NOAA National Centers for Environmental Information (NCEI), Charleston, SC*

[4]*Earth System Science Interdisciplinary Center/Cooperative Institute for Satellite Earth System Studies (ESSIC), University of Maryland, College Park, MD.*

[5]*Northern Gulf Institute, Mississippi State University, Stennis Space Center, MS*

***Corresponding Author**
Alexey V Mishonov, Associate Research Scientist, University of Maryland - Earth System Science Interdisciplinary Center (ESSIC)

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Abstract

The advantages of high-resolution oceanographic data analysis stems from an increased ability to capture sharp gradients in frontal zones and across mesoscale entities, especially in the coastal regions and along ocean jet-like currents, relative to coarser resolution analyses. In a sense, the finer-resolution analysis pursues the same goal as the usage of progressively reduced grid sizes in succeeding from coarse-resolution to eddy-permitting and then to eddy-resolving in numerical models of ocean circulation. Thus, the high-resolution regional climatologies are now closing the gaps existing between observations and model simulations allowing meaningful data-model comparisons in critical data-rich regions, such as the Northwestern Atlantic, Northeast Pacific Ocean, and several others. In this paper, we briefly review the locations, timing, purpose, and specificity of the regional ocean climatologies developed at the National Center for Environmental Information of the National Oceanic and Atmospheric Administration. We describe the Northwestern Atlantic Regional Climatology, version 2 in more details and demonstrate how this regional climatology contributes to a better understanding of the long-term climate state and variability.

Keywords: North Atlantic Ocean, Oceanographic Dataset, World Ocean Database, World Ocean Atlas, Regional Climatology

1. Introduction

The climate is formally defined as the ensemble of states that the major components of the planetary climate system – ocean, atmosphere, cryosphere, biosphere, landmass, and its waters – transit through within a certain period, most often defined as thirty years [1,2]. This time interval complies with the World Meteorological Organization (WMO) general recommendation of using 30-year periods of reference. According to this definition and because the time scale of the ocean processes is much longer than those of the atmosphere, the ocean is the key element of the climate system on decadal to centennial time scales. Therefore, the knowledge of the decadal changes of ocean parameters, especially temperature and salinity, is crucial for understanding and predicting climate variability on those time scales comparable to the average span of a human generation.

A fundamental concept used in climatology is the concept of “climate normals.” According to the WMO, climate normals serve as a benchmark for which recent or current observations can be compared. Practically speaking, the normals are averaged climate system parameters (temperature, salinity, pressure, etc.) within selected intervals (months, seasons, and years) over the reference 30-year periods. International Meteorological Organization (IMO-WMO) member nations were first mandated to compute climate normals for their member countries for the 1901–30 period and are required to update these climate normals every 30 years, resulting in the 1931–60 normals and the 1961–90 normals [3].

Since 1956, the WMO has recommended that each member country re-compute their 30-year climate normals every 10 years. Thus, currently the period of 1991-2020 is the preferred 30-year interval for computing climate normals, and the new ocean climate normals for this interval have recently been published by NCEI and are now available at the web site: HYPERLINK "https://www.ncei.noaa.gov/products/world-ocean-atlas"World Ocean Atlas/Climate Normals. It should be mentioned that justifications for using 30-year normals for describing climate are now being questioned [4, 5] and implying that a longer time interval should be used as a reference mean to compute anomalies. Therefore, in ocean heat content calculations, first published in [6], and then updated in 2009 and in 2012 [7, 8] the reference mean or base climatology was set to the entire period from 1955 to 2006, which is 50 years, i.e., much longer than the WMO-recommended 30 years, to reflect the extended time of thermocline water turnover [7].

The last century climatologists and oceanographers invested a great deal of effort and resources compiling reliable climatological products based on observations and developing new generations of ocean and climate models. Over the past few decades, the Earth's climate system has undergone profound and rapid change [9]. Together, in situ observations and modeling provide better understanding of the climate system state and variability, and improved forecasting of potential climate changes.

Understanding the coastal waters and their variability was critical for human activity and safety long before regular observations of the pelagic parts of the ocean basins became viable. Moreover, the oceans and seas and their interaction with the atmosphere became a focal point of climate studies because of their role in global warming [10,11].

The past century, numerous intensive ocean observational programs provided a reasonably comprehensive assessment of the ocean climatic state and its long-term variability. In the North Atlantic, there were many dozens of studies that led to a very detailed view of this part of the World Ocean. Numerous national and international monitoring and research programs, including the International Ice Patrol (IIP) Survey, Ocean Weather Ships (OWS), Mid-Ocean Dynamics Experiment (MODE), US-USSR POLYMODE (Polygon and MODE), World Ocean Circulation Experiment (WOCE), Climate Variability and Predictability (CLIVAR) of the World Climate Research Programme (WCRP), Rapid Climate Change Programme (RAPID) and most recently Argo – to name just a few – contributed to advanced understanding of North Atlantic climate dynamics [see a review in [12]. In the 21st century, the ocean observations were vastly enhanced by the arrival of a new instrumentation—the Argo floats [13-18].

2. Incentives for Building High-Resolution Ocean Climatologies

The time scales of the ocean circulation, which are the key to the ocean's role in the climate dynamics on millennial and shorter time scales, are very different in the upper ocean, in the main thermocline, and in the deep ocean. They can also vary from years at a basin scale to hundreds of years at a global scale. The longest time scales of several centuries are determined by the global thermohaline circulation or inter-basin exchange of thermocline water [19], also known as a "global conveyor" [20]. However, a practical approach to ocean climate diagnostics is to use the data obtained in the last sixty-plus years following the advent of widespread and numerous ocean observations beginning in the middle of the twentieth century, which would cover two 30-year successive periods.

There is a strong consensus among climate scientists that the main climate controls imposed on the earth's climate system by the oceans are via air-sea heat and freshwater exchange. The oceans gain heat in the tropics and subtropics and release it in high latitudes. The meridional overturning circulation that regulates the poleward heat transport by ocean currents facilitates the redistribution of energy between the low and high latitudes in the oceans and, eventually, via air-sea interactions in the climate system. The thermohaline structure of the World Ocean reflects all three factors – ocean-air heat exchange (controls surface water temperature), evaporation-precipitation balance (paired with melting and freezing of sea ice and river runoff, controls surface water salinity), and advection of heat and salt in the ocean-by-ocean currents.

For about 30 years, NODC/NCEI has been analyzing the long-term trends of ocean temperature and salinity from in-situ observational data and mapped to a one-degree latitude-longitude grid. More recently, NCEI has used grids with finer resolution of a quarter of a degree. Although providing better-structured temperature and salinity fields, the quarter-degree spatial resolution is still not enough to resolve the cumulative effects of nonlinear mesoscale dynamics. Such an aggregated effect of mesoscale phenomena is responsible for generating and maintaining the highly dynamic and coherent structures in the most critical regions of the World Ocean—the coastal areas and their surroundings, such as the Gulf Stream, Kuroshio, and other intensive ocean currents regions. The dynamics, structure, and the long- and short-term variability of these currents stem from the interaction of various mesoscale elements, such as the meandering of jet streams, eddies, large vortexes, and filaments. The resulting structure is much finer than can be reflected in low-resolution analysis and therefore cannot be adequately mapped. The quarter-degree resolution is problematic as it essentially results in a misleading interpretation of the dynamics and coherence of the jet-like currents and almost wholly loses the cumulative effect of mesoscale eddies. Moreover, in most places in the World Ocean, a better than one-degree resolution is unattainable due to limited in-situ observations, with only a few areas covered with data sufficient for the quarter-degree resolution. However, a higher resolution mapping has recently become possible in some ocean regions within those limited areas (Figure 1). These regions are relatively well sampled, and in most cases, are extremely important for the ocean and earth's climate studies as well as for ecosystem dynamics assessments.

When computing anomalies from a standard climatology (ocean climate obtained by averaging temperature and salinity fields over several decades), the mesoscale irregularities are smoothed to prevent generation of spurious anomalies and to fill the gaps in the data coverage. The smoothing depends on the spatial grid resolution and therefore can cause differences in computed climatological fields. On finer resolution grids with lesser smoothing, climatological residual of mesoscale eddies with spatial scales larger than grid cell sizes can be directly resolved and the remaining mesoscale background represents the cumulative effect of mesoscale dynamics rather than a noise caused by objective analysis [21]. In this review, the theoretical background for the idea of eddy-resolving regional ocean climatology is briefly outlined based on several recently released products and publications.

We present a review of the NCEI regional climatologies, focusing on the NWA regional climatology (NWARC) as the most exemplary representative of the NCEI Regional Climatology Project. Hereafter, the newest version of the NWARC, version 2 [22] is referred to as simply the NWARC, while the earlier version of this regional climatology, version 1, is referred to as the NWARC v1 [23]. A brief description of NWARC v1 was first published in the Bulletin of American Meteorological Society [24]. Here we present a more elaborate review with more details and new analysis and results from NWARC and recent publications [21, 25-27].

3. World Ocean Database and World Ocean Atlas

To better understand and forecast ocean conditions and future changes, there is a need for quality-controlled ocean observations that are readily available to support ocean-related research. Two main tools were developed by NCEI to answer this call – the World Ocean Database (WOD) and the World Ocean Atlas (WOA).

3.1 World Ocean Database

The entire Earth climate dynamics and its long-term variability can be properly diagnosed only if the ocean changes can be assessed on the time scale of at least several decades. Therefore, the ocean-driven climate paradigm calls for developing oceanographic databases of quality-controlled historic data to reveal ocean thermohaline variability on decadal and longer time scales. One of the largest and most advanced world ocean databases is the WOD compiled at NCEI (formerly NODC) in Silver Spring, Maryland, USA. The first edition of the WOD was developed at NODC in 1994 and has been updated regularly since then. The updates include WOD98, WOD01, WOD05, WOD09, WOD13, and WOD18 (two last digits indicate the year of revision release). The WOD contains several essential oceanic parameters, such as temperature, salinity, oxygen, nutrients, etc. The fundamental element of the WOD is a profile (used to be called "cast' for onboard instrument deployments). A profile is defined as a set of measurements for a single variable (temperature, salinity, etc.) at discrete depths taken as an instrument drops or rises vertically in the water column [28].

The hydrographic profiles in WOD are from in-situ observations collected with various oceanographic instruments. Historical oceanographic temperature and salinity data from bottle samples or "Ocean Station Data" (OSD), Mechanical Bathy-thermographs (MBT; measuring only water temperature), ship-deployed Conductivity-Temperature-Depth (CTD) packages, Digital Bathythermograph (DBT; measuring only water temperature), Expendable Bathythermographs (XBT; measuring only water temperature), profiling floats (PFL), moored (MRB) and drifting (DRB) buoys, gliders (GLD), and undulating oceanographic recorders (UOR) profiles used in all World Ocean and regional climatology projects were obtained from the NCEI/NODC/WDC archives (WDC stands for World Ocean Center for Oceanography) and include all data gathered as a result of the GODAR and WOD Projects.

For climate studies, as well as for much ecosystem research, the key oceanographic values are temperature and salinity. WOD is the quintessential tool for assessing the long-term multi-decadal ocean climate variability in many regions of the World Ocean. The most up-to-date publicly-available published release of this database, WOD18, allows computing statistics and analyses through the end of 2017. The online version of the WOD, which is being updated quarterly, contains over 17.8 million temperature and over 10.5 million salinity profiles. It is available at the NCEI's HYPERLINK "https://www.ncei.noaa.gov/products/world-ocean-database"World Ocean Database website [29].

Temperature and salinity profiles are available for download in a uniform format with associated metadata and quality control flags. With such abundant temperature and salinity data, WOD18 has become even more invaluable for characterizing ocean climate states and trends at many locations and for various time intervals. However, in many applications, there is a strong demand for analyzed rather than raw data sets available through WOD.

3.2 World Ocean Atlas

The idea of calculating and mapping the long-term mean global ocean state using all available historic oceanographic observations was first executed by Sydney Levitus. Recorded oceanographic observations in the world's oceans and seas have more than 300 years of history, yet the first detailed global ocean water property maps were compiled and published in the Climatological Atlas of the World Ocean in 1982, just about forty years ago [30]. That first edition of this Atlas, known under the name of World Ocean Atlas (WOA) in all subsequent editions, was comprised of temperature, salinity, oxygen, and nutrients interpolated to a regular one-degree geographical grid at 33 standard depth levels from the surface to 5500 meters (Table 4, bold numbers). The monthly, seasonally, and annually averaged values of those parameters over the time of several decades were called "ocean climatologies" and used as the descriptors of the climatic state (i.e., averaged over many decades) of the ocean in numerous applications thereafter.

Although WOA has become a tool of choice for many scientific groups and individuals, the community of ocean, climate and earth system modelers is perhaps one of the premier groups of users of ocean observed climatology. At the time when the Climatological Atlas of the World Ocean was published [30], two-to-one-degree spatial resolution was the limit that could be achieved with then existing computing power and availability of data utilized in ocean numerical models [31, 32]. Thus, in the 80s and beginning of 90s, there was a close match between the so-called non-eddy-permitting and early eddy-permitting models with one-degree and sub-one-degree resolution and the WOA (there is a difference between "eddy-permitting" and "eddy-resolving" models, with the latter requiring at least one-tenth of a degree resolution; see below in this section). For example, Semtner and Chervin [32] constrained the computed thermohaline fields between 25 m and sea surface and below 700 m in a global eddy-permitting model with half-degree resolution by restoring them to the gridded data from Climatological Atlas of the World Ocean [30]. It was soon found, however, that some elements of the modeled ocean climate cannot be properly resolved in ocean computer simulations with grid resolution lower than a certain limit specific to those elements. For example, it was found that the spatial grid resolution sufficient for proper simulation of the Gulf Stream dynamics should be one-sixth of a degree or better [33].

What was technically impossible only about 30 years ago, had become feasible in late '90-s following a rapid surge in computing power and improved modeling skills [34-36]. By resolving ever-shorter spatial scale processes in the ocean, climate models have greatly surpassed the one-degree WOA resolution in providing far more detailed ocean simulated climatologies. Employing finer and finer resolutions in ocean and climate models continues with an increasing pace toward fully resolved mesoscale and even shorter spatial-temporal scales of ocean and climate dynamics.

Ocean models now fall in one of three major categories—the coarse-resolution or non-eddy-permitting, eddy-permitting, and eddy-resolving [37-39]. The eddy-resolving ocean models with one-tenths and one-twelfth degree grids are quickly replacing the eddy-permitting ocean models with horizontal grid sizes between half- to quarter-degree resolution [37, 40]; see a review in [41]. Coarse-resolution ocean models are quickly becoming obsolete and are used mostly in qualitative rather than quantitative ocean climate simulations.

To narrow the gap between observed and modeled ocean climatologies and to better serve the oceanographic community who rely on the NODC/NCEI ocean climatology products, quarter-degree temperature and salinity fields were first compiled by [42] at 33 depth levels. At the next step, a new edition - World Ocean Atlas 2018 (WOA18), which is the most recent descendant from the original Climatological Atlas of the World Ocean, was compiled at quarter-degree resolution at 102 depth levels for six decades: HYPERLINK "https://www.ncei.noaa.gov/products/world-ocean-atlas"World Ocean Atlas 2018. With a large number of new profiles added to WOD, this edition of WOA is far more detailed than all previous releases since 1982 [28]. NCEI regional climatologies are now extending this effort to provide one-tenth of a degree resolution in several critical ocean regions.

To comply with modern modeling development pace, the observed climatologies must break through the quarter-degree spatial resolution barrier and settle at one-tenth-degree or better. The main obstacle in attaining such high resolutions is the lack of adequate in-situ data coverage in most parts of the World Ocean except for a few, albeit critically important, regions. To generate high-quality regional climatologies with as high spatial resolution as possible in regions that have enough data coverage, the NCEI introduced in 2011 a Regional Climatology project, which is described in the following section.

4. NOAA Ocean Regional Climatology Projects

With modern computing power, it would be relatively easy to generate ocean climatology on grids with very fine resolution. However, in contrast with numerical models, the grid resolution in observed ocean climatologies is restricted not by computer power, but by availability of field data. The above-mentioned eddy-resolving ocean models can generate high-resolution output uniformly on any chosen grid anywhere, even over the entire World Ocean, but a high spatial resolution ocean climatology is supported by observations only in a limited number of regions of the World Ocean. Therefore, a global "high resolution" ocean climatology would be such in name only. Indeed, many grid cells in WOA18 contain less than three observed values even on the quarter-degree grid (see data distribution maps at World Ocean Atlas 2018), deeming one-tenth degree resolution for the entire World Ocean completely unrealistic.

However, there are a few regions where data availability may support true high-resolution ocean climatologies. A new level of detail is therefore achievable, even if only regionally. Coincidentally, but not surprisingly, all those regions are critically important for climate science, fishery, navigation, etc. Indeed, historically far more attention was directed toward better oceanographic description of those areas where humans needed such a description most.

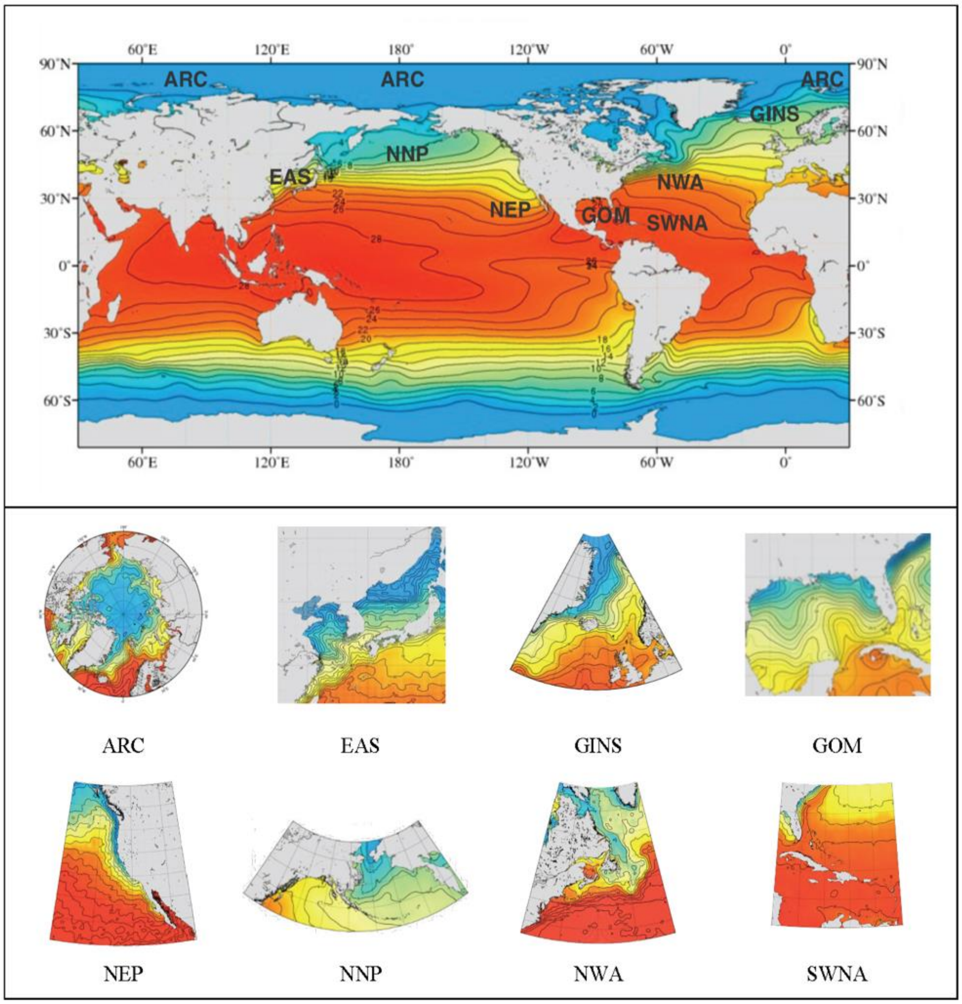


Figure 1: NCEI regional climatologies completed to date marked on the sea surface temperature field from World Ocean Atlas (WOA18). The abbreviations of the regional climatology names are: ARC— Arctic Regional Climatology, EAS—East Asian Seas, GINS—Greenland, Iceland, and Norwegian Seas; GOM—Gulf of Mexico version 2; NEP—Northeast Pacific; NNP—Northern North Pacific; NWA—Northwest Atlantic, and SWNA—Southwest North Atlantic.

The first regional climatology project had emerged and matured as a response to the urgent oceanographic research efforts linked to the Deepwater Horizon Oil Spill disaster in the Gulf of Mexico in April 2010. As a part of a wider multi-institutional project of compiling a new electronic edition of the NOAA Gulf of Mexico Data Atlas, a team of collaborators at NCEI (then NODC), created the Gulf of Mexico (GOM) Regional Climatology with one-quarter and one-tenth degree resolutions. After this first implementation, other projects followed: the *Oceanographic Atlas of the East Asian Seas* (EAS), *Arctic Regional Climatology* (ARC), *Greenland-Iceland-Norwegian Seas* (GINS), *Gulf of Mexico* (GOM) version 2, *Northwest Atlantic* (NWA), *Northern North Pacific* (NNP), *Northeastern Pacific* (NEP), and *Southwest North Atlantic* (SWNA) regional climatologies. All completed to date regional climatologies have been published at the NCEI regional ocean climatologies web portal and are shown in Figure 1.

The locations of the regional climatologies are denoted on the global one-degree annual surface temperature map from WOA18, while the individual regional climatologies are shown below the map in alphabetical order.

Structurally, all regional climatologies are similar to the WOA, with compilation and analyses of regional climatology inheriting all WOA techniques and methodology. The key difference between the regional versus global climatology approach is that observed data in the few selected regions have far fewer spatial and temporal gaps to be filled by interpolation than almost anywhere else in the World Ocean. Importantly, quality control on a finer spatial resolution grid reveals more obvious outliers than on coarser resolution grids. One of the advantages of compiling regional ocean climatologies is more thorough quality control of data performed on higher resolution grids. It in turn is instrumental for improving

WOD and recursively WOA quality by providing additional feedback in the areas of regional climatologies because of the quality control on a finer grid. Yet the most important advantage of regional climatologies is the dense spatial distribution of oceanographic measurements, helping to retain the sharpness of frontal zones and resolving many cumulative mesoscale features (quasi-stationary local vortices, topographic meanders, etc.; see the discussion in Chapter 9. In the next sections, the advanced features of regional climatologies will be demonstrated using the maps on one-, quarter-, and one-tenths of a degree grids for the newest and most up to date advanced regional climatology, the NWARC.

5. Northwest Atlantic Circulation and Climate

Selecting a region for developing a regional climatology is not a trivial task. Firstly, the region should be of high importance for several Earth System science disciplines, e.g., oceanography, climatology, ecology, etc., as well as for applications and allied sciences, such as fisheries, coastal engineering, coastal economics, etc. Secondly, the goal of developing a reliable high-resolution climatology must be achievable, i.e., the density of oceanographic observations must be adequate for high-resolution compilation. The Northwest Atlantic is an exemplary region where the research and practical demands imposed on the needed oceanographic data converge and are supported by data coverage. To understand why this region was selected for detailed analysis and to justify the NWARC project in general, some insights into major characteristics of the NWA dynamics and its climate role are outlined briefly in this and the next sections.

As a component of Earth's climate system, the Gulf Stream and its surroundings is perhaps the most important ocean current system in the World Ocean. The Gulf Stream originates as the Florida Current and flows north and northeastward along the U.S. East Coast to Cape Hatteras, where it separates from the coast and becomes the North Atlantic Current. The Gulf Stream System occupies the western part of the basin, as shown in Figure 2.

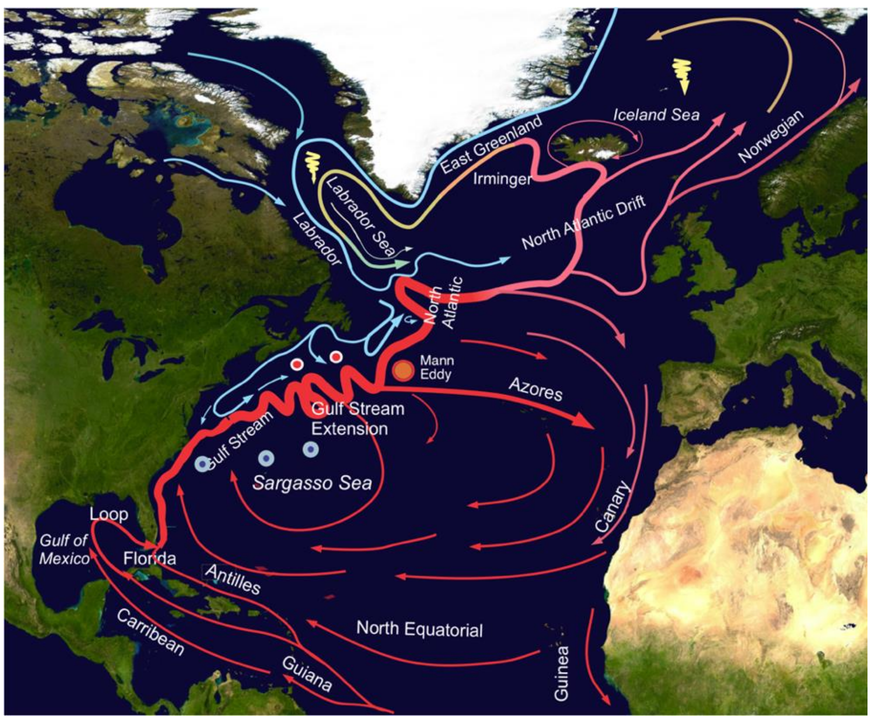


Figure 2: Scheme of the Northwest Atlantic Current System (modified from [24]; initial courtesy of I. Yashayaev). Red lines show warm and blue lines show cold currents; the convection sites in the Labrador and Greenland seas are depicted as yellow downward spirals; warm and cold Gulf Stream rings are shown as small orange and blue circles north and south of the Gulf Stream and its extension.

Many features of the Gulf Stream System are determined by the bottom topography and the structure of the western North Atlantic Ocean shelf break. Along the U.S. East Coast, the Gulf Stream is strengthened by the northern branch of the North Equatorial Current, the warm southern Gulf Stream recirculation gyre, and the cold northern recirculation gyre. In the north, the North Atlantic Current collides with the Labrador Current to form the Mid-Latitude Transition Zone (MLTZ) east of Newfoundland and the Great Banks. The Gulf Stream System, the Labrador Sea currents, the North Atlantic Current, and the MLTZ comprise four main elements of the NWA ocean current system (Figure 2).

The Gulf Stream Current System is perhaps one of the most studied and charted ocean current systems to date. By the middle of the

20th century, oceanographers had already gained rather detailed knowledge of the Gulf Stream, especially in close vicinity to the U.S. East coast [43-46]. Just north of Florida Strait, there is a confluence of the Florida Current and the eastbound parts of the Caribbean and Antilles currents – two derivatives of the westbound North Equatorial Current as it reaches the Antilles Islands –the southwest-most part of the large anticyclonic subtropical ocean circulation gyre generated by the anticyclonic wind stress curl over the subtropical North Atlantic. The westward intensification of the Gulf Stream as a western boundary current is caused by the Coriolis Effect on the spherical Earth [46-49]. The jet further intensifies between Florida Strait and Cape Hatteras by the entrainment of the water from two inner recirculation gyres to the north and south of the Gulf Stream core. The position of the stream as it leaves the coast changes throughout the year. In the fall, the core of the Gulf Stream shifts to the north, while in the spring it shifts to the south [47,50]. Newest analysis indicates that the main core of the Gulf Stream between 70°W and 50°W is very robust over many decades, with almost no changes in position of the jet axis, while the Gulf Stream extension east of 50°W shows far stronger south-north migration over several decades thus playing an important role in shifting of the Gulf Stream-adjacent ocean climate [26,27].

The two upper-ocean recirculation gyres mentioned above are the cold and warm gyres north and south of the eastbound Gulf Stream core. The cold water from the Labrador Sea flows westward along the coast (this flow is also known as the Slope Water Current). The warm water south and east of the Gulf Stream and its continuation circulates around the Sargasso Sea and comprises the Gulf Stream Recirculation Gyre [51, 52], also known as the Worthington Gyre, between 55ºW and 75°W [51]. Both currents feed the eastbound stream and contribute to the Gulf Stream transport increase between the Florida Strait and Cape Hatteras and especially further on along the Gulf Stream Extension.

After breaking from the continental shelf, the eastbound Gulf Stream becomes the Gulf Stream Extension and continues to strengthen before it turns north at the eastern flank of the Great Banks and finally becomes the North Atlantic Current [47,53]. The Gulf Stream Extension is a free baroclinic jet penetrating to the ocean bottom and its structure changes from a single, meandering front to multiple, branching fronts with a great deal of mesoscale activity and increasingly large meanders. Around 65°W the meandering envelope is nearly 500 km wide, which is five times the jet width at the separation point near Cape Hatteras. The water transport almost doubles downstream between Cape Hatteras and approximately 55°W resulting from the water fed by the Northern Recirculation Gyre (the Slope Water Current) and the Worthington Gyre.

The meanders and mesoscale eddies west of the North Atlantic Current comprise the MLTZ (see above) where cold and relatively fresh eastward flowing water from the Labrador Sea mixes with the warm and salty north-northeast flowing water of the Gulf Stream and North Atlantic Current (see Figure 3). Thus, the Gulf Stream, being a highly stratified (both vertically and horizontally) and very unstable jet current, serves both as a barrier and a blender of warm and cold waters along its edges. Blending, or mixing, of those waters is enabled by meanders and mesoscale eddies [54]. Further mixing is done by the so-called sub-mesoscale streamers that transition between eddy-induced mesoscale geostrophic mixing and smaller-scale turbulent mixing. New research shows that this type of mixing is especially important at the Cold Wall of the Gulf Stream, where the outer warm core of the Gulf Stream contacts the cold water that originated in the Labrador Sea[55, 56] (see also Figure 3).

There are two types of meanders: those generated by internal dynamic instability like in a free turbulent flow, and the quasi-stationary ones caused mostly by bottom topography. The large-amplitude meanders occasionally break off from the jet to form warm- and cold-core Gulf Stream rings (Figure 2). Anticyclonic warm core rings are found north of, and cyclonic cold core rings are found south of the Gulf Stream core. The rings migrate westward and occasionally remerge with the Gulf Stream.

The rings and meanders facilitate effective heat and salt exchange across the Gulf Stream frontal zone. Another source of mesoscale activity that can cause large-scale variability on longer time and space scales are the mesoscale eddies that are also known as geostrophic turbulence [57, 58]. analogous to atmospheric eddy-like motion [59]. Nonlinear eddies are important mixing agents of the large-scale ocean circulation capable of rather efficient transport of water parcels and their associated physical, chemical, and biological properties across strong frontal zones (e.g., [54, 60-62]). In general, the kinetic energy of mesoscale eddies surrounding strong jet-like currents is larger than the kinetic energy of the averaged mean flow. Those eddies are also thought to generate upscale energy flow to intensify large-scale currents [33, 57, 63, 64]. The thermohaline structure of the Gulf Stream reflects eddy-jet dynamics [65]. Snapshots of sea surface temperature in the Gulf Stream region using satellite imagery or eddy-resolving models show very intense mixing and turbulent structure with clearly seen mesoscale eddies, meanders, and rings, as shown in Figure 3.

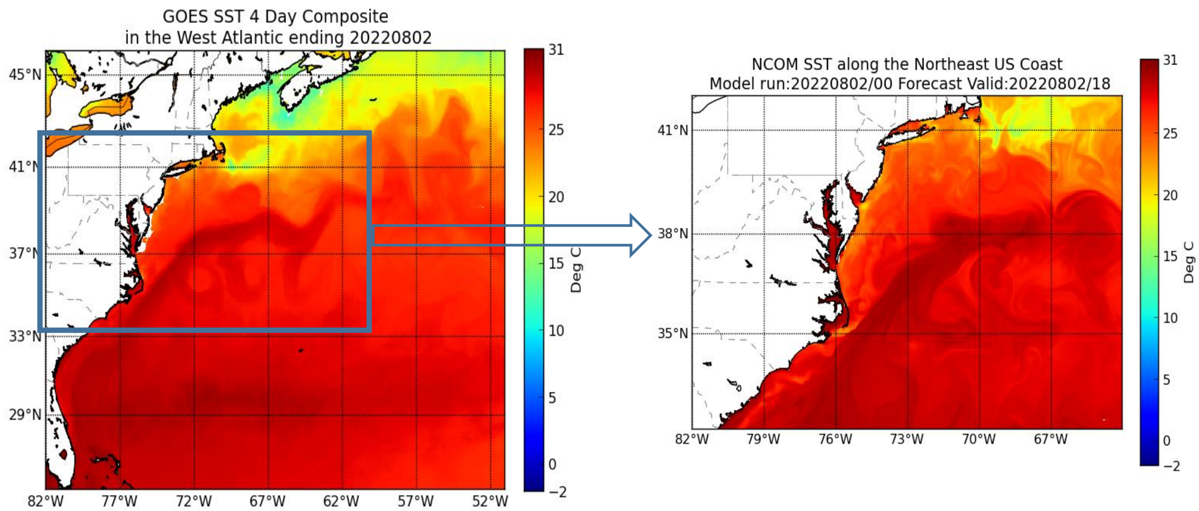


Figure 3: Snapshot of observed and modelled sea surface temperature in the Gulf Stream region: (left) from GEOS satellite-derived sea surface temperature record, and (right) from US Navy NCOM High Resolution Ocean Model (source: NOAA Ocean Prediction Center NCOM High-resolution Ocean Model).

As mentioned before, the east-northbound Gulf Stream along the North America east coast and the Gulf Stream Extension are energetic baroclinic currents with a strongly stratified warm and salty core shoaling downstream. In contrast, the east-southbound Labrador Current is much more barotropic with both upper and lower branches flowing south-east along the Canada and U.S. eastern shelf and continental slope, known also as the Western Boundary Current or WBC (upper branch) and Deep Western Boundary Current or DWBC (deep-sea branch) of the Labrador Sea. The DWBC is the deep limb of the Atlantic Meridional Overturning Circulation—one of the key elements of global ocean circulation and one of the most important oceanic climate controls.

6. Atlantic Meridional Overturning Circulation

One of the major purposes of NCEI climatologies is to support ocean climate research, especially the exploration of global and regional ocean thermohaline circulation shaping the Earth's global climate and thus being a focus of modern climate studies. The NWARC is specifically targeting a region that is fundamentally important for the entire climate system. Indeed, of all branches of the global thermohaline circulation [19], also known as a "global conveyor belt" [20], the most important is the Atlantic branch, usually referred to as the Atlantic Meridional Overturning Circulation (AMOC). The AMOC is thought to be the most important driver of ocean climate variability on decadal and longer time scales [66-73].

The AMOC's near-surface, warm northward flow is compensated by a colder southward return flow at depth. The AMOC carries warm water to high latitudes where heat loss to the atmosphere leads to the formation of the North Atlantic Deep Water (NADW) in the northern North Atlantic, Nordic and Labrador Seas. The deep southward flow of NADW comprises the deep branch of the AMOC. The strength of the AMOC, i.e., its meridional water transport, and its meridional heat transport are estimated as 17.2 Sv (1 Sv=106 m3s-1) and 1.25 PW (1 PW=1015 W) ([74]; maximum recorded transport was as high as 18.7 Sv [75].

Changes in the AMOC can contribute to climate changes on regional and even global scales in ways that are yet to be completely understood. On interannual to decadal timescales, AMOC changes are primarily caused by buoyancy anomalies on the western boundary and in the MLTZ (see above), or a "western transition zone" between the subtropical and subpolar gyres [68]. A decline in AMOC transport over the past couple of decades has been reported in a number of publications [67, 76-79], although some authors believe that there was no slowdown of the Gulf Stream seen in observations on a longer time scale [80-82]; see a recent review in [83]. It is instrumental to see if the interannual and decadal variability of the AMOC is manifested clearly in historical oceanographic data, or, alternatively, how the AMOC long-term variability connects to ocean changes revealed in the in-situ decadal-scale oceanographic observations integrated in WOA18 and NWARC.

One of the important questions linked to AMOC functionality is about the large temperature and salinity anomalies in the Gulf Stream area due to the jet wobbling and path shifts. The Gulf Stream path shift attracted much attention over the years, e.g., [26, 84-88]. Many factors could influence the Gulf Stream path shifts if such a shift had indeed occurred on the decadal time scale. The high-resolution NWARC could be used to verify whether decadal shifts of the thermal front can be diagnosed from historic hydrographic data. As the jet width itself is on the order of ten to a hundred kilometers, the minimum latitude-longitude resolution that is sufficient to pursue this goal is 0.1°x0.1° or better. Thus, this is another obvious motivation for compiling a high-resolution climatology in this region. In fact, the Gulf Stream path shift is clearly seen in an earlier high-resolution NWARC v1 analysis [21] and has been studied in detail using in-situ data. It has been shown that the Gulf Stream axis migration caused by the overall warming trend in the Gulf Stream surrounding is quite substantial, especially in the last decade, e.g., [25-27].

7. Northwest Atlantic Ocean Climate and Ecosystem Dynamics

The NWA is a resource-rich coastal zone with abundant fisheries and other substantial natural resources. Its economic significance and climatic importance spurred intensive observational and research programs spanning many decades. Climate change has always affected fisheries e.g., [89], but the North Atlantic fisheries dependence on long-term ocean climate variability was an especially acute topic of many research efforts [90]. The variability of the Gulf Stream System and its connection to fisheries, and more generally to the regional marine ecosystem is now under the spotlight in many ecosystem research and review papers[91-97].

Aquatic ecosystems are extremely sensitive to oceanographic conditions and to ongoing ocean and climate change [98-101]. Especially important as climate change increases global temperatures, are coastal zones with exceptionally high biological productivity and high rates of biogeochemical cycling [101, 103]. The migration of the frontal zones was a critical driver for marine ecosystems through ages [94] as the composition of the water masses affect the marine biodiversity that can thrive in the area affected.

The Northwest Atlantic near the U.S. and Canadian coastal zones has been the focus of intensive research linked to fisheries and ecological health of the coastal water [97, 98, 104-107]. A substantial effort has been made to find connections between ecosystem dynamics and variability with large-scale ocean circulation and major climate indices such as the North Atlantic Oscillation (NAO), Atlantic Multidecadal Oscillation (AMO), etc. [25, 108-113]. Vulnerability of fisheries in the coastal zones of North America's eastern coast in response to ocean and climate change has been specifically addressed as a prime topic of fisheries-climate connections [89, 90, 97, 108, 114, 115].

As described above, the NWA region is characterized by a very complex circulation pattern with fine-structured circulation and recirculation gyres, meandering jets, nonlinear baroclinic waves, meanders and rings strongly interacting with the Gulf Stream, Gulf Stream Extension, and the Labrador Current. Many research efforts point toward an intricate but clearly observed connection between biological indicators, such as chlorophyll and phytoplankton concentration and variability, and the eddy regime in the Gulf Stream System [116-119]. To provide a meaningful and useful observational oceanographic background for fisheries and ecosystem research, a spatial resolution that can resolve ocean jets, meanders, and the cumulative effects of mesoscale eddies with the grid sizes of just a few tens rather than hundreds of kilometers, is in strong demand.

Indeed, for an eddy with the size of 50 km, which is approximately half of the baroclinic Rossby wavelength, one-degree spatial resolution does not resolve this wavelength at all, while the quarter degree gives only five points per wavelength and thus provides just a borderline resolution of baroclinic eddies. The one-tenth-degree longitude-latitude grid, on the other hand, has 8 to 10 grid points in mid-latitudes and thus provides sufficient resolution for the spatial scales of the baroclinic Rossby deformation radius. Additionally, the seasonal cycle, which may have spatial shifts of currents of tens to hundreds of kilometers, is superimposed on interannual variability and is essential for all elements of marine ecosystems [73, 117]. The decadal-scale changes in seasonal cycles in this dynamically complex and highly variable ecosystem are of paramount importance, especially for fish stocks. Global models that can resolve regional scale are essential for understanding the connections between the regional processes and large-scale climate variability [120]. Validation of these models is principal and depends on high-resolution observations integrated in the regional climatologies. We can conclude, based on climate research and application demands, that selection of the NWA region for a more detailed analysis and mapping is timely and justified.

8. Northwest Atlantic Regional Climatology

The NWARC domain is bounded by 80.0°W and 40.0°W longitudes and 32.0°N and 65.0°N latitudes (see Figure 4). The NWARC data suite consists of analyzed temperature and salinity fields computed at three grid resolutions (one-, quarter-, and one-tenth-degree) to map the mean state of the ocean in the NWA area and to assess long-term climatological tendencies in this important region. The set includes objectively analyzed temperature and salinity fields on all grids as well as auxiliary variables (explained below) that may be useful for applied climate studies. The analyzed and statistical fields are annual, seasonal, and monthly providing a climatological year, four climatological seasons, and twelve climatological months for each decade.

All data from the WOD18 between 1955 and 2017 in the NWARC domain were used to calculate six decadal climatologies within the following time periods: 1955-1964, 1965-1974, 1975-1984, 1985-1994, 1995-2004, and 2005-2017 (Table 1; see WOA18 Documentation for more details). The ~60-year climatology was calculated by averaging the six individual decades listed above, e.g., [28]. For all three grid resolutions mean bottom depth values were extracted from the ETOPO2 World Ocean bathymetry data set.

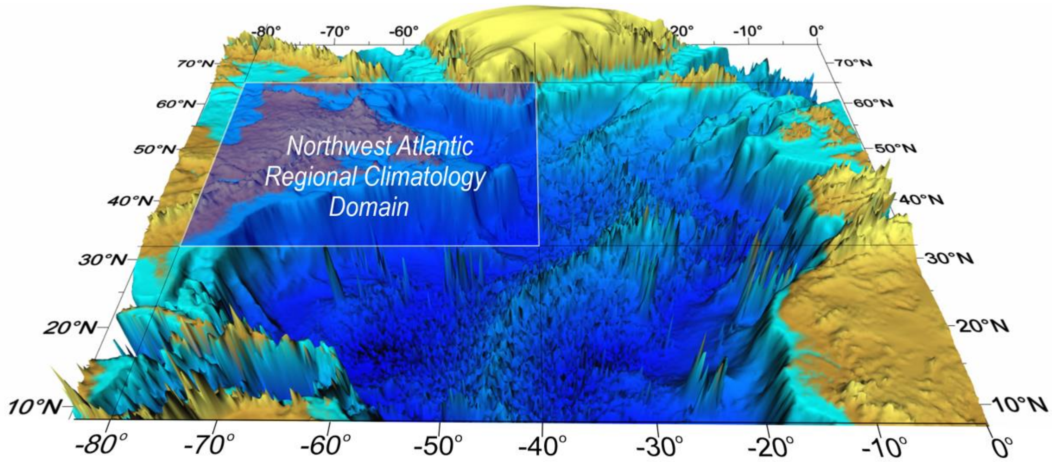


Figure 4: Bottom topography of the North Atlantic Ocean (ETOPO2 Global Relief Model from NOAA) with the outline of the NWA regional climatology domain.

The NWARC is designed similarly to WOA18, and therefore all characteristics of WOA18 applies to NWARC. Hence, the following description of NWARC mostly follows WOA18 [121, 122] NWARC v1 [23] publications. The specific features of NWARC are addressed further in the text regarding the data coverage, objective analysis, and quality control in the NWA region.

Time span	Abbreviation	Comment
1955 – 1964	5564	First decade with sufficient data for climatological mean fields
1965 – 1974	6574	
1975 – 1984	7584	
1985 – 1994	8594	
1995 – 2004	95A4	The coverage includes Argo floats
2005 – 2017	A5B7	
1955 – 2017	*decav*	Average of six decadal means (*decav* = *dec*adal *av*erage)

Table 1: Time spans in WOA18 and NWARC.

Analyzed, statistical, and auxiliary variables included in NWARC are compiled at 102 standard depth levels for one-, quarter-, and one-tenth-degree spatial resolution grids. Here is a short description of those fields:

● Objectively analyzed climatologies: objectively interpolated mean fields for an oceanographic variable at each standard depth level. The statistical mean: the average of all data values that pass quality control checks in each grid cell which contain at least one measurement for the given oceanographic variable at each standard depth level.

● The number of observations of each variable in each grid cell at each standard depth level.

● The standard deviation from the statistical mean of each variable in each grid cell at each standard depth level.

● The standard error of the mean of each variable in each grid cell at each standard depth level.

● The seasonal or monthly climatology minus the annual climatology at each grid cell at each standard depth.

● The statistical mean minus the objectively analyzed climatological mean at each grid cell at each standard depth. This value is used as an estimate of interpolation and smoothing error.

The depth levels chosen as follows: in the first one hundred meters the depths increment is 5 meters, between 100m and 500m the increment is 25m, between 500m and 2000m the increment is 50m, and below 2000m to the last depth level of 5500m, the increment is 100m. Because of sparseness of monthly data below 1500m, the monthly climatology is defined for the upper 57 levels only.

Temperature	1955-1964	1965-1974	1975-1984	1985-1994	1995-2004	2005-2017	1955-2017
January	8,983	11,448	7,811	6,402	5,840	12,445	52,929
February	10,863	10,829	9,618	7,935	7,627	13,129	60,001
March	12,654	16,822	13,866	10,018	9,016	19,167	81,543
April	17,233	18,749	15,956	11,574	28,920	20,604	113,036
May	21,459	24,126	18,461	14,102	35,510	23,529	137,187
June	24,191	23,163	19,245	14,225	17,539	18,372	116,735
July	23,400	24,875	19,824	12,534	18,061	31,943	130,637
August	22,625	25,662	20,115	14,618	17,531	38,749	139,300
September	18,134	22,860	15,640	11,643	14,623	52,662	135,562
October	15,534	20,409	18,218	11,437	14,863	40,393	120,854
November	16,736	18,314	15,422	13,110	15,371	19,821	98,774
December	10,635	10,977	7,156	7,114	10,415	13,269	59,566
Total	*202,446*	*228,234*	*181,326*	*134,711*	*195,315*	*304,083*	*1,246,116*

Table 2: Number of temperature profiles in NWA region for each decade from 1955 to 2017.

Seasonal and annual means were computed as averages of monthly fields above 1500m and as averages of all data for seasonal fields below that level. The annual fields were computed by averaging the seasonal fields. There is almost no seasonal cycle signal below 1500m depth, except for the region of deep convection, with the convection intensity depending on seasons.

Tables 2 and 3 show the number of temperature and salinity profiles held in WOD18 (after automatic and manual quality control performed) within the NWA domain by months for each decade and for the entire 1955-2017 period. Thus, number of temperature profiles collected in January of each year over 1955-1964 decade is shown as January profile number in '1995-1964' column of Table 2. The rightmost column shows total profiles count from 1955 to 2017.

Data density is generally quite high; in fact, the data coverage is much denser in the NWA domain than in most of the World Ocean. Nonetheless, the availability of temperature and salinity profiles varies in space and time within the NWA domain quite substantially, and there is also a significant variation of data availability between the decades and between the seasons in each decade.

Salinity	1955-1964	1965-1974	1975-1984	1985-1994	1995-2004	2005-2017	1955-2017
January	858	2,396	3,207	2,757	3,303	7,064	*19,585*
February	1,254	2,473	3,309	3,155	5,084	6,934	*22,209*
March	1,493	3,544	5,040	4,257	5,703	13,317	*33,354*
April	2,976	5,832	6,161	6,585	25,239	15,928	*62,721*
May	2,744	6,395	7,348	7,657	31,538	19,260	*74,942*
June	3,355	6,761	8,085	7,269	8,591	15,393	*49,454*
July	4,082	7,690	10,430	7,808	10,248	29,017	*69,275*
August	3,910	7,811	10,133	8,947	10,024	35,893	*76,718*
September	2,270	5,573	6,417	6,744	8,861	49,992	*79,857*
October	1,609	4,343	6,708	6,810	8,224	37,088	*64,782*
November	1,663	4,307	5,566	7,192	8,474	15,546	*42,748*
December	,891	1,992	2,574	3,664	4,518	9,788	*23,427*
Total	*27,105*	*59,117*	*74,978*	*72,845*	*129,807*	*255,220*	*619,072*

Table 3: Number of salinity profiles in NWA region for each decade from 1955 to 2017.

Figures 5a, and 5b provides a better than in Tables 2 and 3 visualization of the monthly coverage in the six decades. Its reveal an interesting tendency that could not have been anticipated a priori, namely, a decreasing number of in-situ observations in the NWA over the period of record, except for the last decade of 2005-2017, when the number of observations exploded.

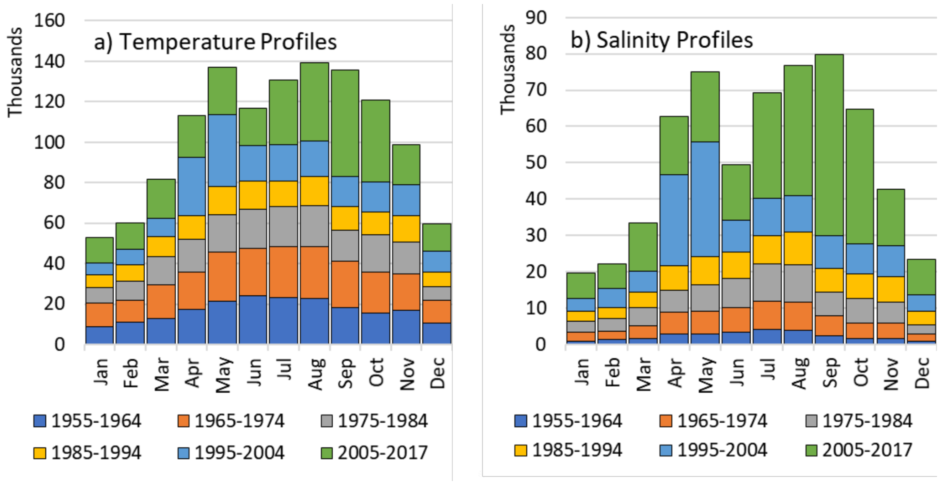


Figure 5: Number of (a) temperature and (b) salinity profiles in NWA region for each month of each decade from 1955 to 2017.

Even considering that the last "decade" is three years longer than others, the increase of the temperature observation numbers is notable—over 100,000 more than in the previous decade of 1995-2004. Adjusted for the extended duration of the last "decade", the number of profiles is still somewhat smaller than in the 1965-1974 period, when the Gulf Stream region was most intensively observed [12]. Comparison of temperature and salinity by instruments gives a hint to why the number of observations has decreased in recent years, and why the last decade shows such an impressive increase of profiles. Figures 6a, and 6b show the number of temperature and salinity profiles, respectively, for each of the six decades obtained using different instruments.

In Figure 6, the abbreviations stand for: OSD–Ocean Station Data (bottles); MBT–Mechanical Bathythermograph; XBT–Expendable Bathythermograph; CTD–Conductivity-Temperature-Depth; PFL–Profiling Float; UOR–Undulating Oceanographic Recorder; GLD– Glider (see text), APB–Autonomous Pinniped Bathythermographs. Note that we do not show the data from MRB (Moored Buoys) because they provide large amounts of data, but in fixed locations, whereas all other instruments are responsible for areal coverage (i.e., MRB data are included in the NWARC, but are not accounted for in the Tables and Figures).

As the older instruments, like MBT, left the scene and the new ones, like PFL (which is mainly Argo), came into use, the number of profiles per decade in the region changed accordingly. This is another caveat of replacing onboard measurements (e.g., from ships or stationary buoys) with data from passive drifters of any type. Both are important and should be used concurrently rather than interchangeably. Argo floats, or any drifters for that matter, are not designed to target specific sites or provide specific regional coverage as they tend to disperse and follow circulation patterns rather than to remain in a selected region, as would be the case in the in-situ observations from ships or stationary buoys. Contrasting to ship-based observations usually targeting specific regions, the drifters tend to cover some regions more homogeneously, with lesser observation density in specific areas, which may or may not be the desired outcome depending on research goals. Figure 6 reveal the surge in PFL profiling during the last 13 years. In 2005-2017 there were 45,813 PFL observations in the NWA region—compared to 17,626 in the previous decade. The future of in-situ observational oceanography clearly leans toward the overwhelming dominance of Argo and other autonomous platforms like gliders.

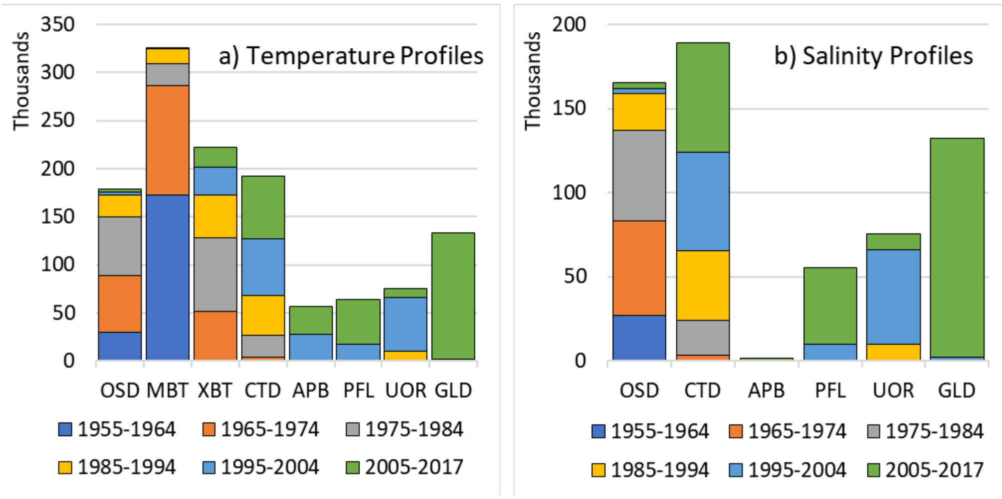
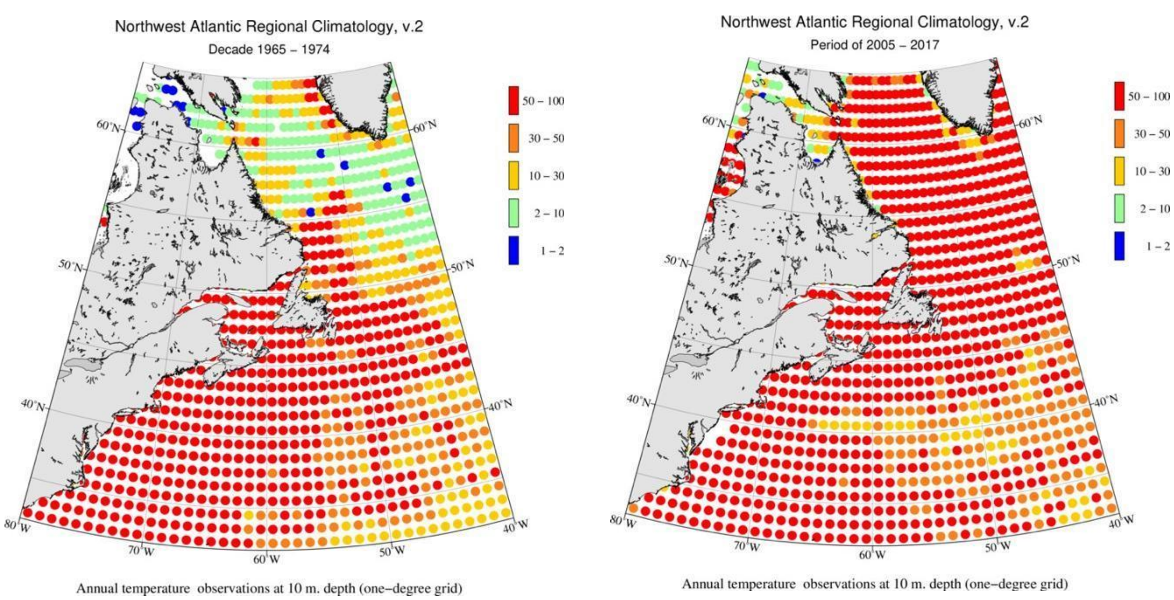


Figure 6: Number of (a) temperature and (b) salinity profiles in NWA region for each decade per instrument.

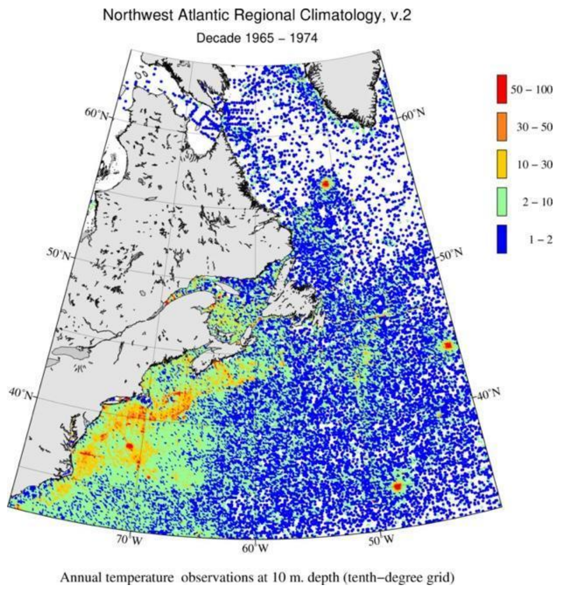
Figures 7a and 7b shows the density of annual temperature observations in the NWA domain on the one-degree grid at 10m depth for 1965-1974 and 2005-2017 decades respectively.

Figures 8a and 8b shows the density of annual temperature observation for the same decades but on the one-tenth-degree grid. (Entire collection of data coverage maps for both temperature and salinity for all climatological months, seasons, years, at all depths and grids can be found at the NWARC website).

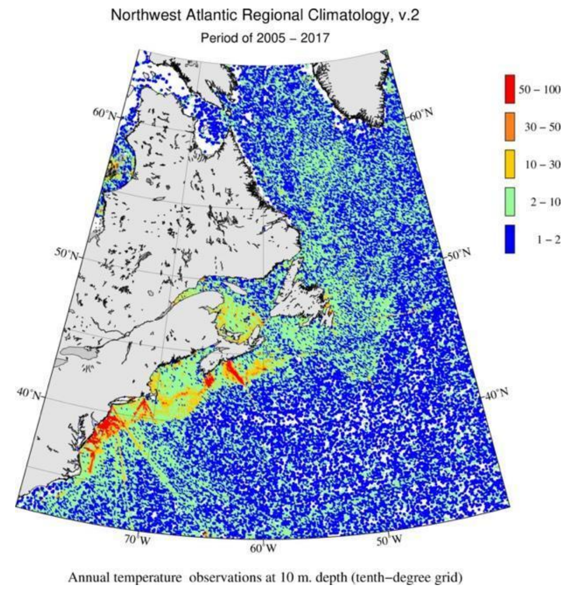


a) b)

Figure 7: Density of annual temperature observations (number of observations per grid box) at 10 m depth for periods of (a) 1965 - 1974 and (b) 2005 – 2017 within one-degree grid boxes.



a)



b)

Figure 8: Density of annual temperature observations (number of observations per grid box) at 10 m depth for periods of (a) 1965 – 1974 and (b) 2005 – 2017 within one-tenth-degree grid boxes.

There are significantly fewer spatial gaps between observations or empty cells in the more recent decade of 2005-2017 than in 1965-1974, particularly at higher latitudes. However, the Gulf Stream and U.S. coastal areas, where many massive oceanographic programs were conducted in 1965-1974 [12], are noticeably better covered by observations than in 2005-2017 [12]. That is, modern technology helps to cover wider areas, often under-sampled by traditional instruments, especially away from the coastline in rogue weather area, but at the expense of fewer focused observations which were characteristic of the earlier decades when intensive studies of the Gulf Stream in the 60's and 70's and mesoscale ocean eddies in the 70's and 80's occurred. On the other hand, the finer resolution is better facilitated by newer technology that helps to close the gaps and allows compiling high-resolution regional climatologies, as in the NWA case. For example, the Labrador Sea is far better covered in 2005-2017 when compared to 1965-1974 (Figures 7a and 7b), with improved coverage due to the introduction of Argo floats and gliders. At the same time the Gulf Stream between the Florida Strait and Cape Hatteras was better covered in 1965-1974, when many special programs studying the Gulf Stream were conducted (compare Figures 5a and 5b). Obviously, there are more PFL and GLD profiles in 2005-2017, also because this period covers 13 years (see Tables 2 and 3 and Figure 6), yet mostly because the PFL and GLD are becoming the most advanced and common modern observing platforms.

Even in the very well covered NWA region, there are more profiles in summer than in winter (Tables 2 and 3 and Figure 5 above), and there are noticeable differences between colder and warmer months. If the seasonal or annual fields were calculated using all annually and seasonally available profiles, they may become biased toward warmer months within seasons and to summer months in annual average. Such bias in data collecting patterns is because sea-going expeditions are more often planned for the seasons with better weather conditions. To alleviate such a possibility, the new approach to aggregating data using climatological months to compute climatological seasons and years was first used in both WOA13 and NWARC v1 and then continued in WOA18 and all regional climatologies after NWARC v1 (see Figure 1). The seasonal fields are computed as the average of three months comprising each season, and the annual fields are computed as the average of four seasons. Although monthly fields are computed at all levels and principally could have been used to calculate seasonal fields at all levels, in the NWARC the monthly fields are used to compute seasons and are shown only in the upper 1500 m, while seasonal fields are computed using all data within a season and shown below 1500 m. The caveats of using monthly and seasonal fields in the deep ocean will be discussed further.

Notably, NWARC has one-tenth-degree spatial resolution for annual, seasonal, and monthly temperature and salinity fields for all six decades. The compilation of fields at such high resolution in both temperature and salinity provides a tool for assessing high-resolution ocean climate records based solely on historical in-situ hydrographic observations over sixty years, which is twice the WMO-recommended climate definition length. Moreover, the quality control on a higher-resolution grid reveals more outliers than on coarser resolution grids, as more observed profiles are found within fronts, stationary meanders, etc. Compared to lower resolution, the structure of the gridded fields with one-tenth-degree resolution is far better captured, especially in areas with sharp gradients of the essential oceanographic parameters (temperature, salinity, etc.). Such gradients and other persistent mesoscale features are better preserved in the generated climatological fields, which makes high-resolution climatologies more valuable for ocean modeling and other applications. (Importantly, were they not persistent, mesoscale features would have been filtered out by decadal averaging, even at high spatial resolution; see further in the text).

9. Data Processing and Objective Analysis

This section provides a summary of how profile data from WOD are processed to create a gridded climatology following the detailed descriptions in the Temperature and Salinity volumes of the WOA18 [121,122]. Further information on the data sources used in WOA18 and detailed descriptions of the methods and techniques, which are fully applicable to NWARC, can be found in [28].

To understand the procedures for taking individual oceanographic observations and constructing climatological fields, it is necessary to define the terms "standard level data" and "observed level data." We refer to the actual measured value of an in-situ oceanographic variable as an "observation", and to the depth at which such a measurement was made as the "observed level depth." We refer to such data as "observed level data." All standard depth levels used in WOA18 and in NWARC are listed in Table 4. The procedure of interpolating data from actual depths of observations onto the standard depths is described in the WOA18 documentation [28, 121, 122].

Quality control of the temperature and salinity data is a major task, the difficulty of which is directly related to availability of data and metadata upon which to base statistical checks. The quality of oceanographic datasets and their usability for a given application critically depend on the data coverage. Data coverage as used here is not just the volume of data in the region, but refers particularly to the spatial distribution of data, which is the key indicator of the quality of the data set used to obtain climatological means. The data coverage varies hugely in different regions of the World Ocean. Thus, the success of compiling a meaningful and useful regional climatology critically depends on how much data is available and how they are distributed over a selected domain. Fortunately, as was mentioned above, the NWA region is one of the best data-covered regions of the World Ocean thus giving an optimism for compiling a meaningful high-resolution regional decadal climatology. It can therefore be anticipated that NWARC will provide a solid oceanographic foundation for ocean climate studies and numerous practical applications with embedded dependencies on long-term ocean climate change.

Standard Level #	Standard Depths (m)	Standard Level #	Standard Depths (m)	Standard Level #	Standard Depths (m)	Standard Level #	Standard Depths (m)
1	**0**	27	**250**	53	**1300**	79	3200
2	5	28	275	54	1350	80	3300
3	**10**	29	**300**	55	**1400**	81	3400
4	15	30	325	56	1450	82	**3500**
5	**20**	31	350	57	**1500**	83	3600
6	25	32	375	58	1550	84	3700
7	**30**	33	**400**	59	1600	85	3800
8	35	34	425	60	1650	86	3900
9	40	35	450	61	1700	87	**4000**
10	45	36	475	62	**1750**	88	4100
11	**50**	37	**500**	63	1800	89	4200
12	55	38	550	64	1850	90	4300
13	60	39	**600**	65	1900	91	4400
14	65	40	650	66	1950	92	**4500**
15	70	41	**700**	67	**2000**	93	4600
16	**75**	42	750	68	2100	94	4700
17	80	43	**800**	69	2200	95	4800
18	85	44	850	70	2300	96	4900
19	90	45	**900**	71	2400	97	**5000**
20	95	46	950	72	**2500**	98	5100
21	**100**	47	**1000**	73	2600	99	5200
22	**125**	48	1050	74	2700	100	5300
23	**150**	49	**1100**	75	2800	101	5400
24	175	50	1150	76	2900	102	**5500**
25	**200**	51	**1200**	77	**3000**		
26	225	52	1250	78	3100		

Table 4: Standard depth levels used in NWARC.

The data used in ocean climatology calculations needs to be pre-processed to ensure the quality of the gridded and analyzed fields. First, duplicate profiles and obvious outliers must be removed prior to visual inspection and final manual quality control preceding climatology compilation. Because both in-situ temperature and salinity data are received from many sources, it is possible that, in some instances, the same data set is received at the NCEI archived more than once bearing slightly different time and/or position and/or data values due to different generalization and rounding applied by data originators, and hence are not easily identified as duplicates. To detect and eliminate the repetitive data values, WOD is constantly being checked for the presence of exact and "near" exact duplicates using several sets of different criteria combinations. The initial set of checks involve identifying stations with exact position/date/time and data values; the next checks involve offsets in position/date/time, etc. Profiles identified as duplicates in the checks with a large offset were individually verified to ensure they were indeed duplicate profiles.

Range checking (i.e., checking whether a measured value is within a preset minimum and maximum limits as a function of depth and ocean region) was performed on all temperature and salinity values as a first step of a quality control to flag and withhold from further use the relatively few values that were grossly outside expected oceanic ranges. The procedure is detailed in Johnson et al. (2013).

As summarized in WOA18 publications, e.g., [121], initially the five-degree square statistics were computed, and the data flagging procedure was used to provide a preliminary data set. Each five-degree square box was designated as coastal, near-coastal, or open ocean, depending on the number of one-degree latitude–longitude grid boxes in the five-degree box which were land areas. The data exceeding three, four and five standard deviations in the open-ocean, near-coastal and coastal areas, respectively, were flagged to be excluded from computing and re-computing the climatology.

After the initial cleaning of data is completed and outliers identified, the one-degree square statistics are computed, and the data flagging procedure described above was used to form a preliminary data set. Next, new one-degree-square statistics were computed from this preliminary data set and used with the same statistical check to produce a new, cleaner data set. At the first step of the two-step statistical check any grossly erroneous or non-representative data are found and flagged. At the second step, the values with smaller differences that are still non-representative are identified.
Each cast containing both temperature and salinity was checked for static stability, E, as used by [123] and is given by:

$$E = \frac{1}{\rho_0}\frac{\delta\rho}{\delta z} \qquad (1)$$

where: ρ_o= 1.02 kg•m^{-3}.

As noted by, static stability "is the individual density gradient defined by vertical displacement of a water parcel (as opposed to the geometric density gradient) [123]. For discrete samples the density difference (δρ) between two samples is taken after one is adiabatically displaced to the depth of the other". For the results at any standard level (k), the computation was performed by displacing parcels at the next deeper standard level (k+l) to level k.

The final and most time-consuming step in data pre-processing is a subjective, manual review where the data are contour-plotted and so-called "bullseyes" are visually detected and marked to remove the data from part of the profiles or sometime the entire profiles from subsequent recalculation of the climatology. The quality control for the NWARC was done on all three grids: a one-, a quarter-, and a one-tenth-degree. For the one-degree analysis, the temperature and salinity data were averaged by one-degree cells for input to the objective analysis program. After initial objective analyses were computed, the input set of one-degree means still contained questionable data contributing to unrealistic features, yielding intense "bullseyes" or unlikely spatial gradients. If bullseyes or unrealistic gradients were found the data were flagged. The procedure was repeated for the quarter- and one-tenth-degree grids.
After subjective manual quality control procedures were completed on all grids for all decades, the new first guess field was calculated on a one-degree grid and then all climatologies were recomputed and the objective analysis was performed on all grids and all accompanied statistics were recalculated. The first-guess field for each of these climatologies is the temperature and salinity fields compiled using all available data.

Summarizing, the zonal mean fields are used as the first guess for compiling one-degree fields. Then one-degree fields are used as the first-guess field for compiling quarter-degree fields, and the quarter-degree fields are used as the first guess for compiling the one-tenth-degree fields. Usually, several iterations of manual quality control and subsequent climatology re-run procedure was executed to ensure the best possible quality within reasonable time and effort.
These data processing procedures comprise the entire sequence of steps resulting in compiling a climatology or a set of climatologies. The NWARC contain six decadal climatologies, and decav (the average of six decadal) climatology. Compilation of the climatologies consists of several technical sub-procedures described in depth in a number of WOA publications and in some research papers based on various versions of WOA,e.g., [8, 42, 124, 125].

The NWARC, like all previous versions of WOA and all regional climatologies, was built using a procedure widely known in geophysics as objective analysis of irregularly distributed data [126]. The objective analysis scheme adopted in all editions of WOA since WOA98 was introduced in [127] and then updated in [128] and [129]. Here, an objective analysis scheme as implemented at NCEI is described. A three-pass correction is used that begins with the 'first-guess' fields described above. The second step is finding all data that are available within an influence radius around the center of the grid cell being analyzed. The correction to the first-guess values at all grid points is then computed as a distance-weighted mean of all grid point difference values that lie within the influence radius. This correction procedure is repeated twice more, each time with a decreasing search radius, for a total of three passes.

The idea behind the use of the influence radius in the objective analysis scheme used, can be briefly outlined following [8, 30] and, e.g., [121]. For computing the objectively analyzed values of an oceanographic parameter, e.g., temperature, salinity, etc., on the one-degree grid, at each standard depth level all data within each one-degree grid cell are averaged and first-guess values are subtracted to produce a mean anomaly value. A definition of an influence region is introduced based on an influence radius, R, around each one-degree cell to compute a "correction" using all one-degree square values in the influence region based on a Gaussian-shaped, distance-related weight function. At each one-degree cell, the correction is added to the first-guess field to produce an "analyzed" value. The goal of the entire procedure is to fill all gaps in data coverage and produce relatively smooth yet realistic fields of ocean variables on a regular grid.

More details about the objective analysis scheme used to generate the climatological fields can be found in the In addition to the WOA documentation cited above, the mathematical background of the technique is revisited in the Appendix of the above cited publication Levitus et al. [8]. The Appendix in Levitus et al. also provides a description of how the statistical errors of an objectively analyzed gridded field can be estimated using a general formula for error propagation [131].

The influence radius is different for different grid resolutions and varies in the three-pass objective interpolation procedure for one, one-fourth and one-tenth degree grids respectively (see Table 5; more detailed explanation in the next section).

Pass Number	1° Radius of Influence	1/4° Radius of Influence	1/10° Radius of Influence
1	892 km	321 km	253 km
2	669 km	267 km	198 km
3	446 km	214 km	154 km

Table 5: Radii of influence used in objective analysis for one-degree, quarter-degree and one-tenth-degree NWA climatologies.

Thus, as seen in Table 5, the radius of influence in one-tenth-degree resolution is 30% shorter than in the quarter-degree one, which restrict influence from geographically compact region with finer resolution of the objectively analyzed field, if the data availability is high (as in most regions of the NWA). In a way, if compared to numerical models, shortening the radius of influence is similar to decreasing the lateral turbulent mixing causing sharper current and more pronounced mesoscale hydrography structures. Importantly, the radius of influence, and the number of five-point smoothing passes can be varied in each of the three sequential iterations in the three-pass variation of the implemented objective analysis procedure. The strategy is to begin the analysis with a large radius of influence and decrease it in each of the subsequent iterations. This technique allows analysis of progressively smaller scale phenomena in subsequent iterations.

The radius of influence (discussed in more detail in [24, 42, 121]) essentially defines the area surrounding a grid cell from which the data are taken for interpolation to the cell center. Within the radius of influence, data points closer to the cell center are assigned higher weights. The robustness of the interpolation improves with increasing amounts of data inside the radius of influence. The radii of influence in the three-pass objective analysis on the one-tenth-degree grid is 50% to 40% shorter than on one-degree and by 34% to 13% shorter than on quarter-degree grid, e.g., [42, 121, 124] (Table 5). Importantly, the radii of influence on a one-tenth-degree grid are on the scale of the Rossby baroclinic deformation radius of ~ 50 km in mid latitudes and even shorter in subpolar and polar regions. For quarter-degree resolution, the radius of influence is comparable with Rossby baroclinic deformation radius characterizing mesoscale eddies, whereas this radius is greater than the cell sizes for one-tenth-degree resolution in mid-latitudes. Having cell sizes shorter than the Rossby radius facilitates better statistics and more realistic patterns in the areas with high mesoscale activity (e.g., high variance is better captured around the fronts and shelf breaks).

Figure 9 illustrates how much finer details were achieved by decreasing the radius of influence and thus allowing mesoscale features to be captured by the analysis.

After computing the first-guess fields, the temperature and salinity data were re-analyzed using the newly produced analyses as first-guess fields described as follows. As was mentioned above, a new annual mean was computed as the mean of all 12 monthly analyses for the upper 1500 m, and the mean of the four seasons below 1500 m depth. This new annual mean was used as the first-guess field for new seasonal analyses. These new seasonal analyses in turn were used to produce new monthly analyses yielding slightly smoother means. The monthly mean objectively analyzed temperature fields were used as the first-guess fields for each of the "decadal" monthly climatologies. Likewise, seasonal, and annual climatologies were used as first-guess fields for the seasonal and annual decadal climatologies.

In some cases, data-sparse regions are so large that a seasonal or monthly analysis in these regions is meaningless. On the contrary, the geographic distribution of observations for the "all-data" an(-for example, see appendices in [121]), has very small gaps and for the task of objective analysis it covers the World Ocean almost entirely. For the NWA region, the data distribution for "all-data" is especially dense, at least in the upper layers of the ocean. By using an "all-data" annual mean first-guess field, regions where data exist for only one season or month will show no contribution to the annual cycle. By contrast, if we used a zonal average for each season or month, then, in those latitudes where gaps exist, the first-guess field would be heavily biased by the few data points that exist. If these were anomalous data in some way, an entire basin-wide belt might be affected.

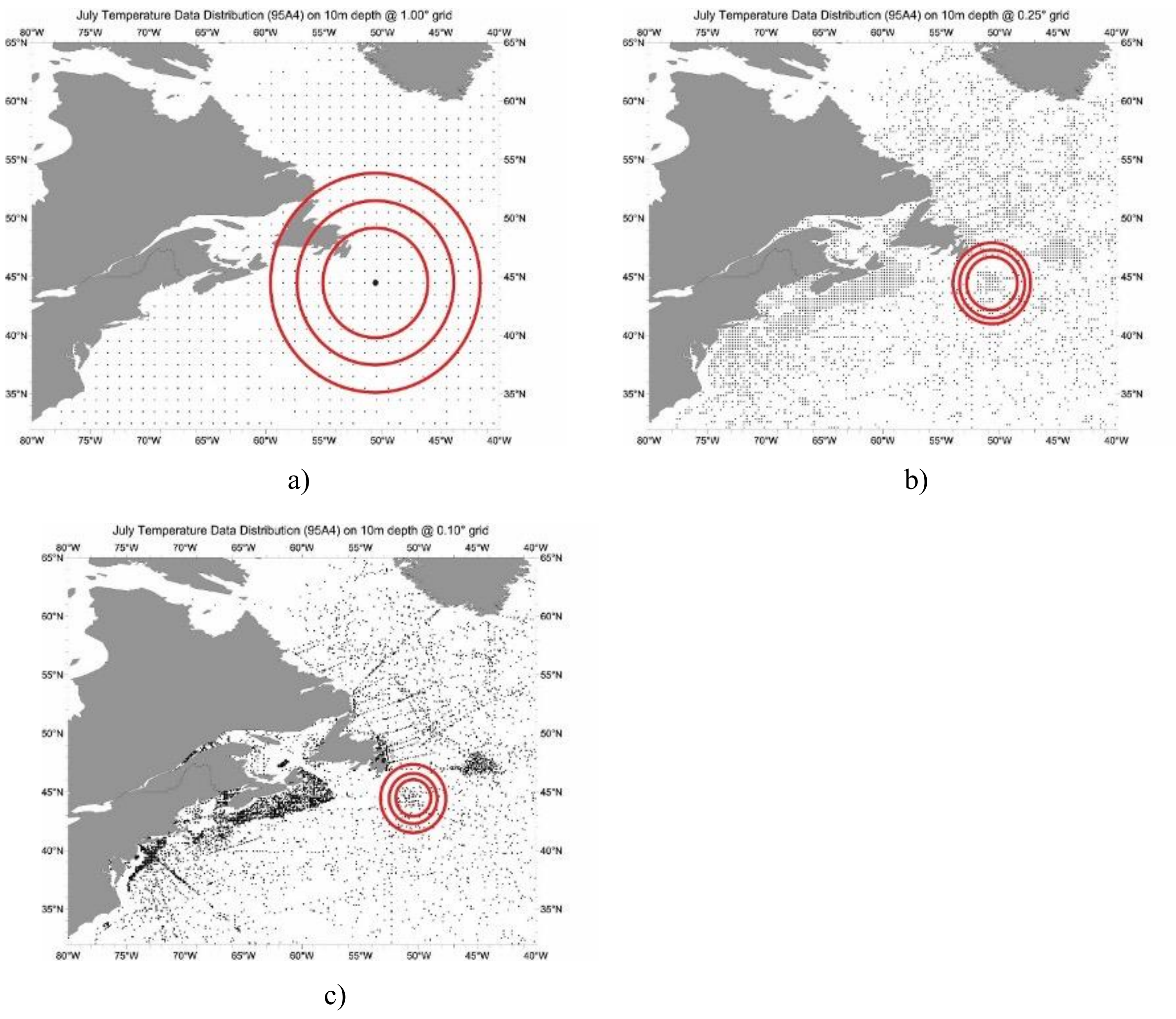


Figure 9: Temperature observation density at 10 m depth for the decadal July of 1995 – 2004 on grids of (a) 1°x1°, (b) 1/4°x1/4°, and (c) 1/10°x1/10° resolutions. The dots indicate that there is at least one profile in a grid cell. Red circles schematically show the radii of influence of the three passes for the different resolutions during the objective analysis procedure (see text and Table 5). Reproduced from Seidov [21].

One advantage of producing "global" fields for a compositing period (even though some regions are data-sparse) is that such analyses can be modified by investigators for use in modeling studies. Moreover, the descendant regional climatologies, in this case the NWARC, use more "time-granular" fields that are another strong advantage of the granular global approach.

Special care is needed near the domain boundaries, i.e., ocean coastal zones and near the bottom. Thus, corresponding masks are to be used while gridding the data. The analyses employed in the NWARC use ETOPO2 land-sea topography to define ocean depths at each grid-point (ETOPO2, 2006). From the ETOPO2 land mask, a quarter-degree land mask was created based on ocean bottom depth and land criteria. The details of the masks in the WOA18 can be found in Locarnini [121].

As was mentioned above, the density field computed using temperature and salinity must be stabilized according to Equation 1. Temperature and salinity climatologies are calculated separately, as there are some profiles with salinity measurements that are not always paired with temperature measurements and vice versa. As a result, when density is calculated from standard level climatologies of temperature and salinity, instabilities may result in the vertical density field (stability defined in previous section). While instabilities do occur in the ocean on an instantaneous time frame, these instabilities are usually short-lived and not characteristic of the mean density field. The stabilization of density is done globally in WOA and thus is not described here in detail. The Appendices A (Section 8.1) and B (Section 8.2) in [121]. in Locarnini describe a technique that was employed to minimally alter climatological temperature and salinity profiles in order to achieve a stable water column everywhere in the world ocean [121]. The technique is based on the method of [132]. The final temperature and salinity climatologies reflect the alterations due to this process.

10. Online NWARC Maps and Data

The maps are arranged by composite time periods: annual, seasonal, and monthly. All climatological maps of the objectively analyzed fields, and associated statistical fields at all standard depth levels are available online NWARC.

The sample standard deviation in a grid-box was computed using:

$$s = \sqrt{\frac{\sum_{n=1}^{N}(x_n - \bar{x})^2}{N-1}} \tag{2}$$

where x_n = the n-th data value in the grid-box, $\underline{x}$= mean of all data values in the grid-box, and N = total number of data values in the grid-box. The standard error of the mean was computed by dividing the standard deviation by the square root of the number of observations in each grid-box.

All objectively analyzed fields and all statistical data fields can be obtained online in ASCII comma-separated value (.csv), netCDF (.nc), and ArcGIS shape (.shp) formats through the NWA regional climatology webpage mentioned above. Other NCEI regional climatologies completed to date, can be found at NCEI regional climatology webpage NCEI Regional Ocean Climatologies. A pilot study was published by [124]. which shows an example of using these new high-resolution regional climatologies in oceanographic research. There are several published scientific publications specifically targeting the NWA region, with focus on the Gulf Stream and surrounding areas [21, 25-27].

It is important to note that the high-resolution monthly temperature and salinity data coverage on the one-tenth-degree grid have more gaps than seasonal and annual fields computed from the monthly fields. In general, all high-resolution analyzed fields should be reviewed carefully before using them in mission-critical applications. It is especially important when working with the high-resolution monthly fields. Users are advised to review the data distribution and statistical mean maps before deciding whether to use the high-resolution analyzed temperature and salinity fields or their climatological means. Moreover, the monthly maps of objectively analyzed data on one-tenth-degree grid may show some possibly spurious eddy-like irregularities in some regions due to interpolation and plotting artifacts combined. Although such cases are very rare, a more careful review of the fields with such occurrences is needed before using analyzed variables in research or applications.

Displaying only monthly fields that are shallower than 1500 m requires more explanation. Indeed, we do not know how deep the seasonal signal can penetrate the ocean. Were the mixing in the ocean only limited to the upper mixed layer with turbulent diffusion below that layer, the seasonal signal would be confined to the upper several hundred meters. In most of the ocean volume this would probably be true, but in regions of strong upwelling and convection, especially seasonal deep convection in high latitudes, seasonal variability can penetrate quite deep, which is seen in the analyzed fields. On the other hand, the scarcity of data below 1500 m depth makes any seasonal analysis questionable, at the very least. It may soon improve, as Argo floats, which reach 2000 m depth, become more abundant, but for the time being the data below 1500 m in the NWARC area are still noticeably scarcer compared to the upper ocean. Thus, a reasonable solution was to show decadal monthly fields above 1500 m only. Although seasonal fields are shown below 1500 m, they should be considered rather cautiously. In contrast, the aggregated annual fields computed by averaging all data can be deemed as more reliable than "seasonal" fields, as more data is available and additional smoothing is applied while averaging over the four seasons. This issue needs more careful consideration in future research to determine how variability in the deep ocean is to be treated.

10. Discussion

The most important feature of the new NWA high-resolution regional climatology is the six-decade-long timespan, which makes NWARC a useful tool for assessing ocean long-term variability. Notably, although spatial and temporal changes can be assessed to some degree using the WOA18 on the quarter-degree grid, many features of the NWA regional ocean climate dynamics cannot be evaluated properly because the spatial scales of the processes in this region cannot be adequately represented on the grid coarser than one-tenth of a degree (or better, if possible).

In fact, one can refer to NWARC or any RC with 0.1°x0.1° or better resolution, as an "eddy-resolving" regional climatology as it can reveal the cumulative effect of the mesoscale processes in the climatological fields [21,24]. The basis for this lies in the fundamental structure of the ocean currents and related hydrological fields. As mentioned previously, a parameter called the Rossby baroclinic radius of deformation, R, e.g., [133], provides the condition for resolving oceanic mesoscale motion in numerical models or in ocean data mapping. The grid size needed for resolving mesoscale motion must be shorter than R. In the middle latitudes, R is ~30–40 km, which is roughly the latitudinal dimensions of one to two grid cells with 0.25°x0.25° grid resolution (~25 km spatial resolution in latitude). A hydrographic front ~50-70 km wide, which is approximately the width the Gulf Stream, can be relatively well resolved on a 0.1°x0.1° grid (~10 km spatial resolution in latitude and ~8 km in longitude in mid-latitudes), and would be just barely "permitted" on the 0.25°x0.25° grid. Such a front would be completely unresolved at coarser resolutions (e.g., 1°x1° with a scale of ~100 km in latitude).

Seidov and co-authors (2019) argue that the seasonal signal carries the superimposed repetitive mesoscale signals and thus decadal climatologies—monthly, seasonal, and annual—reflect the cumulative effect of mesoscale dynamics on mapping of the large-scale regional ocean climate state and variability [21]. This will be discussed further in the text when the mesoscale features of the NWARC are compared to some available satellite observations of sea surface temperature.

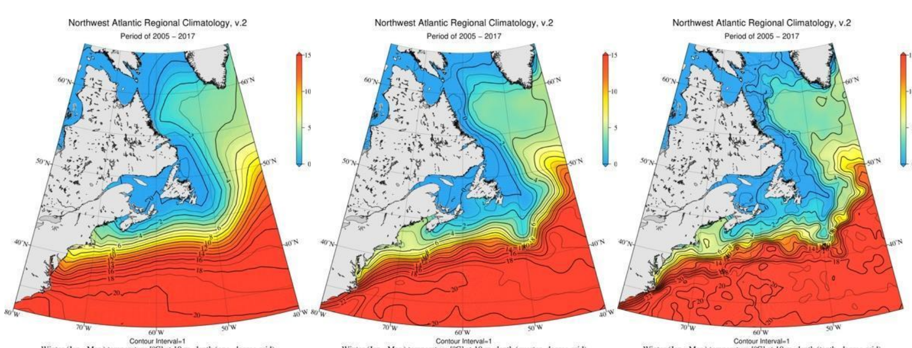
Figures 10 and 11, showing winter temperature and salinity for the 2005-2017 respectively, provide the examples of difference in climatologies with different resolutions. In general, an important advantage gained by using fine spatial resolution, obvious in Figures 10 and 11, is that the Gulf Stream and Gulf Stream Extension features are more coherent in one-tenth degree analysis than in the quarter-degree one, and of course far more coherent than in the analysis on the one-degree grid. All frontal zones are noticeably narrower on the finer grid and far better reflect the cumulative effects of mesoscale dynamics characteristic for this area.

One feature of the fine-resolution maps that really stands out in Figures 10 and 11 is the Gulf Stream structure in the southwest corner of the domain. The jet is highly coherent and parallel to the continental shelf break in the one-tenth of a degree grid (Figures 10c and 11c), while on the quarter-degree grid this pronounced jet character is completely lost. The slope water north of the Gulf Stream Extension is also better resolved on the finest-resolution grid. The Gulf Stream jet looks very narrow, as it should be. It is about half of the width of the jet emerging in the quarter-degree maps and is up to three to four times narrower if compared to one-degree plots where the Gulf Stream completely loses its narrow jet nature.

Employing one-tenth degree resolution allows locating the correct position of the jet separation from the shelf at Cape Hatteras (see the discussion in [95]) and depicts a more complex and realistic MLTZ. A clearer representation of the cold and fresh water carried by the Labrador Current south of Nova Scotia along the New England shelf with one-tenth-degree resolution is obvious when compared to one-degree or quarter-degree resolutions. The Slope Water Current looks better aligned in its recirculation path to form the Gulf Stream "northern wall" [85, 134].

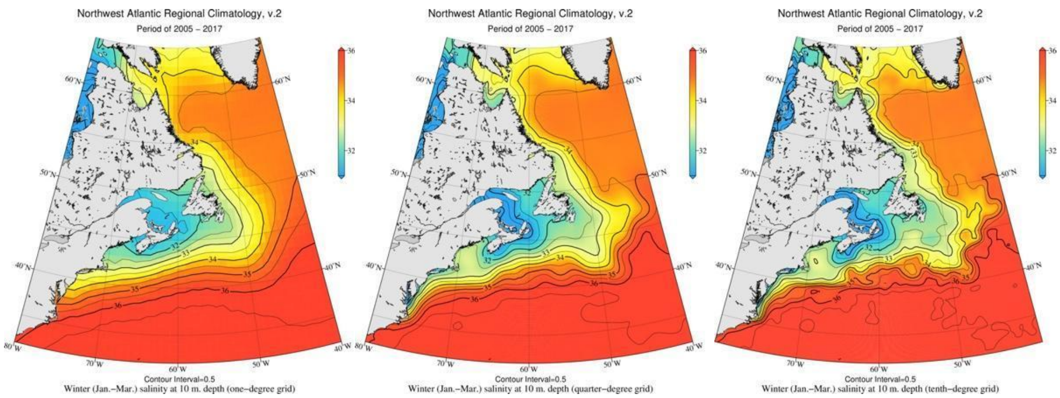
Salinity in Figure 11c shows the frontal features like the thermal front (to form the density front of the same quality) shown in Figure 10c and it is well pronounced and narrow, as usually seen in advanced eddy-resolving numerical models.

The temperature and salinity fields shown in Figures 10 and 11 were computed using the objective analysis technique, which, while indisputably powerful, has its own weaknesses, as have all interpolation techniques; it may generate artificial features if the gaps between data filled cells are too numerous. As the NWA is a region rather densely covered by observations, the simple statistical mean can be used to assess the quality of the objectively analyzed fields in this domain (Figures 12 and 13).



a **b** **c**

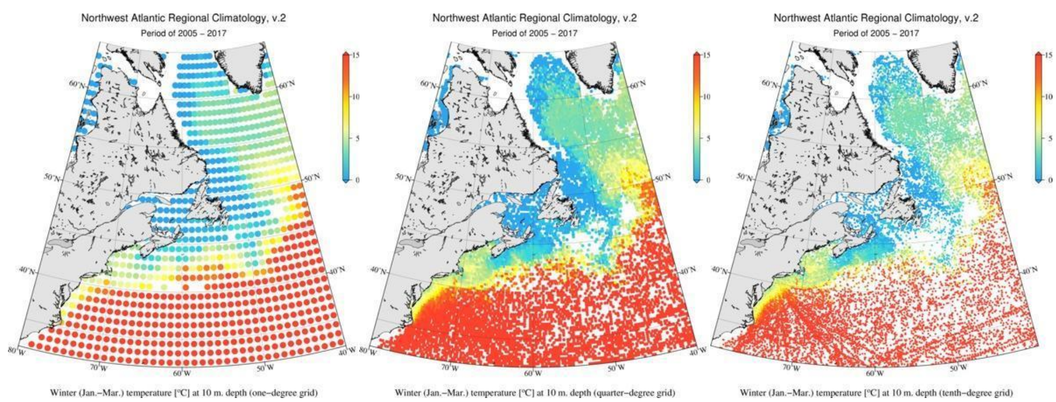
Figure 10: Winter objectively analyzed temperature averaged over the period of 2005-2017 at 10 m depth in three analyses on: (a) one-degree, (b) quarter-degree, and (c) one-tenth-degree grids.



a **b** **c**

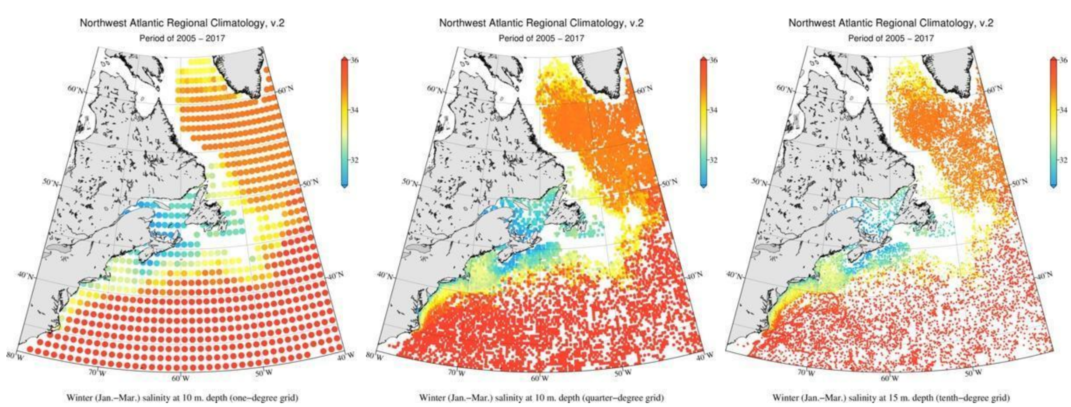
Figure 11: Winter objectively analyzed salinity averaged over the period of 2005-2017 at 10 m depth in three analyses on: (a) one-degree, (b) quarter-degree, and (c) one-tenth-degree grids.

The standard error of the mean is noticeably reduced in many places on the finer grid, as can be expected. Indeed, the standard error for the three resolutions (the same time interval and depth as in all other maps above) shows substantial improvement at the finer grids, especially in the Gulf Stream area from Florida Strait up to Nova Scotia and in the Labrador Sea (Figure 14).



a **b** **c**

Figure 12: Winter statistical mean temperature averaged over the years 2005-2017 at 10 m depth in three analyses on: (a) one-degree, (b) quarter-degree, and (c) one-tenth-degree grids.

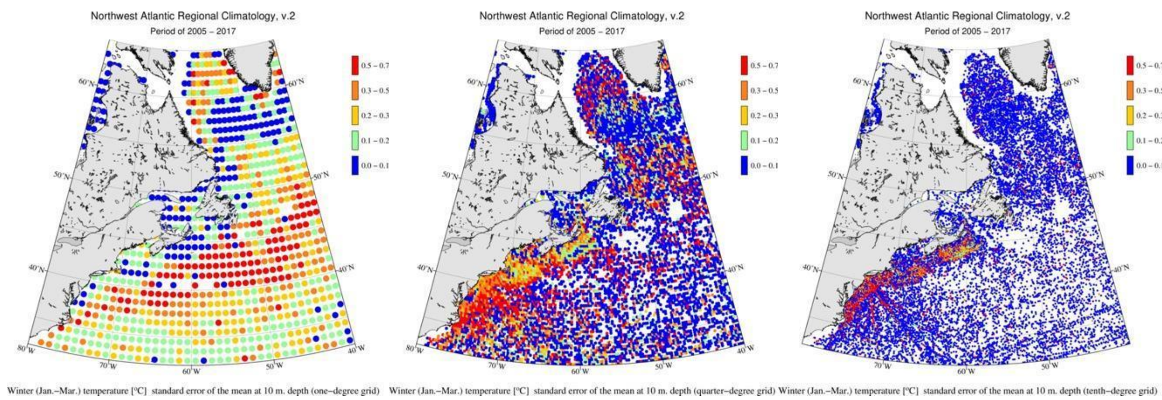


a **b** **c**

Figure 13: Winter statistical mean salinity averaged over the years 2005-2017 at 10 m depth in three analyses on: (a) one-degree, (b) quarter-degree, and (c) one-tenth-degree grids.

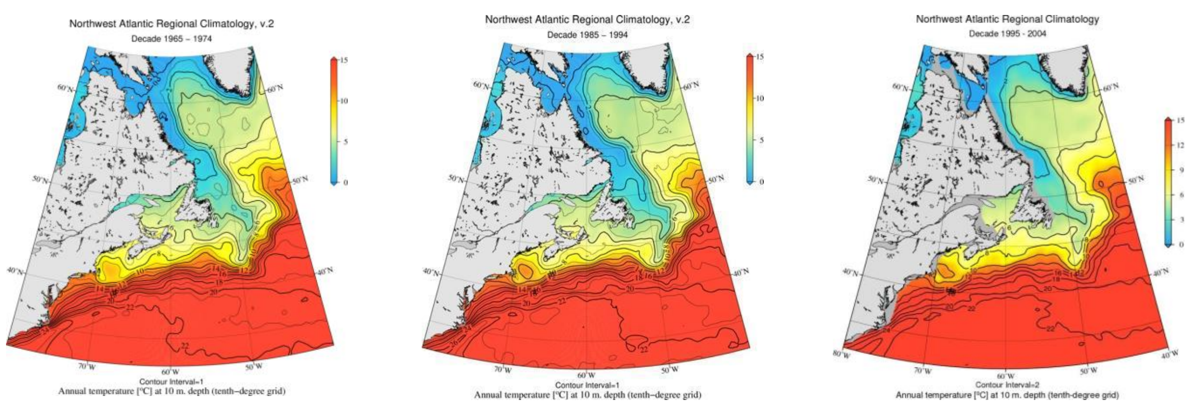
Another important feature of the high-resolution climatological fields is the far more pronounced seasonality of the Gulf Stream jet revealed in hydrological fields, which is shown on Figures 15, 16, and 17.

There is a fundamental issue about the observation-based decadal climatologies regarding the "cumulative" mesoscale effects, or the mesoscale activity averaged over a decadal timespan. The seasonal variability is stronger than the mesoscale variability, as is confirmed when reviewing the annual climatologies for any decade. Figure 15 shows the annual temperature climatologies for three decades. Temperature at 10 m depth for winter and January for the same three decades is shown in Figures 16 and 17, respectively. The jet and its meandering are strongest in January if compared to the winter or annual fields (and much stronger compared to warmer seasons and months).



a b c

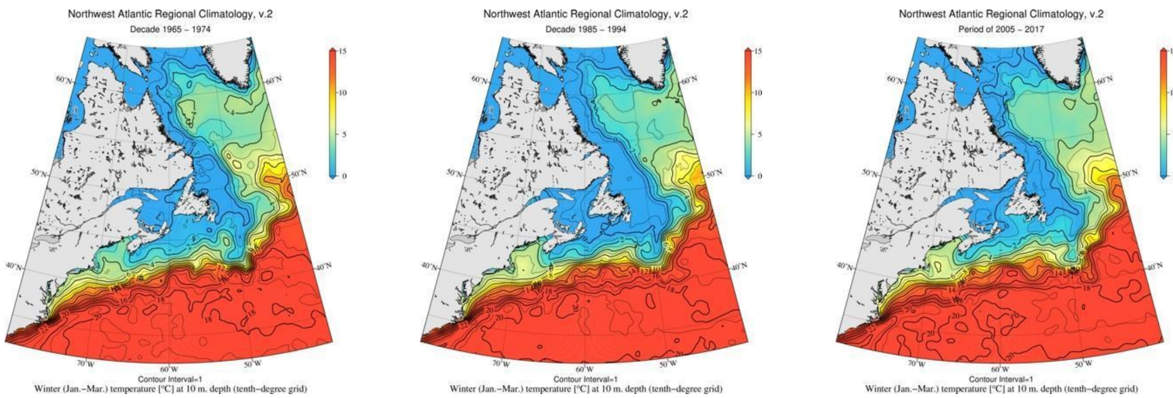
Figure 14: Standard error of temperature at 10 m depth for winter averaged over the period of 2005-2012 in three analyses on: (a) one-degree, (b) quarter-degree, and (c) one-tenth-degree grids.



a b c

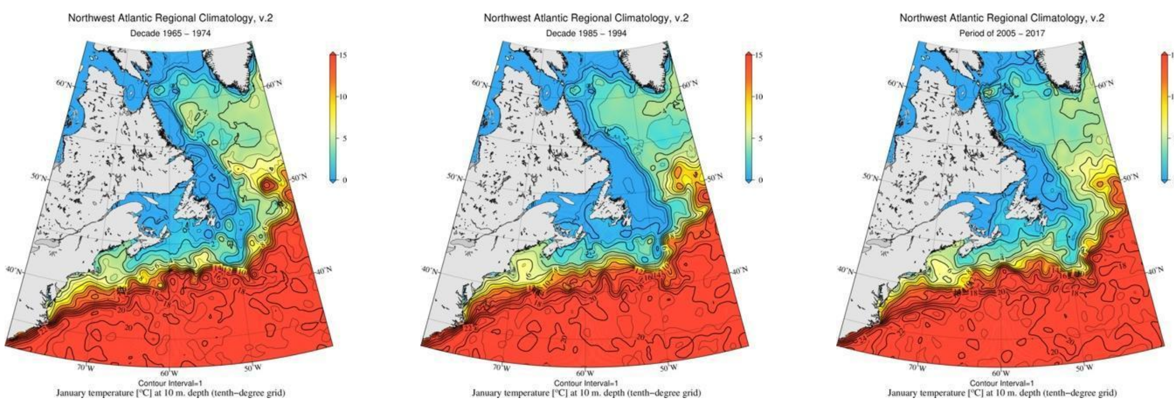
Figure 15: Annual mean temperature at 10 m depth for three decades: (a) 1965-1974, (b) 1985-1994, and (c) 2005-2017 on one-tenth-degree grid.

The striking feature in Figures 16 and 17, where the climatological winter and climatological January are shown, is the repetitiveness of major mesoscale features in climatological seasonal and monthly fields. The fact that very similar mesoscale patterns (meanders and Gulf Stream eddies) are seen in all decades implies that there is a cumulative effect of mesoscale activities overlaying a clear seasonal signal. The seasonal signal is obviously stronger than the signal generated by mesoscale eddies, but the eddy-type motion is amplified by the seasonal signal. Indeed, repetitive mesoscale patterns superimposed over the seasonal variability must repeat statistically not only every year in each decade, but also every year in all decades since 1955. On the other hand, as the seasonal maps show, there are also distinctive differences between the seasons in the 1965-64, 1985-94, and 2005-2017 sequence indicating stochastic nature of mesoscale variability superimposed over the carrying seasonal signal with multi-decadal quasi-periodical cyclicity.



a b c

Figure 16: Winter mean temperature at 10 m depth for three decades: (a) 1965-1974, (b) 1985-1994, and (c) 2005-2017 on one-tenth-degree grid.



a b c

Figure 17: January mean temperature at 10 m depth for three decades: (a) 1965-1974, (b) 1985-1994, and (c) 2005-2017 on one-tenth-degree grid.

Snapshots of sea surface temperature from both satellite imagery and eddy-resolving numerical simulations (see an example in Figure 3) disclose a strong structural resemblance between the NWA monthly observations-based high-resolution regional climatologies and the remotely sensed and numerically simulated fields. Importantly, the monthly temperatures averaged over a decade show an aggregated realization of the Gulf Stream and mesoscale eddies. There was no guarantee that averaging over a long period, such as a decade, would yield such resemblance (years and decades compared to week and months as a characteristic time scale of the mesoscale variability). Nonetheless, there is a line of thinking that mesoscale variability is interlocked with seasonal cyclicity and that there is a great deal of repetitiveness of specific patterns surrounding unstable jet currents, especially the Gulf Stream and Gulf Stream Extension, e.g., [135].

As discussed above, the spatial resolution of a regional climatology, either in climate reconstructions using observed data or in climate modeling, is the key for better understanding the role of regional dynamics in such critical areas such as the Gulf Stream, Kuroshio, etc. Moreover, it is becoming obvious that long-term climate forecasting is impossible without detailed knowledge of decadal variability [136]. Even atmosphere-only sensitivity experiments have demonstrated the impact of increasing horizontal resolution and have indicated that seasonal variability of the Gulf Stream has a substantial impact on the troposphere dynamics [137]. In their numerical simulations, Minobe and co-authors [137]. showed that an atmospheric general circulation model with about 50 km resolution responds quite noticeably to the observed sharpness of the Gulf Stream front, and they showed that the Gulf Stream affects the entire troposphere. In fact, a poorly resolved Gulf Stream presents a structural problem for atmospheric climate models preventing them from capturing observed decadal climate variability in the North Atlantic [136]. That is, the sharpness, internal dynamics, and cumulative effect of mesoscale eddies and other transients on decadal scale may become critical for the success of long-term climate forecasting. The key to understanding why decadal climatologies are so important is that they emphasize the repetitiveness or statistical periodicity of the major elements of mesoscale processes in the Gulf Stream system.

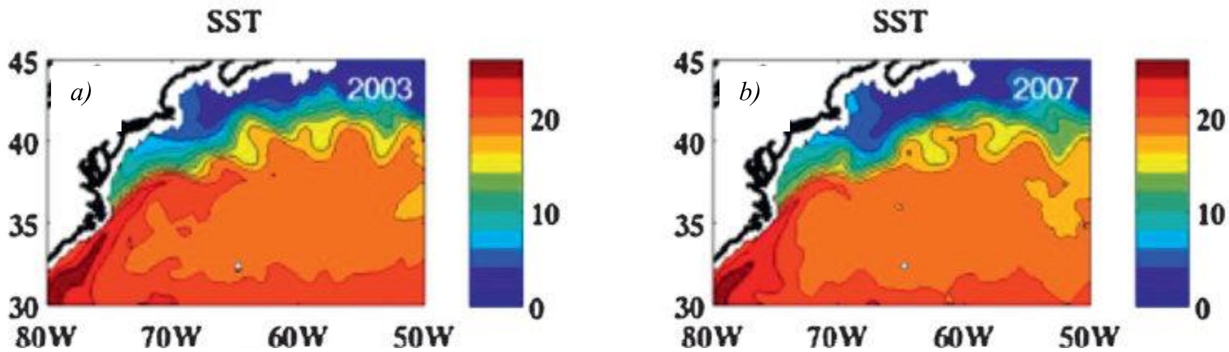


Figure 18: March averages of SST for (a) 2003 and (b) 2007. SST fields are from the Remote Sensing Systems on a 0.258° grid spatial resolution from [135].

Figure 18 reproduces two monthly-averaged satellite-derived sea-surface temperature snapshots, four years apart, in March of 2003 and in 2007, in the Gulf Stream region [135]. As can be seen in Figure 18, although the patterns are not exactly the same (and they would not and should not be expected, of course), they are surprisingly similar implying the quasi-stationary character of mesoscale variability in the Gulf Stream jet vicinity. In previous paragraphs, we discussed the striking repetitiveness of the mesoscale temperature patterns, as shown in Figure 18. When the NWARC v1 became available [23], the idea of retaining some of repetitive mesoscale variability in the observed ocean climatology was put forth [21, 24]. The following is a brief outline of the premise that the mesoscale variability can at least partly be present in the monthly ocean climatologies.

To verify the hypothesis that the seasonal signal carries superimposed repetitive mesoscale features that can be seen in averaged seasonal climatologies, the seawater temperature in the NWA region was compared with the sea surface temperature (SST) from satellite observations [24]. This SST was extracted from the Coral Reef Temperature Anomaly Database version 5 (CoRTADv5). The CoRTADv5 SST arrays are derived from the Advanced Very High-Resolution Radiometer (AVHRR) Pathfinder v5.2 data and are available for the time span between 1982 and 2012 [138]. The approximate spatial resolution of the data is 4 km (~1/20th of a degree at mid-latitudes) with one-week temporal resolution.

To make the satellite-derived SST comparable with the NWARC v1 near-surface in-situ temperature, the weekly satellite SST data were averaged into monthly fields for every year over the 1982-2012-time period. Then, to compute the decadal satellite SST climatology, we took each month of the decades 1985-1994, 1995-2004, and 2005-2012 and averaged them within each decade.

Repetitive mesoscale features can be seen in Figure 19, which look like those shown in Figure 18. Some of the meanders, squirts, and filaments are marked by black circles for easier spotting. As was indicated in and , both NWARC and satellite-based ocean surface (or near-surface) mapping are consistent with the hypothesis that mesoscale variability is interlocked with the seasonal cycle and that there is a great deal of repetitiveness of specific patterns surrounding unstable jet currents, especially the Gulf Stream and its extension, e.g., [135].

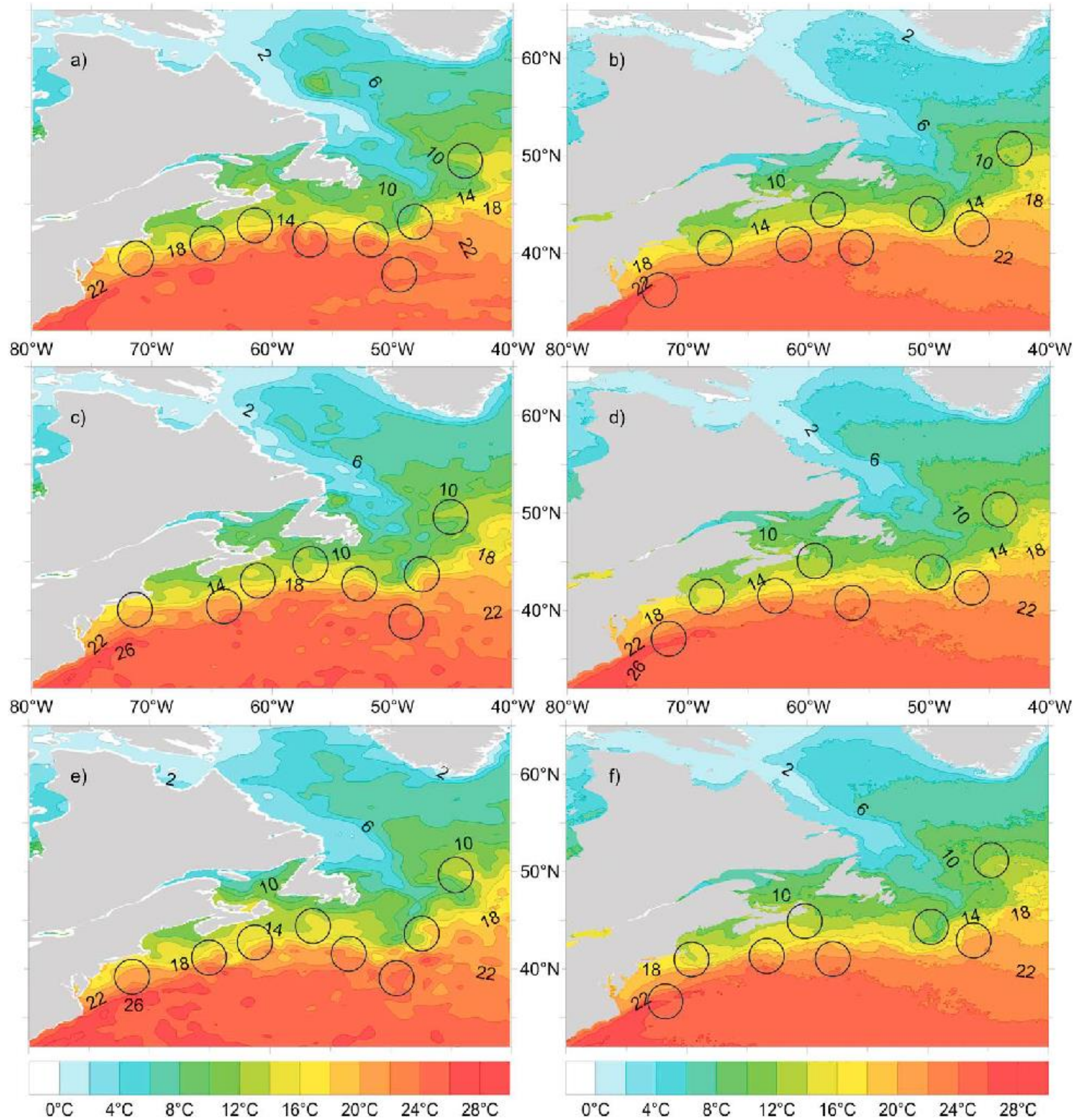


Figure 19: October seawater temperature from Northwest Atlantic regional climatology at 10-m depth (left column) and sea surface temperature from AVHRR Pathfinder satellite observations (right column) for the decades: (a, b) 1985–1994, (c, d) 1995–2004, and (e, f) 2005–2012. Examples of repetitive filaments in the Gulf Stream area are denoted by the black circles (reproduced from) [21].

High-resolution regional climatologies may be especially useful for comparison between results of numerical simulations and observed data. Therefore, we include a part of the previous analysis to show an example of the model-data comparison. The following discussion is based on the NWARC v1, but everything fully applies to NWARC v1 [23]. As the NWARC v1 became available, it was tempting to compare the in-situ climatologies with an eddy-resolving model. Therefore, to further substantiate the hypothesis that repetitive mesoscale variability can be revealed in the observed high-resolution ocean climatology, the extractions from NWARC v1 were compared with those from eddy-resolving numerical simulations. The model employed for the data-model comparison is the Nucleus for European Modelling of the Ocean (NEMO) modeling system [139]. with a global 1/12th-degree grid, which is close to NWARC one-tenth of a degree resolution. The NEMO is a state-of-the-art modeling framework for oceanographic research, operational oceanography seasonal forecasting, and climate studies. (More details about the NEMO modeling can be found at the NEMO ocean model website). The detailed comparison of the NWARC v1 and the snapshots from NEMO eddy-resolving simulations can be viewed in the NWARC v1 publication: [23].

High-resolution ocean climatologies, like NWARC, may have many uses in climate forecast models, but the most important one may be the use of sea surface salinity (SSS) for correcting for long-term drift in model simulations of ocean circulation, which is critical for ocean climate simulations and especially in long-term climate forecasts. As was found in early simulation experiments with coupled ocean-atmosphere models, the freshwater fluxes in such models must be pre-computed using observed SSS to avoid the so-called climate drift, which is an artifact caused by poorly-resolved freshwater fluxes across the ocean surface in practically any coupled ocean-atmosphere model [60, 140, 141]. After a long time since [141] first identified such a drift was first identified in, forecast models use the restoring to observed SSS method to suppress such artificial climate drift. Moreover, it turned out that the one-degree fields SSS from earlier editions of WOA were not enough as they are too smooth because of infilling the gaps and objective interpolation on a coarse-resolution grid, e.g., [142]. New WOA18, with quarter-degree resolution may already provide sufficiently detailed SSS for such numerical simulations, while for the regions covered by high-resolution climatologies, the best would be using one-tenth-degree grid whenever possible. Providing high-resolution sea surface salinity on quarter- and one-tenth-degree grids with well-resolved frontal structures may be critical for improving long-term ocean climate forecasts.

11. Summary

We have presented the description and results of the Northwest Atlantic Regional Climatology project aimed at generating objectively analyzed historical ocean temperature and salinity data fields. The effort of creating NWARC v1 Atlas [23] yielded several research papers, e.g., [21, 24-27]. new updated version of NWARC—NWARC v2 —that includes new observations as well as data rescued from earlier cruises, is now available. The advantages of high-resolution regional climatologies along with an updated discussion of how such climatologies may align with remote sensing of sea surface and with eddy-resolving ocean numerical modeling were also presented. It is argued now that a high-resolution regional climatology like the NWARC may be viewed as eddy-resolving in-situ climatology [21].

Currently, only temperature and salinity decadal climatologies have been created with one-tenth-degree spatial resolution. These climatologies were compiled to provide investigators from various branches of oceanography, climatology, fisheries, and other related disciplines with oceanographic foundations that define long-term ocean climate change inferred from observations. Coarse-resolution maps and data for other important oceanographic parameters can be assessed at the NCEI Ocean Climate Laboratory website Ocean Climate Ocean Climate Laboratory; see also [143, 144].

When computing anomalies from a standard climatology, it is important that the synoptic field be smoothed to the same extent as the climatology, to prevent generation of spurious anomalies simply through differences in smoothing. However, on finer resolution grids mesoscale eddies are directly resolved and the remaining mesoscale background probably represents a cumulative effect of mesoscale dynamics rather than a noise generated by objective analysis. The advantage of a high-resolution grid becomes obvious as the shorter radii of influence used in the objective analysis leads to less diffusive fields in the frontal zones, which bear sharp gradients, especially in the coastal regions. In a sense, the finer-resolution analysis suits the same goal as reducing grid sizes in numerical models.

The high-resolution regional climatologies narrows the gaps between observations and modeling and allow meaningful data-model comparisons in critical regions, such as the Northwest Atlantic Ocean. Moreover, in a new class of long-term ocean climate forecast modeling, the analyzed regional climatologies can be used for restoring the simulated fields to the observed ones (especially sea surface salinity) and thus prevent the climate drift effect that plagues even the most advanced climate models.

As in all WOA editions and regional climatologies, the main goal is to create objectively analyzed fields and data sets that can be used as a “black box” in applications. The new and significant feature we now offer are six high-resolution decadal climatologies that can be used in assessing “true” ocean climate change backed up by aggregated historical oceanographic in-situ observations. Naturally, some quality control procedures used are somewhat subjective. Moreover, monthly decadal fields are less reliable because of more data gaps than in seasonal or annual fields, so some mesoscale features could still be affected by artifacts caused by lack of data. However, seasonal, and annual fields are very well supported by data, especially in recent decades.

Disclaimer

Users of the NCEI high-resolution regional climatologies are advised to inspect very carefully the data distributions, statistical means, standard errors, etc., before deciding to what extent they can rely on the objectively analyzed data and maps in their mission-critical research and application developments. For users who wish to make their own choices, all data used in WOA18 and NCEI regional climatologies, both at standard and observed depth levels, are available at World Ocean Database.

In very rare cases, some maps at some depths in monthly fields, especially in earlier decades, may show some peculiarities that may be due to non-representativeness of data and have not yet been flagged by manual quality control described in the text. Although we have made all reasonable efforts to eliminate as many of these features as possible by flagging the data that generate such features, some could still be undetected and remain unflagged. Some may eventually turn out not to be artifacts, but rather represent real features. In such rare cases, we are not capable yet to describe and explain them in any meaningful way due to lack of data. In any of such cases, which are very few, users are advised to be extremely cautious and make all possible efforts to recognize where the analyzed fields are sufficiently supported by observations by using the supplied additional statistical fields, such as simple statistics, number of available observations, standard errors, etc.

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