

REGIONAL CLIMATOLOGY OF THE NORTHWEST ATLANTIC OCEAN

High-Resolution Mapping of Ocean Structure and Change

DAN SEIDOV, ALEXEY MISHONOV, JAMES REAGAN, OLGA BARANOVA, SCOTT CROSS, AND ROST PARSONS

High-resolution regional in situ ocean climatologies have recently become available for climate studies and other applications.

If counted from Captain Cook's ocean temperature measurements in 1772, subsurface oceanographic observations in the World Ocean have been ongoing for well over two and a half centuries. Yet, the first detailed global ocean water property maps were compiled and published, in the form of the Climatological Atlas of the World Ocean, only 35 years ago by Sydney Levitus at the National Oceanic and Atmospheric Administration (NOAA; Levitus 1982). This original edition in the *World Ocean Atlas* (WOA) series—the name adopted for all descendants

of the Climatological Atlas in 1994—contained a set of global maps of ocean temperature, salinity, and oxygen on a regular 1° geographical grid at 33 depth levels from the surface to 5,500 m. The monthly, seasonal, and annual averaged values of those parameters over time periods of several decades were called “ocean climatologies,” a term used here to describe the long-term mean state of the ocean. As the volume of observations has been growing, six releases of WOA have been published since 1982.

The Climatological Atlas and all subsequent WOA editions are built using a technique widely known in geophysics as the objective analysis of irregularly distributed data (e.g., Thomson and Emery 2014) to produce relatively smooth yet realistic fields of ocean variables on a regular grid. The procedure ensures that all grid cells without observed data (i.e., data gaps) are filled by weighted interpolated values using a first-guess field and all available data within the so-called “influence radius.” The first-guess field is the best initial estimate of a climatological mean field structure while the influence radius eventually determines the smoothness of the interpolated field, including the interpolated values in the initially empty grid cells. A detailed description of the procedure can be found in Boyer et al. (2005). The entire procedure of compiling an ocean climatology

AFFILIATIONS: SEIDOV, BARANOVA, CROSS, AND PARSONS—NOAA/ National Centers for Environmental Information, Silver Spring, Maryland; MISHONOV AND REAGAN—NOAA/National Centers for Environmental Information, Silver Spring, and Cooperative Institute for Climate and Satellites, University of Maryland, College Park, College Park, Maryland

CORRESPONDING AUTHOR: Dan Seidov, dan.seidov@noaa.gov

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can be called “mapping” or projecting the ocean’s essential variables (temperature, salinity, oxygen, etc.) onto a regular grid using irregularly spaced observed in situ data.

There are two important elements of the objective analysis procedure: the *first-guess fields* and *influence radius*. The first-guess fields provide a starting point for the objective analysis procedure; it is especially valuable where data density is low. However, the most significant element is the influence radius. First, the more data within the influence radius, the more weight the observed data would have relative to the first-guess values; conversely, data-poor regions with many gaps will be weakly influenced by observed values and thus be primarily based on the first-guess field. Second, the higher the resolution of the grid onto which the data are interpolated, the shorter the influence radii in the successive mapping iterations (Table 1; see details and explanations in Boyer et al. 2005; Locarnini et al. 2013; Seidov et al. 2016). Additionally, it is important to note that WOA is compiled in *z* coordinates, while there are alternative approaches to projecting gridded data onto isopycnal surfaces such as the Monthly Isopycnal and Mixed-Layer Ocean Climatology (MIMOC) described in Schmidt et al. (2013). Discussing MIMOC and other geopotential versus isopycnal surface data mapping is beyond our objectives, so we just mention that such alternatives do exist.

The objective analysis technique inherently works best in cases where there are fewer gaps in data coverage and enough data in the adjacent cells to fill gaps confidently. Unfortunately, there are only a few regions in the World Ocean where the density of observations is sufficient for data mapping with spatial resolutions higher than 1°. The northwest Atlantic (NWA) is one of those few data-rich regions—comprising the Northwest Atlantic Regional Climatology (NWARC)—where a spatial resolution of gridded temperature and salinity fields below 1° has recently become feasible (Seidov et al. 2016).

The data distributions reveal the important specificity of the NWA regional data coverage.

TABLE 1. Influence radii (km) for the three passes of the objective analysis on different grids.			
	1° × 1°	1/4° × 1/4°	1/10° × 1/10°
1	892	321	253
2	669	267	198
3	446	214	154

Unsurprisingly, almost all cells in the 1° × 1° grid are relatively well covered, at least annually and seasonally, for the six decades targeted in this analysis (1950s to 2000s). In most cases, there are more than five profiles in a 1° cell, sometimes many more. This is important because the 1° × 1° averages serve as the first-guess field for the objective analysis at higher resolutions. The 1/4° × 1/4° grid reveals overall sparser, but in most places still rather dense, data coverage. Finally, despite far more data gaps on the 1/10° × 1/10° grid, the Gulf Stream system (GSS) is still rather densely covered, with almost all cells having at least one profile in annual and seasonal distributions for nearly all decades (NWARC data distributions can be found at www.nodc.noaa.gov/OC5/regional_climate/hwa-climate/).

The critical parameter for resolving oceanic mesoscale motion is the Rossby baroclinic radius of deformation *R* (e.g., Gill 1982). In the midlatitudes, *R* is approximately 30–40 km, which is roughly the longitudinal–latitudinal dimensions of one to two 1/4° × 1/4° grid boxes, thus allowing eddies to be simply “permitted” (i.e., exist) on such a grid. If a hydrographic front is ~70–100 km wide, as in the Gulf Stream (GS), the structure of the front can be resolved on a 1/10° × 1/10° grid (~10-km spatial resolution in latitude; in longitude, 1/10° should be multiplied by cosine of the latitude), barely resolved on 1/4° × 1/4° (~25-km spatial resolution in latitude) grid, and completely unresolved at coarser resolutions.

Numerical ocean models before the late 1970s were what are now referred to as “coarse resolution” ocean circulation models, with a spatial resolution of 1° in latitude and longitude at best and far exceeding *R* (see a review in Haney 1979). Driven by increased computer power, ocean circulation models with a grid resolution of less than 1° have significantly evolved from the late 1970s through the 1990s, giving way first to “eddy permitting” (minimum 1/4° resolution) and then to “eddy resolving” (minimum 1/10°) models, which are now considered state of the art in ocean circulation modeling.

There are a number of efficient eddy-resolving ocean model implementations, as stand-alone or parts of coupled ocean–atmosphere models (e.g., Barrier et al. 2015; Madec 2008; Maltrud et al. 1998; Marzocchi et al. 2015; Masumoto et al. 2004; Shriver et al. 2007; Smith et al. 2000; Treguier et al. 2005); an extended review can be found in Hecht and Hasumi (2008). Spatial resolutions of such models are much finer than what the WOA could offer until recently. To converge data, model, and satellite mapping of the ocean, a new edition of WOA with two

grids—a $1^\circ \times 1^\circ$ and a $1/4^\circ \times 1/4^\circ$ spatial resolution at 102 depth levels—was released in 2013 (Boyer et al. 2014; Locarnini et al. 2013; Zweng et al. 2013). Both versions are available online (www.nodc.noaa.gov/OC5/woa13/).

With the evolution in computing power, ocean climatologies can now be relatively easily generated on grids with very fine spatial resolutions. However, in contrast with numerical modeling, where grid resolution is limited by computing power, resolution in a climatology should be matched to the density of data. In most regions of the World Ocean, a climatology on a finer grid would be only seemingly “high resolution” because too many grid cells would be without data and thus would show the 1° grid first-guess field simply interpolated onto the finer grid with no further betterment over 1° mapping. Despite substantial improvements in some data-rich regions (Boyer et al. 2014), the $1/4^\circ$ version of WOA13 provides less refinement in other areas.

To initiate high-resolution mapping where it is feasible, the NOAA/National Centers for Environmental Information (NCEI) has recently begun developing regional high-resolution ocean climatologies in several relatively data-rich regions (www.nodc.noaa.gov/OC5/regional_climate/). The NWARC is used here to illustrate the advantages of high-resolution local in situ ocean mapping.

The NWARC domain (80.0° – 40.0° W, 32.0° – 65.0° N) is shown as a white frame in Fig. 1, which illustrates the circulation pattern of the North Atlantic Ocean. NWARC is composed of objectively analyzed temperature and salinity fields that represent the mean ocean condition in the NWA during different time periods, namely, six decadal climatologies from 1955–64 to 2005–12 (the latter is not strictly a “decadal” climatology as it covers

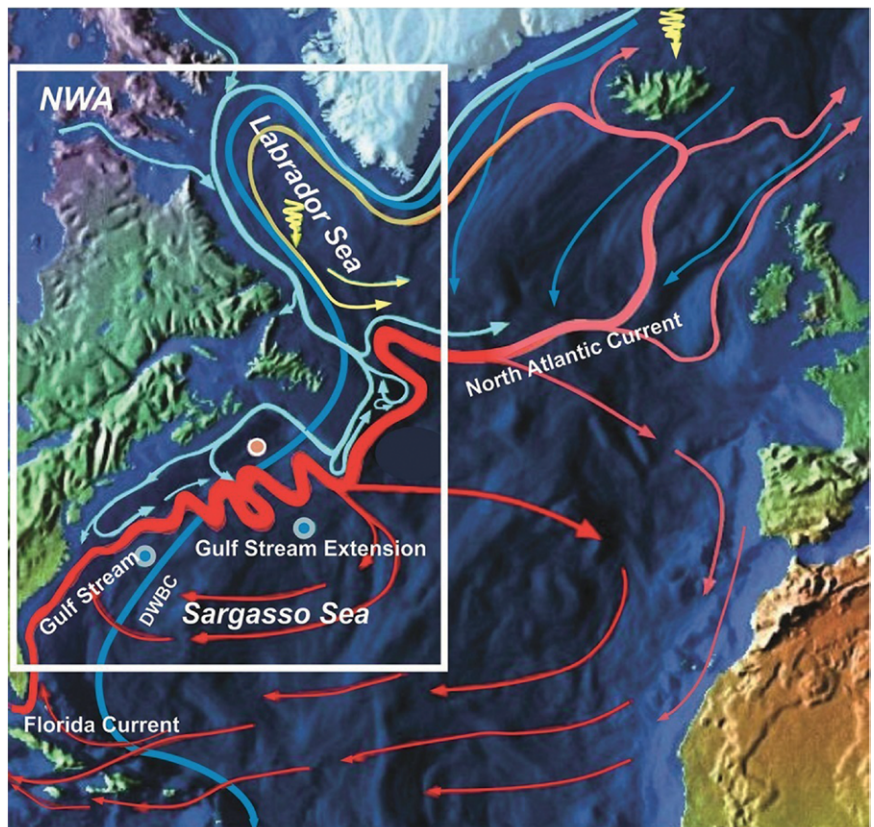


FIG. 1. Scheme of the NWA current system (modified with permission from the original drawing by I. Yashayaev at www2.mar.dfo-mpo.gc.ca/science/ocean/woce/climatology/.htm). Large white rectangle shows the NWA regional climatology domain; deep-ocean currents and some current names were added. Red and cyan lines show warm and cold currents, respectively. Convection sites in the Labrador and Greenland seas are depicted as yellow downward spirals. Warm and cold GS rings are shown as small orange and blue circles north and south of the GS and its extension.

only 8 years). Additionally, NWARC contains some statistical parameters that may be useful in ocean climate studies (data and maps are available at www.nodc.noaa.gov/OC5/regional_climate/nwa-climate/). NWARC is computed on three grids: two base resolutions of $1^\circ \times 1^\circ$ and $1/4^\circ \times 1/4^\circ$ and the higher $1/10^\circ \times 1/10^\circ$ resolution to match that of the eddy-resolving models and satellite imagery. Higher-resolution analyzed fields uncover more outliers than analyses on coarser grids. Thus, detecting outliers on $1/10^\circ \times 1/10^\circ$ fields and flagging them in WOD improves not only the $1/10^\circ \times 1/10^\circ$ mapping but also the $1/4^\circ \times 1/4^\circ$ and $1^\circ \times 1^\circ$ mapping because the flagged data are no longer used in any of the analyses.

As the analyzed fields are being computed, the first-guess fields are extensively modified through the three-pass objective analysis procedure (Boyer et al. 2005) with the influence radii shown in Table 1. Thus, the role of the first-guess fields decreases in data-rich

regions like NWA. To streamline the procedure, the objectively analyzed fields on the $1^\circ \times 1^\circ$ grid are used as the first-guess fields for both higher-resolution grids.

As mentioned, the overall quality of high-resolution data mapping depends on the in situ observation density. The uncertainty of the mean value (or standard error) for a particular grid cell decreases as the number of observations within that grid cell increases and, conversely, increases as the variance of the observations (or squared standard deviation) within the grid cell increases. Uncertainty varies from grid point to grid point, and also from region to region. For example, the density of observations in areas close to the GSS and U.S. East Coast is high, yielding lower uncertainty. At the same time, in the Sargasso Sea (see Fig. 1), the density of observations is low, which leads to higher uncertainty. Thus, variance is high in the GSS because it is highly variable, and one grid cell could have many different values, yet the uncertainty in that grid cell will be much lower because of the large number of observations. On the other hand, in the Sargasso Sea and similarly less data-covered areas, the variance is low because the presiding currents are less variable, yet the uncertainty is high because of the scarcity of observations.

The utility of higher spatial resolution is illustrated by a monthly climatology for one of the decades. Figure 2 shows 2005–12 October decadal temperature at 100 m on three grids: $1^\circ \times 1^\circ$, $1/4^\circ \times 1/4^\circ$, and $1/10^\circ \times 1/10^\circ$. The $1/4^\circ \times 1/4^\circ$ field (Fig. 2b) barely represents the major elements of the GS dynamics (jet width, separation point, etc.), while the $1/10^\circ \times 1/10^\circ$ mapping (Fig. 2c) properly reveals these frontal structures of the GSS and is comparable to what is seen in eddy-resolving model climatologies (Hecht and Hasumi 2008). Coarse-resolution mapping on the $1^\circ \times 1^\circ$ grid fails to reflect the observed and modeled structure of the GSS.

A more detailed climatology is important for diagnosing ocean climate change because it is more physically consistent with the observed mesoscale variability. It allows for meaningful comparisons with ocean climatologies calculated from high-resolution model outputs and can be used as better initial conditions for model forecasts and hindcasts. For example, only eddy-resolving ocean models with $1/10^\circ$ or better resolution can properly resolve the GS separation from the coast within the Cape Hatteras vicinity—the task that coarser-resolution models could not accomplish (e.g., Chassignet and Marshall 2008; Hecht and Hasumi 2008). This issue has been addressed and mostly resolved, theoretically and

numerically (e.g., Chassignet and Marshall 2008; Ezer 2016; Gangopadhyay et al. 1992). We recognize that our eddy-resolving NWARC does not contribute to the vast current knowledge of this and other issues of the GS dynamics. However, it cannot be overstated that historical in situ observations, if mapped on $1/10^\circ \times 1/10^\circ$ grid, do reveal similar details of the GS structure, showing correct GS separation along with the correct jet width and overall mesoscale structure of the mean flow as shown in Fig. 2c (although no ocean climatology resolves mesoscale dynamics *per se* because it maps data on a far longer time scale; see the discussion below). Coarse-resolution mapping completely fails in this realm. In other words, ocean climatologies should be compiled, if possible, with the details approaching the details of eddy-resolving ocean models and, in the upper layers, satellite observations of the sea surface (see below).

One of the important goals of in situ ocean climate data mapping is to support ocean and climate change research. Because of the ocean's large heat capacity, the ocean is changing at a much slower rate than the atmosphere or land and plays an important role in Earth's climate change over decadal and longer time scales. Water temperature and ocean heat content averaged over 30-yr periods characterize the ocean climate in terms of the climate normals defined by WMO (2011). Ocean climate change (or, more accurately, climate shift) can be inferred from the differences between two consecutive 30-yr intervals. As the first practical use of the $1/4^\circ$ WOA13 edition, the climate shift of ocean heat content over the entire North Atlantic was recently investigated (Seidov et al. 2017). It was shown that heat is accumulated in the North Atlantic heterogeneously, in localized pockets, with the strongest heat gain in the subsurface of the GSS. Figure 3 presents a 3D visualization of the 30-yr climate shift in seawater temperature between 1955–84 and 1985–2012 in the NWA domain at the $1^\circ \times 1^\circ$ and $1/10^\circ \times 1/10^\circ$ spatial resolutions as derived from the NWARC. The coarse-resolution mapping (Fig. 3a) simply reveals general subsurface temperature increases in the GS vicinity, while the fine resolution shows far more detailed structure of warming in the NWA concentrated in several pockets of warmer water near the GSS, as well as cooling in the central Labrador Sea (Fig. 3b).

Another aspect of eddy-mean interactions in high-energy currents, such as the GS, Kuroshio, etc., is the cumulative effect of mesoscale transients on thermohaline structure of the ocean on decadal and longer time scales. Eddy-mean flow interactions play an important role in rectifying the mean current

and impact the net oceanic heat transport (e.g., Jayne and Marotzke 2002; Qiu and Chen 2010; Treguier et al. 2017). Individual mesoscale eddies cannot be seen in ocean climatologies in principle; however, the *cumulative effect* of mesoscale dynamics is reflected in decadal and long-term averaged temperature, salinity, and other tracer fields. It was shown (see reviews in Kamenkovich et al. 1986; Robinson 1983) that the final long-term averaged thermaline fields are very different in model simulations on coarse- and fine-resolution grids, and this result is consistent with what is seen when mapping in situ data climatologies on coarse- and fine-resolution grids, as Figs. 2 and 3 confirm.

The key to understanding why decadal climatologies are so important is that they put emphasis on the repetitiveness or stochastic periodicity of the major elements of mesoscale processes in the GSS seen in satellite imagery (e.g., Kelly et al. 2010) and in eddy-resolving models (e.g., Molines et al. 2014). Decadal-averaged months for all six decades at different depths in the NWARC were compared to each other, and it was found that on the $1/10^\circ \times 1/10^\circ$ grid there are identifiable repetitive mesoscale patterns in all decadal climatologies for all months in the upper-1,000-m layer. Based on this capability of high-resolution decadal monthly in situ climatologies, a hypothesis was put forth that *the seasonal signal carries superimposed repetitive mesoscale activity and therefore decadal in situ climatologies reflect the cumulative effect of the mesoscale dynamics* (Seidov et al. 2016).

To test this hypothesis, we compared NWARC's monthly decadal near-surface temperature to sea surface temperature (SST) 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 (Casey et al. 2015). The ap-

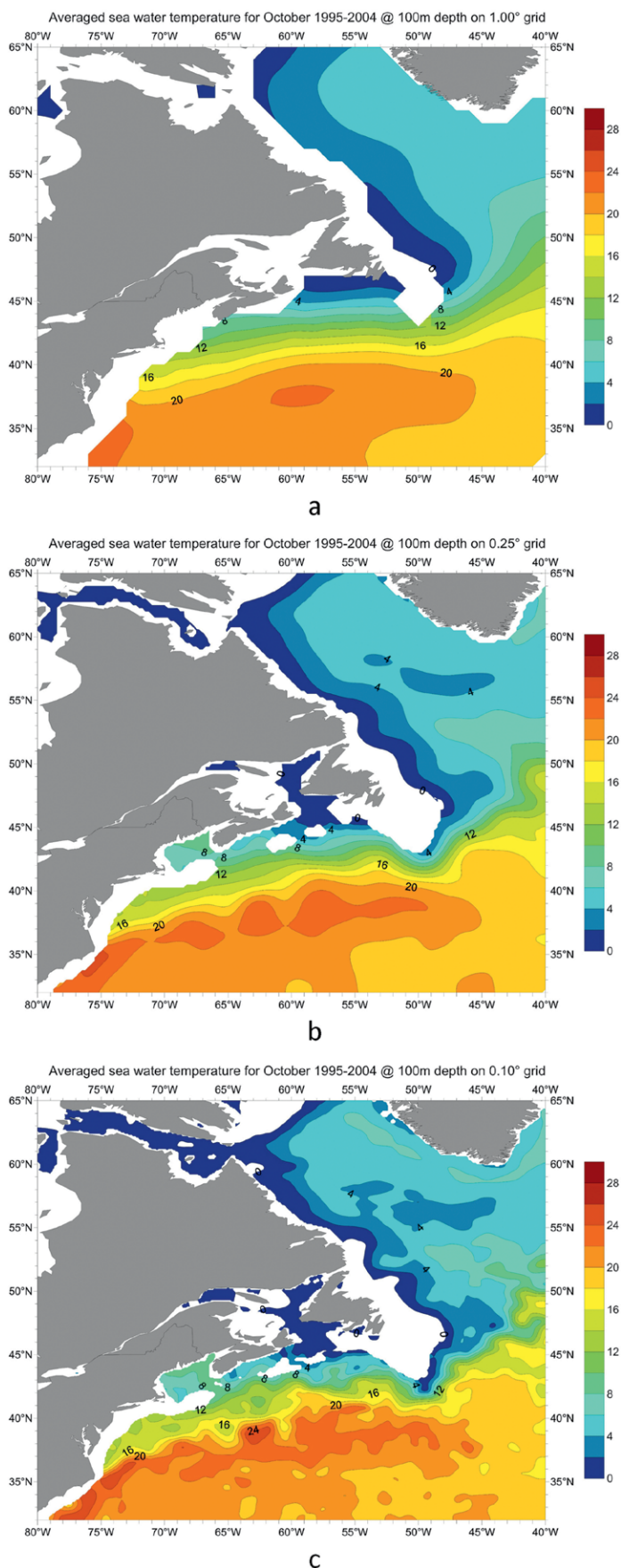


FIG. 2. Climatological Oct seawater temperature averaged over the period of 2005–12 at 100 m depth in the three analyses on (a) 1° , (b) $1/4^\circ$, and (c) $1/10^\circ$ grids.

proximate spatial resolution of the data are 4 km ($\sim 1/20^\circ$ at midlatitudes) with one-week temporal resolution. To make the satellite SST comparable with the NWARC near-surface temperature, we averaged the weekly satellite SST data 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 1985–94, 1995–2004, and 2005–12 and averaged them within each decade.

Figure 4 shows October decadal temperature from NWARC at 10 m depth for 1985–94, 1995–2004, and 2005–12 (left panels) and decadal October SST assembled from CoRTADv5 (right panels). Note that

the satellite SST looks smoother than those from NWARC, which may be due to weekly averaging inherent in CoRTADv5 versus individual profiles from WOD. Repetitive disturbances, filaments, and mesoscale features can be seen in many areas, especially in the GS vicinity. For example, there are perturbations of the frontal zone with filaments of warm and cold water at the northern and southern boundaries of the GS extension (shown by small black circles in Fig. 4), similar to what was shown in Kelly et al. (2010). The sizes and shapes of the mesoscale perturbations vary from decade to decade. There are varying intrusions of warm water in the

southwest corner of the domain, variable shapes of the topographically induced cold meander off the Scotian Shelf, and other stochastically repetitive mesoscale elements seen in both NWARC and CoRTADv5 climatological October maps (Fig. 4). Similarly, in any given month of any decade, the mesoscale motion signatures emerge as repetitive features superimposed on the more pronounced seasonal decadal variability and on topographically induced quasi-stationary meanders. Because of the stochastic nature of jet–eddy interactions, the remnants of mesoscale elements (meanders, filaments, etc.) imprinted in the mean fields of decadal climatologies can never be exactly the same from decade to decade. Nonetheless, as Fig. 4 demonstrates, these mesoscale elements of the decadal monthly temperature fields can appear in approximately the same locations for three different decades and show similar, yet not the same, intra-annual development from month to month, thus demonstrating their inher-

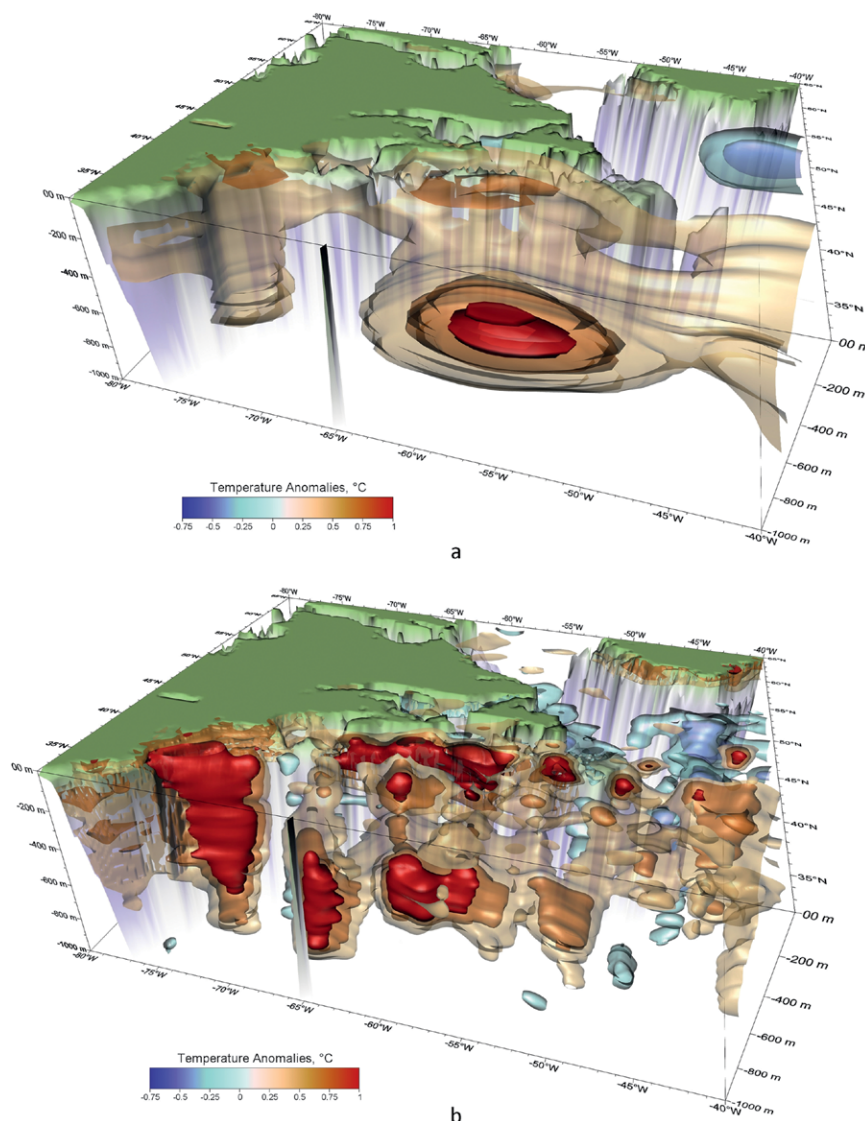


FIG. 3. Seawater temperature differences between two 30-yr ocean climates (1985–2012 minus 1955–84) within the NWA domain (80° – 40° W, 32° – 65° N) in the 0–1,000-m-depth layer on the (a) $1^\circ \times 1^\circ$ and (b) $1/10^\circ \times 1/10^\circ$ grids. The isothermal surfaces of $\Delta T = -0.5^\circ$, -0.25° , 0.25° , 0.5° , 0.75° , and 1° C are shown by different colors.

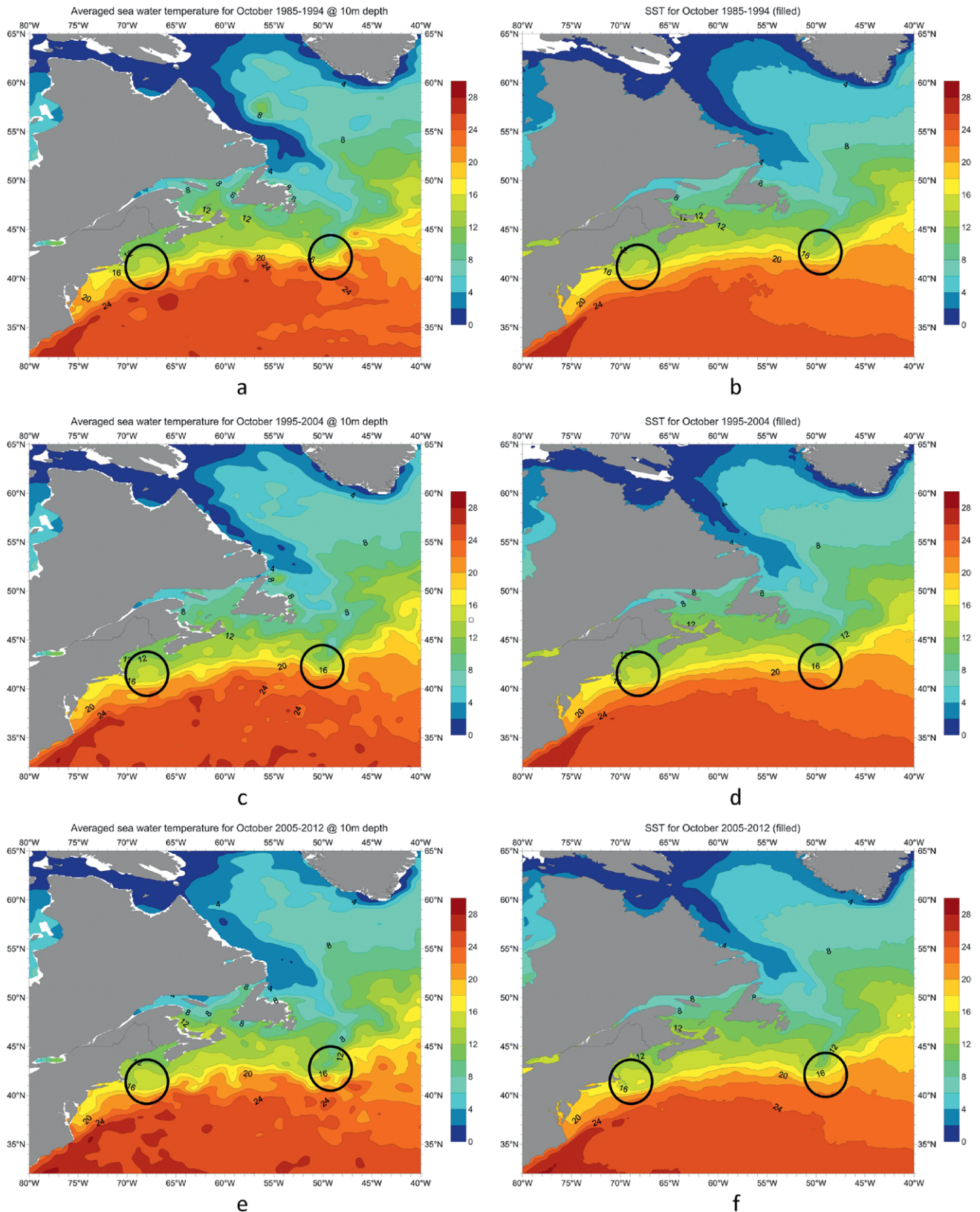


FIG. 4. Climatological Oct seawater temperature from (left) NWARC at 10 m depth and (right) SST from satellite observations for the decades 1985–94, 1995–2004, and 2005–12. The satellite SST maps are created from CoRTADv5 (Casey et al. 2015). Examples of repetitive filaments in the GS extension area are denoted by the black circles.

ently stochastic nature. (The intra-annual monthly progression of mesoscale disturbances in each decade can be viewed online at www.nodc.noaa.gov/OC5/regional_climate/nwa-climate/).

Similar to the above-outlined comparison between monthly decadal satellite SST and near-surface in situ temperature, Seidov et al. (2016) compared the monthly observed high-resolution decadal climatologies from NWARC with the decadal climatologies compiled using the model output from the Nucleus for European Modeling of the Ocean (NEMO) eddy-resolving model (Madec 2008; Molines et al. 2014) (courtesy of Jean-Marc Molines of University of Grenoble, France; Figs. 17–20 in Seidov et al. 2016). The important conclusion derived from the model–data comparison was that the cumulative impact of mesoscale motion on large-scale circulation dynamics is apparently of the same nature in both observed and modeled climatologies.

NWARC salinity climatologies show similar transitions as temperature from coarse to eddy-permitting to eddy-resolving resolutions and likewise may be expected to be useful in climate simulations and satellite data validation. From the perspective of climate modeling, mapped sea surface salinity (SSS) may be used in a model spinup of ocean circulation, which is critical for ocean climate simulations, especially in the long-term climate forecasts. As was found in early simulation experiments using coupled ocean–atmosphere models, the freshwater fluxes in such models must be precomputed 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 all coupled ocean–atmosphere models (Bryan 1998; Huang et al. 2015; Manabe and Stouffer 1988). Many forecast models still practice the same method of restoring computed SSS to the observed fields to suppress such artificial climate drift by precomputing freshwater fluxes reflecting the observed SSS patterns. The SSS from earlier editions of WOA on a $1^\circ \times 1^\circ$ spatial grid was not practical for modern eddy-resolving models as the WOA SSS was too smooth on coarse-resolution grids (e.g., Molines et al. 2014). Thus, using high-resolution mapped SSS on $1/4^\circ$ and $1/10^\circ$ grids with well-resolved frontal structures may help to improve long-term ocean climate forecasts.

The main objective of our report was to emphasize that using high-resolution climatologies, such as NWARC, can be instrumental in detailing local assessment of ongoing global ocean climate change and can help the scientific community better understand long-term variability and trends. In a broader outline,

NCEI’s approach to building regional ocean climatologies encompasses an important area of connecting data processing and research and opens a new perspective on understanding ocean climate change.

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“It has become clear that natural disasters are at the very center of the problem of economic and social development.”

— TYLER COWEN, *Professor of Economics, George Mason University*

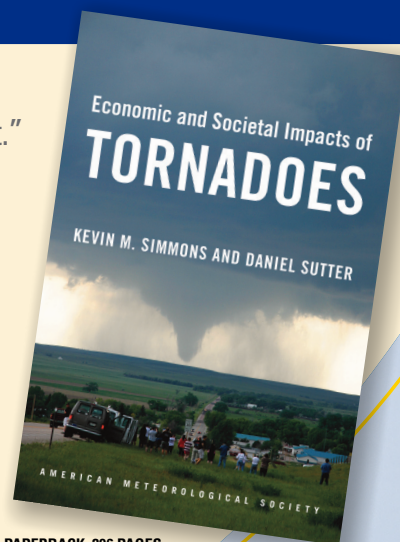
Economic and Societal Impacts of Tornadoes

KEVIN M. SIMMONS AND DANIEL SUTTER

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