The Modular Ocean Data Assimilation System (MODAS)*

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ABSTRACT

The Modular Ocean Data Assimilation System (MODAS) is used by the U.S. Navy for depiction of three-dimensional fields of temperature and salinity over the global ocean. MODAS includes both a static climatology and a dynamic climatology. While the static climatology represents the historical averages, the dynamic climatology assimilates near-real-time observations of sea surface height and sea surface temperature and provides improved temperature and salinity fields. The methodology for the construction of the MODAS climatology is described here. MODAS is compared with Levitus and Generalized Digital Environmental Model climatologies and with temperature and salinity profiles measured by SeaSoar in the Japan/East Sea to illustrate MODAS capabilities. MODAS with assimilated remotely sensed data is able to portray time-varying dynamical features that cannot be represented by static climatologies.

1. Introduction

Climatologies consist of data averaged over well-defined spatial grids and over time periods such as months, seasons, or years. A broad distribution of the data in time and in space is best for the formulation of representative vertical profiles in the construction of climatologies. Data-sparse situations require special averaging and interpolation techniques. Climatologies have many applications, including climate studies, quality control of new data, and design of experiments. In addition, accurate climatologies are particularly important for numerical model development and evaluation. Climatologies provide boundary conditions and first-guess fields for models.

Levitus (1982) published the first worldwide ocean climatology and has made updates in Levitus and Boyer (1994), Levitus et al. (1994), Antonov et al. (1998a,b,c), Boyer et al. (1998a,b,c), and in Conkright et al. (1999). His climatology (hereafter referred to as the Levitus Climatology, or simply Levitus) is based on objectively analyzed, gridded sets of temperature and salinity fields obtained from all data available through 1998 from the National Oceanographic Data Center (NODC), Washington, D.C. The data were analyzed on annual, seasonal, and monthly timescales and were gridded in 1° latitude–longitude cells at standard oceanographic levels between the surface and bottom (maximum depth 5500 m).

Another climatology being considered here, the Generalized Digital Environmental Model (GDEM, current version 2.5; Teague et al. 1990), was developed at the Naval Oceanographic Office (NAVOCEANO). GDEM provides global coverage of temperature and salinity on grids ranging from ½° in the deep ocean to ⅙° in selected coastal regions. The Japan/East Sea (JES) is one of these high resolution regions. The primary source of data for GDEM is the Master Oceanographic Observation Data Set (MOODS; Teague et al. 1990), the ocean temperature and salinity observations data base for the U.S. Navy maintained and updated at NAVOCEANO with data holdings of over three million observations, comparable to data holdings at NODC. GDEM consists of coefficients of mathematical expressions describing the vertical profiles of temperature and salinity. Profiles of temperature and salinity are generated from equations using the stored coefficients. Vertical profiles of tem-

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perature and salinity extending from the surface to the bottom can be computed from the coefficients for any day of the year.

The Modular Ocean Data Assimilation System (MODAS), recently developed at the Naval Research Laboratory, is a tool for using climatological and real-time data. MODAS is predominately used by the U.S. Navy. MODAS is a static climatology in one mode of usage. However, MODAS is more than just a static climatology. MODAS also provides a vehicle for assimilating real-time observations, either surface observations that are projected vertically, or in situ observations that are assimilated directly. This mode, referred to as Dynamic MODAS, combines observed ocean data with climatological information to produce a quality-controlled, gridded analysis field as output. The analysis uses an optimum interpolation (OI) data assimilation technique (Gandin 1963; Bretherton et al. 1976; Lorenc 1981), which combines remotely sensed sea surface temperature (SST) and sea surface height (SSH) data with other local observations from ships, aircraft, or buoys to produce a three-dimensional analysis of the ocean temperature and salinity structure. Grids of MODAS climatological statistics range from ½° in the open ocean to ¼° in coastal seas and ⅛° near the coasts. These grids can be interpolated to any desired spacing.

Dynamic MODAS, although not a replacement for static climatologies, is an important tool that can be used in conjunction with static climatologies. The vast majority of the ocean is not sampled with in situ conductivity–temperature–depth (CTD) or expendable bathythermograph (XBT) casts very frequently and generally static climatologies are relied on to estimate present day ocean conditions. Dynamic MODAS allows for the influence of front and eddy features that are detected through remote sensing of sea surface height and temperature. This adjusted climatology can more closely represent the in situ ocean than a static climatology and is useful for many applications. It provides a better first guess when in situ profile data are available for assimilation. The closer the first guess field is to the truth, the better the optimum interpolation will perform.

Both MODAS and GDEM are used by the U.S. Navy for many of its operational systems. The Levitus climatology is used by both the academic community and the U.S. Navy (particularly when global coverage is required). GDEM does not have the spatial resolution of MODAS. GDEM exists globally on a ½° grid. Higher grid resolutions are available for a few selected regions but represent only a small fraction of the world's coastlines. Both MODAS and GDEM relax to Levitus in the deep layers. The main selection criterion for the user is likely accessibility. GDEM is gaining more widespread usage since its public release in 1991. The GDEM and Levitus climatologies were compared by Teague et al. (1990). In this paper, the capability and methodology of MODAS are described. MODAS output fields and both Levitus (Levitus et al. 1994; Levitus and Boyer 1994; Antonov et al. 1998a,b,c; Boyer et al. 1998a,b,c) and the GDEM climatologies are evaluated against high-resolution in situ temperature and salinity observations obtained from a ship-towed, undulating profiler (SeaSoar) in the JES. Such observations provide ''snapshots'' of oceans.

In section 2, an overview of the construction of MODAS and its capabilities is given for the first time in the open literature. A brief description of SeaSoar and its mode of operation in the JES are provided in section 3. MODAS, Levitus, and GDEM output fields are evaluated against SeaSoar fields in section 4. The climatologies are discussed in section 5. Conclusions are given in section 6. More details of MODAS construction are provided in the appendix.

2. MODAS

MODAS is one of the present U.S. Navy standard tools for production of three dimensional grids of temperature and salinity, and derived quantities such as density, sound speed, and mixed layer depth (Harding 1999). It is a modular system for ocean analysis and is built from a series of FORTRAN programs and UNIX scripts that can be combined to perform desired tasks. Programs are included for quality control, data importation, profile extension, data sorting, parameter derivation, data decimation, data cross-validation, data gridding, data assimilation, and many other utility operations. MODAS was designed to combine observed ocean data with climatological information to produce a quality-controlled, gridded analysis field as output. The analysis uses an OI data assimilation technique to combine various sources of data.

MODAS 1.0 was first incorporated into the Navy's Oceanographic and Atmospheric Master Library (OAML) in November 1995. An intermediate version (Carnes et al. 1996) was used in a real-time ocean nowcast/forecast system demonstration in the North Pacific. The new climatology developed for the present version (2.1) is the subject of this paper. MODAS is a static climatology similar to the Levitus climatology in one mode of usage while in another mode, Dynamic MODAS, it assimilates remotely sensed temperature and sea surface height data and provides an adjusted climatology. Dynamic MODAS represents an extension of traditional climatologies. Traditional climatologies represent long-term averages and do not claim to reproduce realistic instantaneous (i.e., synoptic) variability. Dynamic MODAS uses remotely sensed data in an attempt to accurately reproduce synoptic mesoscale three-dimensional variability.

The full version of MODAS is available to U.S. government agencies and contractors, and to scientists with U.S. Navy contracts. Many universities have contracts with the U.S. Navy and thus qualify. Subsets of MODAS are also available on a case by case request basis.

a. Static MODAS climatology

The static MODAS climatology used in the JES is a subset of the global MODAS temperature and salinity climatology which is stored bimonthly in time on a variable resolution mesh in space. In the upper 1500 m of water, it is computed from historical temperature and salinity profiles from MOODS. These profiles have undergone rigorous editing in which every profile has been visually inspected prior to its inclusion in formation of the climatology. Observation profiles are excluded if the deepest point on the profile is less than half of the bottom depth for depths less than 600 m. For depths greater than 600 m, profiles shallower than 300 m are excluded. After editing, there are 2.6 million profiles remaining, 0.93 million of which include salinity. The observations are gridded by optimum interpolation to form a bimonthly temperature climatology at each grid node and depth. The background field for this OI is the *World Ocean Atlas 1994* (*WOA'94*) temperature and salinity climatology (Levitus and Boyer 1994; Levitus et al. 1994). In regions where historical observations are sparse, the OI relaxes toward the *WOA'94* climatology. At each desired grid node, an expanding envelope in space and time is formed until an acceptable number of historical profiles are found. To prevent incompatible observations from being merged between geographically close but physically distinct regions, the various basins and straits of the world are provinced. For example, profiles in the JES can be combined with profiles in the Korea (Tsushima) Strait but not with profiles outside the JES in the Kuroshio region. At each position, depth, and time of year, the relationship between salinity and temperature is determined by linear regression from the subset of observations having both temperature and salinity. Temperature and salinity variability at each grid node and depth are also computed at this stage.

As mentioned earlier, the climatology is stored on a variable resolution grid with grid spacing varying from ⅛° near land, then ¼° over shallow shelves (100 to 200 m or so), and then ½° in the open ocean. A triangular mesh of grid points is used in the JES (Fig. 1). In this area, the climatology grid spacing ranges from ⅛° to ¼°. The climatology files are formed on a bimonthly temporal sampling, starting with January (centered on 15 January, 15 March, etc). Temperature and salinity means and standard deviations are included within the files. The climatology is output at 37 depth levels ranging from 0 to 6500 m but is only computed from historical profiles for the first 26 levels, that is, the upper 1500 m. It is then spliced onto the Levitus ¼° annual climatology for levels 27 through 37 after smoothing the ¼° temperatures and salinities using a nine-point Shapiro filter 20 times.

To extract a MODAS climatology for a given spatial location and date, the climatology data are bilinearly interpolated horizontally, linearly interpolated in depth, and linearly interpolated between bimonthly averages in time for a specific day of the year. A horizontal data resolution of ⅛° was selected for the climatology comparisons in the JES.

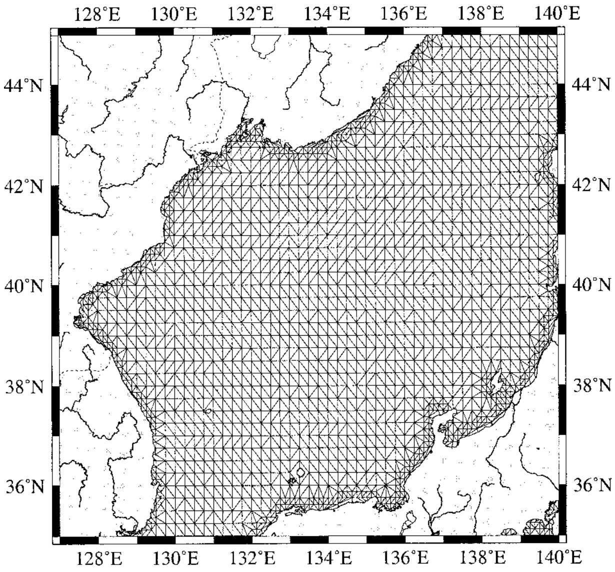

FIG. 1. MODAS grid mesh in the Japan/East Sea.

b. Dynamic MODAS climatology

One of the most significant components of MODAS is its ''dynamic climatology,'' referred to as Dynamic MODAS. Climatologies normally represent historical averages of ocean conditions. For example, at a particular time of year and location in the ocean, the temperature and salinity in the water column are expected to have a mean and variability that can be estimated by summarizing all the historical data available in the area. Conventionally, the historical data are condensed into an average profile but additional information can be extracted from the historical profiles in the area. In particular, the surface temperature and dynamic height (quantities which can be estimated from satellites) are correlated to variations in the subsurface temperature. Further, relationships may be derived to estimate salinity from temperature at each depth. This allows the development of a dynamic climatology which starts with a simple mean profile of temperature and salinity but then corrects this mean using height and temperature measurements from space-borne sensors.

The technique of using surface height and temperature to generate a ''synthetic profile'' of temperature was reported by Carnes et al. (1990), based on earlier work by deWitt (1987) in which surface properties were projected downward using empirical orthogonal functions derived from historical profile data in the area. In the MODAS dynamic climatology, these regressions are direct linear relationships between surface temperature and dynamic height with the temperature at a given depth. Synthetic temperature profiles extending to a maximum depth of 1500 m are computed from these regression relationships.

The dynamic climatology stores the relationships, obtained from archives of historical temperature and salinity profiles, between subsurface temperature with steric height anomaly and surface temperature. However, the typical application constructs synthetic temperature profiles, using the stored regression relationships, from observed total SSH anomalies and SST. The SSH and SST values can be from a single measurement or from interpolated fields. The SSH used in the derivation of the MODAS dynamic climatology is steric height anomaly that varies in the ocean due to deviations in temperature and salinity. Measurements of total height relative to prescribed means, such as from altimeter measurements, must be interpreted and adjusted to produce data appropriate for use with the MODAS regression. Typically, a 2D interpolation of point observations (at ⅛°) provides the SSH and SST grids for derivation of synthetic profiles. The 2D SSH and SST fields are computed by optimal interpolation (with prescribed error covariances) of the observations into a first-guess field, or prior analysis field. SST error covariance takes an isotropic Gaussian form with a 20-km length scale and 60-h timescale. SSH error covariance is defined on a 2° × 2° latitude–longitude grid and is determined by fitting a Gaussian covariance function to multiple years of altimeter data. Length scales of the SSH covariance range from 50 to 250 km zonally and 20 to 100 km meridionally on timescales of 20 to 70 days.

In practice, the MODAS 2D SST field uses the analysis from yesterday's field as the first guess, while the MODAS 2D SSH field uses a large-scale weighted average of 35 days of altimeter data as a first guess. The first guess field is subtracted from the new observations, and the resulting deviations from the first-guess field are interpolated to produce a field of deviations from the first guess. The field of interpolated deviation from the first guess is added to the first-guess field to produce a final 2D analysis. At the first time the OI is performed, the first-guess field is the MODAS climatology for SST and is zero deviation for SSH. Thereafter, the first-guess field is yesterday's analysis field for SST and the large-scale weighted average for SSH. The synthetic profile depends on the surface values at a given location. If the SSH and SST do not deviate from the climatological mean, then the synthetic profile reverts to the climatological profile. If the SSH and SST deviate from the climatological mean, then the synthetics estimate the deviation of temperature at each depth. The final synthetic temperature profile is the sum of the climatological profile and the profile of temperature deviations. Salinity is predicted from the synthetic temperature according to a climatological temperature–salinity relationship.

The process described above is illustrated at a location in the SeaSoar area in Fig. 2. The heavy black line shows the MODAS static climatology at this location and time of year. The sea surface temperature is 0.4°C warmer than normal but the height anomaly derived from altimetry is 14 cm lower than normal, indicating the total water column is colder than climatology. The line marked with asterisks shows the synthetic profile generated using only the 0.4°C surface temperature anomaly, which ''warms up'' the entire profile slightly. The line marked by triangles displays the synthetic generated using only the 14-cm low altimeter value, cooling the entire profile. The line marked by squares is the synthetic produced using both the surface temperature and height anomaly, which cools the profile on average but warms it near the surface.

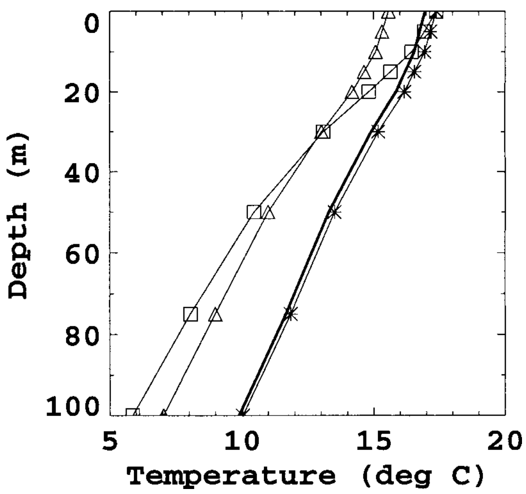

FIG. 2. A MODAS climatology profile (thick black line) and the synthetic profile development are shown for a location (36.2°N, 132.1°E, 27 May 1999) in the Japan/East Sea. The synthetic profiles are generated using SST only (asterisks), SSH only (triangles), and both SST and SSH (squares).

MODAS includes an optimum interpolation module to assimilate in situ XBTs and CTDs. The dynamic climatology is used as the 3D first-guess field for the optimum interpolation of the XBT and CTD data. The in situ temperature profiles are subtracted from the first-guess field to obtain the residuals. A standard optimum interpolation is performed to produce an updated 3D temperature field. The MODAS climatology temperature and salinity relationships are then used to produce an estimated salinity field, based on the temperature field just produced. The salinity profiles are assimilated by optimum interpolation, using the 3D salinity field just produced as a first-guess field.

3. SeaSoar

The 1999–2001, Office of Naval Research–sponsored JES program provides an opportunity to evaluate MODAS performance through intercomparison with high-resolution in situ measurements of upper ocean variability. Extensive measurements were acquired in the region of the subpolar front of the JES during May–

June 1999 using a towed, undulating profiler (SeaSoar). At typical tow speeds of 8 kt, SeaSoar provides 3-km along-track horizontal resolution while profiling between the surface and approximately 350 m. SeaSoar measured temperature, conductivity, chlorophyll fluorescence, light transmission, and a variety of bio-optical variables, while shipboard sensors collected meteorological measurements and profiles of upper ocean velocity. These observations were tailored to resolve the mesoscale variability MODAS strives to reproduce and thus offer a basis for a detailed study of MODAS's performance. Here, we use data from a 400-km-long section that extends west–east across the basin and required approximately one day to complete. SeaSoar measurements were processed in a manner similar to that described in Lee et al. (2000) to yield vertical profiles with approximately 3-km horizontal resolution and 4-m vertical resolution. Water depths along the SeaSoar section exceed 2000 m for much of the section but JES waters are nearly homogeneous below 400 m and have little seasonal signal. Geostrophic velocities computed from deep JES CTD casts contain a range of only about 1 cm s^{-1} in the waters below 400 m. The section captures significant mesoscale variability both at the surface and within the pycnocline, providing a variety of challenges through which we can investigate the capabilities of MODAS.

4. Comparisons

Temperature and salinity were measured by SeaSoar along a section in the JES and will be compared here to the static and dynamic climatologies. The region in the vicinity of the section is typified by meandering currents and eddy activity (Preller and Hogan 1998). The Tsushima Current transports warm, salty water through the Korea Strait and influences the formation of fronts and eddies in the southern JES. Since the flow pattern and eddy variability are complicated, temporal averaging used to create climatology temperature maps diffuses the fronts and can produce a nonrepresentative picture. Hence, rapid measurements of the temperature and salinity structure by SeaSoar, provides a rigorous test for climatological representativeness of the JES.

Temperature sections computed from Levitus, GDEM, MODAS, and Dynamic MODAS are directly compared against temperatures along an east–west SeaSoar Section at 37.5°N in the southwestern JES. The section begins just off Korea and extends for approximately 5° longitude. To illustrate the effect of incorporating remotely sensed SST and SSH, Dynamic MODAS is computed using just SST (MODAS_SST) and just SSH (MODAS_SSH), and then both SST and SSH (MODAS_SST&SSH). In addition, synthetic profiles are computed at each SeaSoar profile location using SeaSoar SST and SeaSoar-derived SSH for simulation of perfect remotely sensed SSH and SST products. A reference level of 302 m is used to calculate dynamic height anomaly for each SeaSoar profile. Nearly all of the dynamic height variability is in the upper 300 m. The synthetic profiles using SeaSoar SST and SSH are referred to as MODAS_Syn and should produce better estimates of temperature and salinity fields than the Dynamic MODAS when using actual remotely sensed SST and SSH. Dynamic MODAS is equivalent to MODAS_Syn when errors in the altimetric SSH and satellite multichannel sea surface temperature (MCSST) measurements are very small.

Temperature measured along the SeaSoar section is contrasted with temperature derived from Levitus, GDEM, MODAS, Dynamic MODAS, and MODAS_Syn (Fig. 3). The monthly Levitus climatology (1° grid) and the seasonal GDEM climatology (½° grid) are used. These data have been interpolated in time to day of the year. SeaSoar temperatures are denoted by the thin lines in each plot. SeaSoar temperatures contain more detail since the horizontal and depth resolution from the SeaSoar data are more highly resolved (about 0.04° zonally and 4 m in depth) than the climatologies. The Levitus and GDEM climatologies have been regridded to a ⅛° grid and have been interpolated to the same vertical levels as SeaSoar levels for the analysis. MODAS fields have also been extracted on a ⅛° grid at SeaSoar levels. MODAS synthetic profiles are plotted at the same resolution as the SeaSoar profiles.

An anticyclonic eddy feature is evident in the western portion of the section by the strong dip in the isotherms near 130°E. Another dip in the isotherms, corresponding to another anticyclonic eddy feature, is found on the eastern end of the section (Fig. 3). Corresponding features are also apparent in SeaSoar salinity (not shown). These features are about 130 km wide (about 1.5° longitude at this latitude). At 1° grid spacing, the Levitus climatology cannot resolve such features (Fig. 3a). At ½° resolution, GDEM very faintly indicates the western current feature (Fig. 3b). The MODAS climatology, although at a finer resolution of ⅛° and smoother, is similar to GDEM in indicating the possible existence of a western current feature (Fig. 3c). Dynamic MODAS constructed using only remotely sensed SST (Fig. 3d) does not provide any improvement over the MODAS climatology in this case. However, the two observed eddy features have weak SST signatures and the signatures that they do have are cold, rather than warm, despite the fact that the eddies are subsurface warm eddies. Additionally, SST coverage obtained from MCSSTs in this region is often poor due to cloud cover. Dynamic MODAS constructed using just remotely sensed SSH (Fig. 3e) provides a significant improvement in the representation of the temperature field. The strong dips in the isotherms on the western and eastern ends of the section are captured, but the vertical structure of the synthetic profiles within the eddy features lacks the isothermal layer between 100 and 200 m. Although Dynamic MODAS with remotely sensed data

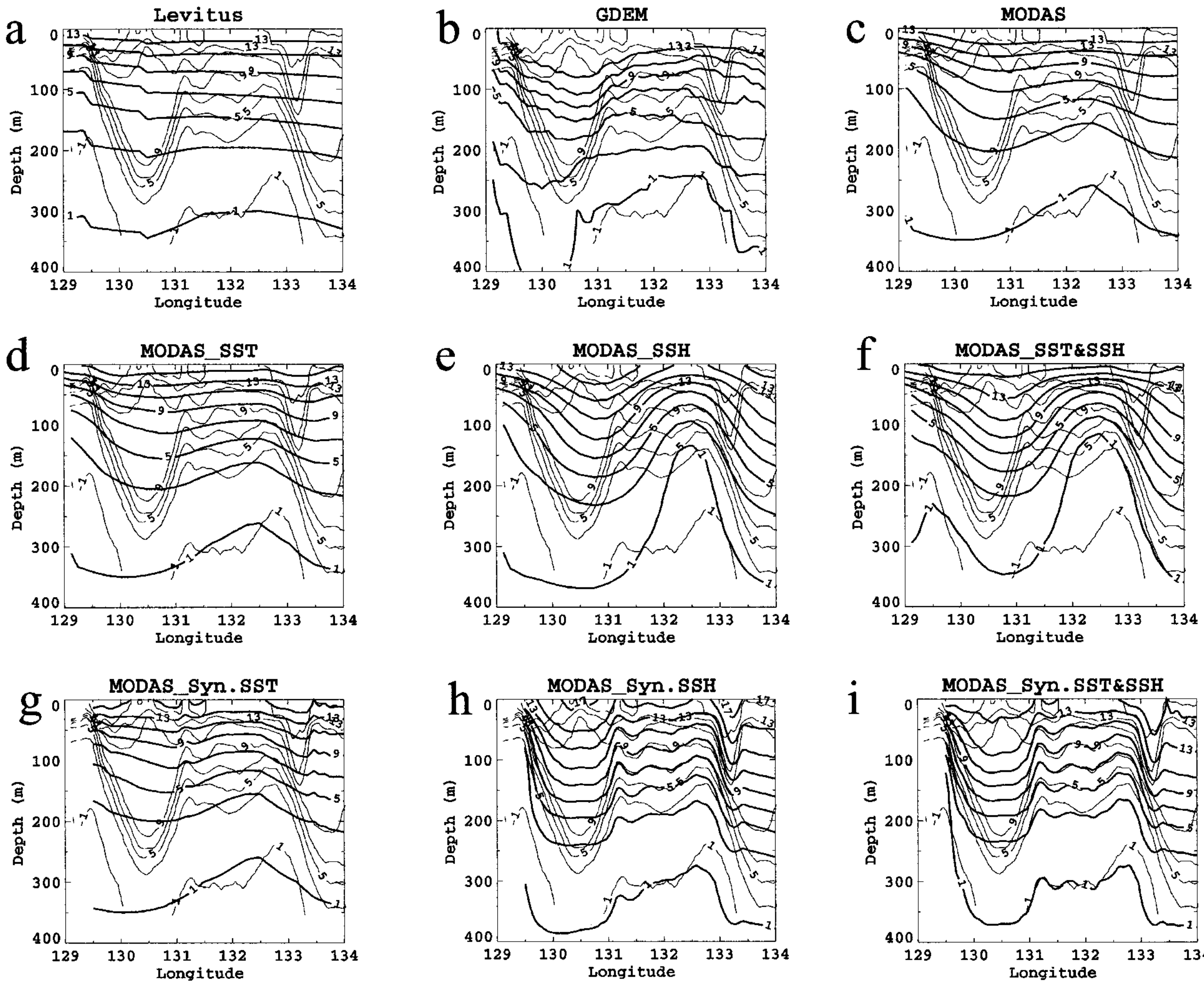

FIG. 3. The SeaSoar temperature section (thin lines) is presented with temperature sections from (a) Levitus, (b) GDEM, (c) MODAS, and (d)–(f) Dynamic MODAS. Dynamic MODAS is constructed from satellite data using (d) just SST, (e) just SSH, and (f) both SST and SSH. Similarly, temperature sections are shown using synthetic profiles constructed from (g)–(i), SeaSoar SST, SSH, and both SST and SSH, respectively. The contour interval is 2°.

reproduces some of the horizontal structure of the western eddy, the resulting feature is smeared (too wide) and offset to the east. The smaller feature, about 50 km in width on the eastern half of the section, corresponding to a strong narrow current feature is not resolved. Dynamic MODAS utilizing both remotely sensed SST and SSH offers some additional improvement in derived temperature field (Fig. 3f).

Perfect remotely sensed measurements are simulated using the SeaSoar data. Synthetic profiles calculated using just SeaSoar SST (Fig. 3g) provide improved temperature fields in the near-surface but otherwise are very similar to the Dynamic MODAS, which uses remotely sensed SST (Fig. 3d). Synthetic profiles constructed with just SeaSoar SSH (Fig. 3h) provides a much improved temperature field in comparison with Dynamic MODAS using remotely sensed SSH (Fig. 3e). Synthetic profiles obtained using both SeaSoar SST and SSH provide the best derived temperature field (Fig. 3i). The width of the western current feature is particularly well represented while vertical structure in the interior of this feature is not. The smaller eastern current feature is also well resolved horizontally but not as well resolved vertically. The temperature field in the quieter region between the current features is well resolved.

Smearing of the eddy features using the remotely sensed data is primarily caused by temporal and spatial aliasing of the coarsely spaced satellite along-track data. Temperature discrepancies within the eddy features are in part due to use of a simple linear relationship between height anomalies and subsurface temperature anomalies in this version of MODAS. The true relationship in this example, is apparently nonlinear with temperature becoming nearly constant for sufficiently high height anomalies. A nonlinear relationship

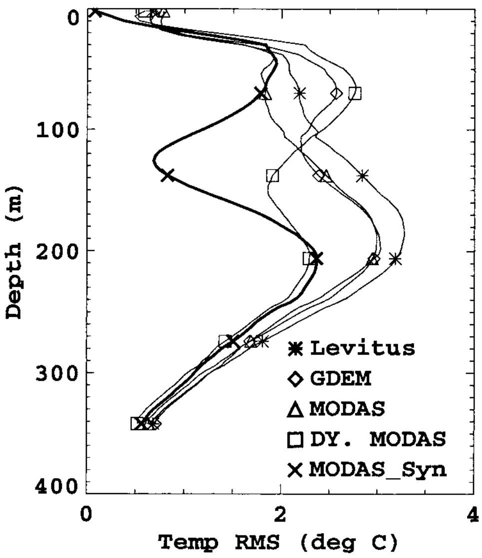

FIG. 4. Rms temperature differences between SeaSoar profiles and Levitus, GDEM, MODAS, Dynamic MODAS, and MODAS_Syn along the SeaSoar section. Symbols are used to denote the various climatologies, with the thickest line used for MODAS_Syn.

could be derived to better fit these cases, but for regions of strong mesoscale variability, there will likely not be a single relationship that relates surface observations to subsurface structure. Typically, however, the linear relationship is adequate.

Dynamic MODAS and MODAS_Syn salinities strongly indicate both current features but do not represent the actual vertical salinity structure well. MODAS salinities reflect a vertical salinity structure corresponding to the MODAS temperatures. However, salinity ranges in the current features are small, with salinity differences in the upper 400 m of just 0.2 to 0.4 psu. GDEM and MODAS salinities are only slightly indicative of current features.

Temperatures from each of the climatologies, Dynamic MODAS, and MODAS_Syn were differenced with SeaSoar temperatures along the section. Temperature rms values were computed from the differences (Fig. 4). Smaller rms indicates a better representation of the environment. Below 70 m, MODAS_Syn temperature rms is generally the smallest and Dynamic MODAS is next smallest. Levitus, GDEM, and MODAS temperature rms values are tightly clustered. Above 50 m and below 300 m, Dynamic MODAS, MODAS, Levitus, and GDEM temperature rms are often comparable to MODAS_Syn rms values. Average rms differences in salinity were similar between the static and dynamic climatologies.

Comparisons of the climatologies and Dynamic MODAS are similar for other areas of the world ocean. Rms differences were computed between the climatologies and Dynamic MODAS using the historical temperature and salinity profiles available from 1 January 1998 through 30 April 2000 for the global ocean (92 975 profile pairs), Kuroshio region in the Pacific Ocean (3364 profile pairs), and Gulf Stream region in the Atlantic Ocean (1813 profile pairs). Based on profiles of temperature rms differences (Fig. 5), the static climatologies provided similar results in each case while the Dynamic MODAS provided significantly better results. Similarly, rms differences were computed for salinity for the global ocean, Kuroshio region, and Gulf Stream region (Fig. 6). Salinity rms errors are very similar between Dynamic MODAS, MODAS, and Levitus. GDEM rms error is comparable except for the upper 200 m. Salinity rms error is lowest for Dynamic MODAS and highest for GDEM. However, salinity differences are not considered significant between Dynamic MODAS, MODAS, and Levitus, and with GDEM for depths greater than 200 m.

5. Discussion

Static ocean climatologies are designed to be representative of mean oceanic conditions. Climatological profiles may never exactly match a single in situ profile. Climatologies normally represent historical averages of ocean profiles. SeaSoar profiles in the JES provide a near snapshot of oceanic conditions. Features observed in synoptic SeaSoar temperature sections are not encountered in a static climatology unless similar features are persistent over some large fraction of the time period used to form the climatology.

Dynamic MODAS was developed by making use of additional information contained in the historical profiles. Regression relationships were developed that related SST and SSH observations (quantities that can be estimated from satellite observations) to subsurface temperature. Further relationships were derived to estimate salinity at each depth. SeaSoar measurements of temperature and salinity profiles along sections completed within about one day provide near-real-time frontal delineation and therefore offer a reality check for Dynamic MODAS. Dynamic MODAS is able to distinguish the transient frontal features while the static climatologies cannot. Dynamic MODAS attempts to extend traditional climatologies by using limited data assimilation in an effort to make predictions of instantaneous mesoscale variability.

Data assimilation allows Dynamic MODAS to adjust climatological fields to more accurately portray instantaneous mesoscale temperature and salinity variability. Assimilated observations define the horizontal extent of mesoscale features and are used to create synthetic vertical profiles of temperature and salinity. Relying solely on remotely sensed observations of sea surface temperature and sea surface height (dynamic topography), MODAS reproduced observed horizontal variability, though mesoscale features were smeared and offset in space relative to the observations. The TOPEX altimeter measurements assimilated into MODAS were taken on a 10-day repeat cycle with 7 km (200 km) along-

(across-) track resolution. Given the 10- to 100-km scales of the observed fronts and eddies, TOPEX provides adequate resolution only when features lie directly under one or more tracks. Spatial and temporal aliasing in the sea surface height measurements may thus explain the smearing and shifting of features (Fig. 3f). Given unaliased SeaSoar-derived sea surface heights and temperatures, MODAS reproduces the observed horizontal variability without smearing and shifting (Fig. 3i). Additional corrections may be applied to satellite data to improve accuracy, but increased resolution (and thus decreased aliasing) would require tighter cross-track spacing and shorter repeat cycles. In the absence of in situ profiles, MODAS was unable to accurately reproduce the vertical structure within mesoscale features. Ultimately, MODAS may require a small number of in situ profile measurements [e.g., XBT drops, CTD casts, or Profiling Autonomous Lagrangian Circulation Explorer (PALACE) float measurements] at selected locations within previously identified features to constrain the predictions of vertical structure and generate accurate results. This requirement should not be an issue in areas outside of mesoscale features, where climatology provides a reasonable measure of vertical structure.

In this analysis, Dynamic MODAS results closely approximated MODAS_Syn. SSH errors can arise from erroneous long-term mean surface heights or the geoid determination, as well as from a multitude of satellite orbit errors. Height signals due to effects other than variations in temperature and salinity must be more precisely removed from SSH for MODAS; these height signals are uncorrelated with subsurface temperature and salinity. Higher-order regional corrections in altimetric heights, such as planetary wave removal, need to addressed. Improvements in horizontal covariances will enhance accuracy of interpolations in time and space between observations. Different regions of the world ocean can be optimized in MODAS to more accurately portray the temperature and salinity fields. Structure in coastal regions can almost certainly be improved by tailoring length and timescales in the OI analyses. MODAS has not been optimized in the JES for the example presented here.

Dynamic MODAS clearly provides a better representation of in situ thermal structure than a static climatology. More work is required in the regression development to accurately portray mesoscale variability. Regressions for salinity estimation need more work, but the present historical data base for salinity may be inadequate to develop significantly more accurate rela-

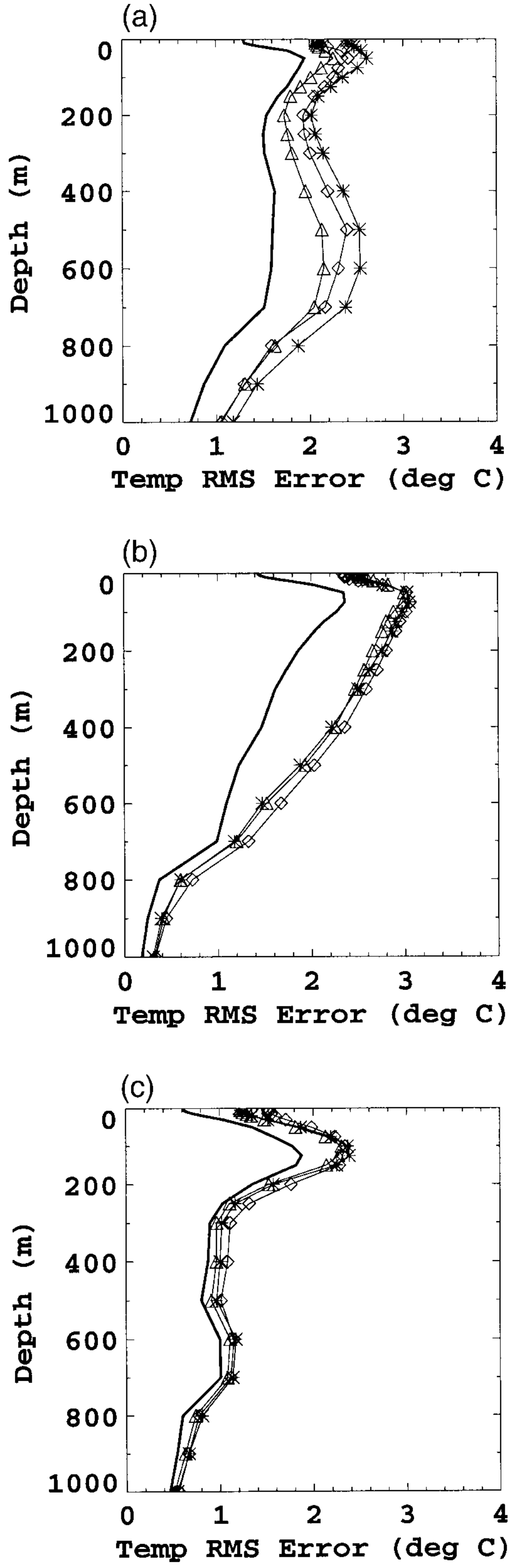

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FIG. 5. (a) Rms temperature differences between Levitus, GDEM, MODAS, and Dynamic MODAS with historical profiles in the western North Atlantic (thick line: Dynamic MODAS; asterisk: Levitus; diamond: GDEM; triangle: MODAS). (b) As in (a), but for the western Pacific Kuroshio region. (c) As in (a), but for the global ocean.

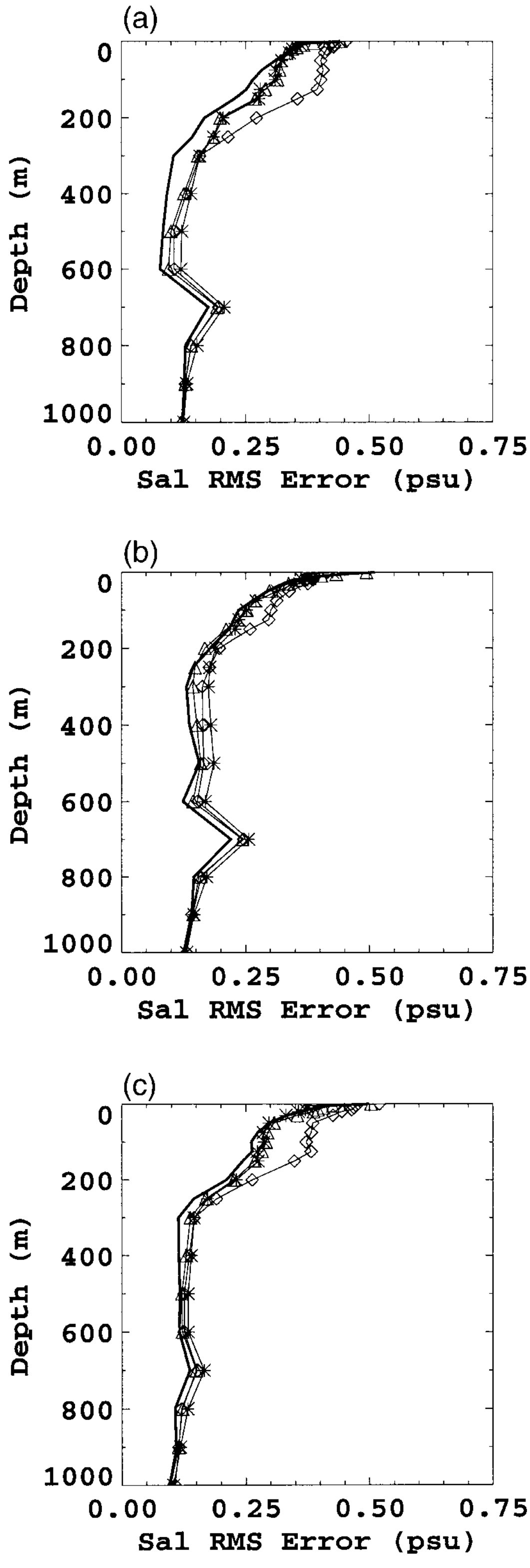

FIG. 6. (a) Rms salinity differences between Levitus, GDEM, MODAS, and Dynamic MODAS with historical profiles in the western North Atlantic (thick line: Dynamic MODAS; asterisk; Levitus; diamond; GDEM, triangle; MODAS). (b) As in (a), but for the western Pacific Kuroshio region. (c) As in (a), but for the global ocean.

tionships. Dynamic MODAS salinity sections are indicative of the frontal activity since the salinity is estimated from the temperature profiles. However, the static climatologies still provide better overall estimates of absolute salinity values in comparisons with SeaSoar salinities.

Dynamic MODAS which uses remotely sensed data provides a much more accurate and detailed estimate of the ''true ocean'' than a conventional climatology. Dynamic MODAS is constructed for the global ocean. It uses the MODAS climatology as an initial first guess field. Thereafter, a satellite-based grid is used as a first-guess field for an optimum interpolation process which then blends in any actual in situ data that has been acquired.

6. Conclusions

In summary, MODAS provides a static climatology, similar to the Levitus climatology in one mode of usage while in another mode, MODAS provides a Dynamic climatology that assimilates in situ measurements such as SST and SSH, and predicts the subsurface structure by constructing synthetic profiles formed through regression analyses. The static MODAS climatology temperature and salinity fields are at least as high quality as comparable fields from the Levitus climatology. However MODAS provides increased horizontal resolution in some regions. Levitus is 1° globally while MODAS is ½° in the open ocean, ¼° in coastal regions, and ⅛° near land.

Static climatologies cannot usually provide an accurate picture of present day ocean conditions. Historical profiles of temperature can relate subsurface thermal structure to SST and SSH measurements from satellites, which can be used to update static climatologies. In general, Dynamic MODAS can portray day-to-day ocean thermal conditions far better than a static climatology as illustrated in the JES comparisons with SeaSoar data where accurate frontal locations and length scales were calculated. Dynamic MODAS salinity estimates need enhancement to clearly surpass salinity estimates from static climatologies. Improvements in Dynamic MODAS will be gained in the future with improved regression relationships, and increased accuracies and coverage of satellite measurements. Dynamic MODAS is not a replacement for static climatologies but instead offers a new analysis tool for many applications. Most importantly, Dynamic MODAS provides a mechanism for assimilating remotely-sensed and in situ measurements into numerical ocean models.

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APPENDIX

Climatology Construction

This appendix describes procedures used in the construction of the static and dynamic climatologies. Observations are first sorted by longitude and by latitude. Each profile is interpolated to the climatology standard depths. The resulting temperature and salinity observations are $T_{i,k}$ and $S_{i,k}$, where i is the unique identification index for each observation and k is the standard depth index.

Temperature mixed layer depths (MLDs) are constructed from each temperature profile. The MLD, $D_{i,j}$, has 11 values indicated by the j index for each profile i, computed as the depths where the temperature is lower than the surface value by $-0.5°$, $-0.25°$, $-0.1°$, $-0.05°$, $0.0°$, $0.05°$, $0.1°$, $0.25°$, $0.5°$, $1.0°$, and $1.5°$C. The negative values apply to near-surface thermal inversions. The temperature mixed layer depth seasonal climatology and the models of mixed layer depth, for the 11 standard values of mixed layer depth, as functions of sea surface temperature and height are generated in essentially the same manner as for temperature described below.

The climatology is computed at only a subset of the nodes of a ⅛° grid covering each particular 10° × 10° geographic analysis block. For each block, there are coincident 1°, ½°, ¼°, and ⅛° resolution grids that overlay the block, and the nodes of a grid occur at every other node of the next higher resolution grid. The desired resolution at each position is extracted from a global file, and evaluated at each node of the ⅛° grid. The climatology analysis is performed at that grid node only if the node is coincident with a node of the grid with the desired resolution. The final set of nodes used forms an irregular grid.

The geographic grid position nodes, (x_i, y_i), $i = 1$, nodes, of the database form an irregular grid because the grid resolution is allowed to vary from a grid node separation of ⅛° to 1°. To simplify the process of interpolating the final database values to any position onto the grid, the set of position nodes is organized as the vertices of a set of nonoverlapping triangles covering the entire sea-covered part of the 10° × 10° database region, and stored in the data base along with the data. The ''nnodes'' grid node latitude and longitude positions are first output to an ASCII file. A two-dimensional quality mesh generator and Delaunay triangulator written by Shewchuk (1996) is used.

a. Temperature seasonal climatology

The temperature observations $T^o_{j,k}$ at locations j are gridded by optimum interpolation to form the temperature climatology, $T^c_{i,k}$, at each grid position i and depth k. The mean temperature is computed as the sum of weighted anomalies of the observations,

$$T^c_{i,k} = T^{\mathrm{WOA}}_{i,k} + \sum_{j=1}^{N} w_{i,j}(T^o_{j,k} - T^{\mathrm{WOA}}_{j,k}), \qquad (\mathrm{A1})$$

where $T^{\mathrm{WOA}}_{j,k}$ is the *World Ocean Atlas 1994* (Levitus and Boyer 1994) temperature interpolated to the required position, depth, and time of year. The N weights, $w_{i,j}$, are computed as the solution of the system of equations,

$$C_i \mathbf{W}_i = \mathbf{F}_i \qquad (\mathrm{A2})$$

where $w_{i,j}$, $j = 1$, N, are the components of $\mathbf{W}_i$. The matrix C_i, with components, $c_{m,n}$, is the covariance of the errors of the first-guess temperature (*WOA'94*), $c^{fg}_{m,n}$, plus the covariance of the observation errors, $c^o_{m,n}$, between all pairs of observations at locations $\mathbf{r_m}$ and $\mathbf{r_n}$. The ''truth'' from which these two errors are computed is the true climatology, not the true observation. Except near small-scale climatological features, which may be smoothed out, the *WOA'94* is expected to be a good estimate of the ''true'' climatology. The observations are samples of the ''real ocean,'' not the mean ocean, so the expected errors (relative to the true seasonal mean) contain two terms, the error covariance of the observation from the real ocean value at the time of the observation, $c^e_{m,n}$, and the covariance of the true ocean about the mean, $c^t_{m,n}$. This second term is often called the error in representativeness. The covariance is then

$$c_{m,n} = c^{fg}_{m,n} + c^t_{m,n} + c^e_{m,n} \qquad (\mathrm{A3})$$

The components, $f_{m,i} = c^{fg}_{m,i}$, of $\mathbf{F}_i$ are the covariances of the first-guess errors between each observation position, $\mathbf{r_m}$, and the analysis position $\mathbf{r_i}$ (and time of year). We assume that the covariances can be written in the form, $c = \upsilon b$, where υ is the variance and b is the correlation. To simplify the analysis, we assume that the variance is locally constant and that any parameters in the correlation function are locally constant. Also, due to lack of good estimates of any of these parameters, and because trial and error indicate that this is a reasonable approach, we assume that the variance of the first-guess error covariance is equal to the sum of both terms of the observation error variances, and that the observation error correlation is zero except when the space and time lags are zero. As a result, $c_{m,n} = \upsilon_{i,k}(b_{m,n} + \delta_{m,n})$, where $\delta_{m,n}$ is the Dirac delta function and $f_{m,i} = \upsilon_{i,k} b_{m,i}$. The solution for the weights is therefore independent of the regional variance. We use a simple, separable, and locally homogeneous, form for the correlation function,

$$b_{m,n} = \exp\{-[(x_m - x_n)/L_x]^2 - [(y_m - y_n)/L_y]^2 - [(t_m - t_n)/L_t]^2\} \qquad (\mathrm{A4})$$

where x and y are the east–west and north–south positions, t is the time of year, and L_x, L_y, and L_t are length and timescales. The timescale used is 1000 h, and the length scales are dependent on latitude, λ (in degrees), and given in units of kilometers by

$$L_x = 120\,000/(0.35\lambda^2 + 300)$$
$$L_y = 120\,000/(0.35\lambda^2 + 400), \qquad (A5)$$

but both are limited to a minimum of 150 km in the Northern Hemisphere and 250 km in the Southern Hemisphere. The optimum interpolation analysis is performed at each grid location holding the length scales constant and equal to the value at the analysis location (no change at observation locations at different latitudes). The length scales are based roughly on a constant factor times the average first-baroclinic Rossby radius as a function of latitude (Houry et al. 1987). The covariance, $c_{m,n}$, between two observation locations is set to zero if the two positions are not of compatible water types.

Only data within 45 days of the analysis day of the year (independent of the year each observation was made) are used in each analysis. Only observations with a water type compatible with the water type at the analysis position are used in the analysis. A search is made outward from the analysis position for profiles. The search stops when a specified minimum number of acceptable profiles, $N^{\mathrm{OI}}_{\min} = 100$, is found, but all profiles within the distance L_x, east and west, and L_y, north and south, of the analysis position are used unless that number is greater than $N^{\mathrm{OI}}_{\max} = 500$. Profiles at distances greater than four times the two length scales are excluded from the analysis.

The expected error standard deviation of the climatology analysis is computed as

$$\epsilon^T_{i,k} = \left[v_{i,k} - \sum_{j=1}^{N} f_{i,j} w_{i,j}\right]^{1/2}. \qquad (A6)$$

Once the mean temperature, $T^c_{i,k}$, is computed at location i and depth k, the weighted standard deviation is computed using the same set of N observations as

$$\sigma^T_{i,k} = \left[\frac{\sum_{j=1}^{N} b_{i,j}(T^o_{j,k} - T^c_{i,k})^2}{\sum_{j=1}^{N} b_{i,j}}\right]^{1/2}, \qquad (A7)$$

where the weights are the correlations, not the weights determined by the optimum interpolation. A deficiency in computing the standard deviation in this manner is that the mean removed from each observation is the mean from the analysis position, i, not from the observation position, j. Thus, part of the mean variation is included in the standard deviation which will make it artificially high, particularly where the mean gradient is high, such as in fronts. However, this procedure is used because it allows all calculations to be performed at one analysis location at one time.

b. Salinity as a function of temperature

At each position, depth, and time of year, the relationship between salinity and temperature,

$$S_{i,k}(T) = \overline{S_{i,k}} + a^{\mathrm{S1}}_{i,k}(T - \overline{T_{i,k}}), \qquad (A8)$$

is determined by locally weighted linear regression from the subset of observations having both temperature and salinity, where

$$\overline{S_{i,k}} = \frac{\sum_{j=1}^{N^{\mathrm{TS}}} b_{i,j} S^o_{j,k}}{\sum_{j=1}^{N^{\mathrm{TS}}} b_{i,j}} \qquad (A9)$$

$$\overline{T_{i,k}} = \frac{\sum_{j=1}^{N^{\mathrm{TS}}} b_{i,j} T^o_{j,k}}{\sum_{j=1}^{N^{\mathrm{TS}}} b_{i,j}} \qquad (A10)$$

$$a^{\mathrm{S1}}_{i,k} = \frac{\sum_{j=1}^{N^{\mathrm{TS}}} b_{i,j}(T^o_{j,k} - \overline{T_{i,k}})(S^o_{j,k} - \overline{S_{i,k}})}{\sum_{j=1}^{N^{\mathrm{TS}}} b_{i,j}(T^o_{j,k} - \overline{T_{i,k}})^2}, \qquad (A11)$$

and b is the local correlation function (A4), but with length scales twice the size of those defined in (A5).

Each analysis uses a minimum of 600 observations unless that number is not found within a distance of four length scales, but all observations within one length scale distance are used unless that number is greater than 6000. Only observations with a water type compatible with the water type at the analysis location are used. For each analysis, the temperature and salinity at the analysis location and time of year is extracted from the *WOA'94* climatology (Levitus and Boyer 1994; Levitus et al. 1994) and added to the set of observations. This procedure pushes the mean values back toward the *WOA'94* climatology where observations are very sparse. When the sum of correlations, Σb, is less than 1.1, the coefficient, a, is set to zero. The weighted salinity standard deviation is computed as

$$\sigma^S_{i,k} = \left[\frac{\sum_{j=1}^{N} b_{i,j}(S^o_{j,k} - \overline{S_{i,k}})^2}{\sum_{j=1}^{N} b_{i,j}}\right]^{1/2}, \qquad (A12)$$

and the salinity model error standard deviation is

$$\epsilon^{S(T)}_{i,k} = \left[\sum_{j=1}^{N} b_{i,j}(S^o_{j,k} - \overline{S_{i,k}} + a^{\mathrm{S1}}_{j,k}(T^0_{j,k} - \overline{T_{i,k}}))^2\right]^{1/2}. \qquad (A13)$$

Note that the mean values of temperature and salinity are constant in each calculation as explained above.

The salinity climatology is defined to match the temperature climatology (previously computed by optimum interpolation) as

$$S^c_{i,k} = S_{i,k}(T^c_{i,k}) = \overline{S_{i,k}} + a^{\mathrm{S1}}_{i,k}(T^c_{i,k} - \overline{T_{i,k}}). \qquad (A14)$$

c. Temperature as a function of steric height anomaly and SST

A database of linear relationships between subsurface temperature and both surface temperature and steric height anomaly is constructed. The steric height anomaly is defined as in the atlas by Olbers et al. (1992) as the height difference between a constant-mass water column with temperature $T(z)$ and salinity $S(z)$ and a water column of fixed temperature at 0°C and salinity at 35 psu,

$$h = \int_0^H \frac{[\upsilon(T, S, p) - \upsilon(0, 35, p)]}{\upsilon(0, 35, p)} dz, \quad \text{(A15)}$$

where υ is the specific volume of sea water and H is the bottom depth. Only about a third of the profiles have both temperature and salinity observations, and many of those do not reach to the bottom. Since we want to use as many profiles as possible to perform the regression analyses, our approach is to extend most short temperature and salinity profiles to the bottom and to predict salinity from temperature where salinity observations are not available. Full salinity profiles are computed from temperature profiles, when needed, using the salinity relationship [Eq. (A8)]. Full profiles of temperature are constructed by splicing a synthetic profile, T_k^{syn}, onto a short observed profile, which ends at index, kmax, according to

$$T_k = T_k^{\text{syn}} + [T_{k\max}^o - T_{k\max}^{\text{syn}}] \exp[-(z_k - z_{k\max})/L_z],$$
$$z_k > z_{k\max}, \quad \text{(A16)}$$

where L_z is a vertical length scale set here to 200 m. Each synthetic temperature profile is computed by fitting the observed short profile to the mean temperature plus the empirical orthogonal function, $\mathbf{E}_k$, associated with the largest eigenvalue. Use of EOFs to identify the primary modes of variation while filtering out smaller-amplitude and less-correlated variations is often used. The EOFs are the eigenvectors of the symmetric matrix of covariances of the scaled temperature anomalies computed among all depth pairs and evaluated at the analysis location i from observations at locations j. The matrix of covariances has components, between depths indexed by m and n, given by

$$c_{i,m,n} = \frac{\sum_{j=1}^{N} b_{i,j(m,n)}(T_{j,m}^o - \overline{T_{i,m}})(T_{j,n}^o - \overline{T_{i,n}})/(\sigma_{i,m}^T \sigma_{i,n}^T)}{\sum_{j=1}^{N} b_{i,j(m,n)}}. \quad \text{(A17)}$$

Here, $\overline{T_{i,n}}$ is the weighted mean at location i and depth n (A10), $\sigma_{i,n}^T$ is the weighted standard deviation of temperature at location i and depth n (A12), $b_{i,j(m,n)}$ is the correlation between positions i and j (A4), but with length scales double those defined in (A5). The subscript (m, n) of b is meant to indicate that the set of weights and their sum are computed separately for each depth pair, (m, n), to account for missing values, particularly at greater depths. Whenever the sum of correlations is less than 1.2, the correlation, $c_{i,m,n}$, is set to zero. If there are M standard depths and M_j are available in observed profile j, and the components of the EOF with the largest eigenvalue, $\mathbf{E}_1$, (accounts for the largest amount of variance) are e_k, then the synthetic profile to be spliced onto the short observed profile [Eq. (A16)] is

$$T_{j,k}^{\text{syn}} = \overline{T_{i,k}} + g_j e_k,$$

where g_j, the amplitude of the largest EOF, estimated for profile j is

$$g_j = \frac{\sum_{k=1}^{M_j} w_k[e_k(T_{j,k}^o - \overline{T_{i,k}})]}{\sum_{k=1}^{M_j} w_k}.$$

The weights, w, are designed to emphasize a match between the synthetic profile and the observation at the deeper depths where the observed profile becomes truncated. The weights are defined as $w_k = (z_k - z_{k-1})^{1/4}$ for $k = 2, M_j$, and $w_1 = w_2$.

Once the steric height anomaly, h, and the surface temperature, sst, for each temperature profile has been identified, the coefficients to the following models are determined by locally weighted linear least squares regression, T(sst): Temperature as a function of surface temperature, location (i), depth (k), and time of year,

$$T_{i,k}(\text{sst}) = \overline{T_{i,k}} + a_{i,k}^{T1}(\text{sst} - \overline{T_{i,1}}).$$

$T(h)$: Temperature as a function of steric height anomaly, location (i), depth (k), and time of year,

$$T_{i,k}(h) = \overline{T_{i,k}} + a_{i,k}^{T2}(h - \overline{h_i}).$$

$T(h$, sst): Temperature as a function of sst, steric height anomaly, location (i), depth (k), and time of year,

$$T_{i,k}(\text{sst}, h) = \overline{T_{i,k}} + a_{i,k}^{T3}(\text{sst} - \overline{T_{i,1}}) + a_{i,k}^{T4}(h - \overline{h_i}) + a_{i,k}^{T5}[(\text{sst} - \overline{T_{i,1}})(h - \overline{h_i}) - \overline{h\text{sst}_i}],$$

where $\overline{h\text{sst}_i}$ is the weighted mean of the product, $(\text{sst}_j - \overline{T_{i,1}})(h_j - \overline{h_i})$, and j is the observation index and i is the location index.

The regression model errors, $\epsilon^{T(\text{sst})}$, $\epsilon^{T(h)}$, $\epsilon^{T(\text{sst},h)}$, are computed as the locally weighted root-mean-square difference between the observations used to derive the model and the model predictions, in the same manner as the error model for salinity was computed [Eq. (A13)].

d. Steric height anomaly annual mean

Stored regression relationships are used to compute profiles of temperature from input surface temperature and sea surface height. The input height, h_{alt}, will typically be the total sea surface height deviation from the long-term (6 yr) mean obtained from satellite altimeter measurements. To use this deviation, the required steric height anomaly is approximated by adding the long-term mean steric height anomaly, $\overline{h}_{ann}$, averaged over all times of year, to the altimeter-derived height deviation, that is, $h = h_{alt} + \overline{h}_{ann}$. The mean steric height anomalies at each grid location for all 6 months (bimonthly) are used in the computation of the average, $\overline{h}_{ann}$.

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