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Evaluation of the U.S. Navy's Modular Ocean Data Assimilation System (MODAS) Using South China Sea Monsoon Experiment (SCSMEX) Data

PETER C. CHU*, WANG GUIHUA and CHENWU FAN

Naval Ocean Analysis and Prediction Laboratory, Department of Oceanography, Naval Postgraduate School, Monterey, CA 93943, U.S.A.

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The Navy's Modular Ocean Data Assimilation System (MODAS) is an oceanographic tool to create high-resolution temperature and salinity on three-dimensional grids, by assimilating a wide range of ocean observations into a starting field. The MODAS products are used to generate the sound speed for ocean acoustic modeling applications. Hydrographic data acquired from the South China Sea Monsoon Experiment (SCSMEX) from April through June 1998 are used to verify the MODAS model. MODAS has the capability to provide reasonably good temperature and salinity nowcast fields. The errors have a Gaussian-type distribution with mean temperature nearly zero and mean salinity of –0.2 ppt. The standard deviations of temperature and salinity errors are 0.98°C and 0.22 ppt, respectively. The skill score of the temperature nowcast is positive, except at depth between 1750 and 2250 m. The skill score of the salinity nowcast is less than that of the temperature nowcast, especially at depth between 300 and 400, where the skill score is negative. Thermocline and halocline identified from the MODAS temperature and salinity fields are weaker than those based on SCSMEX data. The maximum discrepancy between the two is in the thermocline and halocline. The thermocline depth estimated from the MODAS temperature field is 10–40 m shallower than that from the SCSMEX data. The vertical temperature gradient across the thermocline computed from the MODAS field is around 0.14°C/m, weaker than that calculated from the SCSMEX data (0.19°–0.27 °C/m). The thermocline thickness computed from the MODAS field has less temporal variation than that calculated from the SCSMEX data (40–100 m). The halocline depth estimated from the MODAS salinity field is always deeper than that from the SCSMEX data. Its thickness computed from the MODAS field varies slowly around 30 m, which is generally thinner than that calculated from the SCSMEX data (28–46 m).

Keywords:
· MODAS,
· data assimilation,
· South China Sea Monsoon Experiment,
· thermocline,
· halocline,
· skill score,
· bias,
· root-mean square error.

1. Introduction

An advanced version of the Navy's Modular Ocean Data Assimilation System (MODAS-2.1), developed at the Naval Research Laboratory, is in operational use at the Naval Oceanographic Office to provide twice-daily, three-dimensional temperature and salinity fields. The data can be downloaded from the website: http://www.navo.navy.mil. Its data assimilation capabilities may be applied to a wide range of input data, including irregularly located in-situ sampling, satellite, and climatological data. Available measurements are incorporated into a three-dimensional, gridded output field of temperature and salinity. The MODAS-2.1 products are used to generate the sound speed field for ocean acoustic modeling applications. Other derived fields, which may be generated and examined by the user, include such two-dimensional and three-dimensional quantities as vertical shear of geostrophic current, mixed layer depth, sonic layer depth, deep sound channel axis depth, depth excess, and critical depth. These are employed in a wide variety of naval applications.

The first generation of this system, MODAS-1.0, was initially designed in the early 1990's to perform deep-water analyses that produced outputs that supported deep-water anti-submarine warfare operations. However, MODAS-1.0 was constrained at depths greater than 100

* Corresponding author. E-mail: pcchu@nps.navy.mil

location then the deviation at each depth is estimated. Adding these estimated deviations to the climatology produces the synthetic profiles.

4.4 MODAS special treatments

Two treatments distinguish MODAS from ordinary optimum interpolation schemes: (1) "synthetic" temperature profiles generated using surface height and temperature, and (2) salinity as a function of temperature. The MODAS first treatment is to establish linear regression relationships between (SST, SSH) with temperature at a given depth. Synthetic temperature profiles extending to a maximum depth of 1500 m are computed from these regression relationships. The MODAS second treatment is to determine the relationship between salinity and temperature at each position, depth, and time of year, by locally weighted linear regression from the subset of observations having both temperature and salinity (Fox *et al.*, 2002).

5. Methodology of Verification

Observational and climatological data are needed for MODAS verification. Both MODAS and climatological data are compared with the observational data. Observational data are used for determining error statistics. Climatological data are used to verify the added value of the MODAS model. The MODAS has added value if the difference between MODAS and observational data is less than the difference between climatological and observational data. MODAS, climatological, and SCSMEX data ψ (temperature, salinity) are represented by ψ_m, ψ_c, and ψ_o.

5.1 Climatological data

An independent climatological dataset should be used as reference to verify MODAS. Since the World Ocean Atlas (WOA) 1994 (Levitus and Boyer, 1994a, b) is used to build MODAS climatology (Fox *et al.*, 2002), the Navy's GDEM climatological monthly mean temperature and salinity dataset with 1/2° resolution is taken as the reference. Observational data for building the current version of GDEM climatology were obtained from the Navy's Master Oceanographic Observational Data Set (MOODS), which contains records of more than 6 million temperature and 1.2 million salinity profiles since early last century. The GDEM data can be obtained from the website: http://www.navo.navy.mil.

The basic design concept of GDEM is the determination of a set of analytical curves that represent the mean vertical distributions of temperature and salinity for grid cells through the averaging of the coefficients of the mathematical expressions for the curves found for individual profiles (Teague *et al.*, 1990). Different families of representative curves have been chosen for shallow, mid-depth, and deep ranges, each chosen so that the number of parameters required to yield a smooth, mean profile over the range was minimized. The monthly mean three-dimensional temperature and salinity fields obtained from the GDEM dataset is similar to the climatological monthly mean fields computed directly from the MOODS, as depicted in Chu *et al.* (1999b).

5.2 Error statistics

If the observational data are located at (x_i, y_j, z, t), we interpolate the MODAS and GDEM data into the observational points and form modeled and climatological data sets. The difference in ψ between modeled and observed values

$$\Delta_m\psi\left(x_i,y_j,z,t\right)=\psi_m\left(x_i,y_j,z,t\right)-\psi_o\left(x_i,y_j,z,t\right), \quad (1)$$

represents the model error. The difference in ψ between climatological and observed values

$$\Delta_c\psi\left(x_i,y_j,z,t\right)=\psi_c\left(x_i,y_j,z,t\right)-\psi_o\left(x_i,y_j,z,t\right), \quad (2)$$

represents the prediction error using the climatological values. We may take the probability histogram of $\Delta\psi$ as the error distribution.

The bias, mean-square-error (MSE), and root-mean-square error (RMSE) for the MODAS model

$$\begin{aligned}
&\mathrm{BIAS}(m,o)=\frac{1}{N}\sum_i\sum_j\Delta\psi_m\left(x_i,y_j,z,t\right),\\
&\mathrm{MSE}(m,o)=\frac{1}{N}\sum_i\sum_j\left[\Delta_m\psi\left(x_i,y_j,z,t\right)\right]^2,\\
&\mathrm{RMSE}(m,o)=\sqrt{\mathrm{MSE}(m,o)}, \qquad (3)
\end{aligned}$$

and for the reference model (e.g., climatology),

$$\begin{aligned}
&\mathrm{BIAS}(c,o)=\frac{1}{N}\sum_i\sum_j\Delta\psi_c\left(x_i,y_j,z,t\right),\\
&\mathrm{MSE}(c,o)=\frac{1}{N}\sum_i\sum_j\left[\Delta_c\psi\left(x_i,y_j,z,t\right)\right]^2,\\
&\mathrm{RMSE}(c,o)=\sqrt{\mathrm{MSE}(c,o)}, \qquad (4)
\end{aligned}$$

are commonly used for evaluation of the model performance. Here N is the total number of horizontal points.

5.3 MODAS skill score

MODAS accuracy is usually defined as the average m because it used climatological data from the original Generalized Digital Environmental Model (GDEM) established from the Master Observational Oceanographic Data Set (MOODS). The capabilities of MODAS-1.0 were increased when GDEM was initially augmented with a shallow water database (SWDB), but at the time, SWDB was limited to the northern hemisphere. The NOAA global database, which has less horizontal resolution than GDEM, was used as a second source for the first guess field in MODAS-1.0. In addition, in MODAS-1.0 some of the algorithms for processing and for performing interpolations were designed for speed and efficiency in deep waters, at the cost of making some assumptions about the topography. This shortcut method extended all observational profiles to a common depth, even if the depth was well below the ocean bottom depth, by splicing onto climatology. The error introduced using this shortcut method is amplified when this method is applied to shallow water regions.

The second generation, MODAS-2.1, was created to overcome the limitations of MODAS-1.0. One of the major implementations was the development of MODAS internal ocean climatology (Static MODAS climatology) for both deep and shallow depths. Static MODAS climatology is produced using the historical T, S profile data, i.e., the MOODS. Static MODAS climatology covers the ocean globally to a minimum depth of 5 meters and has variable horizontal resolution from 7.5 minutes to 60 minutes. The static MODAS climatology also contains important statistical descriptors required for optimum analysis of observations that include bi-monthly means of temperature, coefficients for calculation of salinity from temperature, standard deviations of temperature and salinity, and coefficients for several models relating temperature and mixed layer depth to surface temperature and steric height anomaly. MODAS-2.1 performs separate optimum interpolation analysis for each depth above the ocean bottom.

The Naval Oceanographic Office (1999) conducted an operational test of MODAS 2.1 using temperature observations from April 15 to May 14, 1999 for six areas: Kamchatka Sea (13 profiles), Bay of Biscay (58 profiles), Greenland-Icelandic-Norwegian (GIN) Sea (120 profiles), Northwest Atlantic (profiles: 133), and Northeast Pacific (profiles: 166), and Japan Sea (profiles: 692). The root-mean-square (rms) errors between MODAS products and observations were usually smaller than that between the climatology (i.e., GDEM) and observations. Another encouraging fact is the small rms errors occurring in the Japan Sea, the Northwest Atlantic, and the GIN Sea area—all have high spatial variability. MODAS 2.1 thus displays improved capability over a GDEM-based MODAS analysis in fairly complex ocean regimes. However, the test was only on the comparison of temperature fields. No evaluation was given of the MODAS salinity field. Furthermore, the MODAS capability for nowcasting thermocline/halocline has not been evaluated.

A recent development is to use the MODAS temperature and salinity fields to initialize an ocean prediction model such as the Princeton Ocean Model (Chu *et al.*, 2001). There is thus an urgent need to evaluate the MODAS salinity field as well as the thermocline/halocline structures. The South China Sea Monsoon Experiment (SCSMEX) provides a unique opportunity for such an evaluation. The SCSMEX data have not been assimilated into MODAS. Hydrographic data acquired from SCSMEX for April through June 1998 are used to verify MODAS temperature and salinity products.

2. South China Sea

The South China Sea (SCS) is a semi-enclosed tropical sea located between the Asian land mass to the north and west, the Philippine Islands to the east, Borneo to the southeast, and Indonesia to the south (Fig. 1), covering a total area of 3.5×10^6 km^2. It includes the shallow Gulf of Thailand and connections to the East China Sea (through Taiwan Strait), the Pacific Ocean (through Luzon Strait), Sulu Sea, Java Sea (through Gasper and Karimata Straits) and to the Indian Ocean (through the Strait of Malacca). All of these straits are shallow except Luzon Strait, the maximum depth of which is 1800 m. The complex topography includes a broad, shallow shelf in the south/southwest; the continental shelf of the Asian landmass in the north, extending from the Gulf of Tonkin to Taiwan Strait; a deep, elliptical shaped basin in the center, and numerous reef islands and underwater plateaus scattered throughout. The shelf that extends from the Gulf of Tonkin to the Taiwan Strait is consistently nearly 70 m deep, averaging 150 km in width; the central deep basin is 1900 km along its major axis (northeast-southwest) and approximately 1100 km along its minor axis, extending to over 4000 m deep. The south/southwest SCS shelf is the submerged connection between southeastern Asia, Malaysia, Sumatra, Java, and Borneo and reaches 100 m depth in the middle; the center of the Gulf of Thailand is about 70 m deep.

The SCS is subjected to a seasonal monsoon system. From April to August, the weaker southwesterly summer monsoon winds result in a monthly mean wind stress of just over 0.1 N/m^2. From November to March, the stronger northeasterly winter monsoon winds correspond to a maximum monthly mean wind stress of nearly 0.3 N/m^2. During monsoon transition, the winds and surface currents are highly variable.

Many studies have shown that the SCS circulation has a multi-eddy structure. A survey by Wyrtki (1961) revealed complex temporal and spatial features of the surface currents in both the SCS and the surrounding

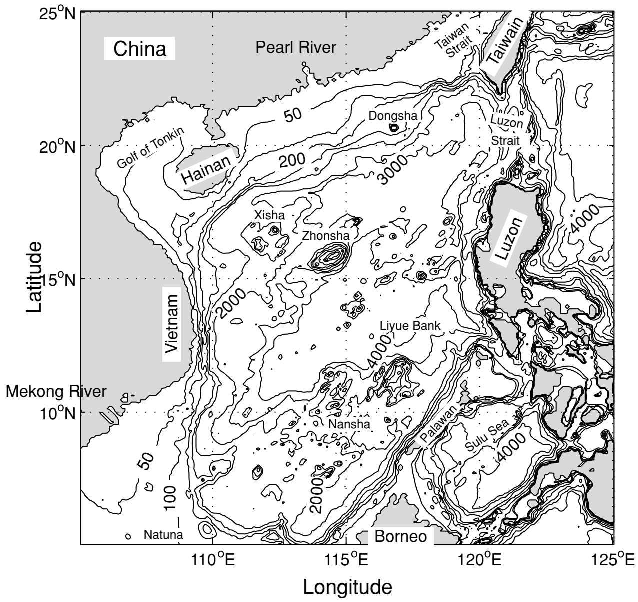

Fig. 1. Geography and isobaths showing the bottom topography of the South China Sea. Numbers show the depth in meter.

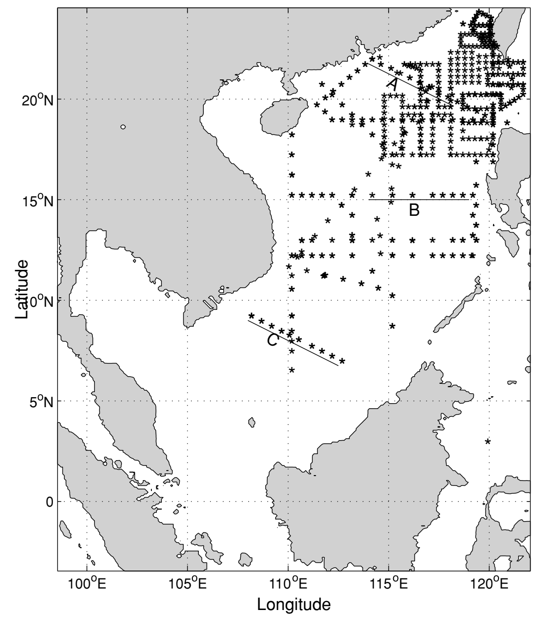

Fig. 2. The SCSMEX CTD stations.

waters. The general circulation of the SCS is predominantly cyclonic in winter and anticyclonic in summer. Chu *et al.* (1997a) identified the existence of a central SCS surface warm-core eddy in mid-May from a historical data set: the U.S. Navy's Master Observational Oceanographic Data Set (MOODS). From their composite analysis of the U.S. National Centers for Environmental Prediction (NCEP) monthly sea surface temperature (SST) fields (1982–1994), Chu *et al.* (1997b) found that during the spring-to-summer monsoon transition (March–May) a warm anomaly (greater than 1.8°C) is formed in the central SCS at 112°–119°30′ E, 15°–19°30′ N. From an extensive airborne expendable bathythermograph (AXBT) survey in May 1995 and historical salinity data, Chu *et al.* (1998) identified six eddies of the SCS using the P-vector inverse method: dual warm-core anticyclonic eddies in the central SCS and four surrounding cool-core cyclonic eddies located northwest of Luzon Island (i.e., NWL cold-core eddy), southeast of the Hainan Island, South Vietnamese coast, and Liyue Bank. In the upper layer the tangential velocity of the dual central SCS anticyclonic warm-core eddies is around 30–40 cm/s and that of the four cyclonic cool-core eddies varies from 10 cm/s to 40 cm/s. The tangential velocity decreases with depth, becoming less than 5 cm/s for all eddies at 300 m depth. Furthermore, several numerical models (Chao *et al.*, 1996; Chu *et al.*, 1999; Isobe and Namba, 2001; Cai *et al.*, 2002) also simulated the existence of the multi-eddy structure in the SCS. Among these eddies, an eddy northwest of Luzon Island (hereafter referred to as the NWL eddy) is of interest because its location may affect the Kuroshio water entering the SCS. Recently, an upper layer thermohaline front across the SCS basin from the South Vietnamese coast (around 15°N) was identified using GDEM monthly mean temperature and salinity data on $0.5° \times 0.5°$ grid (Chu and Wang, 2003). It is quite challenging to produce three dimensional temperature and salinity fields for such an energetic regional sea.

3. Oceanographic Observations during SCSMEX

SCSMEX is a large scale experiment to study the water and energy cycles of the Asian monsoon regions with the goal (SCSMEX Science Working Group, 1995) of providing a better understanding of the key physical processes responsible for the onset, maintenance and variability of the monsoon over Southeast Asia and southern China, leading to improved predictions. The experiment involves the participation of all major countries and regions of East and Southeast Asia, as well as Australia and the United States.

SCSMEX had both atmospheric and oceanic components. The oceanic intensive observational period (IOP) was from April through June 1998 with shipboard measurements, Autonomous Temperature Line Acquisition System (ATLAS) moored array, and drifters. The hydrographic data collected during the SCSMEX IOP went through quality control procedures such as min-max check (e.g., disregarding any temperature data less than –2°C and greater than 40°C), error anomaly check (e.g., rejecting temperature data deviating more than 7°C from climatology), ship-tracking algorithm (screening out data with obvious ship position errors), max-number limit (limiting a maximum number of observations within a specified and rarely exceeded space-time window), and buddy check (rejecting contradicting data). The climatological data used for quality control are depicted in Chu *et al*. (1997a, b). After the quality control, the SCSMEX oceanographic data set contains 1742 conductivity-temperature-depth (CTD) and mooring stations (Fig. 2). The majority of the CTDs were nominally capable of reaching a maximum depth of 2000 m.

4. MODAS

MODAS is one of the present U.S. Navy standard tools for producing three-dimensional grids of temperature and salinity, and derived quantities such as density, sound speed, and mixed layer depth (Fig. 3). It is a modular system for ocean analysis and is constructed from a series of FORTRAN programs and UNIX scripts that can be combined to perform desired tasks. 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 optimal interpolation (OI) data assimilation technique to combine various sources of data (Fox *et al*., 2002).

4.1 Static and dynamic MODAS

MODAS has two modes of usage: static MODAS and dynamic MODAS. Static MODAS climatology is an internal climatology used as MODAS' first guess field. The other mode is referred to as the dynamic MODAS, which combines locally observed and remotely sensed ocean data with climatological information to produce a near-real-time, gridded, three-dimensional analysis field of the ocean temperature and salinity structure as an output. Grids of MODAS climatological statistics range from 30-minute resolution in the open ocean to 15-minute resolution in shallow waters and 7.5-minute resolution near the coasts in shallow water regions.

4.2 Synthetic temperature and salinity profiles

Traditional oceanographic observations, such as CTD, expendable bathythermograph (XBT), etc., are quite sparse and irregularly distributed in time and space. It becomes important to use satellite data in MODAS for establishing real-time three-dimensional T, S fields. Satellite altimetry and SST provide global datasets that are useful for studying ocean dynamics and ocean prediction. MODAS has a component for creating synthetic temperature and salinity profiles (Carnes *et al*., 1990, 1996), which are functions of parameters measured at the ocean surface, such as satellite SST and SSH. These relationships were constructed using a least-squares regression analysis performed on an archived historical database of temperature and salinity profiles.

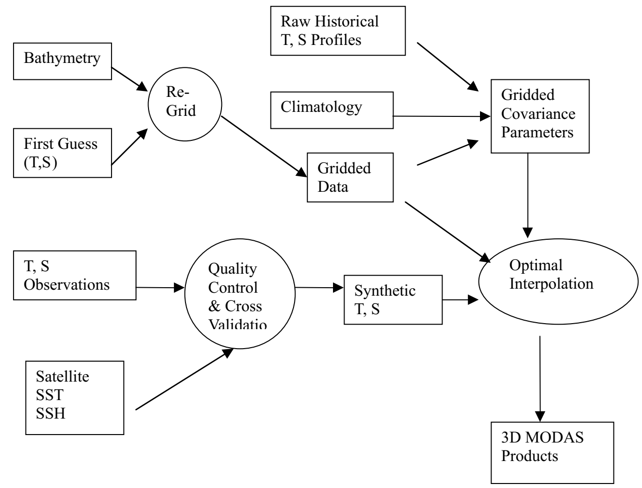

Fig. 3. Flow chart of MODAS operational procedure.

Three steps are used to establish regression relationships between the synthetic profiles and satellite SST and SSH: (a) computing regional empirical orthogonal functions (EOFs, Chu *et al*., 1997a, b) from the historical temperature and salinity profiles, (b) expressing the T, S profiles in terms of EOF series expansion, and (c) performing regression analysis on the profile amplitudes for each mode with the compactness of the EOF representation allowing the series to be truncated after only three terms while still retaining typically over 95% of the original variance (Carnes *et al*., 1996).

4.3 First guess fields

The MODAS SST field uses the analysis from the previous day's field as the first guess, while the MODAS' two-dimensional SSH field uses a large-scale weighted average of 35 days of altimeter data as a first guess. The deviations calculated from the first guess field and the new observations are interpolated to produce a field of deviations from the first guess. A final two-dimensional analysis is then calculated by adding the field of deviations to the first guess field. When the model performs an optimum interpolation for the first time it uses the Static MODAS climatology for the SST first guess field and zero for the SSH first guess field. For every data point after the first optimum interpolation it uses the previous day's first guess field for SST, while a large-scale weighted average is used for SSH. Synthetic profiles are generated at each location based on the last observation made at that location. If the remotely obtained SST and SSH for a location do not differ from the climatological data for that location, then climatology is used for that profile. Likewise, if the remotely obtained SST and SSH for a location differ from the climatological data for that

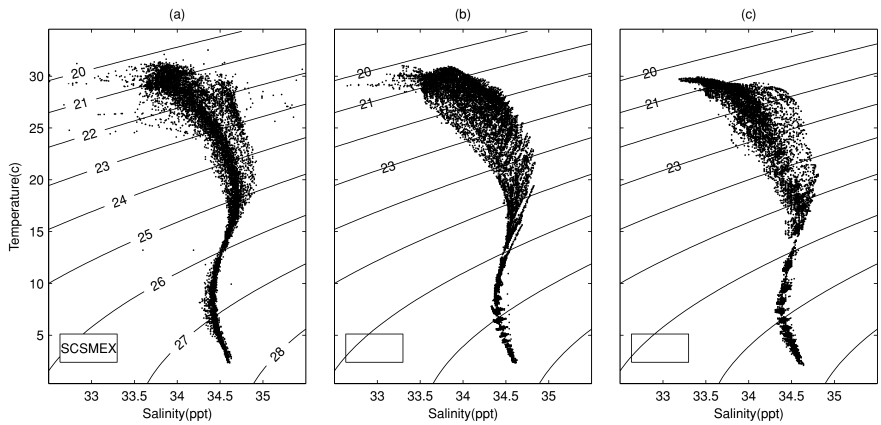

Fig. 4. T-S diagrams from (a) SCSMEX (1,742 profiles), (b) MODAS, and (c) GDEM data.

Table 1. Hydrographic features of the four SCS waters.

Water mass	*T* (°C)	*S* (ppt)	Depth (m)
SCSSW	25.5–29.5	32.75–33.5	<50
SCSSSW	19.8–22.2	33.85–34.72	50–200
SCSIW	5.3–10.0	34.35–34.64	200–600
SCSDW	2.0–6.0	34.4–34.64	>1000

degree of correspondence between modeled and observational data. Thus, the MSE or RMSE represents a prototype measure of accuracy. MODAS skill, on the other hand, is defined as the model accuracy relative to the accuracy of a nowcast produced by some reference procedure, such as climatology or persistence. To measure the model skill, we may compute the reduction of MSE over the climatological nowcast (Murphy, 1988; Chu *et al.*, 2001),

$$SS = 1 - \frac{\mathrm{MSE}(m,o)}{\mathrm{MSE}(c,o)}, \tag{5}$$

which is called the skill score. SS is positive (negative) when the accuracy of the nowcast is greater (less) than the accuracy of the reference nowcast (climatology). Moreover, SS = 1 when MSE(m, o) = 0 (perfect nowcast) and SS = 0 when MSE(m, o) = MSE(c, o). To compute MSE(c, o), we interpolate the GDEM climatological monthly temperature and salinity data into the observational points (x_i, y_j, z, t).

6. Evaluation of MODAS

We compare the MODAS and GDEM data against the SCSMEX CTD data for the whole domain to verify the model's capability.

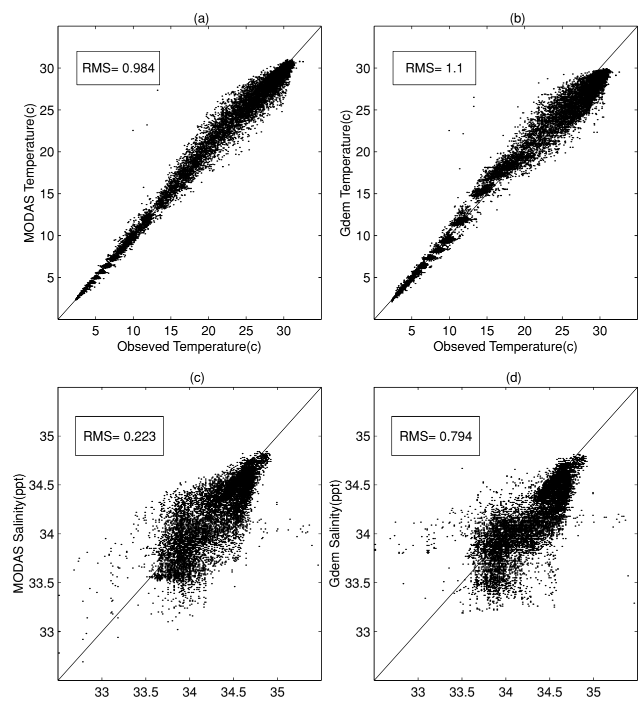

Fig. 5. Scatter diagrams of (a) MODAS versus SCSMEX temperature, (b) MODAS versus SCSMEX salinity, (c) GDEM versus SCSMEX temperature, and (d) GDEM versus SCSMEX salinity.

6.1 T-S diagram

Figure 4 illustrates the T-S diagrams from SCSMEX (1,742 profiles), MODAS, and GDEM data. All three diagrams (opposite-S shape T-S curves) clearly show the existence of four water masses: the SCS Surface Water (SCSSW, warm and less fresh), the SCS Subsurface Water (SCSSSW, less warm and salty), the SCS Intermedi-

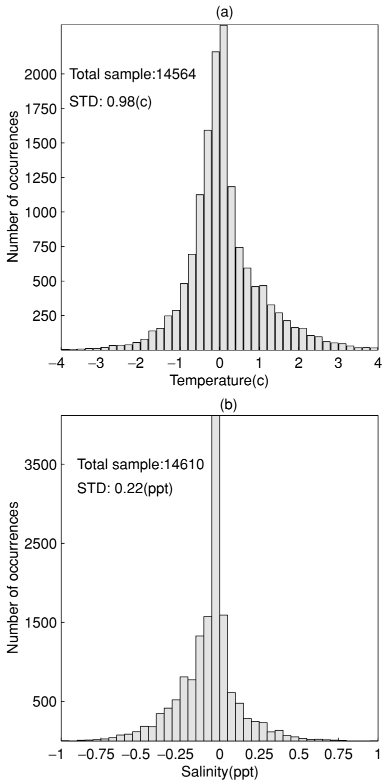

Fig. 6. Histogram of MODAS errors of (a) temperature (°C) and (b) salinity (ppt).

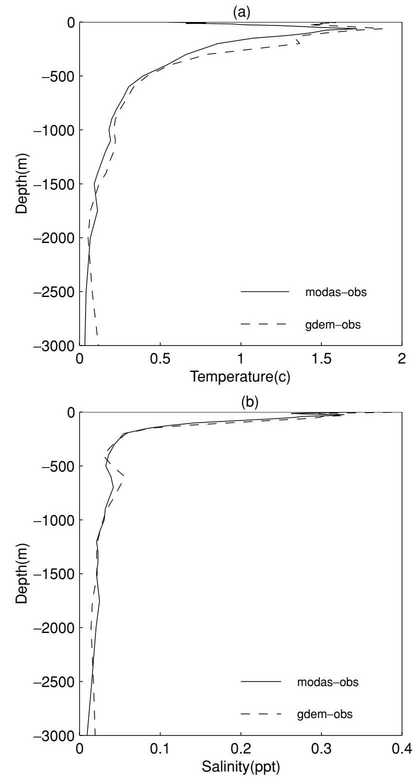

Fig. 7. The RMSE between the MODAS and SCSMEX data (solid) and between the GDEM and SCSMEX data (dotted): (a) temperature (°C), and (b) salinity (ppt).

ate Water (SCSIW, less cool and fresh), and the SCS Deep Water (SCSDW, cool and fresher). The characteristics of the four water masses are illustrated in Table 1.

6.2 *Statistical evaluation*

The easiest way to verify MODAS performance is to plot the MODAS data against SCSMEX CTD data (Fig. 5). The scatter diagrams for temperature show the points clustering around the line of $T_m = T_o$. The scatter diagrams for salinity show a greater spread of the points around the line of $S_m = S_o$. This result indicates better performance in temperature nowcast than in salinity nowcast.

The errors for temperature and salinity nowcast have a Gaussian-type distribution with zero mean for temperature and –0.048 ppt for salinity and with standard deviation (STD) of 0.98°C for temperature and 0.22 ppt for salinity (Fig. 6). This result indicates that MODAS usually under-predicts the salinity.

6.3 *Error estimation*

The RMSE of temperature (Fig. 7(a), Table 2) between the MODAS and SCSMEX data increases rapidly with depth from 0.55°C at the surface to 1.72°C at 62.5 m and then reduces with depth to near 0.03°C at 3000 m deep. The RMSE of salinity (Fig. 7(b), Table 3) between the MODAS and the SCSMEX data has a maximum value (0.347 ppt) at the surface. It decreases to a very small value (0.009 ppt) at 3000 m.

The MODAS mean temperature is slightly (0.1°C) cooler than the SCSMEX mean temperature at the surface and 2.5 m depth. The difference decreases with depth. Below 30 m depth, the MODAS mean temperature becomes warmer than the SCSMEX mean temperature with the maximum BIAS (about 0.6°C warmer) at 100 m deep. Below 100 m depth, the warm BIAS decreases with depth to 500 m. Below 500 m, the BIAS becomes very small (less than 0.1°C).

The MODAS mean salinity is less than the SCSMEX mean salinity at almost all depths (Fig. 8(b), Table 3). At the surface, the MODAS salinity is less (0.117 ppt) than the SCSMEX mean salinity. Such a bias increases with depth to a maximum value of 0.148 ppt at 62.5 m depth and decreases with depth below 62.5 m depth.

The skill score of the temperature nowcast (Fig. 9(a), Table 2) is positive except at depth between 1750 and 2250 m. The skill score of the salinity nowcast (Fig. 9(b), Table 3) is less than that of the temperature nowcast, especially at depths between 300 and 400 m, where the skill score is negative.

Table 2. Bias, rms error between MODAS (GDEM) and SCSMEX data and the MODAS skill score (temperature, °C).

Depth (m)	Bias (MODAS)	Bias (GDEM)	RMS error (MODAS)	RMS error (GDEM)	Skill score (MODAS)
0.000	–0.099	–1.329	0.553	1.536	0.640
2.500	–0.106	–1.343	0.548	1.546	0.645
7.500	–0.052	–1.279	0.784	1.598	0.510
12.500	–0.037	–1.215	0.660	1.491	0.558
17.500	–0.019	–1.071	0.942	1.525	0.382
25.000	–0.034	–0.838	1.014	1.416	0.284
32.500	0.004	–0.647	1.222	1.527	0.200
40.000	0.053	–0.536	1.361	1.651	0.175
50.000	0.128	–0.378	1.488	1.758	0.154
62.500	0.320	–0.303	1.720	1.880	0.085
75.000	0.386	–0.402	1.529	1.725	0.114
100.000	0.586	–0.295	1.436	1.533	0.063
125.000	0.501	0.127	1.293	1.389	0.069
150.000	0.364	0.621	1.075	1.337	0.196
200.000	0.225	0.931	0.859	1.365	0.371
300.000	0.163	0.294	0.662	0.790	0.163
400.000	0.122	–0.162	0.538	0.557	0.035
500.000	0.010	–0.176	0.394	0.420	0.061
600.000	–0.057	–0.052	0.304	0.335	0.093
700.000	–0.059	–0.047	0.271	0.297	0.087
800.000	–0.049	–0.034	0.232	0.255	0.089
900.000	–0.020	–0.030	0.199	0.222	0.102
1000.000	–0.013	–0.020	0.182	0.213	0.144
1100.000	0.047	–0.049	0.192	0.222	0.133
1200.000	0.035	–0.058	0.161	0.213	0.244
1300.000	0.057	–0.043	0.136	0.185	0.262
1400.000	0.055	–0.024	0.112	0.164	0.317
1500.000	0.046	–0.004	0.090	0.120	0.249
1750.000	0.055	–0.018	0.111	0.067	–0.655
2000.000	0.047	–0.014	0.066	0.052	–0.265
2500.000	0.018	–0.061	0.040	0.078	0.485
3000.000	0.023	–0.101	0.032	0.117	0.724

7. Capability for Nowcasting Thermocline and Halocline Structure

It is very difficult for any model to nowcast thermocline and halocline structure. To test MODAS capability on this issue, we compare the MODAS and SCSMEX T, S cross-sections at three observational lags (Fig. 2) and T, S time series at five mooring stations.

7.1 Observational lags

We compare the MODAS, GDEM fields to the SCSMEX data at three observational lags: Lag-A conducted by R/V Shiyan-3 on April 25–26, 1998; Lag-B conducted by R/V Haijian-74 on May 3, 1998; and Lag-C conducted by R/V Haijian-74 on April 27–29, 1998.

7.1.1 Lag-A

The lag-A is across the northwest SCS shelf from the Pearl River (third largest river in China) mouth toward the northwestern tip of Luzon Island. Vertical temperature cross-sections of MODAS (Fig. 10(a)), SCSMEX (Fig. 10(b)), and GDEM (Fig. 10(c)) show much less difference between MODAS and SCSMEX (less than 0.5°C) than between GDEM and SCSMEX (larger than 2°C) in upper layer (0–50 m depth), and comparable evident difference (1–2°C) between MODAS and SCSMEX to between GDEM and SCSMEX below 50-m depth. MODAS minus SCSMEX temperature (Fig. 10(d)) is almost zero near the surface and much smaller than GDEM minus SCSMEX temperature with a maximum difference of (–2.5°C) (Fig. 10(e)) in the upper layer (0–50 m depth). Below 50-m depth, MODAS minus SCSMEX temperature is comparable to GDEM minus SCSMEX temperature (1–2°C).

Vertical salinity cross-sections of MODAS (Fig. 11(a)), SCSMEX (Fig. 11(b)), and GDEM (Fig. 11(c)) show comparable evident difference (>0.2 ppt) between MODAS and SCSMEX to between GDEM and SCSMEX

Table 3. Bias, rms error between MODAS (GDEM) and SCSMEX data and the MODAS skill score (salinity, ppt).

Depth (m)	Bias (MODAS)	Bias (GDEM)	RMS error (MODAS)	RMS error (GDEM)	Skill score (MODAS)
0.000	–0.117	–0.135	0.347	0.410	0.153
2.500	–0.096	–0.135	0.328	0.390	0.159
7.500	–0.056	–0.114	0.297	0.353	0.160
12.500	–0.066	–0.125	0.263	0.298	0.120
17.500	–0.080	–0.135	0.275	0.297	0.072
25.000	–0.114	–0.163	0.323	0.332	0.028
32.500	–0.108	–0.165	0.316	0.331	0.046
40.000	–0.127	–0.186	0.277	0.301	0.080
50.000	–0.140	–0.201	0.267	0.298	0.103
62.500	–0.148	–0.198	0.241	0.278	0.131
75.000	–0.133	–0.192	0.207	0.245	0.154
100.000	–0.095	–0.156	0.143	0.185	0.228
125.000	–0.083	–0.104	0.111	0.130	0.145
150.000	–0.062	–0.058	0.085	0.087	0.021
200.000	–0.026	–0.013	0.055	0.058	0.050
300.000	–0.001	0.000	0.043	0.042	–0.040
400.000	–0.006	0.003	0.036	0.029	–0.235
500.000	–0.021	–0.027	0.032	0.040	0.195
600.000	–0.032	–0.048	0.039	0.056	0.310
700.000	–0.035	–0.043	0.042	0.049	0.149
800.000	–0.031	–0.035	0.037	0.042	0.128
900.000	–0.027	–0.026	0.032	0.034	0.063
1000.000	–0.027	–0.021	0.031	0.029	–0.052
1100.000	–0.019	–0.013	0.025	0.026	0.008
1200.000	–0.014	–0.007	0.021	0.022	0.058
1300.000	–0.015	–0.005	0.023	0.021	–0.078
1400.000	–0.016	–0.004	0.023	0.021	–0.068
1500.000	–0.010	–0.003	0.021	0.022	0.053
1750.000	–0.007	–0.007	0.025	0.016	–0.550
2000.000	–0.015	–0.008	0.020	0.014	–0.427
2500.000	–0.009	0.000	0.015	0.017	0.123
3000.000	0.003	0.013	0.009	0.019	0.518

in the halocline and less difference between MODAS and SCSMEX than between GDEM and SCSMEX elsewhere. MODAS minus SCSMEX salinity (Fig. 11(d)) is smaller than GDEM minus SCSMEX salinity near the Pearl River mouth. MODAS has a strong capability to nowcast surface T, S fields, and a weak capability to nowcast T, S fields in the thermocline and halocline. The maximum error in the MODAS temperature field (Fig. 10(d)) is around 2°C at 50–70 m deep (in the thermocline) near the shelf break. The maximum error in the MODAS salinity field (Fig. 11(d)) is around –0.2 ppt in the halocline (25–50 m deep).

7.1.2 Lag-B

The lag-B is nearly along 15°N latitude. Vertical temperature cross-sections of MODAS (Fig. 12(a)), SCSMEX (Fig. 12(b)), and GDEM (Fig. 12(c)) show much less difference between MODAS and SCSMEX (less than 0.5°C) than between GDEM and SCSMEX (larger than 1°C) near the surface, and comparable evident difference (2–3°C) between MODAS and SCSMEX to between GDEM and SCSMEX in the thermocline.

The location of the thermocline identified from the MODAS (Fig. 12(a)) and GDEM (Fig. 12(c)) coincides with that identified from the SCSMEX (Fig. 12(b)). However, the vertical temperature gradient in the MODAS and GDEM data is weaker than that in the SCSMEX data. The MODAS temperature field is closer to GDEM than to SCSMEX. The maximum temperature difference (3°C) between MODAS and SCSMEX (GDEM and SCSMEX) occurs at the 50–100 m deep, eastern part of the cross-section (Stations 6–8, Figs. 12(d) and (e)), where the strongest thermocline is present (Fig. 12(b)).

The location of the halocline identified from the MODAS (Fig. 13(a)) and GDEM (Fig. 13(c)) coincides with that identified from the SCSMEX data (Fig. 13(b)) in the eastern part. However, both MODAS and GDEM

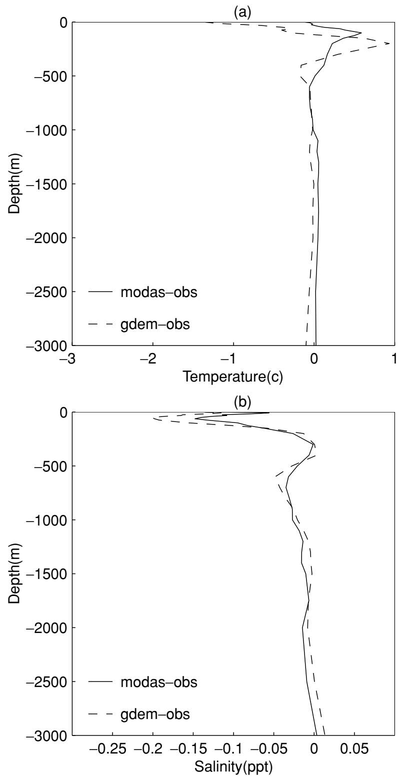

Fig. 8. The BIAS between the MODAS and SCSMEX data (solid) and between the GDEM and SCSMEX data (dotted): (a) temperature (°C), and (b) salinity (ppt).

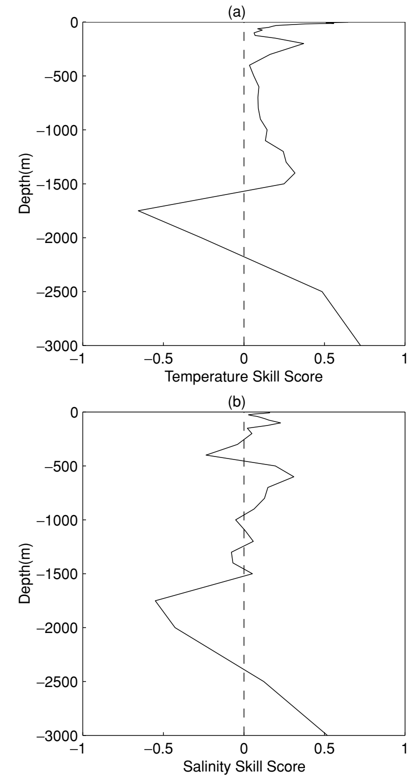

Fig. 9. Skill score of MODAS.

failed to nowcast the outcrop of the halocline in the western part (Fig. 13(b)). Two maximum salinity error centers appear in the halocline in MODAS (Fig. 13(d)) and GDEM (Fig. 13(e)) salinity field with one center in the western halocline outcropping area from the surface to 50 m depth (–0.5 ppt) and the other in the eastern part (–0.4 ppt) at 50 m deep.

7.1.3 Lag-C

The lag-C is across the South Vietnam shelf from the mouth of the Mekong River (largest river in the Indo-China Peninsula) toward the northwestern tip of Borneo. Vertical temperature cross-sections of MODAS (Fig. 14(a)), SCSMEX (Fig. 14(b)), and GDEM (Fig. 14(c)) show little difference near the surface, and large difference in the thermocline (50–125 m). Below the thermocline, the MODAS temperature is closer to the SCSMEX temperature than the GDEM temperature. The location of the halocline identified from the MODAS (Fig. 15(a)) coincides with that identified from SCSMEX (Fig. 15(b)) better than from GDEM (Fig. 15(c)). However, both MODAS and GDEM failed to nowcast the low salinity patchiness in the upper layer shown in Fig. 15(b).

The thermocline and halocline identified from MODAS and GDEM are weaker than SCSMEX data

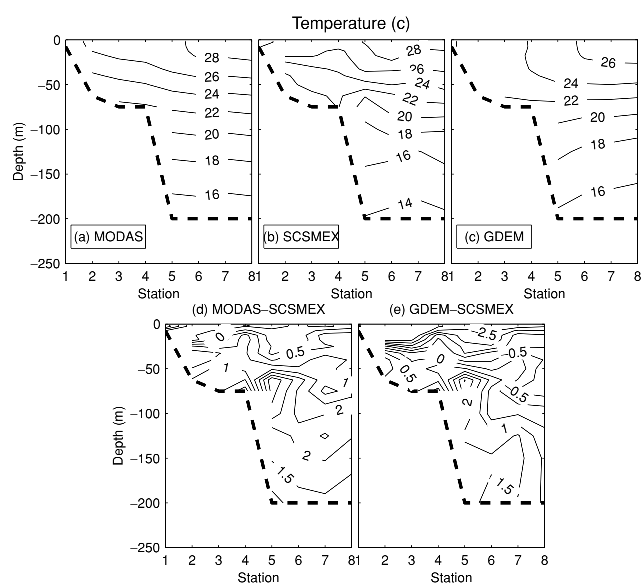

Fig. 10. Comparison among MODAS, GDEM, and SCSMEX temperature along the lag-A cross-section: (a) MODAS temperature, (b) SCSMEX temperature, (c) GDEM temperature, (d) MODAS temperature minus SCSMEX temperature, and (e) GDEM temperature minus SCSMEX temperature.

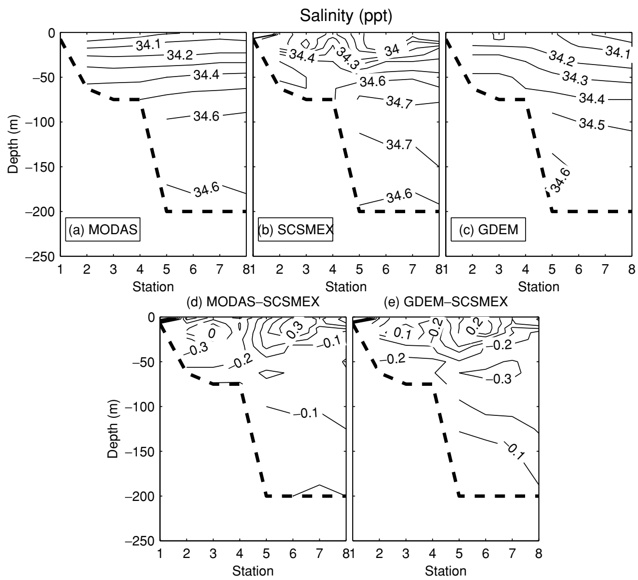

Fig. 11. Comparison among MODAS, GDEM, and SCSMEX salinity along the lag-A cross-section: (a) MODAS salinity, (b) SCSMEX salinity, (c) GDEM salinity, (d) MODAS salinity minus SCSMEX salinity, and (e) GDEM salinity minus SCSMEX salinity.

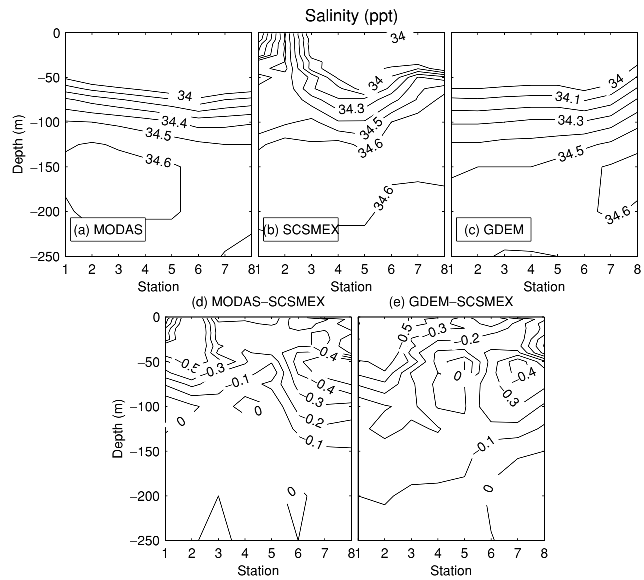

Fig. 13. Comparison among MODAS, GDEM, and SCSMEX salinity along the lag-B cross-section: (a) MODAS salinity, (b) SCSMEX salinity, (c) GDEM salinity, (d) MODAS salinity minus SCSMEX salinity, and (e) GDEM salinity minus SCSMEX salinity.

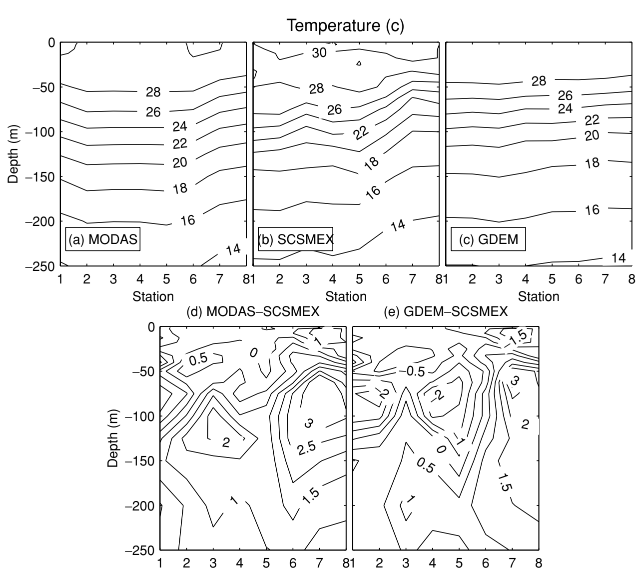

Fig. 12. Comparison among MODAS, GDEM, and SCSMEX temperature along the lag-B cross-section: (a) MODAS temperature, (b) SCSMEX temperature, (c) GDEM temperature, (d) MODAS temperature minus SCSMEX temperature, and (e) GDEM temperature minus SCSMEX temperature.

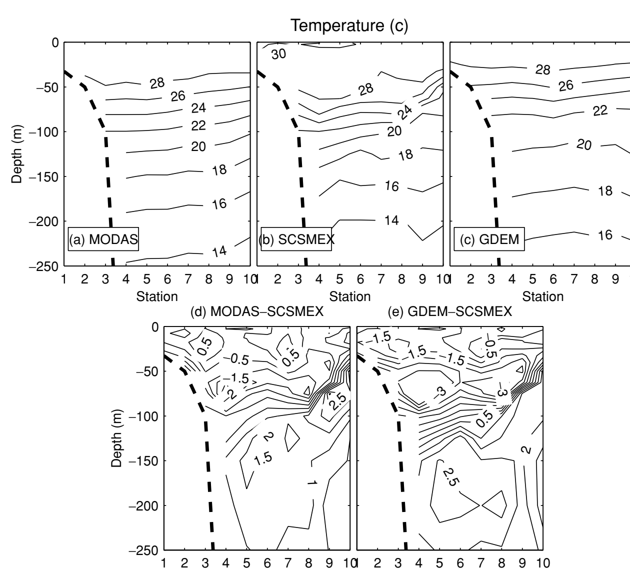

Fig. 14. Comparison among MODAS, GDEM, and SCSMEX temperature along the lag-C cross-section: (a) MODAS temperature, (b) SCSMEX temperature, (c) GDEM temperature, (d) MODAS temperature minus SCSMEX temperature, and (e) GDEM temperature minus SCSMEX temperature.

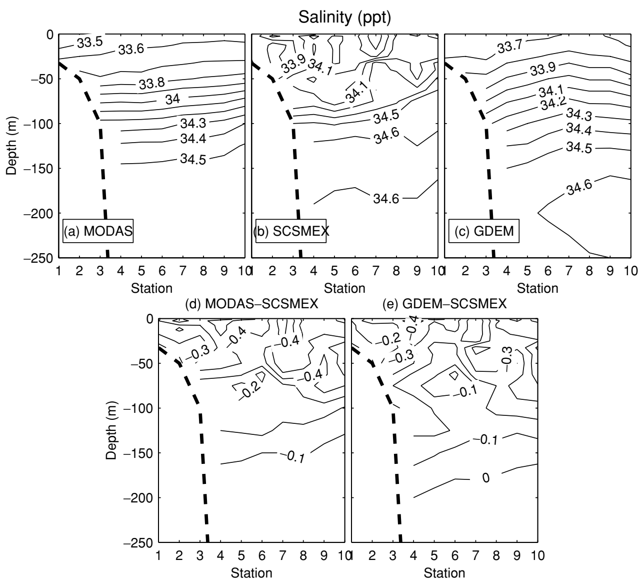

Fig. 15. Comparison among MODAS, GDEM, and SCSMEX salinity along the lag-C cross-section: (a) MODAS salinity, (b) SCSMEX salinity, (c) GDEM salinity, (d) MODAS salinity minus SCSMEX salinity, and (e) GDEM salinity minus SCSMEX salinity.

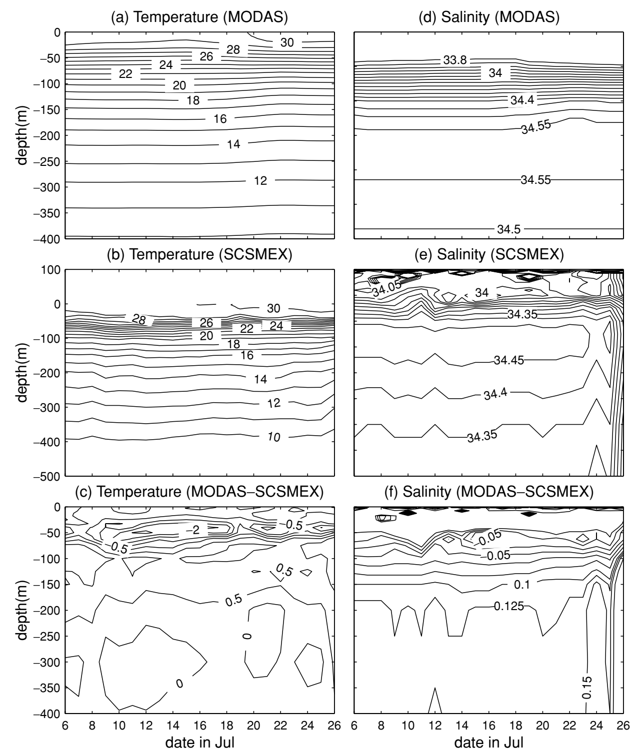

Fig. 16. Temporal-vertical cross-sections at the mooring station (114.38°E, 21.86°N): (a) MODAS temperature, (b) SCSMEX temperature, (c) MODAS temperature minus SCSMEX temperature, (d) MODAS salinity, (e) SCSMEX salinity, (f) MODAS salinity minus SCSMEX salinity.

(Figs. 14 and 15). The maximum error in the MODAS (GDEM) temperature field is around 2.5°C (3.0°C) at 50–75 m deep (in the thermocline) near the shelf break (Figs. 14(d) and (e)). The maximum error in the MODAS (GDEM) salinity field (Figs. 15(d) and (e)) is around –0.4 ppt (–0.3 ppt) in the halocline (25–50 m deep).

7.2 Mooring stations

Five mooring stations were maintained during SCSMEX. The mooring station data are used to verify the MODAS capability for nowcasting the synoptic-scale temporal variability of thermohaline structure. Since GDEM does not represent synoptic scale temporal variability, the comparison is made between MODAS and SCSMEX at the mooring stations. We present the results at one mooring station (114.38°E, 21.86°N) for illustration.

7.2.1 General evaluation

Vertical-time cross-sections of temperature from MODAS (Fig. 16(a)) and from SCSMEX (Fig. 16(b)) show little difference near the surface, and large difference in the thermocline (compare Figs. 16(a) with 16(b)), which confirms that MODAS has a strong capability to nowcast the surface temperature field.

Thermocline and halocline identified from the MODAS temperature (Fig. 16(a)) and salinity (Fig. 16(d)) cross-sections are weaker than SCSMEX data (Figs. 16(b) and (e)). The maximum error in the MODAS temperature field (Fig. 16(c)) is around 2°C at 50 m deep (in the thermocline). The maximum error in the MODAS salinity field (Fig. 16(f)) is around –0.2 ppt in the halocline.

7.2.2 Thermocline parameters

Three parameters are computed for representing the thermocline/halocline characteristics: depth, gradient, and thickness. For thermocline, we calculate the vertical temperature gradient, $\partial T/\partial z$, use its maximum value as the thermocline gradient, identify the corresponding depth as the thermocline depth, and take the distance between 19°C and 28°C isotherms as the thermocline thickness. For halocline, it is hard to compute the vertical gradient since the SCSMEX salinity field shows patchiness at the surface (Fig. 16(e)). We identify the depth of 34.25 ppt as the halocline depth, use the distance between 34.1 and 34.4 ppt isolines as the halocline thickness, and take 0.3 ppt/thickness as the halocline gradient.

The thermocline depth estimated from the MODAS temperature field is 10–40 m shallower than that from the SCSMEX data (Fig. 17(a)). The vertical temperature gradient across the thermocline computed from the MODAS field is around 0.14°C/m (Fig. 17(b)), much weaker and (varying) slower than that calculated from

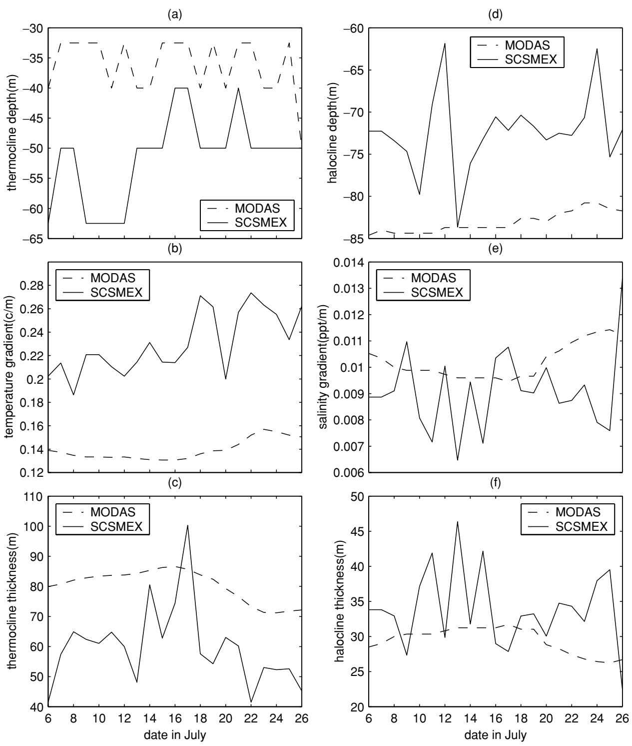

Fig. 17. Thermocline and halocline parameters determined from MODAS (dashed) and SCSMEX (solid) at the mooring station (114.38°E, 21.86°N): (a) thermocline depth, (b) thermocline gradient, (c) thermocline thickness, (d) halocline depth, (e) halocline gradient, and (f) halocline thickness.

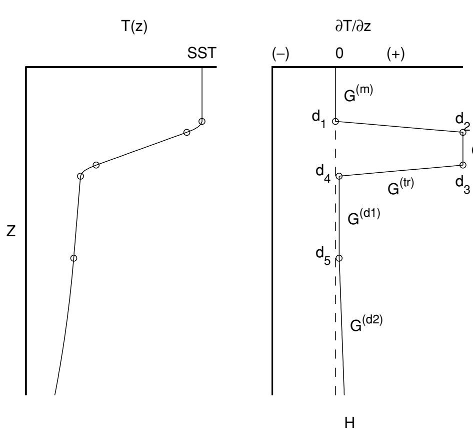

Fig. 18. Characteristics of vertical temperature structure: (a) profile, and (b) gradient.

the SCSMEX data (0.19°–0.27°C/m). The thermocline thickness computed from the MODAS field varies slowly around 80 m, which is lower in its temporal variation calculated from the SCSMEX data (40–100 m).

7.2.3 Halocline parameters

We computed three parameters to represent the halocline characteristics: halocline depth, salinity gradient across the halocline, and halocline thickness. The halocline depth estimated from the MODAS salinity field is always deeper than that from the SCSMEX data (Fig. 17(d)). The vertical salinity gradient across the halocline computed from the MODAS field is around 0.011 ppt/m (Fig. 17(e)), which is generally stronger than that calculated from the SCSMEX data (0.0065–0.011 ppt/m). The halocline thickness computed from the MODAS field varies slowly around 30 m, which is generally thinner than that calculated from the SCSMEX data (28–46 m).

8. Future MODAS Improvement

8.1 MODAS first special treatment

Temperature (salinity) profiles in oceans usually exhibit a multi-layer structure consisting of mixed-layer, thermocline (halocline), and two deep layers. When the two deep layers have the same vertical gradients, they become one deep layer. The vertical thermal structure (i.e., depths and gradients) changes in space and time. Six layers can represent vertical thermal structure if the entrainment zone between the mixed layer and thermocline and the transition zone between the thermocline and the deep layer are added (Fig. 18). Each observed profile is represented by a set of parameters, most of which have physical meaning, including SST, mixed layer depth (MLD), depth of the base of the thermocline, gradient in the thermocline and deep layers, and additional parameters describing vertical gradients (Chu *et al.*, 1997c, 1999b, 2000). For a vertically uniform temperature profile, MLD equals the water depth and thermocline gradient equals zero. Each observed profile is represented by depths and gradients of each layer: H (water depth), d_1 (MLD), d_2 (depth of the thermocline top), d_3 (depth of the thermocline bottom), d_4 (depth of the top of the first deep layer), and d_5 (bottom of the first deep layer), $G^{(m)}$ (~0, mixed layer gradient), $G^{(th)}$ (large, thermocline gradient), $G^{(tr)}$ (mean entrainment zone gradient), $G^{(d1)}$ (mean gradient in the first deep layer), and $G^{(d2)}$ (mean gradient in the second deep layer). Here, the mean entrainment zone gradient is the average of the mixed layer and thermocline gradients.

The depths (d_1, d_2, d_3, d_4, d_5) and gradients [$G^{(m)}$, $G^{(th)}$, $G^{(tr)}$, $G^{(d1)}$, $G^{(d2)}$] represent characteristics of temperature profiles that vary in space and time. It is difficult and unrealistic to archive these characteristics from SST and SSH using the MODAS first treatment. In future MODAS, the synthetic temperature profiles will be obtained from the relationships between (SST, SSH) and (d_1, d_2, d_3, d_4, d_5), gradients [$G^{(m)}$, $G^{(th)}$, $G^{(tr)}$, $G^{(d1)}$, $G^{(d2)}$], rather than from the relationships between (SST, SSH) and temperature at given depth (MODAS first treatment).

8.2 MODAS second special treatment

The assumption underlying the MODAS second treatment is the existence of a dependence of salinity solely on temperature. Chu and Garwood (1990, 1991) and Chu *et al.* (1990) found a two-phase thermodynamics of atmosphere and ocean, each medium having two independent variables: temperature and salinity for oceans, temperature and humidity (or cloud fraction) for the atmosphere. Both positive and negative feedback mechanisms are available between atmosphere and ocean. First, clouds reduce the incoming solar radiation at the ocean surface by scattering and absorption, which cools (relatively) the ocean mixed layer. The cooling of the ocean mixed layer lowers the evaporation rate, which will diminish the clouds. This is the negative feedback. Second, precipitation dilutes the surface salinity, stabilizing the upper ocean and reducing ocean mixed layer deepening. The MLD may be caused to shallow if the downward surface buoyancy flux is sufficiently enhanced by the precipitation. The reduction in MLD will increase SST by concentrating the net radiation plus heat flux downward across the sea surface into thinner layer. The increase of SST augments the surface evaporation, which increases the surface salinity (for ocean) and produces more clouds (for atmosphere). This indicates that no unique *T-S* relationship exists, especially in the upper ocean.

A reasonable way to represent salinity profile is by depths and gradients: d_1 (MLD for salinity), d_2 (depth of the halocline top), d_3 (depth of the halocline bottom), d_4 (depth of the top of the first deep layer), and d_5 (bottom of the first deep layer), $G_S^{(m)}$ (~0, mixed layer gradient), $G_S^{(ha)}$ (halocline gradient), $G_S^{(tr)}$ (mean entrainment zone gradient), $G_S^{(d1)}$ (mean gradient in the first deep layer), and $G_S^{(d2)}$ (mean gradient in the second deep layer). In a future MODAS, synthetic salinity profiles should be independent of the synthetic temperature profiles. They will be obtained from the relationships between surface data (SST, SSH, precipitation) and (d_1, d_2, d_3, d_4, d_5), [$G_S^{(m)}$, $G_S^{(ha)}$, $G_S^{(tr)}$, $G_S^{(d1)}$, $G_S^{(d2)}$].

9. Conclusions

(1) MODAS has the capability to provide reasonably good temperature and salinity nowcast fields. The errors have a Gaussian-type distribution with mean temperature nearly zero and mean salinity of –0.2 ppt. The standard deviations of temperature and salinity errors are 0.98°C and 0.22 ppt, respectively.

(2) The skill score of the temperature nowcast is positive, except at depths between 1750 and 2250 m. The skill score of the salinity nowcast is less than that of the temperature nowcast, especially at depths between 300 and 400 m, where the skill score is negative.

(3) The MODAS mean temperature is slightly (0.1°C) cooler than the SCSMEX mean temperature at the surface. Below 30 m deep, the MODAS mean temperature becomes warmer than the SCSMEX mean temperature with the maximum bias (about 0.6°C warmer) at 100 m deep. Below 100 m depth, the warm bias decreases with depth to less than 0.1°C below 500 m deep.

(4) The MODAS mean salinity is less than the SCSMEX mean salinity at all depths, which indicates that the MODAS under-estimates the salinity field. Such a bias increases with depth from 0.113 ppt at the surface to a maximum value of 0.135 ppt at 60 m depth and decreases with depth below 60 m deep.

(5) Thermocline and halocline identified from the MODAS temperature and salinity fields are weaker than the SCSMEX data. The maximum discrepancy between the two is in the thermocline and halocline. In outcropping halocline, the discrepancy becomes high (0.7 ppt along Lag-B).

(6) The thermocline depth estimated from the MODAS temperature field is 10–40 m shallower than that from the SCSMEX data. The vertical temperature gradient across the thermocline computed from the MODAS field is around 0.14°C/m, which is much weaker than that calculated from the SCSMEX data (0.19°–0.27°C/m). The thermocline thickness computed from the MODAS field varies slowly around 80 m, which falls in its temporal variation calculated from the SCSMEX data (40–100 m).

(7) The halocline depth estimated from the MODAS salinity field is deeper than that from the SCSMEX data. Its thickness computed from the MODAS field varies slowly around 30 m, which is generally thinner than that calculated from the SCSMEX data (28–46 m).

(8) MODAS has two special treatments for creating synthetic temperature and salinity profiles. The first one is to use linear regression relationships between (SST, SSH) with temperature at a given depth. The second one is to assume that salinity is a sole function of temperature and to derive synthetic salinity profiles from synthetic temperature profiles. In a future MODAS, the synthetic temperature profiles should be obtained from the relationships between (SST, SSH) and depths-temperature gradients; and synthetic salinity profiles should be obtained from the relationships between surface data (SST, SSH, precipitation) and depths-salinity gradients.

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