Modeling the diurnal variability of sea surface temperatures

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1. Introduction

[1] In this study a one-dimensional mixed layer ocean model is customized for the purpose of estimating the diurnal signal of temperature in the near-surface ocean layer, generically referred to as sea surface temperature (SST). The model is initially run with data from three mooring locations. It is then demonstrated how operational forecast data sets can be utilized to estimate diurnal signals over a wide area. Daily diurnal variability maps are produced for a weeklong period over the Atlantic Ocean. These maps highlight the transient nature of diurnal SST signals with day to day changes in their magnitude and spatial distribution. The resulting diurnal variability maps are evaluated using a combination of infrared and microwave satellite-derived SST observations taken over the day. These matchups result in a mean error of 0.09°C and a standard deviation of 0.54°C. Advantages of modeling the diurnal cycle as opposed to using a persistence assumption are discussed.

how the rectification of the diurnal cycle of SST onto the daily mean SST affects the magnitude of the variability of intraseasonal SST in coupled atmosphere-ocean simulations. The diurnal variability of SST has a major impact on the time integrated air-sea heat flux calculations as explained by Price et al. [1986], Webster et al. [1996], and Danabasoglu et al. [2006]. Improved accuracy is attained in air-sea heat flux calculations if skin rather than foundation SST is used and temporal averaging of SST values are avoided or limited. Fairall et al. [1996a] found that, averaged over the 70 days sampled during Coupled Ocean-Atmosphere Response Experiment (COARE), the cool skin increases the average atmospheric heat input to the ocean by about 11 W m\(^{-2}\); the diurnal warm layer decreases it by about 4 W m\(^{-2}\) (but the effect can be 50 W m\(^{-2}\) at midday). Diurnal variability also has an important influence on mixed layer dynamics by enhancing the strength of mixing across the thermocline [McCreary et al., 2001; Shinoda, 2005]. In addition Katsaros and Soloviev [2004] and Katsaros et al. [2005] have shown how horizontal SST discontinuities are diminished by diurnal variability. Thus an ability to accurately and effectively simulate and measure the diurnal variability of SSTs will be of great benefit.

[7] A strong boost to support the continuation and improvement of satellite SST measurements would come from their use in operational ocean forecast and NWP models. However, the current generation of these models do not resolve the diurnal SST cycle and therefore problems are encountered when assimilating SST observations which are diurnally 'corrupted', which can result in aliasing. To address some of these issues, particularly the use in operational oceanography, this study focuses on the ability of a numerical model to provide local diurnal warming estimates on the basis of operational ocean and NWP forecast input data.

[8] The study will also use the classification of SSTs that takes into account the vertical temperature structure of the upper ocean as introduced by Donlon et al. [2002] and used by the Global Ocean Data Assimilation Experiment (GODAE) High-Resolution Sea Surface Temperature Pilot Project (GHRSSST-PP) [Donlon et al., 2007].

[9] The paper proceeds as follows: A background to diurnal cycle modeling and the model setup used in this work is given in section 2. Results from some initial experiments performed at upper ocean mooring sites are presented in section 3. This work is then extended to the use of operational data sets in section 4. In section 5 diurnal variability maps in the Atlantic are produced and compared to satellite-derived SST measurements. Finally conclusions are given in section 6.

2. Modeling

2.1. Background

[10] One-dimensional modeling of the oceanic mixed layer has been widely used in the development of turbulence and air-sea flux parameterizations. Such models are also suitable for modeling diurnal variability of SST as they can have a much greater near-surface vertical resolution than can be achieved in a full ocean GCM. Mixed layer modeling can generally be categorized into two broad approaches: bulk and diffusion. Bulk models attempt to model the mixed layer in an integral sense [e.g., Kraus and Turner, 1967; Price et al., 1986]. The governing equations of heat and momentum are integrated over the mixed layer and the balance of heat and momentum over the entire mixed layer are adjusted by the effects of momentum and buoyancy fluxes. On the other hand diffusion models directly parameterize the turbulent mixing and diffusion in the mixed layer [e.g., Mellor and Yamada, 1982; Large et al., 1994; Kantha and Clayson, 1994].

[11] The first detailed modeling study of the diurnal cycle was by Price et al. [1986] who developed a bulk model dependent on the generation of shear instability at the base of the mixed layer. This model was also used by Shinoda and Hendon [1998] and Shinoda [2005] to model diurnal variability in the western equatorial Pacific. The bulk model by Kraus and Turner [1967] was compared to the diffusion model of Kantha and Clayson [1994] in a study by Horrocks et al. [2003]. They found the Kraus-Turner model could predict when diurnal thermoclines would form, but could not accurately determine their magnitude. The main limitation was the reliance on mechanical and buoyancy driven mixing, which under strong solar heating and low wind speeds becomes very low leading to surface heat build up, with no mechanism such as diffusion or conduction to draw heat downward. The diffusion approach of Kantha and Clayson [1994] was more effective at producing downward mixing and thus predicting diurnal amplitudes. Hallsworth [2006] compared the Price bulk model with a diffusion type model called the General Ocean Turbulence Model (GOTM) (see section 2.2) at two mooring sites and also consistently found GOTM performing better at modeling the diurnal cycle of near-surface temperatures.

[12] Model experiments in the western Pacific warm pool suggest an upper layer resolution of order 1 m is required to capture 90% of the diurnal variability [Bernie et al., 2005] from the TAO data. However satellite observations resolve a much thinner layer and Horrocks et al. [2003] used a grid layer of 2 cm, increasing exponentially with depth to 60 cm, when comparing model output to Advanced Along-Track Scanning Radiometer (AATSR) observations.


[14] To attain the temporal resolution for diurnal modeling studies data from the TOGA COARE sites are often used, where high-frequency meteorology (every 15 min) is available [Webster et al., 1996; Shinoda, 2005; Bernie et al., 2005]. Bernie et al. [2005] performed experiments using different flux frequencies and concluded that to capture 90% of the diurnal variability of SST, 3 hourly flux forcing was required. However, Horrocks et al. [2003] used 6 hourly surface fluxes from UKMO NWP analyses and then generated only the solar flux at higher frequency.
These previous studies have guided the modeling choices here.

2.2. Model Setup

For this study the GOTM model was used; originally published in 1999 it has been regularly extended since [Umlauf et al., 2005]. For the purposes of this study we construct a nonuniform grid with 150 vertical levels, resolving a depth down to 150 m. The top grid box is 0.030 m thick, while the bottom box is 3.015 m thick, on the basis of the formula

$$h_i = \frac{\tanh\left(\frac{z}{50}\right) - \tanh\left(\frac{z_i}{50}\right)}{\tanh(3)},$$

where $h_i$ represents the thickness of the $i$th model layer. This grid distribution results in 67 model layers within the top 10 m of ocean. A time step of 30 seconds is used.

We have updated the air-sea flux module in GOTM, replacing the Kondo [1975] air-sea flux parameterization with the superior TOGA-COARE algorithm [Fairall et al., 1996b, 2003], and we have incorporated a cool skin parameterization [Fairall et al., 1995] for use in calculating upwelling longwave radiation as well as sensible and latent heat flux. The ocean radiant heating parameterization of Paulson and Simpson [1977] was replaced with a 9-band parameterization [Paulson and Simpson, 1981] that covers the complete spectral range.

Following Hallsworth [2006], who performed a diurnal SST comparison study of the various turbulence closure schemes incorporated in GOTM, the so-called 2-equation $k-$ turbulence kinetic energy parameterization is employed for the mixing, (see Umlauf and Burchard [2003] for a detailed description of this turbulence closure scheme and the solution procedure). In using a fine near-surface grid the model can become very sensitive to the amount of mixing being generated in the top grid boxes, particularly in low wind speed conditions. Under low wind speed conditions the surface stress is very small and little turbulent kinetic energy (TKE) is generated. Turbulence schemes have a tendency to under produce TKE in such circumstances, but these values are of extreme importance when modeling the diurnal cycle. To prevent the ex-tinguishing of TKE an internal wave (IW) parameterization [Kantha and Clayson, 1994] was included to represent internal wave activity which always leaves a background residue of TKE. To enhance mixing at the surface a wave breaking parameterization [Craig and Banner, 1994] was tested but was not found to improve results and was not used in the results here. Under low wind stress conditions the type of surface boundary conditions (prescribed Dirich-let conditions or a flux boundary Neumann type condition) for TKE and dissipation is important, and Neumann conditions were chosen as they were found to give the best results. Details of these tuning experiments can be found in the thesis by Pimentel [2007].

3. Buoy Simulation Experiments

Initial experiments with the model were performed at three different mooring sites, the results of which are presented in this section.

3.1. Data

Surface meteorological and ocean temperature observations are obtained from the Woods Hole Oceanographic Institution (WHOI) upper ocean mooring data archive. We use time series from three deployments: COARE [Weller and Anderson, 1996], Arabian Sea [Weller et al., 1998], and the Subduction site [Moyer and Weller, 1997]. Details of each time series is given in Table 1. The meteorological variables consist of the wind speed components $u$ and $v$, air temperature $T_a$, relative humidity $q_{rh}$ and air pressure $p$. These measurements were made at heights between 2 and 4 m. In addition measurements were taken of the downwel-ling shortwave radiation (SWR) and longwave, radiation (LWR), $I_1$ and $Q_{h}$ respectively. An estimated typical instant-aneous accuracy is 3% for $I_1$ and 10 W m$^{-2}$ for $Q_{h}$ [see Weller and Anderson, 1996, Table A2]. The ocean temperature observations, $\theta_{sw}(z)$, at various depths $z$ (within the top 150 m there are 29 observation depths in the Arabian Sea, 34 at COARE, and 12 at the Subduction site) are linearly interpolated onto the model grid and are used to initialize and validate the model simulations.

These rare observational time series with good tem-poral resolution are ideal for diurnal warming studies and the particular locations chosen in the tropics and higher latitudes provide a sample of the meteorological conditions found in areas of the globe that experience diurnal vari-ability of SSTs.

3.2. Methodology

The model profile is initialized with the observed temperatures every 24 hours at local sunrise, and forced with sensible and latent heat fluxes calculated from the surface meteorology (Table 1) using the air-sea flux algorithm [Fairall et al., 1996b, 2003] together with downwelling SWR and LWR observations.

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**Table 1.** Locations, Deployment Duration, and Data Frequency at the Three Mooring Sites

<table>
<thead>
<tr>
<th>Sites</th>
<th>Location</th>
<th>Duration</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arabian Sea</td>
<td>15°N, 61°E</td>
<td>17 Oct 1994 to</td>
<td>$\theta_{sw}(z)$ every 15 min $u, v, T_a, q_{rh}$ and $p$ every 7.5 min $I_1$ and $Q_h$ every 15 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>17 Oct 1995</td>
<td></td>
</tr>
<tr>
<td>COARE</td>
<td>1°S, 156°E</td>
<td>1 Nov 1992 to</td>
<td>$\theta_{sw}(z)$ every 15 min $u, v, T_a, q_{rh}$ and $p$ every 7.5 min $I_1$ and $Q_h$ every 15 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 Mar 1993</td>
<td></td>
</tr>
<tr>
<td>Subduction</td>
<td>26°N, 29°W</td>
<td>24 Jun 1991 to</td>
<td>$\theta_{sw}(z)$ every 15 min $u, v, T_a, q_{rh}$ and $p$ every 15 min $I_1$ and $Q_h$ every 15 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>16 Jun 1993</td>
<td></td>
</tr>
</tbody>
</table>

*aCOARE, Coupled Ocean-Atmosphere Response Experiment."
Further experiments were performed with the surface meteorological observations and the downwelling SWR and LWR from the buoys averaged over 6 hourly periods, the normal output format and frequency from NWP models. This allows us to assess the degradation of diurnal modeling skill that could be expected because of the effects of temporal sampling from using the NWP products over much wider areas.

Diurnally varying solar SWR forcing is the essential driver of the diurnal cycle. To meet the challenge of interpolating from 6 hourly mean values, when full direct SWR observations are unavailable, the following method was used. Surface insolation under clear skies, $I_1$, was calculated at every time step using the approach of Rosati and Miyakoda [1988]. The Reed formula [Reed, 1977]

$$I_0 = I_1(1 - C_n n + 0.0019 \beta)(1 - \alpha),$$

is then used to derive the total surface solar radiation, where $n$ is the fractional cloud cover; $C_n$, the cloud cover coefficient is set to 0.62; $\beta$ is the solar noon angle; and $\alpha$ the albedo. This formula is only used for higher cloud amounts $0.3 \leq n \leq 1$, with $I_0 = I_1(1 - \alpha)$ otherwise [Gilman and Garrett, 1994]. However, the cloud values, $n$ are not directly observed at these sites, so the 6 hourly mean observed SWR values are used together with the calculated 6 hourly mean clear sky values to derive 6 hourly values of $n$.

$$n = \left(1 - \frac{I_{obs}}{I_1} + 0.0019 \beta\right) / C_n.$$  

This technique allows the SWR to be calculated at a much finer time resolution (at each model time step) on the basis of a 6 hourly fixed cloud correction.

Equation 2 has been widely used in the oceanographic community and is surprisingly accurate for such a simple expression [Taylor, 2001]. A comparative study of these methods by Dobson and Smith [1988] found that the Reed formula gave the best long-term mean insolation values. Numerous studies have evaluated the precision of equation (2) [e.g., Dobson and Smith, 1988; Schiano, 1996; Kizu, 1998] finding small, but different, regional biases and generally supporting its use for long time average insolation over the ocean. Calibration based on radiometric measurements can improve the accuracy for particular regions, [e.g., Schiano, 1996] over the Mediterranean Sea reduces the transmission coefficient (used in the calculation of $I_1$) from 0.7 to 0.66 on the basis of aerosol and water vapor changes.

Following the suggestion of Schiano [1996] the transmission coefficient and the cloud cover coefficient are adjusted on the basis of the SWR observations taken at the mooring sites. To ensure over 90% of the SWR observations fall between the clear sky and full cloud limits of the Reed parameterization, the transmission coefficient was kept at 0.7 at the Subduction site, reduced to 0.63 at the COARE site, and increased to 0.74 at the Arabian Sea. The cloud cover coefficient remained 0.62 at the Subduction and Arabian Sea sites, but was increased to 0.72 at the COARE site.

The ability of the model to replicate the sea temperature records, given the observed forcing, can be assessed in various ways. Comparisons are made between the observed and modeled ocean temperatures at various depths in the water column. Particular interest is paid to the temperature at the shallowest measurement, $\theta_{min}^z$, (where $z_{obs}$ is 0.45, 0.17, and 1.0 m at COARE, Arabian Sea, and Subduction, respectively) and the ability to model its variability.

The magnitude of diurnal warming is defined as the maximum SST (temperature at the shallowest observed depth, $\theta_{z=0}^w$) minus the minimum SST, over a 24-hour window starting at the initialization time

$$\Delta \theta_{z=0}^w = \max_{0 \leq z \leq 24} \theta_{z=0}^w - \min_{0 \leq z \leq 24} \theta_{z=0}^w. \quad (4)$$

In order to avoid the misinterpretation of a cooling or warming trend over the window the maximum $\theta_{z=0}^w$ is said to occur when the temperature is greatest above the background linear trend (estimated from initialization points in each time window). Similarly the minimum $\theta_{z=0}^w$ over the 24-hour period is defined as the temperature that deviates the most below the estimated linear trend for the time window. The near-surface stratification is also calculated; this is given as the difference between the temperature at the shallowest observation point and the commonly observed 10 m depth, as follows:

$$\text{stratification} = \theta_{z=0}^w - \theta_{10m}.$$

The warm layer depth, WLD, is calculated as the depth at which the modeled/observed temperature drops to 0.1°C below the maximum modeled/observed temperature, within the top 20 m. This is the same criterion used by Weller et al. [2002]. These additional parameters are used to assess the model simulation against observational profiles from the buoys.

3.3. Results

Results, shown in Table 2, reveal root mean square (RMS) $\theta_{z=0}^w$, SST errors below 0.2°C at all sites, while diurnal warming errors are larger. The largest diurnal warming errors are at the COARE site. However, the mean observed diurnal warming over the entire time series is greater at this location, 0.56°C, compared with 0.46°C at Arabian Sea and 0.25°C at the Subduction site.

It should also be remembered that the SST is based on the uppermost observation at each site (i.e., from slightly different near surface depths). The errors in the WLD seem quite large considering the observed temperature profile is used to initialize each day. This could be revealing a sensitivity of the measure to nonlocal changes in the water column. The RMS error in the stratification varies only by

<table>
<thead>
<tr>
<th>Site</th>
<th>$\theta_{obs}$ (°C)</th>
<th>Diurnal Warming (°C)</th>
<th>Warm Layer Depth (m)</th>
<th>Stratification (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>COARE</td>
<td>0.19, 0.21</td>
<td>0.36, 0.39</td>
<td>13.54, 16.65</td>
<td>0.19, 0.2</td>
</tr>
<tr>
<td>Arabian Sea</td>
<td>0.15, 0.19</td>
<td>0.23, 0.29</td>
<td>11.31, 13.10</td>
<td>0.13, 0.17</td>
</tr>
<tr>
<td>Subduction</td>
<td>0.13, 0.15</td>
<td>0.21, 0.21</td>
<td>22.12, 25.22</td>
<td>0.14, 0.16</td>
</tr>
</tbody>
</table>

*Results obtained from model simulations forced with 6 hourly data.*
0.06°C across the sites, and is always below 0.2°C. Drift in the modeled near-surface temperatures over the day are negligible and the daily initialization limits the influence of nonlocal processes within the water column. The TKE is considered to be in quasi-equilibrium, and remains unchanged during the initialization of the temperature profile.

[33] Root mean square differences for hourly $\theta_{c176}$ at each site can be viewed in Figure 1. The largest errors, as expected, occur around midday local time when the SST variability is greatest. The continuing increase in the errors after sunset for the Arabian Sea data could be due to an accumulation of errors resulting from occasional episodes of nonlocal modulation of the water column.

[34] The square of the correlation coefficient, $R^2$, was used to calculate the fraction of variability in the observed data accounted for by the numerical model. The results are presented in Table 3; the correlation for both hourly $\theta_{c176}$ and daily peak $\theta_{c176}$ is strong especially at the Arabian Sea and Subduction sites where over 95% of the variance is explained by the model.

[35] The results of the reduced frequency (6 hours) forcing experiments are only slightly different, as can be seen in the parentheses in Tables 2 and 3. An example of the modeled diurnal warming signals in this case is shown in Figure 2. This covers a 6 day period from the Arabian Sea time series. The diurnal cycles are of the order 1.5°C and the observed variability is well replicated by the model. Some additional rapid variability is seen in the observations particularly at the peak of the cycle during days 162 and 163 of the time series; this could be a result of wind fluctuations or passing clouds that have been smoothed over in the forcing data. Overall the mean modeled diurnal warming signals are 0.56°C, 0.52°C, and 0.35°C at the COARE, Arabian Sea, and Subduction sites, respectively. This compares with the corresponding mean observed diurnal warming signals of 0.56°C, 0.46°C, and 0.25°C. Thus the averages produced by the diurnal model are accurate to within a tenth of a degree for each time series, with the COARE site being most closely replicated. Another measure is the timing of the diurnal peak. For the reduced frequency forcing experiments it was found that the model predicts an earlier peak by 2, 10, and 53 min at the COARE, Arabian Sea, and Subduction sites, respectively.

[36] Results suggest that the diurnal cycle can effectively be modeled with 6 hourly forcing data, although it is possible that there are locations where the occurrence of sharp wind bursts around midday are more prevalent, thus hampering the modeling performance. Nonetheless the standard output from operational weather forecasting centers is 6 hourly and the results in Tables 2 and 3 show that modeling the diurnal cycle of SSTs over the global ocean should be a possibility. This topic is addressed in the next section.

### 4. NWP Forcing Experiments

[37] In this section the GOTM model is set up to use NWP forcing data on a larger spatial domain. The use of NWP data in diurnal variability modeling is far from ideal, particularly with regards to the use of 6 hourly wind stress values, as the diurnal cycle can be extremely sensitive to fine-scale wind structure [Stuart-Menteth et al., 2005]. However the last section showed that when GOTM is forced with 6 hourly mean data at the mooring sites it can reasonably capture the observed diurnal variability. This was achieved by parameterizing the SWR at a finer resolution than 6 hours.

[38] In addition the NWP forcing experiments are compared with satellite measurements of SST which are taken at various times of day in order to test whether the diurnal modeling can successfully capture some of the observed variability. For these satellite comparisons the uppermost model layer at a depth of 3 cm is compared with the subskin SST satellite measurements.

### 4.1. Data

[39] We use the European Centre for Medium-range Weather Forecasting (ECMWF) 1° global meteorological
analyses/forecasts of 6 hourly integrated fluxes at 18:00, 00:00, 06:00, and 12:00 UTC, for surface solar radiation, 10 m wind speed components, 2 m air temperatures, and 2 m dew point temperatures, as well as sea level pressure.

The UKMO Forecasting Ocean Assimilation Model (FOAM) global 1° data provide analyses of ocean temperature and salinity (at depths: 5, 15, 25, 35, 48, 67, 96, and 139 m) at 00:00 UTC.

[40] Satellite observations include a combination of infrared (SEVIRI) and microwave (AMSR-E and TMI) SSTs from the GHRSSST-PP Level-2 Preprocessed (L2P) products. The data used for this study have the GHRSSST estimated bias corrections applied (a correction for long-term mean biases in the sensor) and have proximity confidence values labeled ‘acceptable’, ‘excellent’, and ‘diurnal’. This choice selects observations uncontaminated by cloud (for infrared) or rain (for microwave), but retains observations that potentially have a diurnal signal. Infrared retrieved SSTs are normally recognized as representing a skin SST, whereas the microwave retrieved SSTs are representative of a temperature just below the cool skin effect. However, the SEVIRI retrieval algorithm is validated and corrected against nighttime buoy SSTs and thus the SEVIRI SSTs provided by GHRSSST are designed to be subskin temperatures [Merchant and LeBorgne, 2004].

[41] The OSTIA product, developed at the UKMO is based on GHRSSST-PP L4, combining in situ, microwave and infrared satellite-derived SST, and is used in model initialization. It deliberately excludes diurnal amplitudes by prohibiting daytime observations if wind speeds are below 6 m s⁻¹. For more information on the data processing specifications adopted for GHRSSST products see Donlon and the Global Ocean Data Assimilation Experiment High Resolution Sea Surface Temperature—Pilot Project Science Team [2004].

4.2. Experimental Description

[42] As in the previous section the solar flux is converted to a finer time resolution. ECMWF SWR is given as a 6 hourly integrated value, rather than a mean value. Integrating the Reed formula over a 6 hour window gives

\[ \int_T^{T+6} \left[ I_0 dt - \int_T^{T+6} I_i \left( 1 - 0.62n + 0.0019\beta \right) (1 - \alpha) dt \right] = 0 \]

where \(T\) and \(T+6\) are the 6 hourly forecast times. The left hand side of equation (6) is set equal to the ECMWF value, and equation (6) can be rearranged to find an effective mean cloud value over this window,

\[ n = \frac{(1 + 0.0019\beta) \int_T^{T+6} I_i (1 - \alpha) dt - \int_T^{T+6} I_0 dt}{0.62 \int_T^{T+6} I_i (1 - \alpha) dt} \]

[43] If it is night, so that \( \int_T^{T+6} I_i (1 - \alpha) dt = 0 \), then persistence \( n_k = n_{k-1} \) is assumed. A check is also made to enforce the physical cloud limits \( 0 \leq n \leq 1 \). The net surface SWR, \( I_0 \), used in the model run is calculated every step using the Reed formula (2) with the 6 hourly derived cloud values.

[44] The air-sea fluxes are calculated using the 6 hourly forecast surface meteorology (air and dew point temperature, air pressure, and \( u \) and \( v \) wind speeds) together with the modeled SST from GOTM, whose top layer is 3cm deep, although the air-sea flux algorithm uses the cool skin parameterization to better represent the actual interfacial temperature at which the flux transfer takes place. This dynamic calculation allows feedback between the modeled SST and the fluxes, and preliminary experiments found this to be better than using the prescribed fluxes from ECMWF [Pimentel, 2007].

[45] The change in solar flux with depth into the ocean is parameterized as a sum of exponentials

\[ f(z) = \sum_{\alpha=1}^{n} A_{\alpha} \exp(-k_{\alpha}z). \]

[46] In the previous section this was determined using a 9-band parameterization [Paulson and Simpson, 1981]. Although the 9-band parameterization covered the full spectral range which includes the very rapid absorption at the near-IR wavelengths, the coefficients and exponents in equation (8) are invariant and were determined from laboratory experiments using fresh water conducted in the early 1900s. The ocean, however, contains salt and suspended matter. The coefficients and exponents in the 2-band parameterization can be modified according to the Jerlov water type classification [Jerlov, 1976], an obsolete index of ocean turbidity. It has been shown that variations in solar transmission are explained almost entirely by upper ocean chlorophyll concentration in the euphotic zone, cloud amount, and solar zenith angle [Ohlmann et al., 2000]. These factors are the basis of the Ohlmann and Siegel [2000] parameterization which is the only parameterization to claim to resolve solar transmission variations within the top few meters of the ocean. Global remotely sensed chlorophyll maps replace the crude use of Jerlov water types. It should, however, be mentioned that variations in chlorophyll concentration are of little importance for radiant heating within the upper meter because a significant amount of the total energy exists beyond the chlorophyll sensitive wave bands, as stated by Ohlmann et al. [2000]. In order to adopt the Ohlmann and Siegel approach chlorophyll concentration values are obtained from monthly mean SeaWiFS 9 km chlorophyll-a climatologies. This data set has only been available since September 1997 and hence could not be used in the studies at the mooring sites. Tests were carried out and the Ohlmann and Siegel parameterization together with SeaWiFS data was found to slightly improve RMS errors and reduce extremes when compared with the 9-band parameterization.

[47] The modeled diurnal temperatures can only be validated by comparing with individual satellite SST observations through the day. For this reason it is essential that the model starts from accurate initial temperatures, otherwise the model-observation differences will be characteristic of any initial offset rather than differences developing through the day. The GOTM initial profiles are obtained from the UKMO operational ocean prediction system.
FOAM [Bell et al., 2000], valid at 00:00 UTC each day, modified by OSTIA SSTs throughout the mixed layer to give a nighttime representation as close as possible to the expected conditions.

Figure 3. Maps of the Atlantic Ocean showing daily mean wind stress (τ) and diurnal warming of SST (Δθ₀,015m) for 1–7 January 2006.

[48] The work presented here is based in the Atlantic Ocean and therefore 00:00 UTC always represents a nighttime temperature (otherwise a local time correction would
be needed. Details of this procedure are provided by Pimentel [2007].

5. NWP-Based Predictions

5.1. Modeled Diurnal Cycles

The optimized modeling arrangement incorporating IW mixing, a dynamically calculated air-sea flux, and a SeaWiFS-based solar penetration, was implemented over the Atlantic Ocean (50°S to 50°N and 270°E to 359°E) on a 1° latitude and longitude grid. Modeled diurnal variability maps were produced for the first week of January 2006 and are shown in Figure 3. Also shown in Figure 3 for comparison are graphs of the daily mean wind stress.

The pattern of the modeled diurnal warming signals shows significant variability on a day to day basis. These changes closely follow the shifting wind stress patterns, with areas of low wind stress resulting in stronger diurnal warming. This particular period is during southern hemisphere summer and several places south of the equator reach temperatures close to 20°C. Areas of low wind stress coincide with very strong SWR.

The intermittent nature of the warming pattern is apparent. A particular area can experience very strong diurnal warming one day and then the next day experience negligible diurnal warming as weather systems come and go. For example in Figure 3 on the 2 January 2006 centered at (38°S, 340°E) there is a small pocket of strong diurnal variability surrounded by stronger wind stresses resulting in low diurnal warming. This pattern can be followed in the subsequent days as the weather system moves east and dissipates. In the wake of the strong winds are areas of calm resulting in moderate to strong diurnal warming signals.

5.2. Satellite Validation

To assess the accuracy of the modeled diurnal warming estimates, GHRSST L2P observations from SEVIRI, AMSR-E, and TMI are compared to hourly model output. The results presented in Table 4 show that overall (3rd from last row) the model-observation differences have a mean bias of 0.09°C, a standard deviation (STD) of 0.54°C, and an RMS (error) of 0.88°C. Little bias is seen for SEVIRI, and a slight positive bias, cooler observations than model, for AMSR-E and TMI. This could represent an inherent cool bias in AMSR-E and TMI measured SST compared with the OSTIA SST.

Table 4 also shows that, like the mean, the STD and RMS errors for SEVIRI are much smaller than the other observation types. This indicates a much smaller variable component to the SEVIRI mismatch errors. The overall

Table 5. Comparing OSTIA to GHRSST L2P Satellite Data for the Atlantic Ocean

<table>
<thead>
<tr>
<th>Matchup</th>
<th>Number</th>
<th>Mean</th>
<th>STD</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>OSTIA-SEVIRI</td>
<td>28,447</td>
<td>−0.14</td>
<td>0.31</td>
<td>0.36</td>
</tr>
<tr>
<td>Day: OSTIA-SEVIRI</td>
<td>7693</td>
<td>−0.14</td>
<td>0.27</td>
<td>0.33</td>
</tr>
<tr>
<td>Night: OSTIA-SEVIRI</td>
<td>6376</td>
<td>−0.12</td>
<td>0.32</td>
<td>0.36</td>
</tr>
<tr>
<td>OSTIA-AMSRE</td>
<td>27,364</td>
<td>−0.03</td>
<td>0.55</td>
<td>0.55</td>
</tr>
<tr>
<td>Day: OSTIA-AMSRE</td>
<td>6068</td>
<td>0.06</td>
<td>0.48</td>
<td>0.49</td>
</tr>
<tr>
<td>Night: OSTIA-AMSRE</td>
<td>5803</td>
<td>−0.03</td>
<td>0.60</td>
<td>0.60</td>
</tr>
<tr>
<td>OSTIA-TMI</td>
<td>23,750</td>
<td>−0.01</td>
<td>0.65</td>
<td>0.65</td>
</tr>
<tr>
<td>Day: OSTIA-TMI</td>
<td>6137</td>
<td>0.05</td>
<td>0.60</td>
<td>0.60</td>
</tr>
<tr>
<td>Night: OSTIA-TMI</td>
<td>5382</td>
<td>−0.20</td>
<td>0.72</td>
<td>0.78</td>
</tr>
<tr>
<td>Day: OSTIA-All</td>
<td>79,561</td>
<td>0.05</td>
<td>0.60</td>
<td>0.60</td>
</tr>
<tr>
<td>Night: OSTIA-All</td>
<td>19,898</td>
<td>0.02</td>
<td>0.48</td>
<td>0.48</td>
</tr>
<tr>
<td>Day: OSTIA-All</td>
<td>17,561</td>
<td>−0.11</td>
<td>0.57</td>
<td>0.59</td>
</tr>
</tbody>
</table>

*Area of comparison was 50°S to 50°N and 270°E to 359°E during 1–7 January 2006. Results show number of matchups, mean, standard deviation, and root mean square difference; values in °C. OSTIA was used as the initial condition for the Atlantic model runs. OSTIA, Operational Sea Surface Temperature and Ice Analysis.

Table 6. Comparison of GOTM and OSTIA Against GHRSST L2P Satellite Data for the Atlantic Ocean

<table>
<thead>
<tr>
<th>Matchup</th>
<th>Number</th>
<th>Mean</th>
<th>STD</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>GOTM-SEVIRI</td>
<td>3115</td>
<td>0.20</td>
<td>0.55</td>
<td>0.59</td>
</tr>
<tr>
<td>GOTM-AMSRE</td>
<td>3149</td>
<td>0.33</td>
<td>0.91</td>
<td>0.97</td>
</tr>
<tr>
<td>GOTM-SEVIRI</td>
<td>9073</td>
<td>0.34</td>
<td>0.81</td>
<td>0.88</td>
</tr>
<tr>
<td>Day: GOTM-SEVIRI</td>
<td>3115</td>
<td>0.29</td>
<td>0.52</td>
<td>0.59</td>
</tr>
<tr>
<td>Night: GOTM-AMSRE</td>
<td>2809</td>
<td>−0.16</td>
<td>0.76</td>
<td>0.77</td>
</tr>
<tr>
<td>Night: GOTM-TMI</td>
<td>3149</td>
<td>−0.49</td>
<td>0.88</td>
<td>1.01</td>
</tr>
<tr>
<td>Day: GOTM-All</td>
<td>9073</td>
<td>−0.32</td>
<td>0.74</td>
<td>0.81</td>
</tr>
</tbody>
</table>

*Area of comparison was 50°S to 50°N and 270°E to 359°E during 1–7 January 2006 when the modeled diurnal warming magnitude was greater than 1°C. Results show number of matchups, mean, standard deviation, and root mean square difference; values in °C.

The area of the most significant and frequent diurnal warming is in the latitude band 40° to 20°S. The susceptibility of the latitude band 40° to 20°S to intense diurnal warming during January has been noted before [see Stuart-Menteth et al., 2003, Figures 1 and 4] although

Table 4. Comparing Model Output, \( \theta_{0.015m} \) Against GHRSST L2P Satellite Data (SEVIRI, AMSRE, and TMI) for the Atlantic Ocean

<table>
<thead>
<tr>
<th>Matchup</th>
<th>Number</th>
<th>Mean</th>
<th>SD</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>GOTM-SEVIRI</td>
<td>28,075</td>
<td>0.01</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>Day: GOTM-SEVIRI</td>
<td>7610</td>
<td>−0.02</td>
<td>0.32</td>
<td>0.33</td>
</tr>
<tr>
<td>Night: GOTM-SEVIRI</td>
<td>6264</td>
<td>0.01</td>
<td>0.36</td>
<td>0.36</td>
</tr>
<tr>
<td>GOTM-AMSRE</td>
<td>26,884</td>
<td>0.13</td>
<td>0.59</td>
<td>0.62</td>
</tr>
<tr>
<td>Day: GOTM-AMSRE</td>
<td>6009</td>
<td>0.14</td>
<td>0.51</td>
<td>0.55</td>
</tr>
<tr>
<td>Night: GOTM-AMSRE</td>
<td>5660</td>
<td>0.19</td>
<td>0.55</td>
<td>0.61</td>
</tr>
<tr>
<td>GOTM-TMI</td>
<td>22,269</td>
<td>0.16</td>
<td>0.64</td>
<td>0.68</td>
</tr>
<tr>
<td>Day: GOTM-TMI</td>
<td>6103</td>
<td>0.15</td>
<td>0.64</td>
<td>0.67</td>
</tr>
<tr>
<td>Night: GOTM-TMI</td>
<td>4647</td>
<td>0.07</td>
<td>0.66</td>
<td>0.67</td>
</tr>
<tr>
<td>GOTM-All</td>
<td>77,228</td>
<td>0.09</td>
<td>0.54</td>
<td>0.56</td>
</tr>
<tr>
<td>Day: GOTM-All</td>
<td>19,722</td>
<td>0.08</td>
<td>0.51</td>
<td>0.52</td>
</tr>
<tr>
<td>Night: GOTM-All</td>
<td>16,571</td>
<td>0.09</td>
<td>0.54</td>
<td>0.55</td>
</tr>
</tbody>
</table>

*Area of comparison was 50°S to 50°N and 270°E to 359°E during 1–7 January 2006. Results show number of matchups, mean, standard deviation, and root mean square difference; values in °C. OSTIA was used as the initial condition for the Atlantic model runs. OSTIA, Operational Sea Surface Temperature and Ice Analysis.
model-observation differences are shown to be similar for daytime and nighttime matchups and the RMS and STD vary by only 0.03°C. This does suggest that this diurnal model is able to give as good a match to the satellite measurements during the day as during the night. Daytime here is defined as occurring between the restricted hours 10–16 (local time), and nighttime hours between 22–04 (local time). The model is initialized to OSTIA between the stated nighttime hours.

The satellite observations are also compared directly to the OSTIA combined SST product. Technically OSTIA applies a sensor specific bias correction before it ingests observations [Stark et al., 2007], which is designed to take account of atmospheric phenomena, such as aerosols and dust. In Table 5 the satellite observations all have a negative bias (with only two exceptions), showing that the satellite observations are slightly warmer than OSTIA on average. This should be expected as OSTIA represents an estimate of the foundation SST, i.e., the ocean temperature at a depth which is free of diurnal variations, whereas the matchups here compare all observations, including those that contain a diurnal signal. Although the fact that larger negative biases are found during the nighttime than the daytime for the AMSRE and TMI cases suggests that other factors are also important, notably that OSTIA uses other additional observations and these will have an influence on the biases. When compared to the GOTM-observation comparisons in Table 4 we see that the negative biases are no longer widespread, i.e., GOTM is warmer than OSTIA. The GOTM model is shown to improve on the OSTIA when comparing with SEVIRI data alone. The model is reducing the mean error by removing a bias due to diurnal warming (although this bias may be slightly overestimated by the model). This in turn is decreasing the RMS error, but it is slightly increasing the scatter as seen in the STD, which may be due to the coarse resolution meteorological forcing. The advantage of modeling the diurnal cycle over persistence then would be that more observations (i.e., including those taken during low wind speed days) could be included in the analysis with little or no increase in variability. It appears that SEVIRI observations are much more sensitive in picking up diurnal warming than either AMSRE and TMI, thus the much closer correspondence of SEVIRI in both mean and RMS to the diurnal model. This could be because the SEVIRI observations have a finer spatial resolution, 0.1°, compared with AMSRE or TMI, 0.25°, as well as other potential factors such as a lower base sensor accuracy and the timing and temporal resolution of the measurements. The model also performs better than OSTIA during the nighttime only comparisons, demonstrating the success of modeling the cooling phase of the diurnal cycle. However the model has a slightly larger mean difference to OSTIA during the daytime only comparisons, this is because of the cancellation of OSTIA warm errors relative to AMSRE and TMI, and cold errors relative to SEVIRI. SEVIRI is marginally warmer than the model for the daytime only comparison, supporting the case that the SEVIRI data product records a stronger diurnal cycle than AMSRE or TMI.

Further work is needed to understand and distinguish between various sources of error in the observations and the model so that maximal information content can be acquired from the satellite measurements.

6. Discussion and Conclusions

Progress has been made in understanding and advancing the ability to numerically model diurnal variability of the near-surface ocean. A widely used one-dimensional mixed layer model, GOTM, is optimized for the purpose of diurnal cycle modeling using state-of-the-art parameterizations for air-sea flux and ocean radiant heating. It is tuned against high-frequency observations from buoy data at three different sites representing a range of ocean and meteorological conditions. It is demonstrated that diurnal warming estimates can be reasonably reproduced at these buoy sites using only
6 hourly data, suggesting that 6 hourly NWP data could be used in determining diurnal cycles over wide areas.

The study of Bernie et al. [2005] found that to capture 90% of the diurnal variability at the COARE site a 3 hour or better temporal resolution was required. While this result seems generally consistent with our findings in Table 3 the outlook is much more optimistic for the other sites studied here, where the 6 hour temporal resolution easily captures 90% of the diurnal variability. Major differences between the methods used in this work and that of Bernie et al. [2005] should be noted. These include the use of a different definition of diurnal variability, an alternative air-sea and radiative flux set-up, as well as differing mixing and solar penetration parameterizations.

A grid of 1-D GOTM models were run over a wide area of the Atlantic ocean forced by NWP data, and the results used to produce daily spatial maps of the diurnal warming signal in SST. This mesh of models forced with NWP data is shown to be a very useful method, viz, in identifying areas of diurnal warming and quantifying diurnal signals in observational SST data. The magnitude and spatial distribution of diurnal SST signals are shown to have variability on a day to day timescale. The resulting diurnal warming maps are of interest in building a climatology of the magnitude and extent of diurnal cycles in SSTs, and as such further our understanding of ocean-atmosphere interaction.

For a weeklong period over the Atlantic Ocean a comparison between a combination of IR and MW satellite-derived SST observations and the modeled diurnal cycles resulted in a mean bias of +0.09°C and a STD of 0.54°C.

Maps, such as Figure 3 based on NWP model output, can provide useful information in several ways. They can be produced globally on a daily basis, as they do not rely on particular overpass paths and times or the availability of day/night overlaps in satellite observations. Second, many climate and ocean modelers are reluctant to include a diurnal cycle in their models because of the increased cost of extra vertical resolution, therefore the satellite community need to provide observations for assimilation that are not contaminated by a diurnal signal. These maps can be used either to flag observations likely to have diurnal warming, or better still, model output could be used to remove the diurnal bias. Third, this model approach could potentially be useful for improving accuracy in observational foundation SST products, again by removing the diurnal signal and reducing bias.

The different nature of SST observations and their model counterparts, is highlighted, as well as the lack of GCM model representations of diurnal variability. Different approaches are possible to the assimilation of SST into operational oceanography models. An observation operator could be used to transform model variables of surface temperatures at depth and foundation SSTs into the skin and subskin temperatures of satellite measured SSTs. Alternatively for producing foundation SST observational products SST observations ‘corrupted’ by a diurnal signal need to be converted to the base temperature from which the diurnal thermocline has developed. A 1-D model equipped with fine near-surface resolution and diurnal forcing, as developed here, could be used as an effective dynamic observation operator for the uses outlined above.

These developments in diurnal SST modeling are built on in a separate paper [Pimentel et al., 2008] that describes a novel data assimilation method utilizing diurnal signal information in satellite-derived SST observations together with the modeled diurnal SST to further reduce uncertainties in diurnal warming estimates.

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