REDUCED HORIZONTAL SEA SURFACE TEMPERATURE GRADIENTS UNDER CONDITIONS OF CLEAR SKY AND WEAK WINDS

KRISTINA B. KATSAROS[1,*], ALEXANDER V. SOLOVIEV[2], ROBERT E. WEISBERG[3] and MARK E. LUTHER[3]

[1] *PO Box 772, Freeland, Washington 98249, U.S.A.;* [2] *Oceanographic Center, Nova Southeastern University, 8000 North Ocean Drive, Dania Beach, FL 33004-3078, U.S.A.;* [3] *College of Marine Science, University of South Florida, 140 Seventh Ave S, St. Petersburg, FL 33701, U.S.A.*

(Received in final form 28 July 2004)

Abstract. Consideration of the dependence of various components of the sea-surface heat and momentum fluxes on sea surface temperature (SST) leads to an explanation for the observed reduction in the horizontal temperature gradients in the uppermost layer of the ocean (a few to 10 m in depth). Horizontal temperature gradients within the mixed layer can be masked by a near-surface layer of warm water. This camouflage of horizontal temperature gradients has importance for the remote sensing of SST used by the fishing industry, for the estimation of acoustic transmission, and for the forecasting of hurricane development, among many uses of SST data. Diurnal warming conditions in the Straits of Florida are examined by a simulation calculation and by analysis of observations obtained on moorings deployed on the south-east Florida shelf. When there is net heating (i.e., the solar input is stronger than the combined latent, sensible and longwave radiative heat losses) the originally warmer water experiences less heating than the colder water, leading to a weakening of the horizontal SST gradients as seen by surface buoys or satellites. The warmer water also experiences more mixing and therefore less increase in temperature. The strongest effect of the diurnal heating on wind stress occurs when the SST starts out less than the air temperature and the atmosphere is stably stratified. Diurnal warming can then rapidly increase the SST above the air temperature because of reduced wind stress and reduced upper-ocean mixing. After that the wind stress increases as convectively driven turbulence contributes to the atmospheric exchange.

Keywords: Air-sea fluxes, Diurnal warming, Oceanic horizontal temperature gradients, Remote sensing, Sea surface temperature.

1. Introduction

When employing satellite derived sea surface temperatures (SSTs), one must often merge information obtained from other satellites or *in situ* data for correct interpretation. In the case of weak surface wind speeds, less than approximately 5 m s^{-1}, and a clear sky with strong insolation, two effects can occur that may lead to misinterpretations of remotely sensed SST:

* E-mail: katsaros@whidbey.com

Boundary-Layer Meteorology **00:** 1–11, 2004.

(a) A shallow layer of warm water near the sea surface can develop, which makes the SST not representative of the bulk of the mixed layer of the ocean (e.g., Katsaros et al., 1983; Stramma et al., 1986; Soloviev and Lukas, 1997; Gentemann et al., 2003; Stuart-Menteth et al., 2003).

(b) In addition, if horizontal temperature gradients exist in the surface water, the simultaneous cooling from the sea surface by evaporation, sensible heat loss, and longwave radiation would be larger from the warmer water than from the cooler side of the gradient associated with features such as fronts or eddies, leading to greater net heating on the cool side. This results in a reduction in the horizontal temperature gradients and erroneous inferences about the mixed layer (Katsaros and Soloviev, 2004), which may have consequences for fishing and other activities.

The analysis presented herein includes an additional regulating feedback via a dependence of the wind stress on atmospheric stability. We illustrate the effect of a reduction in the SST horizontal gradients with model calculations and with observations from a mooring array deployed on the shelf off southeast Florida. This mooring array is primarily intended for monitoring the coastal circulation and environmental conditions (Soloviev et al., 2003a, b).

For this study we assume that the air is modified through a deep layer and is relatively well mixed as it flows across the SST gradient (therefore the difference in the overlying air is not great from the warm to the cold SST). Other situations, even such where a mesoscale circulation (analogous to a sea breeze) develops between warm and cold water areas (Mahrt et al., 2004), can occur. We are not focusing on such cases herein, and are, in fact, discussing only a fraction of possible scenarios.

2. Background

The equations for heat, salinity and momentum balance for the upper layers of the ocean are defined in a companion paper (Katsaros and Soloviev, 2004). We will not repeat the development here, but only summarize the procedure. The time dependent equations for the vertical diffusion of heat, salt and the two components of horizontal momentum are solved iteratively, with the turbulent exchange coefficients of these properties being dependent on the gradient Richardson number, which depends on all three variables sought. The surface boundary conditions are the net heat flux due to the three loss terms: latent heat flux, sensible heat flux and net longwave radiative heat loss to the atmosphere and space; the salt flux into the sea as a consequence of the evaporation; and the two components of the wind stress on the sea surface due to atmospheric forcing. The surface fluxes are determined from the Tropical Ocean Global Atmosphere–Coupled Ocean Atmospheric Response

Journal : BOUN SPS Article No. : DO00002421 Dispatch : 5-10-2004 Pages : 11
PIPS No. : DO00002421 ☐ LE ☐ TYPESET
MS Code : BOUN2373-BUS ☑ CP ☑ DISK

Experiment bulk formulation (TOGA-COARE 2.6 algorithm, Bradley et al., 2000). Solar radiation is treated as a volume source of heat for the ocean. We assume clear skies and that the near surface atmosphere has the same air temperature, water vapour content and mean wind speed over the whole region. The grid used has 40 evenly spaced grid points for the top 10 m of the sea, and a small constant vertical velocity gradient (2×10^{-4} s^{-1}) is assumed to avoid extremes in the Richardson number in the first time step. (Katsaros and Soloviev, 2004).

Aspects of this calculation for low-latitude, warm water cases are presented in Figures 1 and 2. Note that there is almost three times as much heat input from the sun as the heat loss due to the turbulence and longwave radiation terms over a 24-h period (Figures 1a and c). This allows us to draw general conclusions even if we do not simulate the fluxes exactly, and even if

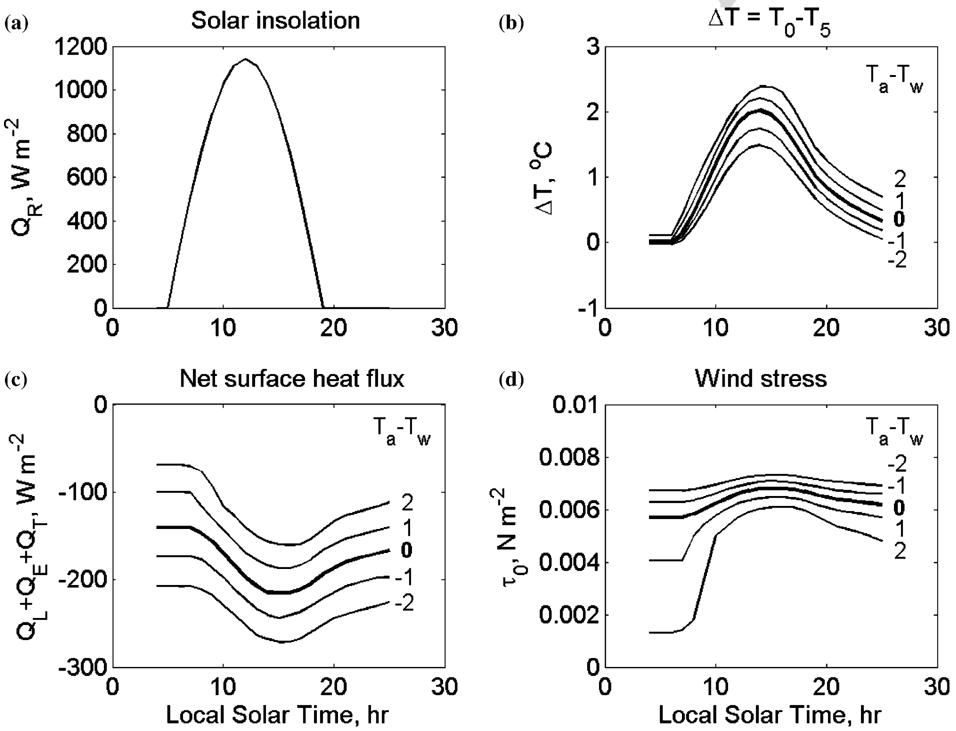

Figure 1. Modelling the effect on SST due to atmospheric regulation. Modeling parameters are representative of the calculated Straits of Florida cases, wind speed 2 m s^{-1}, specific humidity 16 g kg^{-1}, and air temperature 28 °C. (a) March of the insolation rate, (b) model calculation of the temperature difference between the sea surface (T_0) and 5 m depth (T_5) over 22 h of time, (c) the associated values of the net heat loss term and (d) wind stress change. The symbols in (c) represent the following: Q_T, sensible heat loss, Q_E, longwave and Q_L, latent heat loss. The curves in the plot are labeled with the difference between the initial water temperature, T_w, and the fixed air temperature, T_a.

Journal : BOUN SPS Article No. : DO00002421 Dispatch : 5-10-2004 Pages : 11
PIPS No. : DO00002421 ☐ LE ☐ TYPESET
MS Code : BOUN2373-BUS ☑ CP ☑ DISK

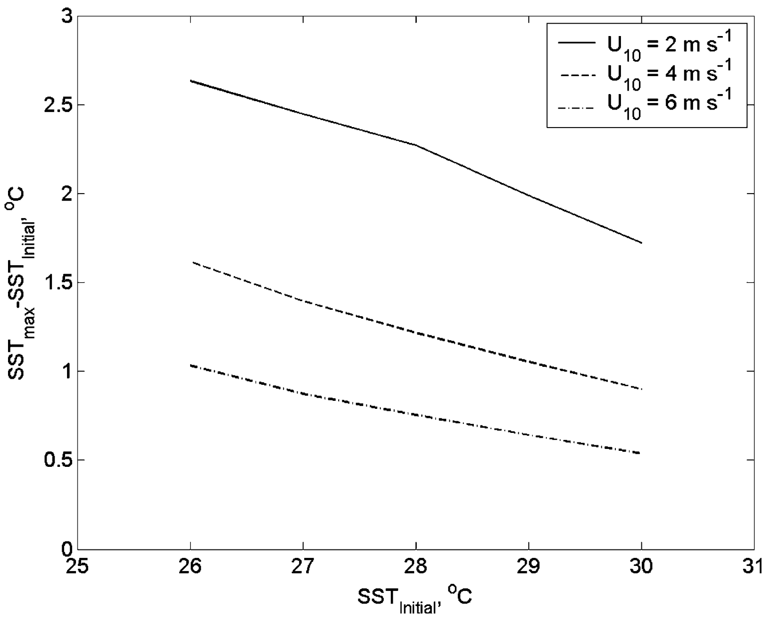

Figure 2. Dependence of the change in SST on the initial water temperature. Modeling parameters are representative of the Gulf of Mexico and the Florida Straits cases, wind speed at a 10-m height from 2 to 6 m s^{-1}, specific humidity 16 g kg^{-1}, and air temperature 28 °C.

the atmospheric temperature and humidity would be somewhat different over the warmer and colder areas during the day. However, even with weak winds, the air flows rapidly across these temperature variations in the water and the atmosphere tends to be well mixed through a rather deep layer if there is unstable stratification.

Figure 1b shows that the diurnal warming peaks shortly after maximum insolation and before the heat-loss-driven convective motions in the ocean generate a new near-surface mixed layer. Figure 1d demonstrates the dependence of the wind stress on the march of the heat fluxes. Initially, the wind stress on the sea surface is reduced for the two cases when the water temperature (T_w) is below the air temperature (T_a) ($T_a - T_w = 2$ °C), hence stable stratification in the atmospheric surface layer. Lower wind stress leads to a higher diurnal warming rate because of reduced mixing in the near-surface layer of the ocean. The SST reaches the value of the air temperature around 1000 local standard time (LST) and the surface wind stress increases due to increased mixing in the atmospheric boundary layer. The air-sea exchange coefficients for momentum, heat and water vapour all increase rapidly at this time.

Our example in Figure 1 gives just one possible scenario, but a typical one for the Straits of Florida region and a wind speed of 2 m s $^{-1}$. Figure 2

Journal : BOUN SPS Article No. : DO00002421 Dispatch : 5-10-2004 Pages : 11
PIPS No. : DO00002421 ☐ LE ☐ TYPESET
MS Code : BOUN2373-BUS ☑ CP ☑ DISK

illustrates the consequences for the SST for the same range in initial water temperatures and the same atmospheric fixed conditions as seen in Figure 1. It also includes plots for the same initial water temperatures and atmospheric conditions, but with greater wind speeds. Even at a mean wind speed of 6 m s^{-1} at 10-m height substantial warming occurs at the surface during maximum solar radiation. Many other combinations of the input variables will occur in a given month and particularly over the course of a year, but these calculated values are representative of the diurnal heating process, which leads to a weakening of horizontal temperature gradients.

Figure 2 also illustrates what happens to the temperature difference, ΔT, between the initial temperature of the well-mixed upper ocean and the topmost grid point of our calculation at 0.25 m, after the diurnal heating cycle under low wind speed conditions. The ΔT is largest in the initially colder water (illustrated by the negative slope of the curve) by an amount that depends on the mean wind speed, all other factors remaining equal. This suggests that, if a front exists in the water, the surface-temperature gradient is reduced after such a day, masking the front from a remote sensing perspective.

3. Experimental Evidence

3.1. Description of the field site

As a part of the South Florida Ocean Measurement Center (SFOMC), NOVA Southeastern University (NSU) and the University of South Florida (USF) deployed a three-dimensional mooring array with acoustic Doppler current profilers (ADCPs) and a combination of inductively coupled and/or self-recording temperature/salinity and pressure sensors. The NSU/USF observations were coordinated with the University of Miami Ocean Surface Current Radar (OSCR) deployments. The bottom instruments work in a self-recording mode, while the surface moorings transmit real time data via spread-spectrum radio. The surface moorings are monitored through the ARGOS satellite network. Figure 3 shows the mechanical construction of the C-buoy and an overview of the location of the field measurements on the south-east Florida shelf.

Measurements collected at the sites relevant to our study are from MicroCat SBE-37SM instruments measuring, every 30 min, sea temperature and conductivity at 0.5, 5, 10, and 15 m on the C-buoy and meteorological variables collected by a coastal climate weather package on the same buoy. (The precision of the temperature sensor on SBE-37SM is better than 0.002 °C). The meteorological variables include, wind speed and direction, surface pressure, air and near-surface water temperature, relative humidity, solar radiation, longwave radiation and the cumulative rainfall (measured every 5 min).

Journal : BOUN SPS Article No. : DO00002421 Dispatch : 5-10-2004 Pages : 11
PIPS No. : DO00002421 ☐ LE ☐ TYPESET
MS Code : BOUN2373-BUS ☑ CP ☑ DISK

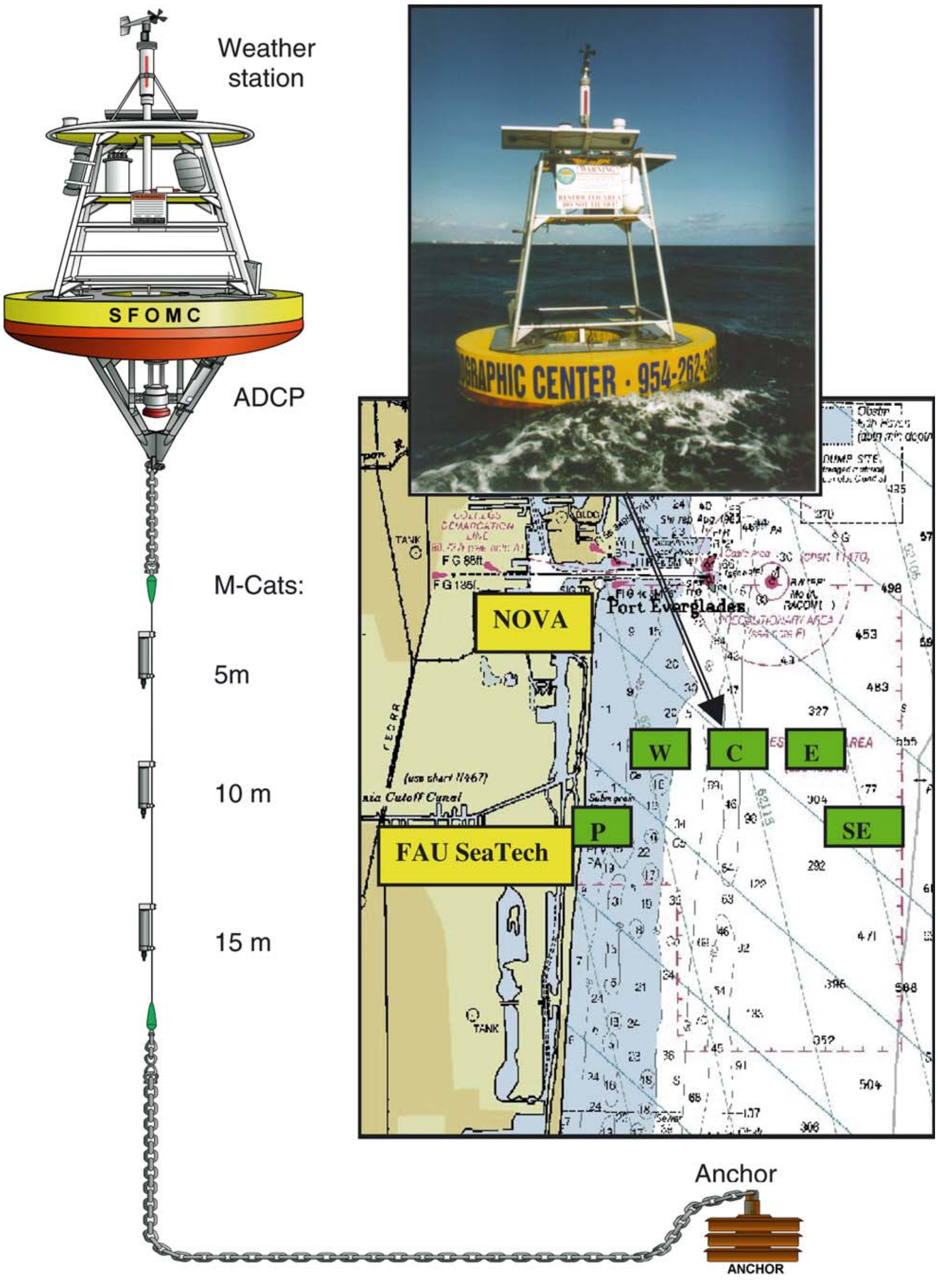

Figure 3. Design of surface mooring C and overview of the measurement site during the Year 2000 experiment. W is the west (bottom) mooring (at 11 m isobath), C is the central mooring (at the 20 m isobath), and E is the east mooring (at 50 m isobath). SE is the University of Miami acoustic mooring and P is the Dania Pier meteorological station. Observations from mooring C are used herein.

Journal : BOUN SPS Article No. : DO00002421 Dispatch : 5-10-2004 Pages : 11
PIPS No. : DO00002421 ☐ LE ☐ TYPESET
MS Code : BOUN2373-BUS ☑ CP ☑ DISK

3.2. Data used

Figure 4 gives a time series of the upper ocean temperature evolution at two depths and the nearby meteorological measurements for June 2–27, 2000,

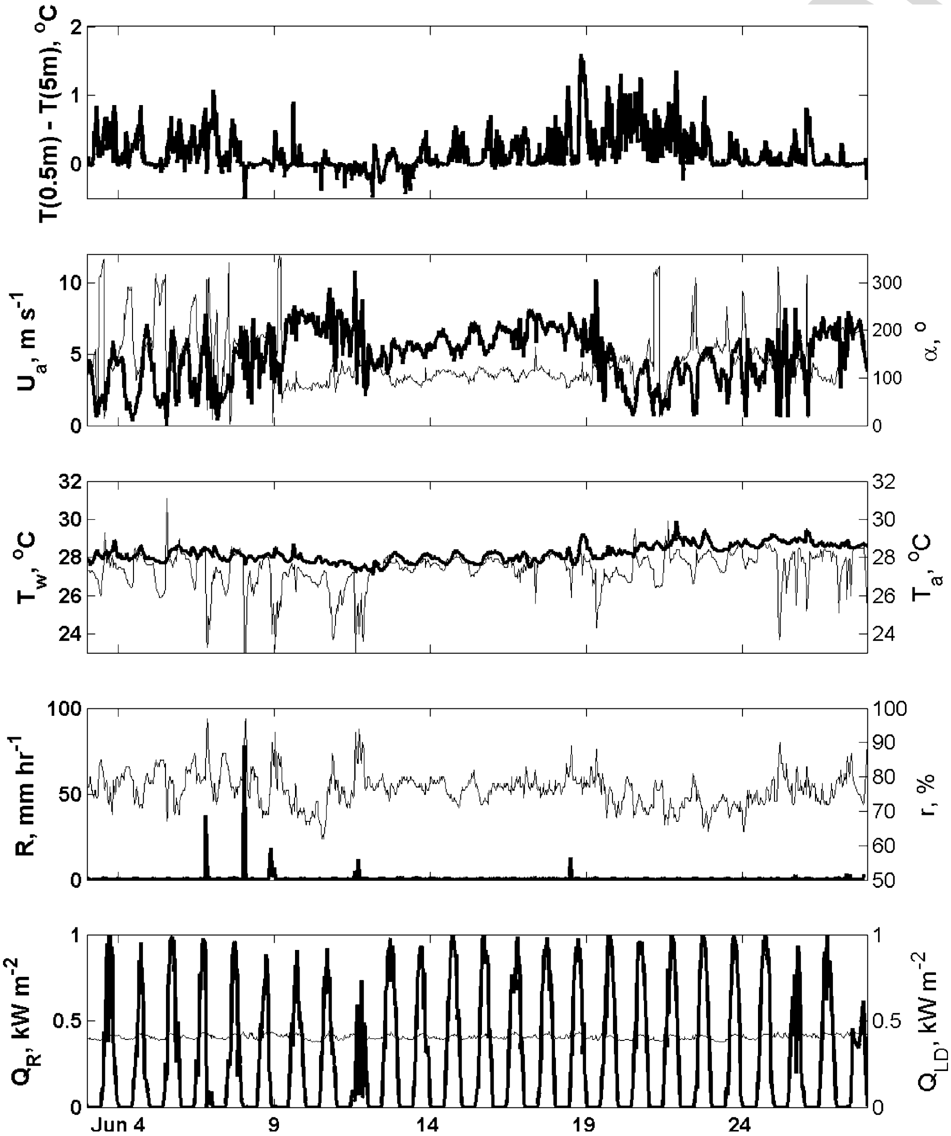

Figure 4. Hydro-meteorological conditions during the June 2000 experiment on the shelf of south-east Florida: (a) temperature difference between 0.5 and 5 m depth; (b) wind speed U_a (bold line) and wind direction α; (c) water temperature T_w (bold line) and air temperature T_a; (d) rain rate R (bold line) and relative humidity r; (e) shortwave solar radiation Q_R (bold line) and downwelling longwave radiation Q_{LD}.

Journal : BOUN SPS Article No. : DO00002421 Dispatch : 5-10-2004 Pages : 11
PIPS No. : DO00002421 ☐ LE ☐ TYPESET
MS Code : BOUN2373-BUS ☑ CP ☑ DISK

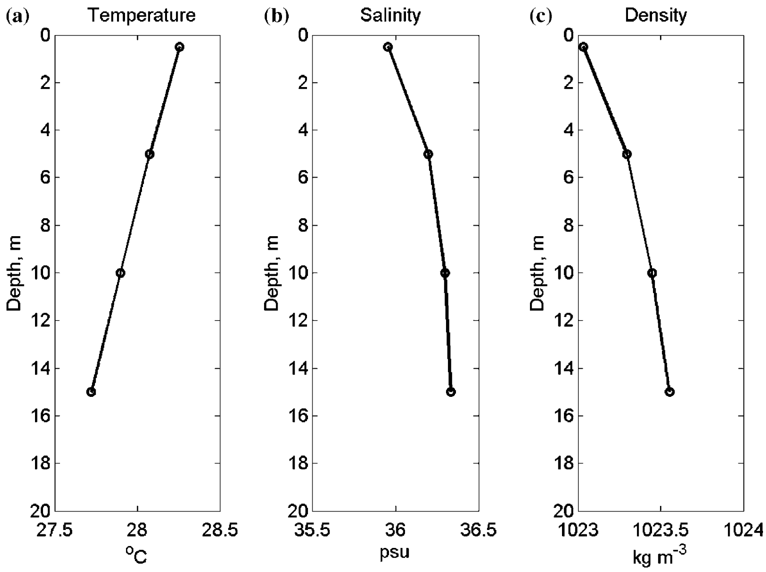

Figure 5. Vertical temperature, salinity, and density profiles at the C-mooring location averaged over a 25-day period.

sampled every 30 min. Figure 5 shows the vertical temperature, salinity and density profiles at the C-mooring location averaged over the 25 days, demonstrating the thermal stratification that was present. We have selected this period for analysis because of the prolonged interval of low wind speeds in the middle of the month.

3.3. Result from Florida Straits

Figure 6a shows a plot of ΔT in the water calculated as the difference between the 0.5 and 5 m measurements. The data are from the same period as in Figure 4. They represent data for all 25 days, night time as well as daytime, using the following selection criteria:

(1) Salinity difference in the upper 5 m less than 0.5 psu (practical salinity units).

(2) The wind speed less than 4 m s^{-1}.

The first criterion was chosen to eliminate cases with strong precipitation effects, while the second criterion was applied to isolate conditions of low wind speed.

After applying these selection criteria, a total of 311 points remained, see Figure 6a, where we see the tendency for the points to follow a declining slope

Journal : BOUN SPS Article No. : DO00002421 Dispatch : 5-10-2004 Pages : 11
PIPS No. : DO00002421 ☐ LE ☐ TYPESET
MS Code : BOUN2373-BUS ☑ CP ☑ DISK

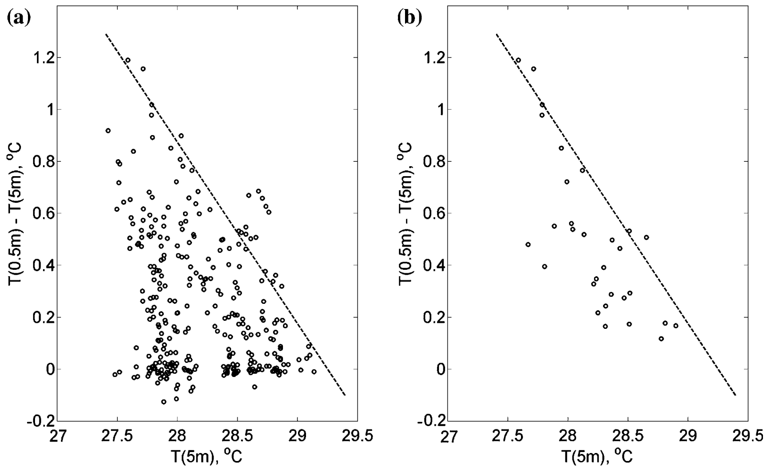

Figure 6. (a) Dependence of the temperature difference, ΔT, between 0.5 and 5 m on the temperature at 5 m depth for 25 days in June 2000 under conditions of no rain and wind speed < 4 m s^{-1}. (b) Same as in subplot (a) but only from 1100 through 1700 LST, and for $T_w - T_a < 1.5$ °C.

as in the simulation of Section 2 (Figure 2) with the largest ΔT occurring in the colder water. In this case there are many points in the triangle below the line of the maximum temperature difference. These points represent times before and after maximum ΔT. There are also many points on the line at zero values of ΔT, which corresponds to periods with strong mixing due to convective cooling when no diurnal layer of warm water is formed.

Diurnal warming could penetrate down to 5 m, so ΔT may not necessarily represent the full diurnal warming. The exponential decay of solar radiation in sea water allows some radiation to be absorbed below the 5 m depth and some heat can be transported to this depth by turbulence. The overall effect of diurnal warming on the water temperature below 5-m depth is relatively small. In order to make our model and measurement results comparable, the model results shown in Figure 2 are given for the same depth range as given by the data in Figure 6. The temperature difference between 0.5 and 5 m could occasionally be affected by sub-mesoscale eddies and/or baroclinic tides, which are strong in this area (Soloviev et al., 2003a, b).

In order to select the cases with a developed diurnal thermocline, an additional, third criterion has been applied for data selection:

(3) Daytime hours from 1100 through 1700 LST and conditions of the water-air temperature difference, $T_w - T_a < 1.5$ °C, have been chosen.

After applying selection criteria 1, 2 and 3, a total of 30 points remained (Figure 6b). The remaining points are less scattered than those in Figure 6a, since the cases of strong convective cooling (nighttime or large water-air temperature differences) have been filtered out. The water column was

Journal : BOUN SPS Article No. : DO00002421 Dispatch : 5-10-2004 Pages : 11
PIPS No. : DO00002421 ☐ LE ☐ TYPESET
MS Code : BOUN2373-BUS ☑ CP ☑ DISK

stratified during this observational period as seen in Figure 5. As a result, the bottom and surface boundary layers were not overlapping. This ensured that the diurnal cycle of solar radiation, rather than barotropic tidal motions, was the main cause of the observed variability of SST.

4. Discussion

The calculation of the exact amount of increase in SST over a 24-h period, and the associated reduction in SST gradients in any particular situation, must be performed with the appropriate upper-ocean mixing, the complete stratification effects and variations in the atmospheric fluxes, for air flowing from warm to cold, cold to warm water, or parallel to the SST gradients. Any advection in the water should also be accounted for, although it is typically not very large over a 1-day period. Our case is not the most extreme, since Gentemann et al. (2003) and Stuart-Menteth et al. (2003) in extensive analyses of satellite data reported even larger day-to-night SST differences.

This example is only indicative of the situations that one would encounter in summer-time at low latitudes, whenever the wind speed is relatively weak and the diurnal heat fluxes result in net heating. Our most important result and that of Katsaros and Soloviev (2004) is that the diurnal heating is not uniform, but will heat the relatively cold water more than the nearby warmer water, thereby masking existing temperature gradients. This may have a particular relevance to the fishing industry in coastal regions. Katsaros and Soloviev (2004) explained the effect of atmospheric regulation by the dependence of air-sea fluxes on the air-sea temperature difference. In our study we have shown that the dependence of the wind stress on the air-sea temperature difference also contributes to the atmospheric regulation of SST. The wind stress feedback is important mainly when the SST is originally below the air temperature, and increases during diurnal warming to a temperature above the air temperature.

Acknowledgments

We express our appreciation for the legacy that Joost Businger has left in air-sea interaction research. K. Katsaros acknowledges support by the National Oceanic and Atmospheric Administration, while she was at the Atlantic Oceanographic and Meteorological Laboratory in Miami at the beginning of this work and assistance by Ms. Gail Derr. The data on the Florida shelf were collected as a part of the NOVA Southeastern University and University of South Florida cooperative agreement under

ONR Grant N00014-98-1-0861 (via a subcontract to Florida Atlantic University) and ONR Grant N00014-02-1-0950.

References

Bradley, E. F., Fairall, C. W., Hare, J. E., and Grachev, A. A.: 2000. 'An Old and Improved Bulk Algorithm for Air-Sea Fluxes', in preprint, *14th Symposium on Boundary Layer and Turbulence, Aspen, CO, August 7–11, 2000*, American Meteorological Society, 45 Beacon St., Boston, MA, pp. 294–296.

Gentemann, C., Donlon, C. J., Stuart-Menteth, A., and Wentz, F. J.: 2003, 'Diurnal Signals in Satellite Sea Surface Temperature Measurements', *Geophys. Res. Lett.* **30**(3), 1140–1143.

Katsaros, K. B., Fiuza, A., Sousa, F., and Amann, V.: 1983, 'Sea surface temperature patterns and air-sea fluxes in the German Bight during MARSEN 1979, Phase I', *J. Geophys. Res.* **88**, 9871–9882.

Katsaros, K. B. and Soloviev, A. V.: 2004, 'Vanishing Horizontal Sea Surface Temperature Gradients at Low Wind Speeds', *Boundary-Layer Meteorol.* **112**(2), 381–396.

Mahrt, L., Vickers, D., and Moore, E.: 2004, 'Flow Adjustments across Sea-Surface Temperature Changes', *Boundary-Layer Meteorol.* **111**(3), 553–564.

Soloviev, A. V. and Lukas, R.: 1997, 'Large Diurnal Warming Events in the Near-surface Layer of the Western Equatorial Pacific Warm Pool', *Deep-Sea Res.* **44**, 1055–1076.

Soloviev, A., Walker, R., Weisberg, R., and Luther, M.: 2003a, 'Coastal Observatory Investigates Energetic Current Oscillations on the Southeast Florida Shelf', *EOS, Transactions, AGU* **84**(42), 441–450.

Soloviev, A. V., Luther, M. E., and Weisberg, R. H.: 2003b, 'Energetic baroclinic super-tidal oscillations on the shelf off southeast Florida', *Geophys. Res. Let.* **30**(9), 1463, doi: 10.1029/2002GL016603.

Stramma, L., Cornillon, P., Weller, R. W., Price, J. F., and Briscoe, M. G.: 1986, 'Large Diurnal Sea Surface Temperature Variability: Satellite and In-Situ Measurements', *J. Phys. Oceanog.* **16**, 827–837.

Stuart-Menteth, A. C., Robinson, I. S., and Challenor, P. G.: 2003, 'A global Study of Diurnal Warming using satellite-derived Sea Surface Temperature', *J. Geophys. Res.* **108** (C5), 3155, doi: 10.1029/2002JC001 534.

Journal : **BOUN** SPS Article No. : **DO00002421** Dispatch : **5-10-2004** Pages : **11**
PIPS No. : **DO00002421** ☐ LE ☐ TYPESET
MS Code : **BOUN2373-BUS** ☑ CP ☑ DISK