Subsurface Expressions of Sea Surface Temperature Variability under Low Winds

J. Tom Farrar and Robert A. Weller
Woods Hole Oceanographic Institution

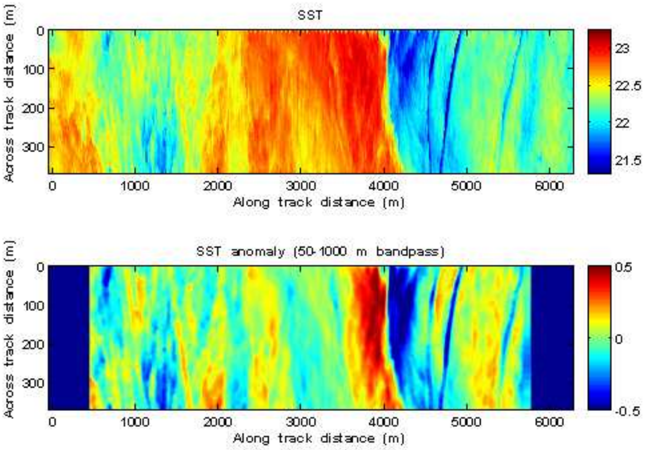
Chris Zappa
Lamont-Doherty Earth Observatory of Columbia University

Andrew T. Jessup
Applied Physics Laboratory, University of Washington

June 15, 2004

1 Introduction

The sea surface temperature field is of fundamental importance to air-sea heat transfer, atmospheric boundary layer stability, and atmospheric dynamics. In aerial surveys conducted during the Tropical Ocean–Global Atmosphere (TOGA) Coupled Ocean–Atmosphere Response Experiment (COARE) and the low wind component of the Coupled Boundary Layer Air-Sea Transfer (CBLAST-Low) oceanographic field programs, sea surface temperature (SST) variability at relatively short spatial scales (10's of meters to kilometers) has been observed to increase dramatically under low wind conditions. Radiometric observations of sea surface temperature taken from aircraft in low-wind conditions during TOGA-COARE reveal spatially organized O(0.5°C) SST perturbations at scales of 1-100 km (Hagan et al.; 1998, Walsh et al., 1998). These SST patterns were observed to propagate at speeds of about 1 m/s, much faster than the surface current (Walsh et al., 1998). This small scale SST variability has been shown to have significant effects on surface heat fluxes (Hagan et al., 1998). Hagan et al. found some evidence that organized bands of clouds can imprint a signal on SST by causing spatial variations in solar heating (1998). In contrast, Walsh et al. suggested that the propagating SST signals are associated with oceanic 2nd mode internal gravity waves (1998). The relative importance of these and other phenomena could be explored by examining the subsurface expression of this SST variability. However, an adequate description of the subsurface expression of these surface signals is lacking due to the lack of coincident radiometric SST measurements and adequately resolved subsurface measurements.



..

Figure 1: Upper panel: IR image of sea surface temperature (°C) recorded from an aircraft flight during the CBLAST-Low field program on August 15, 2003 around 16:30 local time. Lower panel: SST anomaly relative to the 1 km along-track smoothed SST field.

Measurements taken during the recently completed CBLAST-Low field program allow new insight into the subsurface expression of these surface temperature patterns. Both aircraft and ship-based radiometric SST measurements and direct-covariance turbulent flux measurements were collected, and the ship was equipped to measure the corresponding subsurface temperature and salinity structure with high vertical and horizontal resolution. In addition to infrared radiometric SST measurements, one airplane was also equipped with upward and downward looking infrared (IR) imagers which can produce very low noise (<20 mK), very high resolution (0.3m) estimates of the SST field. These spatial measurements are complemented by an oceanic mesoscale array of 14 moorings, which allows a detailed description of the vertical and temporal evolution of temperature, salinity, and velocity in the region. In addition, *in situ* bulk and/or direct covariance air-sea flux measurements were made at four spatially separated (fixed) locations in the approximately 20 × 30 km study region.

The CBLAST-Low observations of the past three summers have indicated that this low-wind SST variability has no clear relationship to the wind direction and exists at scales of meters to kilometers. Figure 1 illustrates the type of surface temperature variability that is commonly observed from aircraft under low wind conditions. The SST field in the upper panel was constructed from 111 overlapping upward and downward looking IR images collected on August 15, 2003. The plane was flying southward (across isobaths) over water that is about 45 m deep. More detail will be given about the meteorological and oceanographic conditions on the day the imagery was taken, but the important point is that spatially coherent, quasi-periodic variability in SST was observed on scales of meters to kilometers, with an amplitude in excess of 0.25 °C.

These spatially coherent, propagating SST patterns are intriguing, and it is important to understand the nature and source of this coherent SST variability. Without coincident subsurface observations, we cannot be sure that these surface temperature and roughness patterns are anything other than a surface phenomenon. For example, it is conceivable that such surface patterns are associated with organic films or are associated with errors in the estimated SST due to reflections or spatial variability in the surface emissivity. If the features exist only in the upper few millimeters of the ocean, then they are unlikely to have any significant impact on the ocean or atmosphere, since there would be very little variation in heat content associated with them. Furthermore, if these features do have a subsurface expression, then it is important that we learn about the subsurface structure so that we can work toward using observations of the surface to make inferences about the subsurface structure, which is much more time-consuming and costly to observe.

Due to a dearth of sufficiently detailed observations, the reasons for this short scale variability have remained unclear. A number of fundamental questions about this variability remain unanswered. Is the surface temperature signal accompanied by a subsurface temperature signal? Is the spatial and temporal structure in SST accompanied by similar structure in other oceanographic surface properties such as salinity, velocity, and surface roughness? Does this short scale variability persist through the night (when the airplanes were not flying)? Once these questions have been addressed, we may be able to determine the cause(s) of this enhanced SST variability under low winds. The structures appear at a wide range of scales, and it is likely that both oceanic and atmospheric variability is imprinted on the SST field. Potentially important processes include Langmuir circulation, internal waves in the ocean and atmosphere, surface flux variability, and spatial variability in upper ocean mixing.

In this paper, we investigate the subsurface expressions of appreciable small scale SST variability using the CBLAST-Low data set. In order to limit the analysis, attention here will be focused on spatial scales of several 10's of meters to about 1 km. By determining the nature of the subsurface expressions of this small scale SST variability, we hope to promote further progress toward understanding the physical processes responsible for enhanced surface temperature variability under low winds. We present observations which suggest that the spatially organized small-scale SST patterns occurring under low-wind conditions in the CBLAST experiment are a surface expression of oceanic internal waves, and this prominent surface expression is related to the existence of a strong vertical temperature gradient in the upper few meters of the water column.

2 Data and Methods

The data was collected during the August 2003 Intense Observing Period of the CBLAST-Low field program, which took place in the coastal region south of Martha's Vineyard, Massachusetts. Some key elements of the field program were an array of 14 moorings (figure 2), the Air-Sea Interaction Tower, aircraft surveys, and ship surveys. The field program took place in water depths ranging from 10-50 m. The area is characterized by light to moderate winds, the passage of synoptic weather systems, and a strong thermocline during the summer.

Shipboard operations were conducted from the *F/V Nobska*. The *Nobska* was equipped with upward and downward looking infrared radiometers to accurately measure the ocean skin temperature at a 1 Hz sampling frequency. The *Nobska* also carried a complete direct covariance flux package, radiometers for measuring incident short and long wave radiation, and a towed temperature and conductivity instrument chain that could be deployed with vertical spacing greater than or equal to 0.5 m. The horizontal distance between oceanographic samples depends on the vessel's speed (5-7 kts) and the sampling rate (0.2-1 Hz); the nominal horizontal separation between SST measurements was 2 m and the separation between sequential subsurface measurements was about 8 m.

The primary focus of this study is on the radiometric SST measurements and subsurface temperature measurements collected from the *F/V Nobska*. SST measurements were made using upward and downward looking Heitronics KT19 infrared radiometers, corrected for sky reflections and sampled at 1 Hz. Subsurface temperature measurements were made using 21 Seabird SBE 37's and SBE 39's sampled at 4 or 5 seconds. The instruments were towed from the *Nobska's* boom crane, and care was taken to ensure that the instrument chain was as far as possible to the side of the vessel's wake. Three of the subsurface instruments measured pressure. Prior to analysis, all records were linearly interpolated to a common 4 second time base and the pressure records were used to estimate the actual depth of each instrument through time. Aliasing of surface waves is a concern, but for the low wind days under consideration, the seas were calm

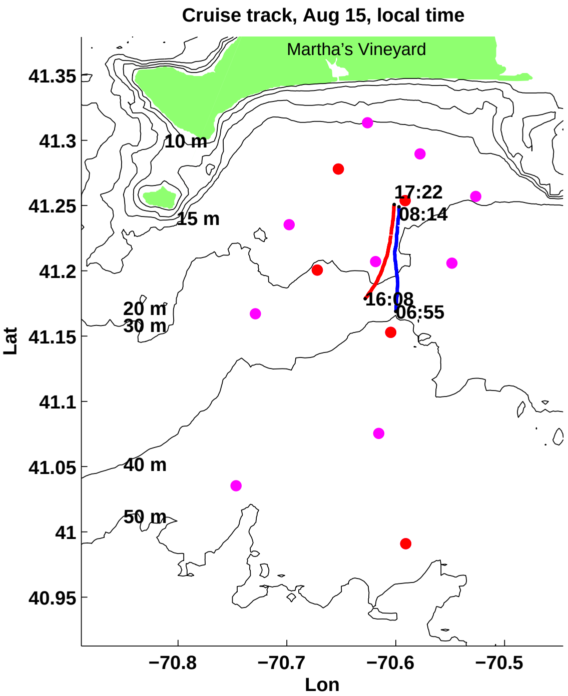


Figure 2: The morning survey section (blue line) and the late-afternoon section (red line) from August 15, 2003. Also shown are the mooring locations for the CBLAST-Low Intense Observing Period of August, 2003 (pink and red circles).

and surface wave activity was minimal.

Unless otherwise specified, all times are local (i.e. Eastern Time, equal to UTC minus four hours), and all smoothing and bandpass filtering is carried out using a Hanning window.

3 Observed Subsurface Expression of Low Wind SST Variability

In order to constrain the scope of this paper, we will focus on two north-south survey sections that were carried out aboard the *F/V Nobska* on August 15, 2003. During both surveys, coincident radiometric SST measurements and subsurface temperature and salinity measurements were collected. Both sections were about 10 km long in a cross-shore direction and spanned water depths of about 22-37 m. Figure 2 shows the two sections with start and stop times.

The evolution of wind speed, surface heat flux, and near surface thermal structure on August 15, 2003 are summarized in Figure 3 using data from a nearby buoy. The pairs of vertical black lines mark the times of the two survey sections that are discussed here. The wind speed was low-to-moderate throughout the day, only exceeding 3 m/s for several hours up to 07:30 (local) and after 18:00 (local). The moderate wind speeds of the early morning hours and nighttime cooling of the sea surface facilitated the formation of a fairly well-mixed surface layer as is indicated by the relatively small temperature difference between the 1 m and 2.2 m levels. Around 08:30 (local), the wind speed dropped below the detection threshold of the anemometer, and near surface thermal stratification increased rapidly. Although this warming of the surface layer is likely due in part to advection and other processes, the rapid warming is largely due to the substantial heat flux into the ocean associated with the low winds and daytime insolation. The lower panel of Figure 3 shows the temperature anomaly relative to a 1 hour running average. As the near surface stratification increased, so did the variability in 1 m temperature. The temperature difference between the 1 m and 2.2 m levels was about 2°C for much of the afternoon, so perhaps it should not be surprising that the temperature variability should be relatively large in the presence of such an extreme temperature gradient.

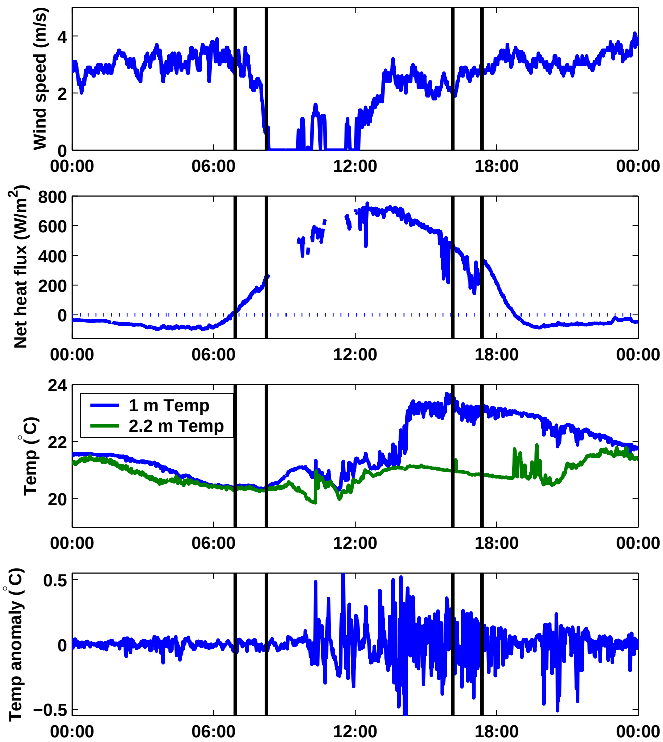


Figure 3: Data from a surface buoy near the termination point of the two transects. The time of each transect is marked by a pair of vertical black lines. Top panel: Wind speed. Second panel: Net heat flux into the ocean. Third panel: Subsuface temperature at the 1 m and 2.2 m levels (blue and green lines, respectively). Lower panel: Temperature anomaly at 1 m depth relative to a 1 hour running average.

The rapid warming of the sea surface during the day is reflected in difference in the SST observed in the morning and afternoon surveys, which exceeded 2.5°C at most locations along the track. Figure 4 shows the observed SST along the two survey tracks and the corresponding

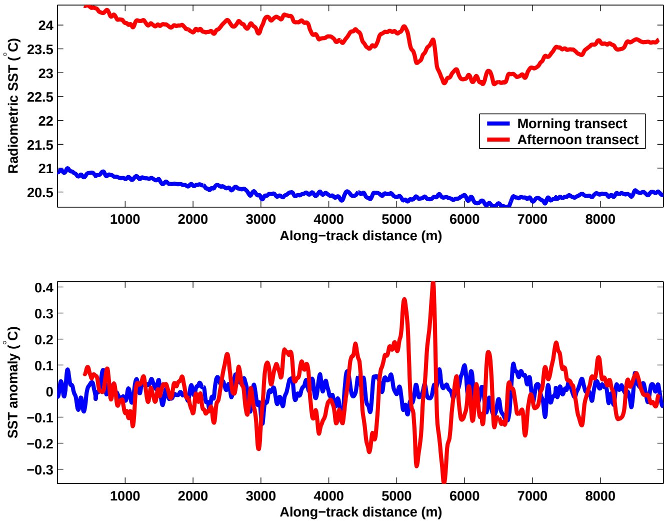


Figure 4: Upper panel: Radiometric SST observed along the morning and afternoon survey tracks. Lower panel: SST anomaly relative to a 1 km running average. Note that the sub-kilometer scale spatial variability in SST was much larger during the afternoon transect.

temperature anomalies relative to a 1 km running average. The spatial variability in SST was significantly larger during the afternoon survey.

The surface and subsurface thermal structure observed during the first survey is shown in the upper panel of Figure 5. Consistent with the temperature data from the mooring (Figure 3), the near surface stratification was relatively weak during the morning survey, and the variability in SST and near surface temperature was small. The white line in each panel indicates the depth where the temperature is 1°C cooler than the observed surface temperature. A strong vertical temperature gradient of O(1°C m^{-1}) was present at 5-15 m depth, and this thermocline deepened and weakened toward the coast. Above this thermocline, surface and subsurface temperature fluctuations were modest during the morning survey. Quasi-periodic isothermal excursions were observed in the main thermocline along the entire track; these fluctuations are associated with vertical displacements of isotherms by the oceanic internal wave field.

The surface and subsurface thermal structure observed during the morning section can be contrasted with that observed during the afternoon section (lower panel of Figure 5). The thermal structure in and below the main thermocline remained relatively similar to that seen during the morning survey. However, over the course of the day, a substantial temperature gradient had developed just below the surface, having a value of about 1°C m^{-1} on the upper meter over most of the section. This very shallow thermocline, located in the upper 2 m of the water column, is of a strength comparable to that of the main thermocline. As a consequence, there are substantial temperature anomalies extending all the way to the surface, presumably in association with vertical advection by the oceanic internal wave field.

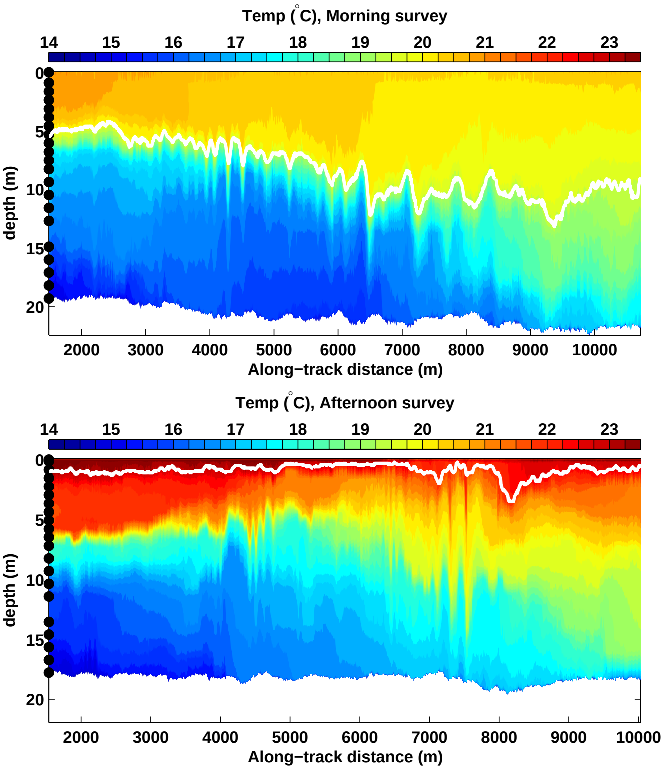


Figure 5: Temperature data from the morning survey section (upper panel) and afternoon section (lower panel). The black dots on the left side of each panel mark the nominal instrument depths, and the heavy white lines marks the depth where the temperature is 1°C less than the SST.

The along track temperature anomalies from the two surveys are shown in Figure 6. These temperature anomalies were computed by band-passing the along-track temperature data at 50-1000 m scales. During the morning survey, temperature anomalies were relatively small above the main thermocline (located at 5-15 m depth), typically less than 0.05°C. In contrast, the afternoon survey shows strong temperature anomalies in the upper few meters, coherent with fluctuations at greater depths.

4 Discussion

In the afternoon survey section, coherent temperature perturbations were observed to extend from the sea surface to the bottom of the instrument chain (17-20 m depth). These perturbations exist at a variety of scales; during this particular survey, prominent scales of surface and subsurface variability ranged from 50 m to >1 km. Figure 7 shows an expanded view of the temperature anomaly relative to the 150 m smoothed temperature (lower panel). The measurements at nine depths in the upper 5 m reveal the presence of highly coherent, quasi-periodic 50-100 m scale temperature fluctuations extending from depth to the sea surface. These vertically

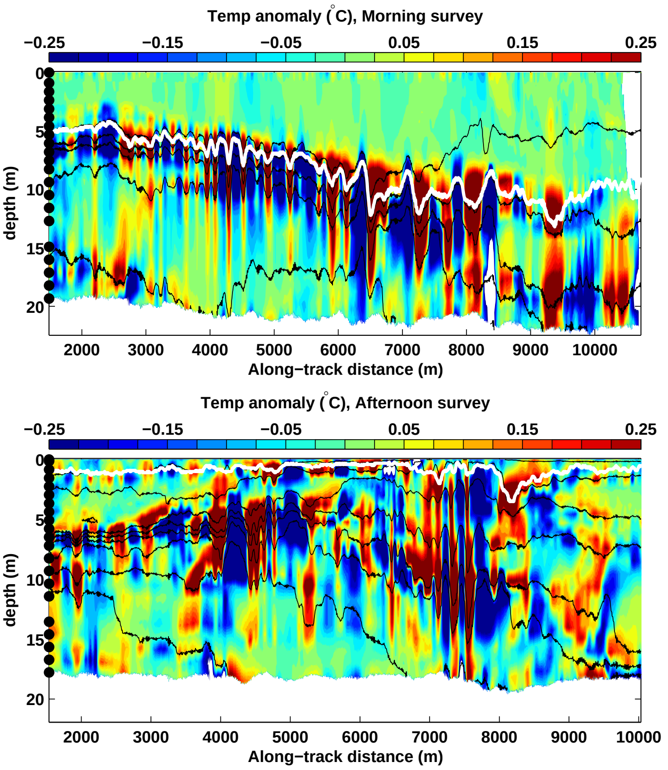


Figure 6: Temperature anomaly along the morning survey section (upper panel) and afternoon section (lower panel). The anomalies are computed by band-passing the temperature at 50-1000 m scales. The black dots on the left side of each panel mark the nominal instrument depths. The black lines mark isotherms at 1°C intervals, and the heavy white lines marks the depth where the temperature is 1°C less than the SST.

coherent temperature fluctuations have the character of internal gravity waves. Figure 7 also shows the isotherm depths at 1°C intervals; the strongest temperature gradient occurs in the upper meter. The fluctuations of the isotherm in the upper 0.25 m can be seen to be in phase with the fluctuations near 5 m. However, the isotherm fluctuations near the surface are much smaller than those at depth, consistent with the expectation that the vertical velocity associated with internal gravity waves should approach zero near the surface.

The notion that these spatially organized SST fluctuations are associated with internal gravity waves is supported by moored observations of temperature and velocity. Figure 8 shows temperature and velocity fluctuations having a period of about 7.5 minutes, along with the corresponding SST field observed at the mooring, which shows a surface temperature signal with a wavelength of about 25-40 m. Using the dispersion relation from a two-layer model of 1st mode internal gravity waves, the expected horizontal wavelength of the internal wave is 30-40 m, consistent with the surface temperature signal.

However, in the context of linear wave theory, it is somewhat surprising that internal waves should have a surface temperature expression. Linear wave theory leads us to expect that internal gravity waves will not cause perturbations to the surface temperature because the vertical velocity at the surface is always zero, so that water initially at the surface will remain at the surface. Of course, the vertical velocity of an internal wave is finite just below the surface, and vertical advection across the strong temperature gradient in the upper meter of the water column is expected to produce substantial horizontal temperature variations within 1 m of the surface (e.g. Figure 7). Given horizontal temperature variations just below the surface, it is easy to imagine that a small amount of vertical mixing near the surface could imprint the signal on the surface.

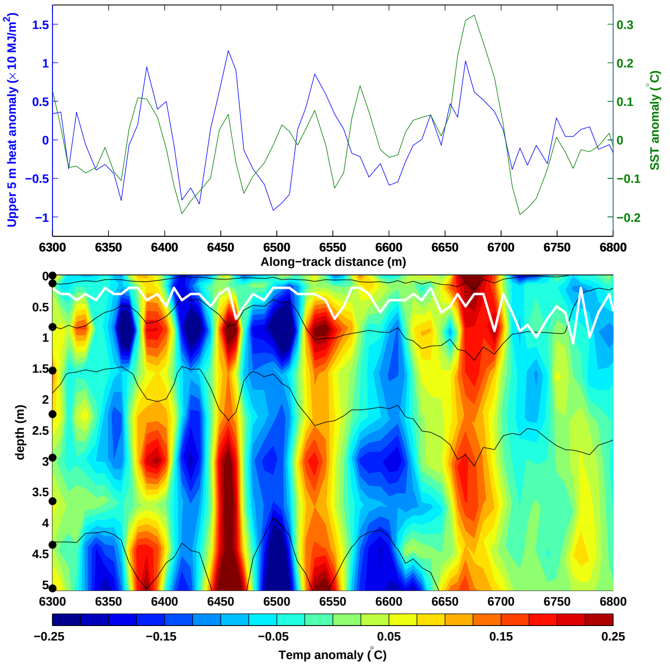


Figure 7: Upper panel: Vertically averaged heat content anomaly on the upper 5 m (left axis) and SST anomaly (right axis). Anomalies are relative to the 150 m smoothed quantities. Lower panel: Temperature anomaly in the afternoon survey. The black dots on the left side of the figure mark the nominal measurement depths. The black lines mark isotherms at 1°C intervals, and the heavy white line marks the depth where the temperature is 1°C less than the SST.

Because these SST signals are associated with substantial subsurface temperature perturbations, there are large variations in upper ocean heat content associated with these signals (see upper panel of Figure 7). The spatial variation in vertically averaged heat content in the upper 5 m is of $O(10^7 J/m^2)$. The existence of such large heat content variations so near the surface points to the possibility that these features could influence the atmospheric boundary layer. For example, a weakly stable atmospheric boundary layer might be pushed toward instability by the presence of these small scale variations in SST. Indeed, Hagan et al. found evidence that SST max-

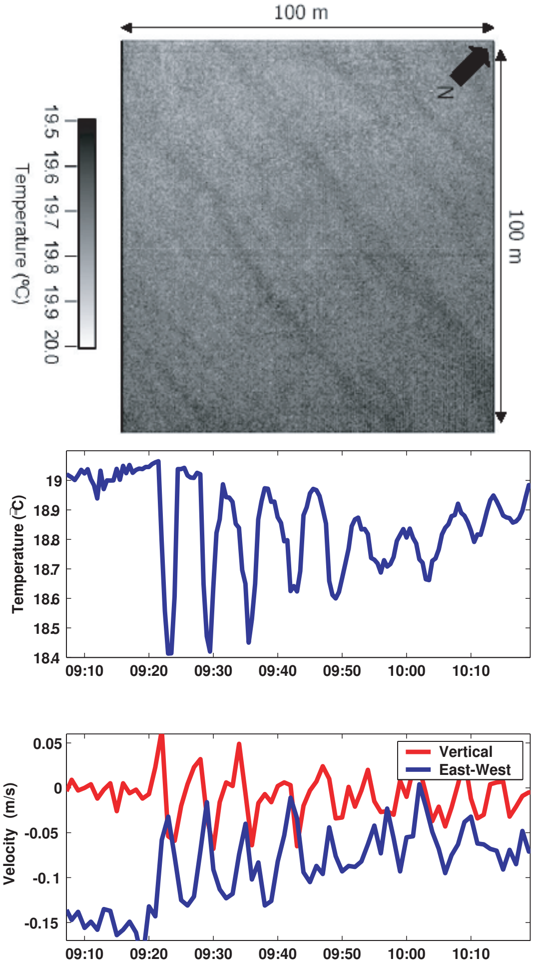


Figure 8: Upper panel: SST field from IR imager, collected during the CBLAST-Low field program on August 1, 2001. Lower panel: Temperature and velocity data from a nearby mooring at the same time.

ima seen during low-to-moderate winds in the TOGA-COARE field program (albeit at larger scales than those investigated here, i.e. O(10-50 km)) enhance the vertical transport of moisture in the boundary layer and affect mesoscale sub-cloud processes.

It is remarkable that there is a surface temperature signal of oceanic internal waves, even if this is only true in the somewhat unusual situation where the oceanic surface mixed layer is very thin or nonexistent. This raises the possibility that we might in the future learn more about the oceanic internal wave field and the subsurface thermal structure through aerial surveys. However, a number of unresolved questions remain about the nature of the relationship between the surface and subsurface thermal structures. Admittedly, a great number of processes act to modify the sea surface temperature field, and there is certainly not a perfect correspondence of subsurface and surface temperature anomalies in the CBLAST-Low data set. We hope that further analysis of the CBLAST-Low data set and future data sets will allow improved understanding of the link between surface and subsurface variability.

5 Conclusion

Observations of coincident surface and subsurface ocean temperature under low to moderate wind conditions were presented. The observations indicate that the spatially organized O(10-500 m) scale SST signals observed under low winds are associated with oceanic internal waves. The low winds and substantial surface heat flux to the ocean facilitated the development of strong near surface thermal stratification, which in turn allowed the oceanic internal wave field to cause significant temperature perturbations within a meter of the sea surface.

Acknowledgements. The authors gratefully acknowledge funding of this work by the Office of Naval Research through the CBLAST Departmental Research Initiative.

References

[1] D. Hagan, D. Rodgers, C. Friehe, R. Weller, and E. Walsh. Aircraft observations of sea surface temperature variability in the tropical Pacific. *J. Geophys. Res.*, 102:15733–15747, 1997.

[2] E. Walsh, R. Pinkel, D. Hagan, R. Weller, C. Fairall, D. Rodgers, S. Burns, and M. Baumgartner. Coupling of internal waves on the main thermocline to the diurnal surface layer and sea surface temperature during the Tropical Ocean-Global Atmosphere Coupled Ocean-Atmosphere Response Experiment. *J. Geophys. Res.*, 103:12613–12628, 1998.

[3] C. Zappa and A. Jessup. High resolution airborne infrared measurements of ocean skin temperature. *Manuscript submitted to Geosciences and Remote Sensing Lett.*, 2004.