

# **Understand the Air-Sea Coupling Processes in High Wind Conditions Using A Synthesized Data Analysis/modeling Approach**

Qing Wang  
Meteorology Department, Naval Postgraduate School  
Monterey, CA 93943  
Phone: (831) 656-7716, Fax: (831) 656-3061, email: [qwang@nps.edu](mailto:qwang@nps.edu)

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## **LONG-TERM GOAL**

The long-term goal of this project is to understand the air-sea interaction processes in the coastal region in high-wind conditions and to improve the boundary layer and surface flux parameterizations for high-resolution mesoscale model (COAMPS) in high-wind conditions.

## **OBJECTIVES**

The objectives of this year's work was to further examine the COAMPS simulated Tehuano events and understand the ocean mixed layer response to the Tehuano events.

## **APPROACH**

A unique aspect of this study is the approach of combining observations and model simulations to understand the air-sea coupling in the high wind environment. We have analyzed observations from a variety of sources: satellite scatterometer wind, ocean temperature from various satellites, aircraft in situ measurements, as well as measurements from aircraft deployed dropsondes and AXTBs. To understand the dominant physical processes that controls the ocean mixed layer response in the gap outflow region, we also used an ocean mixed layer model driven by COAMPS fields.

COAMPS simulations were made by Dr. Shouping Wang (NRL Monterey) for the gap event on Feb 26, 2006. Our efforts in FY06 focused on analysis of the model field, including the temporal and spatial evolution of the gap front and the boundary layer vertical structure in the gap outflow region. Our FY07 efforts continued with this analysis with the emphasize of COAMPS-observation inter-comparison and extend the study to include analyses of the ocean mixed layer variation and simulations

## **WORK COMPLETED**

1. Analysis of aircraft measured boundary layer mean thermodynamic and wind properties and turbulence fluxes from C-130 flight levels. This analysis resulted in spatial variations of the boundary layer characteristics at various location of the gap outflow region.
2. Inter-comparison between COAMPS results and the observations and analysis of the sources of errors in the model.
3. Analysis of satellite observation ocean surface temperature evolution during the Tehuano event.

# Report Documentation Page

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4. Analysis of the spatial variation of the ocean mixed layer and sea surface temperature using AXBT measurements in the GOTEX region. Profiles from the AXBTs are used as initial condition for the ocean mixed layer model.
5. Simulations of the ocean mixed layer evolution during the Tehuano event using the NPS ocean mixed layer model. Efforts were made to run the 1-d ocean mixed layer model for the entire domain of the COMPS inner-most domain using COAMPS results of surface stress, sensible and latent heat fluxes, and solar and infrared radiative fluxes.
6. Future work include extended analyses of the COAMPS surface flux parameterization against the aircraft in situ observations at the flight level and in depth study on the sensitivity of the ocean mixed layer to various components of the surface forcing.

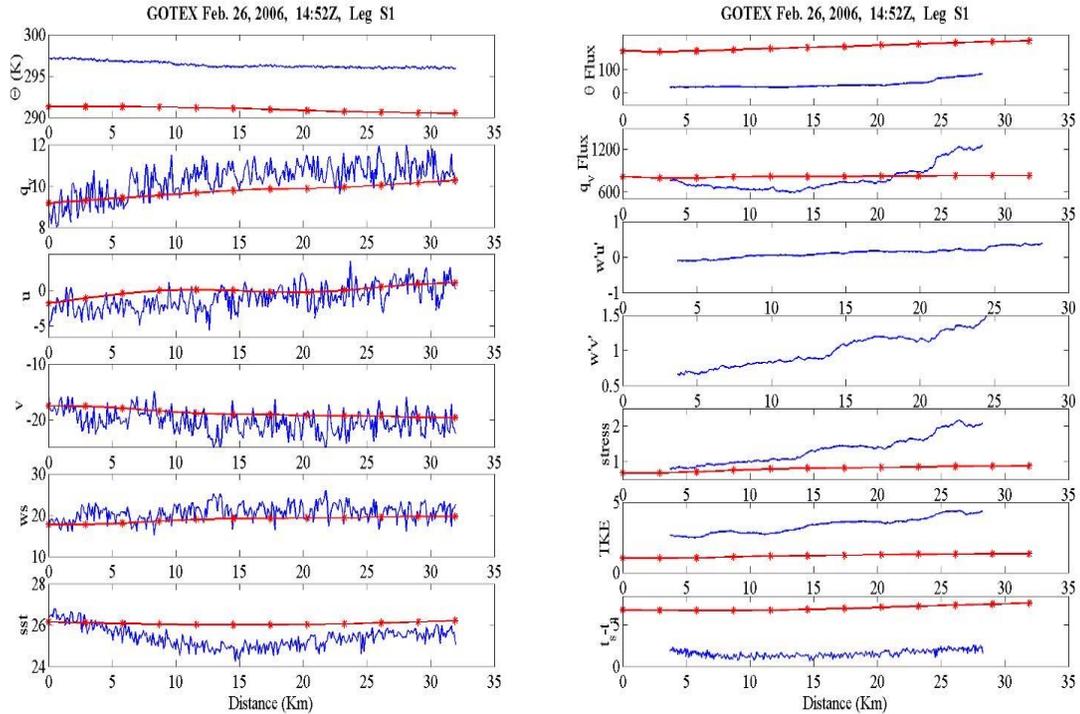
## RESULTS

***COAMPS vs. observations in different stability regimes of the gap outflow:*** Data from specific low-level flight legs were used to calculate surface flux and turbulent properties of the lower boundary layer and compared against COAMPS. Whereas the winds were nearly identical and the atmospheric moisture content was closely represented for some legs, the temperatures of both the atmosphere and the sea surface showed a significant disparity. Spatially and temporally, COAMPS did a reasonable job simulating the major features of the gap outflow especially close to the coast where coastal topography plays a major role. Large discrepancies are seen between COAMPS and observations away from the coast when air-sea exchanges become relatively important.

The difference in SST and in simulated air temperature results in large differences in the sensible heat and latent heat fluxes compared to the GOTEX data. In particular, COAMPS consistently showed unstable stratification in the entire outflow region whereas the GOTEX data showed that some regions were thermally stratified at low levels. Yet turbulence remained strong over these stable areas suggesting the dominant forcing of vertical shear was generating turbulence along the jet core. The wind stress values also diverged in comparison. This indicates a need for improvement in the formulation of the drag and exchange coefficients and the surface roughness since the wind speed itself was well represented.

Figure 1 shows an example of the COAMPS-aircraft comparison in the observed unstable boundary layer. Here we find that the wind speed and direction are nearly perfectly predicted while COAMPS potential temperatures were between 5 and 6 degrees colder than the aircraft measured temperatures. However, the decreasing trend towards the outflow axis was represented well. The sea surface temperature was, on average, warmer than the aircraft measurements by up to 1.5 K. This combination results in a sea-air temperature difference of above 7 K in COAMPS compared to about 1 K difference from observation. Hence, COAMPS is much more convective in this region. Consequently, the modeled sensible heat flux was significantly higher by an average  $150 \text{ W m}^{-2}$  over the magnitude calculated from the aircraft data.

Although the wind components were well predicted by COAMPS, large deviation is seen in the surface stress towards the jet core, which indicate the inadequacy of the surface flux parameterization near the jet core. Similarly, the largest difference in latent heat flux is also seen at the location with significantly higher stress, although the mean water vapor differs only slightly. Turbulent kinetic energy was also significantly under predicted by COAMPS.

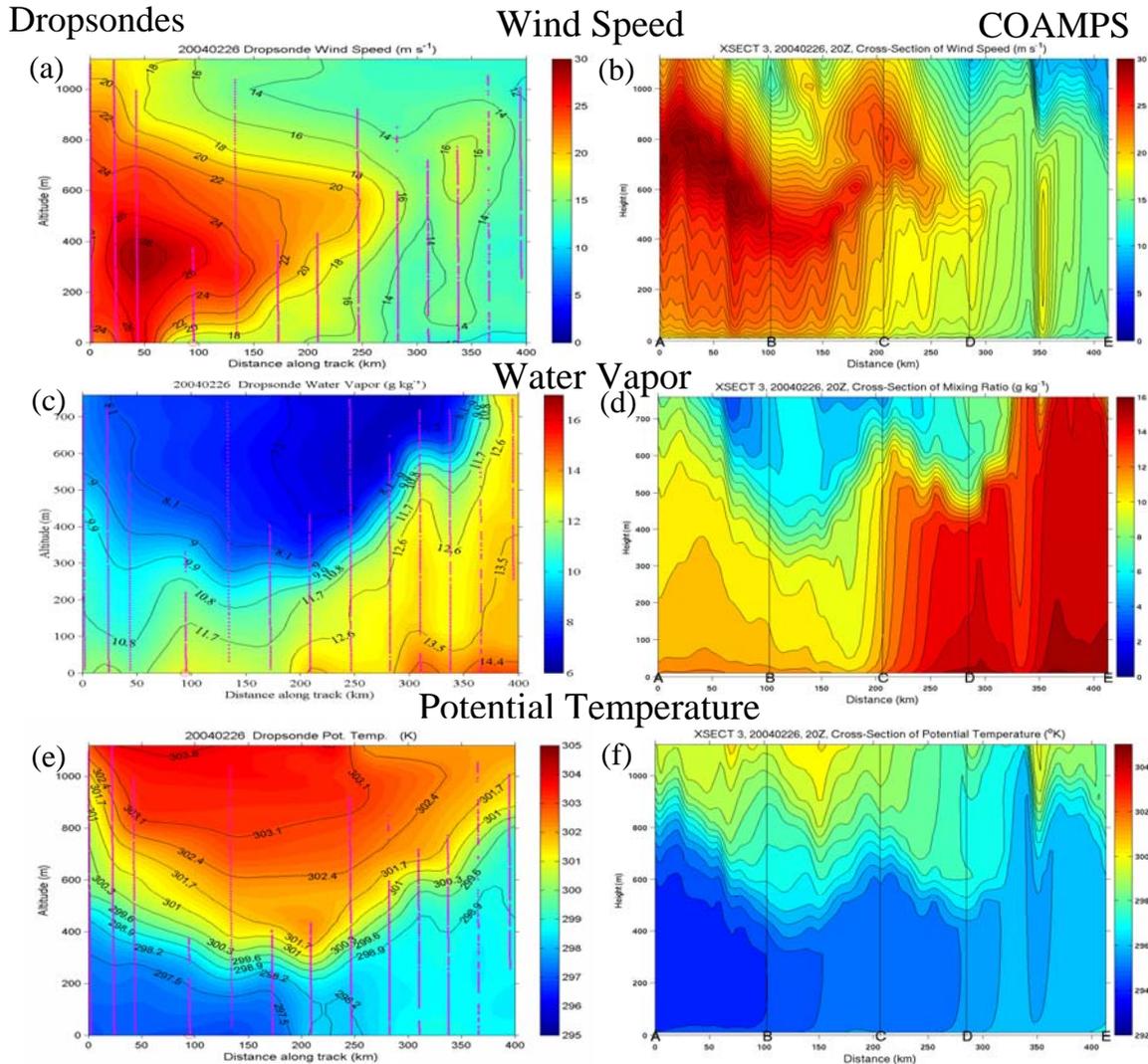


**Figure 1. Comparison between the aircraft measurements (blue line) and COAMPS results (red line) from RF09 Leg 1. The plots on the left from top to bottom are potential temperature ( $^{\circ}\text{K}$ ), mixing ratio ( $\text{g kg}^{-1}$ ), eastward wind component ( $\text{m s}^{-1}$ ), northward wind component ( $\text{m s}^{-1}$ ), wind speed ( $\text{m s}^{-1}$ ), and sea surface temperature ( $^{\circ}\text{C}$ ). The plots on the right from top to bottom are sensible heat flux ( $\text{W m}^{-2}$ ), latent heat flux ( $\text{W m}^{-2}$ ), eastward momentum flux ( $\text{m}^2 \text{s}^{-2}$ ), northward momentum flux ( $\text{m}^2 \text{s}^{-2}$ ), surface wind stress ( $\text{N m}^{-2}$ ), turbulent kinetic energy ( $\text{m}^2 \text{s}^{-2}$ ), and sea surface minus air temperature difference ( $^{\circ}\text{C}$ ).**

**Vertical variation of the mean quantities along the outflow jet core:** The evolution of the outflow along the jet core showed strong dynamical forcing was the dominant influence on the structure of the outflow for the first 200 km with strong vertical shear, weak stratification, and a decreasing boundary layer thickness. After 200 km, as represented by both COAMPS and the dropsonde data, the boundary layer height increases, and temperatures, mixing ratios, and wind speeds are better mixed. This approximate 200 km length could be the point at which the strong dynamical dominance in controlling the boundary layer height yields to the turbulent processes in controlling the boundary layer height.

Figure 2 shows a comparison between the dropsonde measurements close to the jet core and those from COAMPS simulation along the simulated jet core. Both the dropsondes and COAMPS results show a jet maximum that gradually decreases in height between 0 and 120 km down the trajectory. The height of the jet becomes relatively constant between 120 and 150 km and then gradually increases in height after about 150 km. Also, both plots indicate strong vertical shear in the boundary layer. However, a noticeable difference is that the jet is higher in the COAMPS cross section by about 200 to 300 m. Similarly, the potential temperature and water vapor plots also indicate a higher boundary layer top in COAMPS (about 200-300 m higher). Further downstream, COAMPS shows a region of higher winds aloft at about the 200 km from the reference point whereas the dropsondes plot does not indicate these higher winds. However, observing that the dropsondes did not have data aloft between the 130 km and 250 km, this cannot be adequately compared.

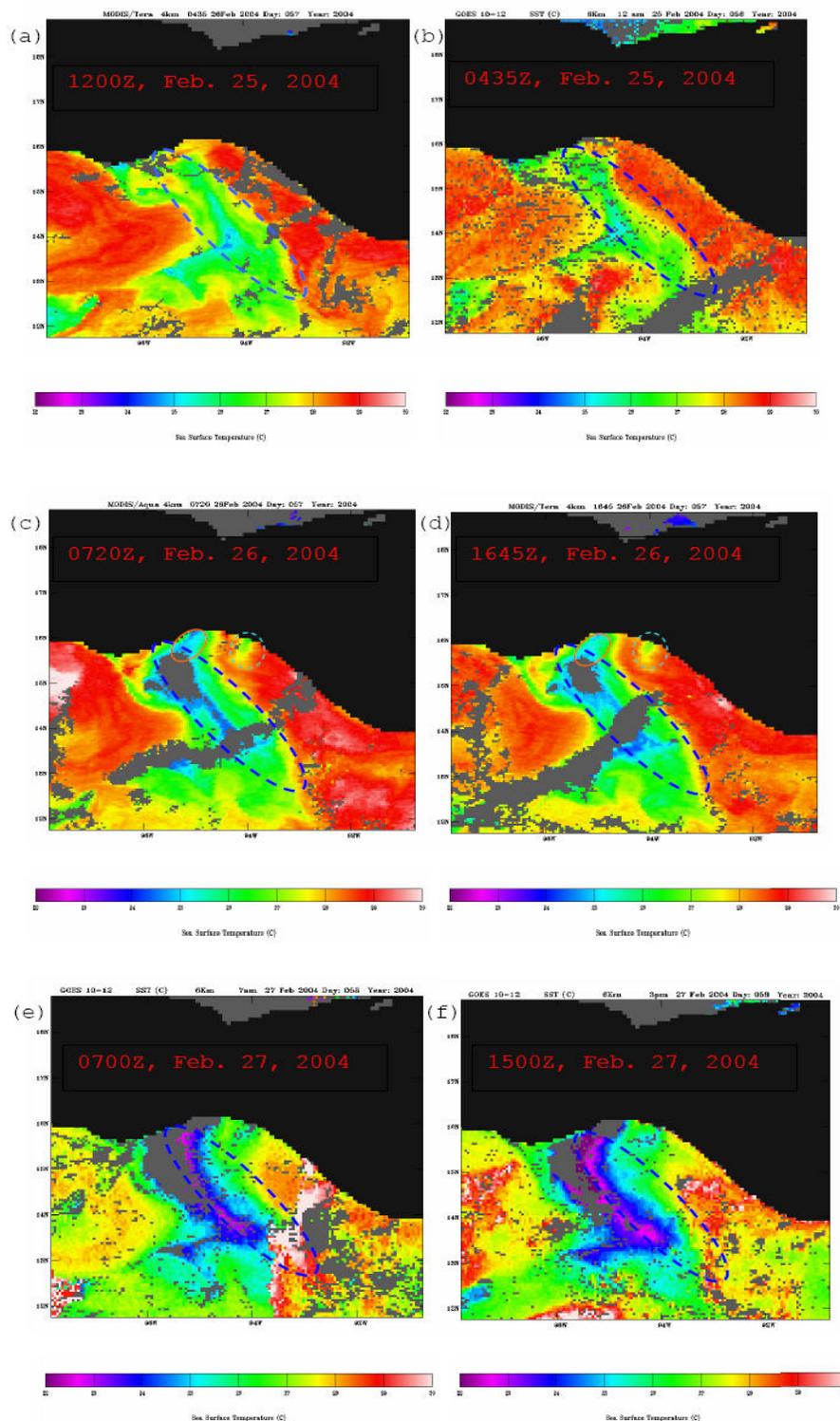
The largest noticeable difference between COAMPS and the dropsonde data is that COAMPS is about 2 to 5 degrees colder. COAMPS also shows a well mixed boundary layer, whereas the dropsondes indicate at least some stability, however weak, from the reference point to about 200 km where the boundary layer top begins to increase with height again. The vertical stratification of water vapor is also observed in both COAMPS and dropsonde results.



**Figure 2. Contour plots of wind speed, potential temperature, and mixing ratio (left column) from the 14 dropsondes released by the NCAR C130 during RF09 and (right column) corresponding COAMPS simulation along the simulated jet core.**

**Evolution of ocean surface temperature during Tehuano event:** The evolution of the sst field during the simulated Tehuano event is shown in Fig. 3 using a composite of satellite-based measurements from several sources (GOES 10-12, MODIS/Tera, and MODIS/Aqua). This figure covers a period of 51 hours between 12Z of February 25 to 15Z of February 27, 2004, starting from about 12 hours before the onset of gap wind event of February 26, 2004 (Fig. 3a). The basic feature of the SST field is the cool strip oriented in the northwest-southeast direction as outlined by the blue oval. The coolest water is located at (14°N, 94.4°W) at 25.3°C, whereas the mouth of the GoT near (16.1°N, 95°W) was

relatively warm at about 28°C. Warm water of about 29°C is observed in most of the GoT region, particularly along the coastline to the east and west of the cool strip. The SST image in Fig. 3b



**Figure 3. Sea surface temperature satellite images from GOES-12, MODIS/Aqua, MODIS/Terra on (a) 25 Feb. 12Z, (b) 26 Feb. 04:35Z, (c) 26 Feb. 07:20Z, (d) 26 Feb. 16:45Z, (e) 27 Feb. 07Z, and (f) 27 Feb. 15Z. The blue oval denotes the location of the cool strip on (a).**

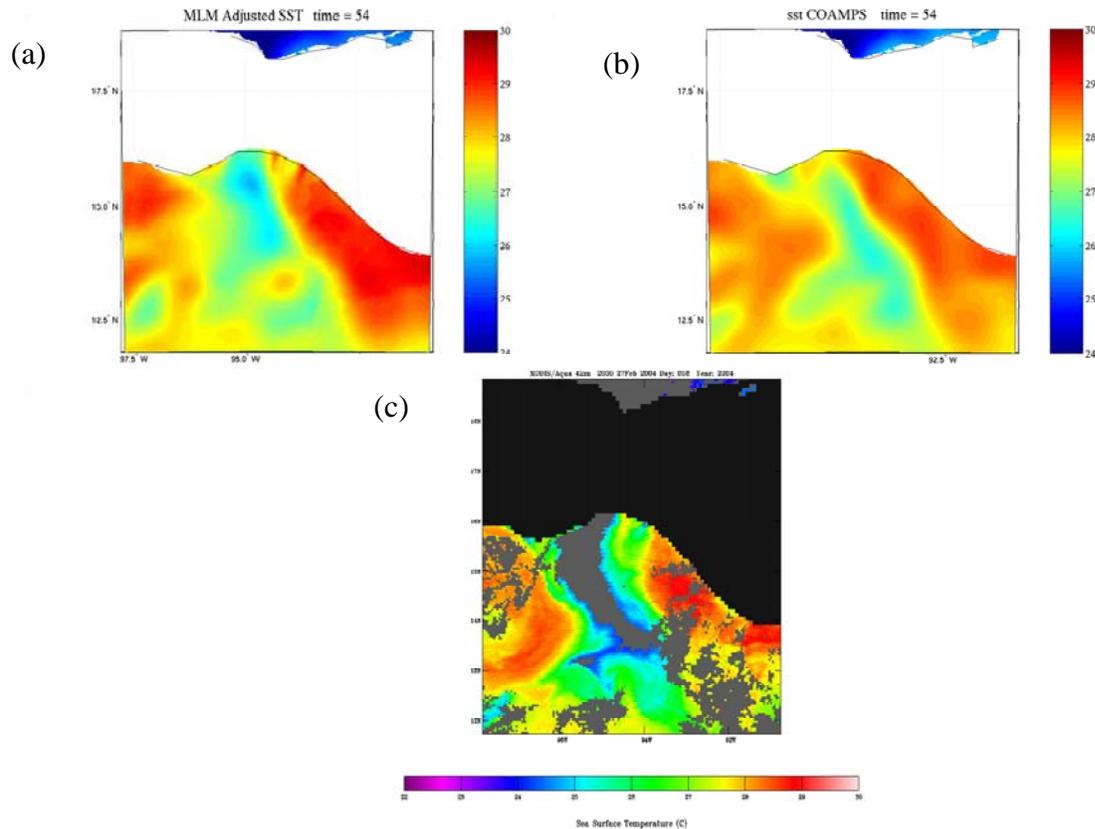
corresponds to about 4 hours after the gap front moved over water. The SST field at this hour is very similar to that 16 hours ago (Fig. 3a) except for some cooling further off the coast near 14N latitude. Significant SST changes occurred between 04:45Z (Fig. 3b) and 07:30Z (Fig. 3c). Figure 3c shows further cooling along the previous cool strip (blue oval), although the orientation remains nearly the same. The largest change occurs near the mouth of the gulf where a new cool strip exits along the northeast-southwest direction (orange oval) with the north-most tip at (16.1°N, 95°W). SST at the mouth of the gulf decreased from 28°C to 24.5°C during this three-hour period. Compare to the measured scatterometer wind field, the location of this new cool strip is collocated with the outflow jet. The cooling is hence a result of the strong atmospheric forcing of the Tehuano. Figures 3c and 3d also show the presence of another cooling spot (cyan circle) that was developed after the onset of the Tehuano, where the SST dropped from 28.5°C in Fig. 3b to 26.5°C three hours later. This newly developed cool spot confirms the existence of the secondary gap outflow that appeared in COAMPS simulations (Cherrett 2006).

Figure 3d shows similar SST spatial variations as in Fig. 3c with slight warming in the cool strips. Significant cooling occurs again from Fig. 3d to 3e (07Z February 27, 2004) and continued to 15Z of February 27 (Fig. 3f). It is seen in Fig. 3e that the coolest spots in the north end of the blue oval cool strip appears to align with the orange cool strip at the mouth, which becomes more evident and extends further to the southwest direction eight hours later in Fig. 3f. These developments suggest that the cooling was directly associated with the Tehuano event. As the nighttime continues from midnight (Fig. 3e) to early morning (Fig. 3f), the entire region cools off and the blue cool strip appears to move towards the southwest direction.

In summary, the SST field from the satellite observations suggest the presence of a permanent cool strip along the northwest-southeast direction that also experience significant cooling in response to the Tehuano. The development of the cool strip near the coast also suggests the rapid response of the upper ocean in response to the Tehuano.

***Ocean mixed layer simulation of the Tehuano event:*** The NPS ocean mixed layer model (OML, Garwood 1977, *J. Phys. Oceano.*, **7**, 458-468) is a one dimensional mixed layer model designed to study the physical processes in the upper ocean. The model predicts mixed layer temperature, mixed layer depth, and ocean current using external forcing of surface momentum flux, sensible heat flux, latent heat flux, net infrared and solar radiation. To simulate the upper ocean response to the Tehuano events, the OML is run for every grid point of the COAMPS inner domain at 3 km grid resolution using the external forcing generated by COAMPS. AXBT measurements of the upper ocean were used as the initial and lower boundary layer condition to the OML simulation.

Figure 4a shows an example of the COAMPS SST field modified by the  $\Delta$ SST from the OML simulation. The original COAMPS SST field and the satellite SST field are shown in Figs. 4b and 4c for comparison. The difference between the original and the OML modified COAMPS SST field is mainly along the predicted jet axis, where the cooling of the upper ocean is explicitly resolved by the OML. Comparing with the satellite images, we find a similar SST pattern. The highest SSTs are displayed to the east and west of the jet axis and very near to the coast. The lowest temperatures are observed very close to the coast in the axis of the gap outflow. Hence, the modified SST field more closely resembles the satellite observations, particularly in the near coast region of the gulf.



**Figure 4. (a) OML adjusted COAMPS SST field on 1800 27 February 2004; (b) same as in (a), except for original COAMPS SST; (c) measurements of SST by MODIS/Aqua at 2030 27 February 2004.**

## IMPACT/APPLICATIONS

The Gulf of Tehuantepec is a natural laboratory for studying air-sea interaction in moderate to high-wind conditions given the frequent occurrence of the gap wind event. Our study in FY07 took a close look at the performance of the Navy's operational forecast model, COAMPS, in its capability in representing the general dynamics of the gap outflow as well as in representing the processes at the air-sea interface. It was found that although COAMPS can represent well the dominant forcing from the coastal topography; it has significant weakness in representing the air-ocean exchanges. In addition to the imbedded flaws in surface flux parameterizations, we have also identified two major factors in COAMPS that resulted in deviations from the measured surface stress and fluxes: under-predicted low-level temperature and fixed SST field. Our simulations using an ocean mixed layer model with external forcing from COAMPS suggest the compelling need of a coupled system to forecast the rapid development in the atmosphere and the ocean during the gap wind events.

## TRANSITIONS

The results of this project will contribute to establish fully coupled atmosphere/ocean models.

## **RELATED PROJECTS**

Related project is the CBLAST project for surface flux parameterization (Award N0001407WX20972 to NRL Monterey and N0001407WR20228) and the Award N0001407WR20229 for surface flux parameterization in Monterey Bay.

## **PUBLICATIONS**

Cherrett, R. C. 2006: Observed and Simulated temporal and spatial variations of the gap outflow region, M.S. Thesis, Meteorology Department, Naval Postgraduate School.

Konstantinou, N. 2006: Ocean mixed layer response to gap wind scenarios, M.S. Thesis, Meteorology Department, Naval Postgraduate School.