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ESTIMATION OF BOUNDARY LAYER FLUXES AND PROFILES OVER THE GULF OF MEXICO USING NEW OBSERVATIONS AND USING THE COARE PROGRAM

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1. INTRODUCTION

There is a need to calculate the transport and dispersion of pollutants emitted from offshore oil and gas exploration and production activities in the Gulf of Mexico. However, much uncertainty exists concerning the atmospheric boundary layer in the region, due to space and time variations caused by variable underlying water temperatures and the effects of mesoscale atmospheric structures. The current study, supported by the Minerals Management Service, has instrumented six oil platforms to obtain boundary layer observations, including 915-MHz radar wind profilers, 2-KHz Radio Acoustic Sounding Systems (RASS), and near-surface routine meteorology instruments. Two of these meteorological stations are operating from May 1998 through September 2001 and four are operating from October 2000 through September 2001. The profilers measure winds and RASS measure virtual temperatures between heights of about 100 m and a few kilometers. The near-surface observations at the oil platforms include sea surface temperature as well as wind speed, wind direction, air temperature, and mixing ratio at a reference elevation, z_r, of about 25 m. These new data, in addition to the traditional data collected by buoys and available from the National Climatic Data Center (NCDC), are being analyzed to investigate the overwater surface energy balance and boundary layer structure for both steady-state horizontally homogeneous conditions and for conditions variable in time and space. These three-dimensional, time-dependent fields will be used for analysis of transport and dispersion from overwater sources. Figure 1 shows a map of the Gulf of Mexico region and indicates the locations of the various observing sites.

The TOGA-COARE marine boundary layer algorithms (Fairall et al., 1996) are being used to calculate a three-year climatology of hourly-averaged and/or monthly-averaged fundamental boundary layer scaling parameters such as the surface roughness length (z_o), the friction velocity (u*), the scaling temperature (T*), the scaling water vapor mixing ratio (q*), and the Monin-Obukhov length (L), in addition to the latent and sensible heat fluxes. From these parameters, the mixing depth (h), and the vertical profiles of wind speed, temperature, and water vapor mixing ratio are also being estimated. The outputs of the COARE program (e.g., boundary layer scaling parameters and energy fluxes) and the estimated profiles are being compared to observations and to simulations by the Eta numerical weather prediction model.

2. BACKGROUND ON THE COARE MODEL

The basic structure of the COARE marine boundary layer model is an outgrowth of the Liu-Katsaros-Businger (LKB) (Liu et al., 1979) method. The COARE algorithm was designed to improve estimates of surface fluxes and scaling parameters over the deep ocean in tropical regions (Fairall et al., 1996). The original version of COARE was released in 1993, and three new COARE versions have been released since the current study began. Version 2.5b, released in May 1997, included updated transfer coefficients and was used for our Gulf of Mexico study until January 2000, when version 2.6b was released. There are six relatively minor differences between versions 2.5b and 2.6b, including changing the Charnook "constant" to a parameter based on wind speed data from Hare et al. (1999) and Yelland and Taylor (1996). Version 2.6b was used for our Gulf of Mexico study until June 2000. In this paper, the summaries of statistical results (e.g., monthly averages) were derived from outputs of Version 2.5b, and the preliminary outputs from the five-day case studies were derived using Version 2.6b. An improved version of COARE (version 2.6bw) was released in June 2000 and will be used in our project after September 2001. An important difference between version 2.6bw and the prior versions is that version 2.6bw incorporates surface gravity wave information, based on wave height and period data. This change should increase the accuracy of the estimates of surface fluxes and scaling parameters over shallow areas, since the characteristics of waves differ from the deep ocean to the shallow coastal waters.

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3. APPLICATION OF THE COARE MODEL

The COARE model requires the following input data: time and site location; wind speed, air temperature, and relative humidity (RH) within the surface layer at reference height z_r; sea surface skin temperature (T_s) or sea temperature near the surface plus radiation estimates; and mixing height. If the near-surface sea temperature is used, then solar and downwelling longwave radiation fluxes need to be estimated from some alternate source in order to correct this temperature to a skin temperature. Precipitation data is not required, but if available, can be used by COARE to estimate the precipitation contribution to the energy balance equation. Wave height and period data are not required, but if available, can be used in future studies with version 2.6bw to account for the different wave structures and theoretically improve the accuracy of the estimates of surface fluxes and scaling parameters over shallow ocean areas. Data were acquired and processed from the following sites: 1998 and 2000 offshore buoy data from seven sites, shoreline CMAN station data from five sites, and data collected as part of this project on the Vermillion (VRM) and South Marsh Island (SMI) oil platforms. Figure 1 shows the locations of the offshore buoys, the CMAN stations, the VRM and SMI platforms, and onshore surface and NEXRAD sites.

The CMAN stations are located in very shallow water on the coast. Since the COARE model is not currently designed to use data collected in such areas, the data from these sites were used only in test exercises to evaluate how COARE would respond compared to open-water sites. The data collected at the VRM and SMI platforms meet the COARE input data requirements. The data collected at buoys meet most of the COARE data requirements, with the exception that solar and longwave radiation were not observed. Instead, radiation fluxes were estimated using 6-hourly ETA model cloud simulations and sun elevation data to calculate the water skin temperatures from water temperatures at depths of about 0.5 to 1.0 m.

The climatological part of the study is discussed first. Using the hourly meteorological data collected from May 1998 through May 1999 at sites 42035, 42040, SMI, and VRM, hourly sensible heat flux, latent heat flux, surface stress, frictional velocity, temperature and relative humidity scaling parameters, z_r/L, and roughness length were calculated using COARE 2.5b. Monthly statistics were then calculated from these hourly values. Monthly averages were not computed if more than 80% of the data in a given month were missing.

The case study part of the analysis is discussed second. In this analysis, time series of hourly-averages of selected meteorological and derived boundary layer parameters were created using version 2.6b, for five-day periods in January, March, July, and October, 2000. The analysis included comparisons of derived outputs from COARE 2.6b with simulations of the Eta model for sensible and latent heat flux, and friction velocity. The Eta model simulations were available on a 6-hourly basis out to 48 hours. Since the Eta model runs every 12 hours, there are four sets of simulations available at any given hour; therefore, the COARE-derived data for any given hour and parameter were compared to four separate Eta model simulations.

4. RESULTS OF CLIMATOLOGICAL STUDY

The key results of the climatological study (comparisons of monthly averages) are briefly summarized in this section. The project report will discuss these points in detail.

The fluxes and scalar parameters calculated by the COARE algorithm in the Gulf of Mexico are physically consistent with our intuitive expectations, and are similar to observations and COARE calculations for TOGA, which took place in the warm western Pacific Ocean near the equator. Calculated sensible heat fluxes in the Gulf of Mexico average about 5 to 30 w/m^2, typical of other over-water sites. Similarly, calculated latent heat fluxes average about 50 to 100 w/m^2, also typical of other overwater sites. Calculated monthly-average sensible heat fluxes were about 1/5 of the calculated monthly-average latent heat fluxes and were generally greatest in the winter and early spring at all sites with the exception of GDIL1, which had no distinct yearly cycle. The approximate 1/5 ratio is found at other open-water sites at this latitude.

The calculated monthly average latent heat fluxes, shown in Figure 2 for buoy 42040, are generally greater in the fall months, probably due to higher water temperatures. The latent heat fluxes shown in Figure 2 range from about 40 w/m^2 in May to about 130 w/m^2 in November. The shallow-water site of GDIL1 generally had the greatest latent heat flux and highest water temperature of all the sites during the spring and summer months.

The COARE-calculated monthly-average sensible heat fluxes at the VRM and SMI oil platforms and at buoy 42040 (see Figure 1 for the locations) are generally within a factor of two of each other. In August and September 1998, the sensible heat fluxes at these sites were within 20% of each other. Slightly higher sensible heat fluxes are calculated in early winter, possibly due to cold air advection over the warmer Gulf of Mexico waters. The reverse occurs in late spring and early summer, when the water temperature is still relatively cool but the air is warming up. This annual variation of calculated sensible heat fluxes agrees with the observed annual variation of the difference between the water and air temperatures.

The calculated total heat flux (sensible plus latent) over a monthly average is in good agreement (within a factor of two) among the sites in the Gulf of Mexico. The magnitude generally follows the annual variation of the sea surface temperature, with maxima in the late fall and minima in the late spring. Sea surface minus air temperature differences average about +1 to +3°C at most sites all year. The difference is less in late spring and is greater in late fall. This persistent positive temperature difference has been noted by Dr. Christopher Fairall at most other sites.

The COARE-calculated monthly average friction velocity, u*, shows an agreement among the sites well within a factor of two and often within 20%. This agreement is important because u* is the key scaling velocity for estimating transport speeds and dispersion rates. u* is calculated to be slightly lower from May through August and peaks in September probably due to hurricanes during the year being analyzed.

The calculated monthly average temperature scaling parameter, T*, and humidity scaling parameter, q*, generally show a factor of two or better agreement among sites. T* and q* tend to be smaller in April and May, when the difference between the surface water temperature and the air temperature is at its minimum, and tend to be larger in October and November, when the difference between the surface water temperature and the air temperature is at its maximum.

5. RESULTS OF CASE STUDIES

Time series of hourly averaged observations, COARE-model calculations, and Eta-model simulations of boundary layer parameters at the observing sites in the Gulf of Mexico have been analyzed for four five-day periods in January, March, July, and October, 2000. Data from the 20-25 January time period from buoy 42040 are discussed here in order to illustrate the analysis methods and the typical results. As seen in Figure 1, buoy 42040 is located several 10s of km to the southeast of the Mississippi River delta.

The time series of observed air and water temperatures and wind speed are plotted in Figure 3, showing large variations in wind and air temperature during these five days with air temperatures 5 to 10°C cooler than the water temperatures for the first two days and for the last day and a half. Wind speeds were moderate to strong (about 5 to 15 m/s) during these periods. However, during the middle of the time period, the air warmed slowly to approach and even exceed the water temperature for over 12 hours. The winds dropped to nearly zero just before a frontal passage at about 3 a.m. on 24 January, after which the air temperature dropped 5°C in an hour and wind speed rapidly increased to 16 m/s.

5.1 Sensible Heat Fluxes

Figure 4 shows the COARE-calculated and Eta-simulated sensible heat fluxes during this time period. The COARE model is using the buoy-observed meteorological variables, and is seen to produce very large (for the ocean) fluxes with magnitudes of about 150 w/m^2 during the beginning and ending periods, when the water-air temperature differences were very large (5 to 10°C) and the wind speeds were high (about 10 to 15 m/s). However, during the 12- to 15-hour period in the middle of the time series, when the air temperature exceeded the water temperature, the COARE-calculated sensible heat fluxes were negative (i.e., towards the water surface) with magnitudes of about 10 w/m^2. The Eta model simulations of sensible heat flux are only about 30% larger than the COARE-calculated values during the periods with large air-water temperature differences. However, during the middle period, the Eta model simulates positive (upward) sensible heat fluxes, although they are small (about 0 to 20 w/m^2). We find this tendency for all sites and periods. That is, occasionally the site shows periods with observed air temperatures warmer than water temperatures, leading to COARE-calculated negative heat fluxes, while the Eta model simulates positive (but small) heat fluxes. During the late spring, when the air temperature is observed to be greater than the water temperature about 20 to 40% of the time, long periods of mismatches can occur in the signs of the COARE- and Eta-simulated sensible heat fluxes.

5.2 Latent Heat Fluxes

Figure 5 shows the COARE-calculated and Eta-simulated latent heat fluxes during this same time period (20-25 January 2000). Relatively large latent heat fluxes of about 500 w/m^2 are calculated by both COARE and Eta for the periods near the beginning and end of the five days. This is the same magnitude as the solar heat flux on a summer day. These large sensible heat fluxes are due to the large air-water temperature differences and the moderate wind speeds. Note from Figure 3 that, even in January, the Gulf of Mexico water temperature is still fairly warm—about 21°C—allowing large latent heat fluxes to occur.

During the 12- to 18-hour period on 23 January, when the air temperature slightly exceeded the water temperature and winds dropped, COARE-calculated latent heat fluxes dropped as low as 20 w/m^2.

The Eta-model simulations in Figure 5 are seen to approximately track the COARE calculations, with differences of only about 30% during the two periods with high fluxes. During the period with small fluxes, the Eta simulations roughly bracket the COARE calculations. No relation is evident between the age of the Eta simulation and agreement with the COARE curve on the figure.

6. FURTHER STUDIES

As stated in the introduction, the data collection phase of this study is expected to be completed in fall 2001. At the present time, the data are still being acquired and subjected to QA/QC procedures. Many types of data have not been discussed in this paper, such as the 915-MHz wind profilers or the RASS systems. These analyses have just begun and will be carried out over the next year. The purpose of the current paper has been to give a flavor of the types of data that are being collected and the types of analyses being carried out.

Many issues still need study, such as the usefulness of the CMAN (coastal) observation sites in the COARE algorithm. We are also studying the meaning of the Eta analyzed fields (EDAS) and to what extent the observations are used in developing those fields. The ultimate goal is to have an optimum set of three-dimensional time-dependent meteorological variables over the Gulf of Mexico for use in air quality simulations. For example, these data could be used to assess the impacts of emissions from oil platforms on the Breton Island National Wildlife Refuge, which is a "Class I" area in the EPA priority scheme.

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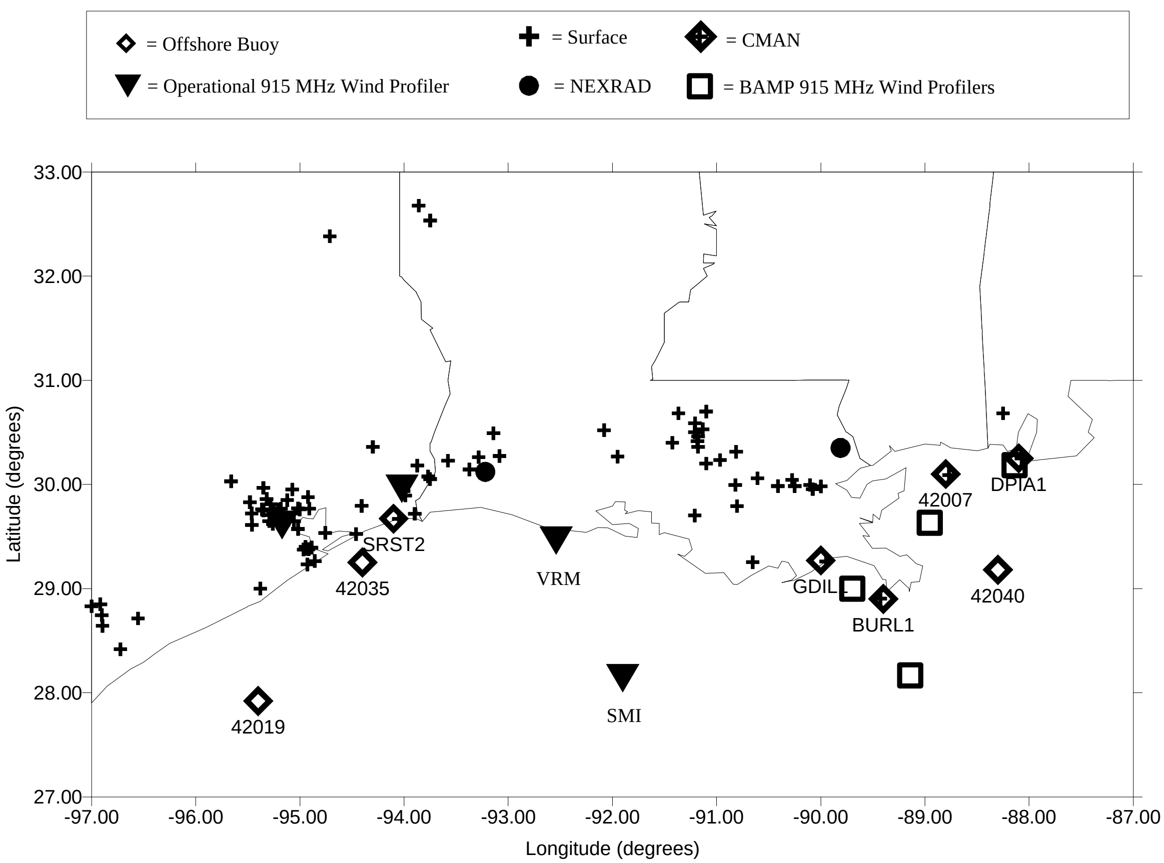

Figure 1. Meteorological Stations in the Gulf of Mexico study domain.

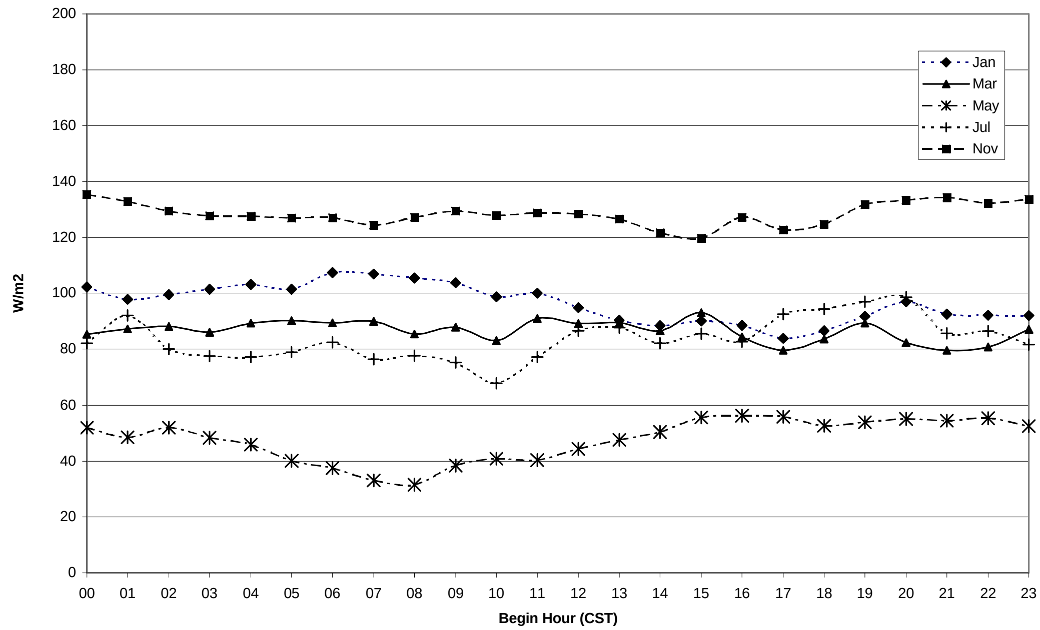

Figure 2. COARE 2.5b model estimated monthly average latent heat flux by hour at buoy 42040 for January, March, May, July, and November.

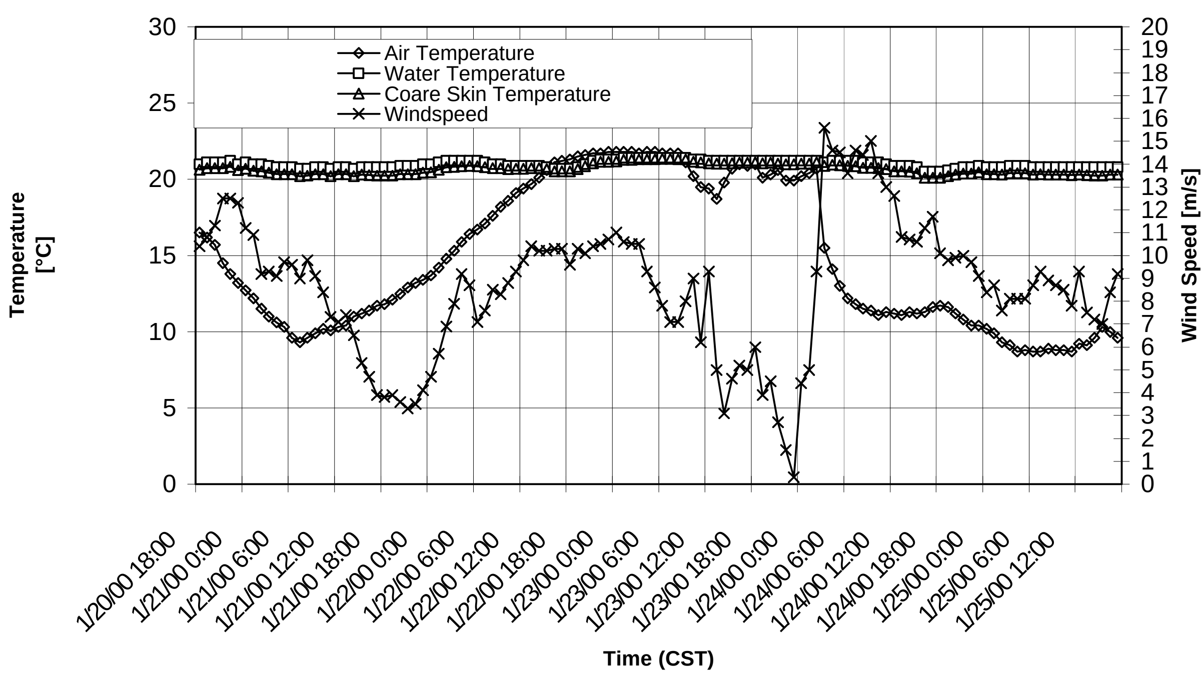

Figure 3. Observed wind speed, ambient air temperature, 0.6 m under water temperature, and COARE 2.6b derived skin temperature at buoy 42040 for 20-25 January, 2000 at 1800 CST.

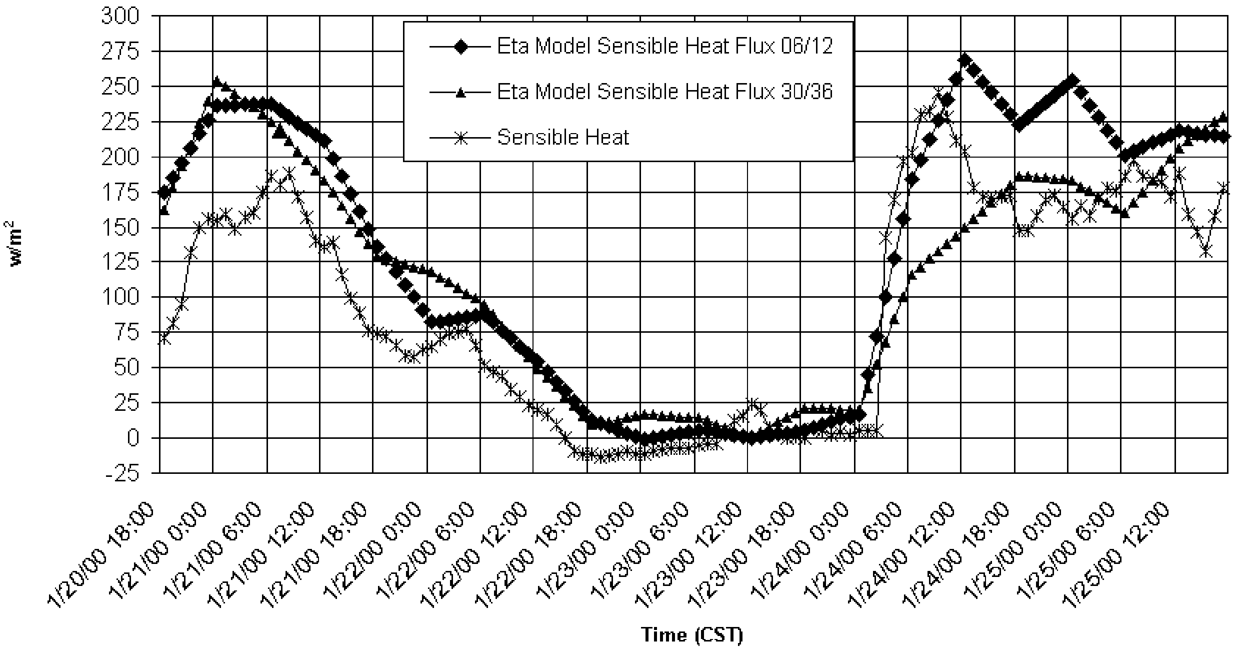

Figure 4. COARE 2.6b derived sensible heat flux at buoy 42040 and Eta model sensible heat flux simulations for the 6- and 12-hour (06/12) and 30- and 36-hour (30/36) forecast periods near buoy 42040 for 20-25 January, 2000 at 1800 CST. Note that the Eta model simulations are available every six hours at 0000, 0600, 1200, and 1800, and have been interpolated to hourly values.

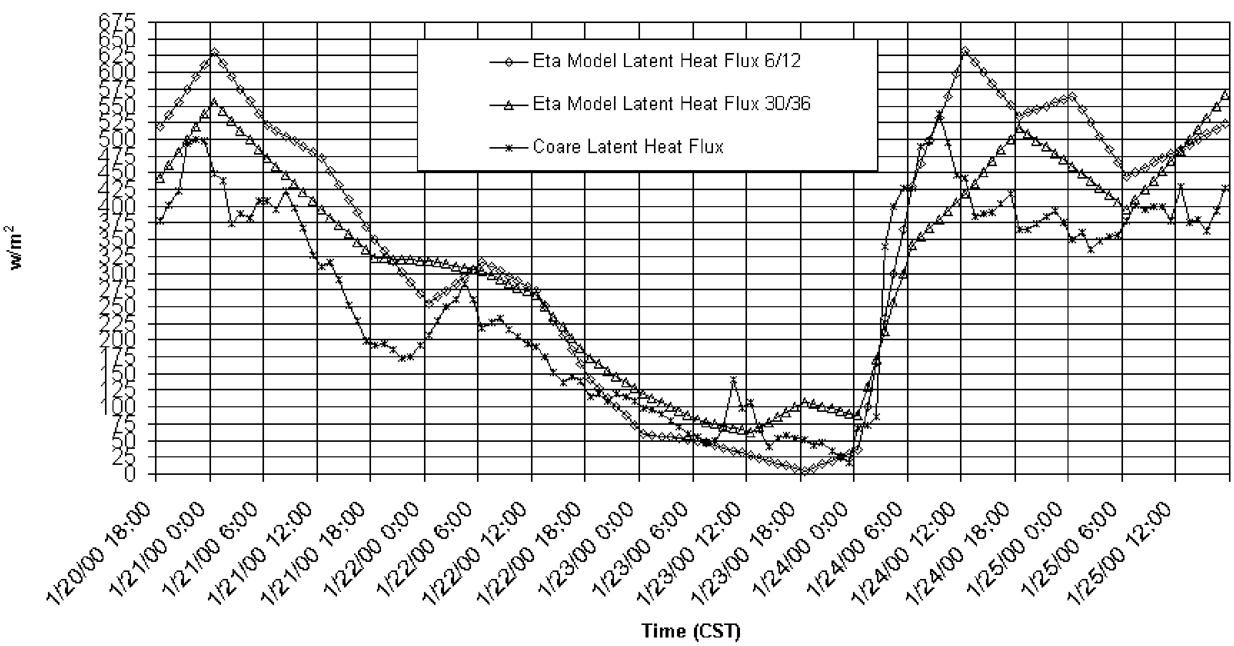

Figure 5. COARE 2.6b derived latent heat flux at buoy 42040 and Eta model latent heat flux simulations for the 6- and 12-hour (06/12) and 30- and 36-hour (30/36) forecast periods near buoy 42040 for 20-25 January, 2000 at 1800 CST. Note that the Eta model simulations are available every six hours at 0000, 0600, 1200, and 1800, and have been interpolated to hourly values.