16A.1 MODELING THE BOUNDARY LAYER OVER GALVESTON BAY AND THE GULF OF MEXICO FOR AIR POLLUTION STUDIES

Wayne M. Angevine[1,2], Mark Žagar[3], Sara C. Tucker[1,2], Chris Fairall[2], Ludovic Bariteau[1,2], Dan Wolfe[2], and Wm. Alan Brewer[2]
[1]Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado, Boulder, Colorado, USA
[2]NOAA Earth System Research Laboratory, Boulder, Colorado USA
[3]Meteorological Service of Slovenia, Ljubljana

1. INTRODUCTION

Coastal areas have large contrasts in mixing height which affect the transport of pollutants. Water warms and cools more slowly than land as the diurnal cycle proceeds. This also leads to sea breeze circulations. In the Houston/Galveston area, the large, shallow Galveston Bay intrudes into the otherwise northeast-southwest coastline. At times, a "Bay breeze" pattern distinct from the larger scale "Gulf breeze" can be distinguished. Because the most intense pollutant sources are near the Bay, this has important effects on concentrations of ozone and aerosol.

Gradients of pollutants can be very sharp, and the scales of important physical phenomena are also small, so rather fine resolution may be required to model these phenomena. The Advanced Research core of the Weather Research and Forecasting model (WRF-ARW) model system has been run for 75 days at moderate (5 km grid) resolution and for six days at fine (1.7 km grid) resolution. We show comparisons with mixing heights measured by Doppler lidar, and with surface fluxes, emphasizing modeling and measurements over the waters of the Bay and Gulf. The weakly convective boundary layer over the water is well captured. We find that the land surface behavior and initialization of the model are the most important items in producing realistic simulations.

Corresponding author: Wayne M. Angevine, NOAA ESRL R/CSD04, 325 Broadway, Boulder, CO 80305-3337, email: Wayne.M.Angevine@noaa.gov, tel: (303)497-3747

2. OBSERVATIONS

During the second Texas Air Quality Study (TexAQS II) in 2006, measurements of mixing heights, mixing strength, and surface fluxes were made from the NOAA Research Vessel Ronald H. Brown. During its deployment from 1 August – 12 September, the ship made several transects of the dredged channel running roughly north-south in Galveston Bay. It also transited the Houston Ship Channel between the Bay and downtown Houston several times, spent time in the Gulf of Mexico along the Texas coast, and tied up or kept station in dock areas. The primary meteorological instruments were the NOAA High Resolution Doppler Lidar (HRDL), radiosondes, and a surface flux package. The ship also carried a comprehensive package of gas-phase and aerosol chemistry instruments.

On land, the study was supported by radar wind profilers operated by several agencies, chemistry ground sites, and radiosonde launches. The airborne component included several aircraft.

Buoyancy flux observations for the entire ship deployment are shown in figures 1 and 2, separated according to whether the ship was in the Gulf or in the Bay. In both places, the flux is almost always positive but small. We might have expected to see negative fluxes in the afternoon and evening, when warm air may be advected off the land, but in fact the water temperatures (not shown) have a distinct diurnal cycle in phase with the sun, so the time of warmest air over land corresponds approximately to the time of warmest water. There is a hint of stronger positive fluxes when the wind is from the north, which most often occurred at night. Over the Bay, there are some larger fluxes in the daytime, which could be due to the influence of land, or to warmer water, since the Bay is quite shallow (about 2 m). Most of the data in the Bay were taken when the wind was easterly or southeasterly, giving a reasonable fetch (at least 10 km) over the water.

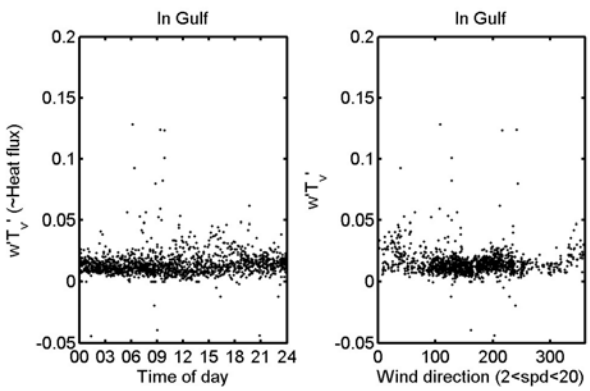

Figure 1: Buoyancy flux over the Gulf, by time of day (local standard time, left) and wind direction at the ship (right).

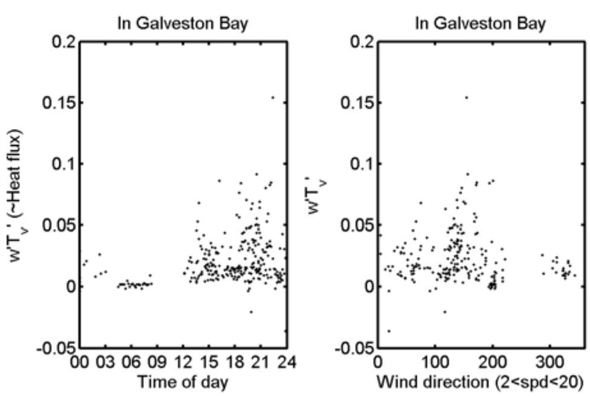

Figure 2: Buoyancy flux over the Bay, by time of day (local standard time, left) and wind direction at the ship (right).

Soundings taken over the Gulf, and especially over the Bay, usually show multiple layers. Finding a clearly-defined boundary layer is difficult. Often a change of wind direction is the clearest indication of a change of layer. The Doppler lidar (HRDL) provides more complete information that allows for greater confidence in defining the boundary layer. The availability of turbulence intensity information, in the form of velocity variances, is the most important addition. It allows us to distinguish between layers that *have been* mixed and layers that are *currently being* mixed.

A technique combining backscatter intensity, wind speed and direction, and vertical velocity variance yields the average mixed layer heights shown in figure 3. Over the Gulf, there is no diurnal cycle, and the mixed layer averages about 600 m deep. In the Bay, there is a weak diurnal cycle in the mean, and the average depth is 400 – 800 m. There is little data at night because the ship was not able to be in the Bay at night. In areas very near or surrounded by land (Barbour's Cut and the Houston Ship Channel), a more or less normal diurnal cycle of mixed layer height is seen.

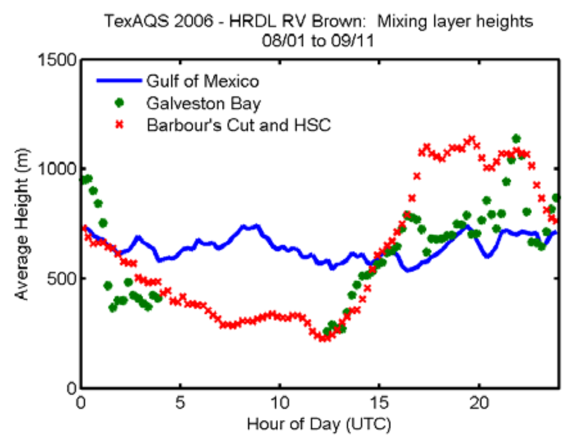

Figure 3: Average mixed layer heights from HRDL by time of day and location.

3. SEPTEMBER 1, 2006 CASE STUDY

The strongest ozone measured during the TexAQS II campaign, and during the 2006 ozone season in Houston, was on 1 September 2006. The ship saw over 180 ppbv in the northern Bay around 1200 LST (1800 UTC). Pollutants were emitted from the industrial concentration around the Ship Channel, advected to the east by light morning winds, and reacted in the fairly shallow mixed layer over the Bay. After noon, the winds shifted, first to east (from the Bay) and then to southeast (from the Gulf), pushing the ozone blob back over Houston.

To simulate the key features, we used a WRF –ARW model setup with nested 15, 5, and 1.67 km grid spacing. The inner grid was 180 points square, centered over Houston. Sixty vertical levels were used. Data from three radar wind profilers was assimilated using FDDA.

Selecting the "best" analysis to initialize the model turned out to be important. We experimented with NAM, GFS, and ECMWF analyses at various analysis times. The 1 September case has non-trivial synoptic forcing, and all the analyses have slightly different synoptic-scale fields, which make important differences in the small-scale features produced by our WRF runs. We settled on the ECMWF analysis at 0Z as the best choice for this case.

The other very important item was the land surface. The default settings gave temperatures that were too cool over the land by several degrees at midday. This completely prevented the development of a sea breeze. After much experimentation, we used the 5-level "slab" land surface scheme, and arbitrarily reduced the soil moisture parameters for most land use types to tune the land surface temperatures.

Figures 4 and 5 show the simulated 10 m winds at noon LST (1800 UTC) and 1700 LST (2300 UTC). The simulation captures the key features, the divergence over the Bay, bay breeze, and gulf breeze. The bay breeze does not penetrate quite far enough to the west into the metropolitan area, nor does the gulf breeze penetrate quite far enough north. The winds in the northern Bay veer somewhat too much compared to observations.

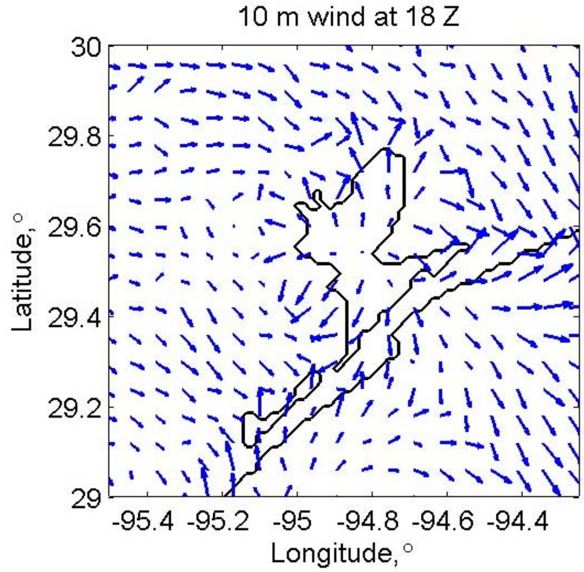

Figure 4: Winds at 10 m AGL in the WRF simulation at 18Z (1200 LST).

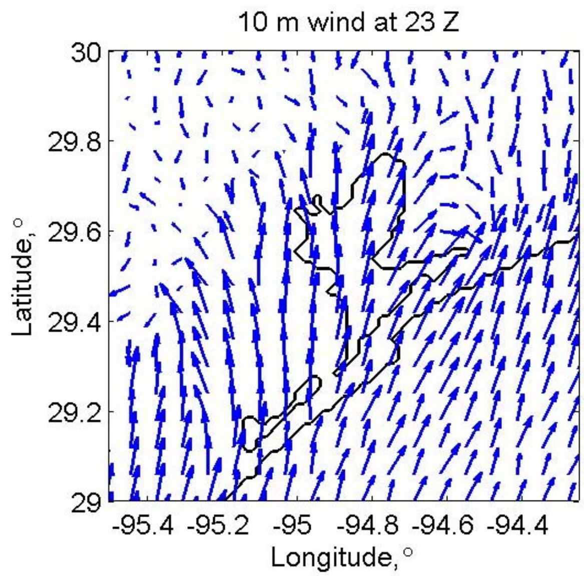

Figure 5: Winds at 10 m AGL in the WRF simulation at 23Z (1700 LST).

4. MODEL – MEASUREMENT COMPARISONS FOR 29 AUGUST AND 1 SEPTEMBER

The winds and transport patterns produced by the model depend on its representation of the atmospheric boundary layer over both land and water. Here we emphasize the over-water boundary layer, which has received little attention in past studies due to a scarcity of observations. Figures 6 and 7 show mixing layer heights and buoyancy fluxes for a day when the ship was in the Gulf (29 August) and a day when it made several transects up and down the Bay (1 September). The observed heights are from the High Resolution Doppler Lidar (HRDL) [Tucker et al., 2008, manuscript submitted to J. Atmos. Technol.] aboard the NOAA Research Vessel Ronald H. Brown. The lidar data at the finest available time resolution (15 min) show a great deal of real atmospheric variability. Because the ship is moving through strong gradients of mixing height and fluxes, we have chosen not to further average the measurements. Buoyancy fluxes at the surface were measured by the NOAA flux system on RV Brown, and reported every 10 minutes. The corresponding fluxes from the model were again taken from the nearest hour and nearest grid point.

The simulated mixing layer heights are broadly consistent with those observed. At midday (1500-2000 UTC) on 29 August (figure 6a), the model underestimates the mixing height relative to the observations, although it is consistent with the lowest of them. On 1 September (figure 7a), the model overestimates the heights in the morning (1000-1500 UTC).

Simulated buoyancy fluxes are in the same range as the observations, with small positive fluxes everywhere over the water at all times. However, the diurnal pattern on 29 August (figure 6b) is opposite to that observed. The model underestimates the wind speed overnight and overestimates it in the afternoon (figure 7c), leading to the erroneous flux magnitudes. Wind directions (figure 6d) are very well simulated along the ship track except in the afternoon during a wind shift. The wind shift is captured in general, but the details of timing, wind speed, and location differ between measurement and simulation. Near-surface air temperatures agree well except in the afternoon, when the model fails to capture the observed warming. Water surface temperatures are slightly underestimated in the model overnight, agree well in the morning, and are substantially underestimated in the afternoon. The modeled buoyancy flux stays roughly in the correct range in the afternoon because of the offsetting errors in the temperatures.

On 1 September, the ship was in the Gulf of Mexico off Galveston during the night, and then made three transits of the Bay between 1400 and 2300 UTC. At night, the model overestimates the buoyancy flux, as it also does on the first transit after 1400 UTC (figure 7b). The overestimated fluxes correspond to overestimates of mixing height mentioned above. In the afternoon, the flux agreement is better. In any case, both measured and simulated fluxes remained small and positive. The diurnal pattern of near-surface air temperature and water surface temperature is similar to that shown for 29 August, with the model again underestimating both temperatures in the afternoon. The water surface temperature is crudely represented in the model. It varies only with position and not with time.

To illustrate pollutant transport, trajectories are commonly used. They provide an integrated view of the wind field as it affects a particular parcel. As an example of the complex trajectories followed by polluted air parcels in this coastal environment, figure 8 shows backward trajectories calculated from the simulated winds at two heights in the lower boundary layer. The starting point is the time and place of the peak ozone measured on the ship, approximately 180 ppbv, near the northern end of the Bay, at 1800 UTC on 1 September. According to the simulation, the air near the surface traveled across the Houston Ship Channel area, picking up large amounts of ozone precursors. It then traveled over the Bay and reversed direction, all the while undergoing photochemical processing. This is a very simple calculation of a single trajectory, on constant model vertical levels only, but it is consistent with the measurements.

5. SUMMARY

The boundary layer over Galveston Bay and the Gulf of Mexico near the Texas coast during August and September 2006 was almost always weakly mixed, with small positive buoyancy flux night and day. Mixed layer depths were 300-600 m most of the time, with no diurnal cycle in the Gulf and a small average diurnal cycle in the Bay. The lower and more weakly mixed boundary layer over the Bay plays a role in strong ozone events in Houston by keeping morning emissions confined.

Simulations with WRF captured the key features of the wind field, including the divergence over the Bay, bay breeze, and gulf breeze. The simulations also showed reasonable agreement with measured mixing heights and surface fluxes. The over-water boundary layer remained in the correct weakly stable regime despite some differences in details. The initial analysis and land surface behavior were the most important items in getting good simulations.

ACKNOWLEDGEMENTS:

We are most grateful to the officers and crew of the Ronald H. Brown for their flexibility in undertaking this unusual mission; to the scientists and engineers who built and operated HRDL, and who launched radiosondes from the ship; and to Bryan Lambeth and Ben Coughran from the Texas Commision on Environmental Quality, who oversaw the LaPorte wind profiler and provided its data.

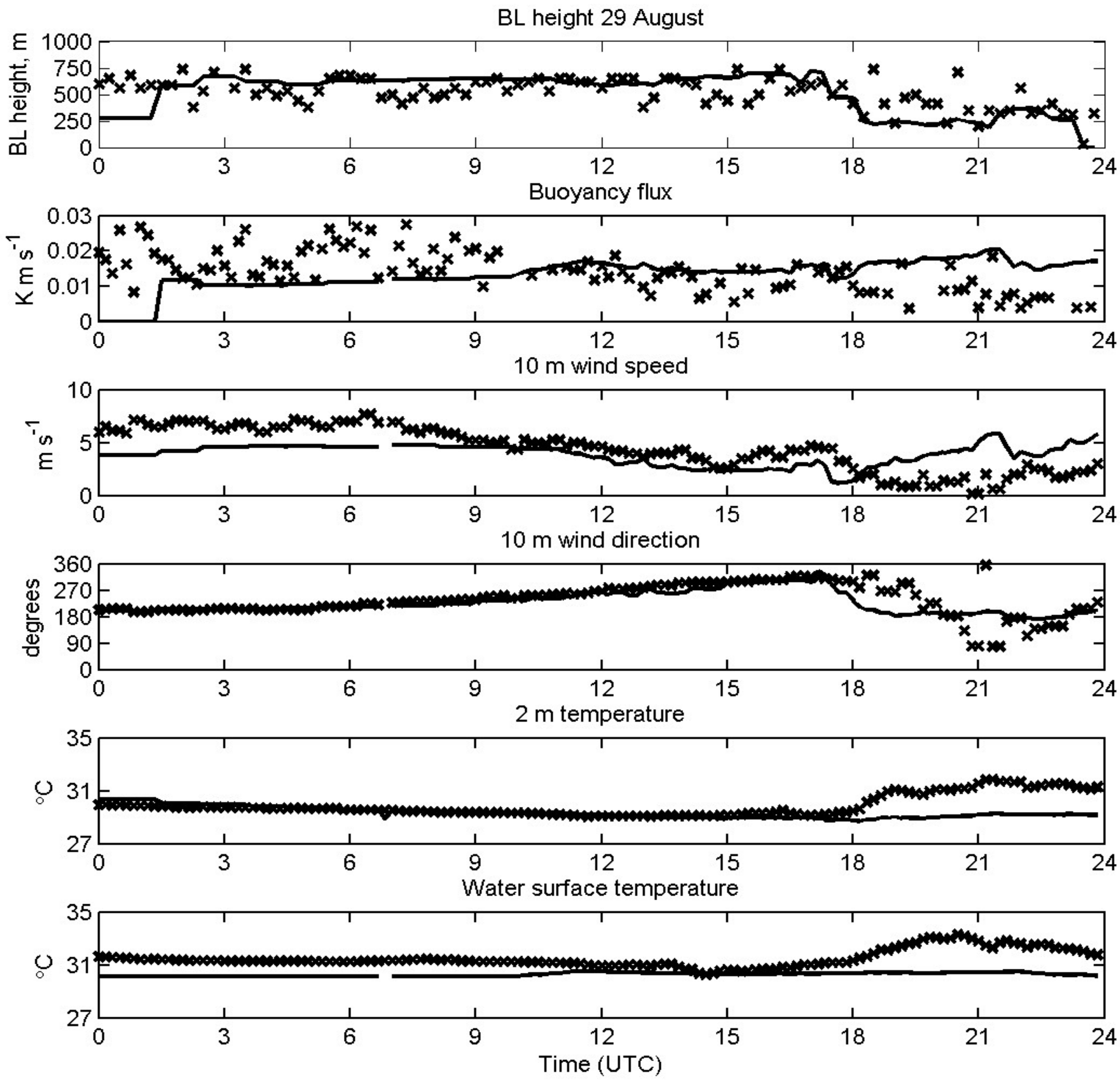

Figure 6: Parameters measured on the ship and simulated by the model on 29 August. Solid lines are the model result and x marks are the measurements. a) Mixing layer heights (measurements from HRDL). b) Buoyancy fluxes. c) Wind speed at 10 m ASL (in-situ measured). d) Wind direction at 10 m ASL. e) 2 m air temperature (model) and 13 m air temperature (measurement). f) Water surface temperature.

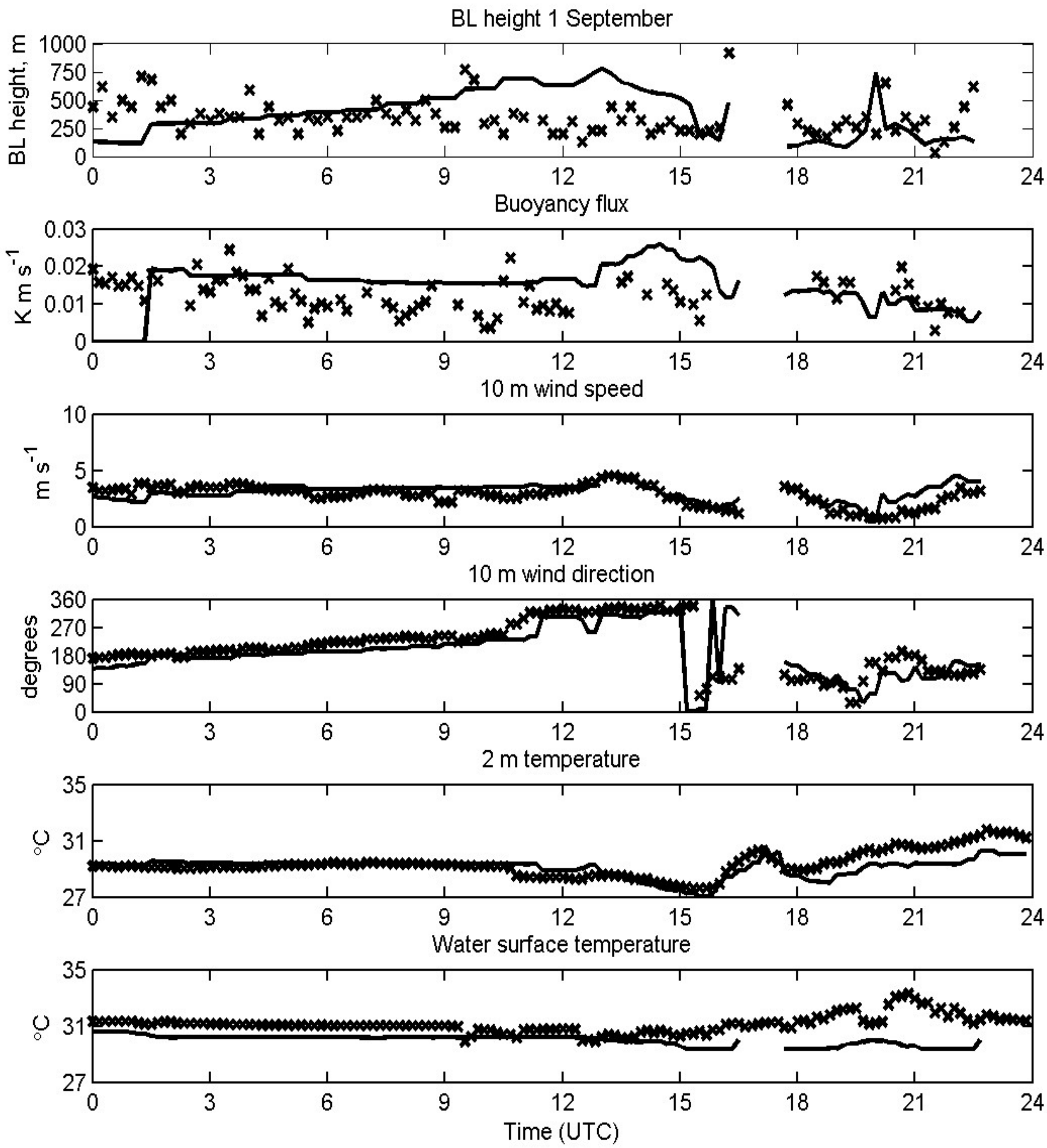

Figure 7: As figure 6 for 1 September.

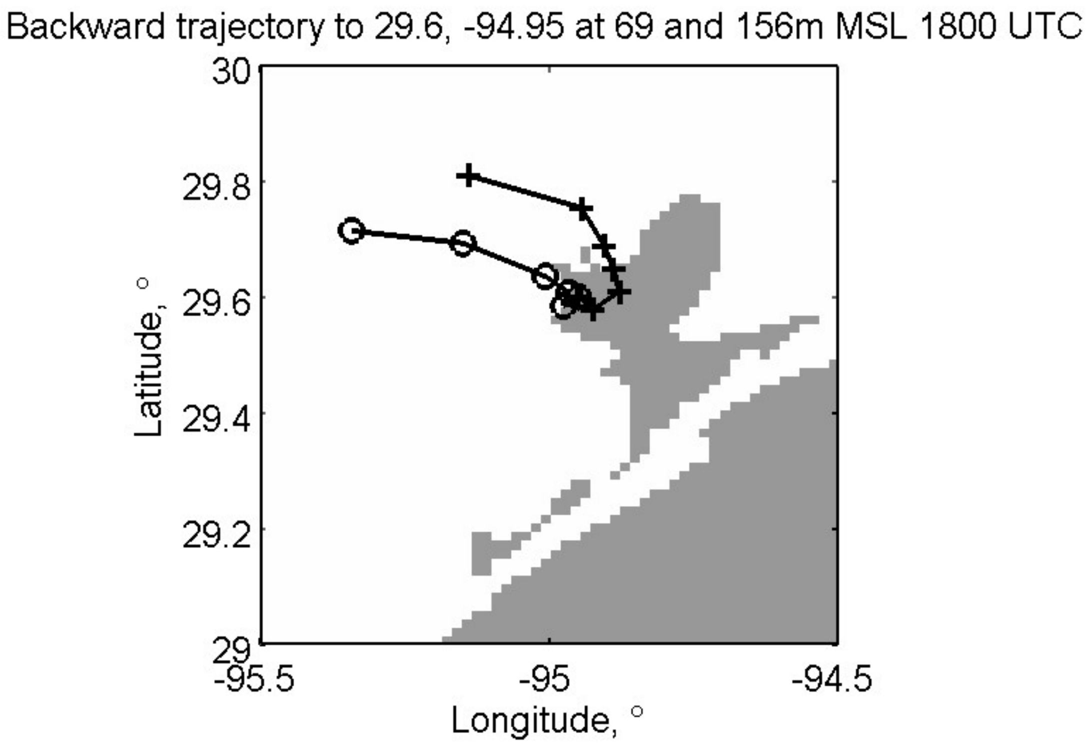

Figure 8: Backward trajectories at the time and place of peak ozone observed at the ship on 1 September. Plus signs mark trajectory at 69 m ASL, circles at 156 m ASL, with marks every hour.