J1.8 STRUCTURE AND FORMATION OF THE HIGHLY STABLE MARINE BOUNDARY LAYER OVER THE GULF OF MAINE

Wayne M. Angevine[1,2], Jeff Hare[1,2], Chris Fairall[2], Dan Wolfe[2], Alan Brewer[2], and Allen B. White[1,2]
[1]Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado,
Boulder, Colorado, USA
[2]NOAA Earth System Research Laboratory, Boulder, Colorado USA

1. INTRODUCTION

The cool waters of the Gulf of Maine cause a shallow stable boundary layer to form in the summer whenever air flows from the adjacent land. Since the prevailing winds are westerly, these stable boundary layers are very common in summer. The structure of the boundary layer controls the transport of pollutants emitted on the continent. In particular, emissions from the urban corridor of the northeastern United States can be efficiently transported long distances (Neuman et al. 2006). Strong concentrations of urban-source pollution routinely reach the coast of Maine, hundreds of kilometers from concentrated sources. Transport as far as Europe in the lower atmosphere has been observed.

Previous papers have described the basic structure of this boundary layer and its effects on pollutant transport. They emphasized observations (Angevine et al. 2004) and mesoscale modeling (Angevine et al. 2006). The observations showed a remarkable degree of similarity of temperature profiles in the lower atmosphere over the Gulf of Maine, nearly regardless of the distance from shore, the transport time, or the time of day when the air left the coast. The key question left unresolved is this: How is the stable boundary layer formed? We will describe the processes that produce the observed profiles, as we have come to understand them from additional measurements and analysis.

In July and August 2004, the International Consortium for Atmospheric Research into Transport and Transformation (ICARTT) was the umbrella for a large-scale study in the northeastern United States, Canada, and the North Atlantic. The part of that study focussed on regional air quality in northern New England (New Hampshire, Maine, and the Gulf of Maine) was called the New England Air Quality Study (NEAQS) 2004. The NOAA Research Vessel *Ronald H. Brown* was a key component of NEAQS 2004. The ship was heavily instrumented for in-situ measurements of gas-phase and aerosol atmospheric chemistry. Meteorological instrumentation included a Dopper lidar, a radar wind profiler, rawinsonde equipment, and a surface flux package. The flux package was the major addition since the NEAQS 2002 study described in our earlier papers.

A few studies of warm air flow over cool water have appeared in the literature (Rogers et al. 1995; Smedman et al. 1997a; Smedman et al. 1997b). The air-sea temperature differences observed here are substantially larger than those studied by other groups, although (Smedman et al. 1997a) did include one case with similar conditions.

2. INVESTIGATING STABLE BL FORMATION: 15-16 JULY

The ship was nearly stationary approximately 10 km offshore from 2000 UTC 15 July until 12 UTC 16 July. During these 16 hours, the wind started at SE and veered to SW where it remained for most of the period.

Figure 1 shows two soundings measured by rawinsondes launched from the ship. Virtual potential temperature, the correct quantity to describe static stability, is plotted. Both the evening and morning soundings show statically stable boundary layers. The sondes are launched from the deck of the ship, and therefore don't show the additional stable temperature difference that exists between the deck and the sea surface. The air temperature over land 10 km upwind of the ship differs by approximately 15 degrees between the times of these two soundings, so how does it come to be that the soundings themselves are so similar?

In figure 2, micrometeorological measurements from the ship during the stationary period are plotted. Three distinct sub-periods can be seen.

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

First, from 2000 UTC 15 July (1500 LST, day 197.84) until 0000 UTC 16 July (1900 LST, day 198.0), the sea surface is substantially (4-6 K) cooler than the air at 15 m. The wind at 15 m is 3-7 m s^{-1}. The sensible heat flux is very small, and the vertical velocity variance (a proxy for turbulence intensity) is moderate. This is the time when a convective boundary layer exists over land, with warm air, light winds due to turbulent mixing, and moderate to strong turbulence. In the next period, from 0000 UTC to 0400 UTC (2300 LST, day 198.17) the sea-air temperature difference is less pronounced, the wind is stronger, the heat flux is larger in magnitude (more negative), and the turbulence intensity is decreasing. During this time, the boundary layer over land is cooling and becoming stable, and its turbulence is decreasing. Finally, from 0400 UTC to 1200 UTC (0700 LST, day 198.5), the sea-air temperature difference holds steady at about -3 K, the wind speed decreases slowly, the heat flux is again very small, and the turbulence intensity is also small. This corresponds to a fully-formed stable nocturnal boundary layer over the land.

The most interesting thing about these observations is what we don't see: There is no period of large negative heat flux that would account for the cooling of the lowest few hundred meters of the temperature profile in the afternoon and evening, when the air over the land is very warm. The winds measured at the ship are definitely offshore, so the column must be cooled before it reaches the ship. The transport time from shore, based on the surface wind measurements at the ship, is only about 20 minutes. Even during the period with the largest negative heat flux, that flux is only sufficient to cool a 100-m layer by 0.2 K during the transport. The observed cooling, assuming a well-mixed layer over land, is approximately 15 K. We must conclude that the cooling is already nearly over before the air reaches the ship.

Wind profiles above the ship are shown in figure 3. One hour-averaged profile is shown from each of the sub-periods mentioned above. In the first period (2130 UTC profile) there is strong directional shear below 50 m and above 150 m. Later, in the 0130 UTC profile, there is little directional shear in the low levels, but a very substantial increase in wind speed with increasing height. Finally, the 0930 profile again has a substantial directional shear between the surface and 250 m, and also a very strong increase in speed with height. Shear measures are shown hourly for the entire period in figure 4. Directional shear in both layers (6-100 m and 6-500 m) is greatest in the early sub-period, when the air-sea temperature difference is large, surface wind speed low, heat flux small, and turbulence most intense. This early sub-period has, however, the smallest vector shear in the 6-100 m layer. The middle sub-period, with moderate air-sea temperature difference, stronger surface winds, larger (negative) heat flux, and decreasing turbulence intensity, has little directional shear and moderate vector shear in the 6-100 m layer. The vector shear then remains roughly constant while the directional shear in the 6-100 m layer increases for the later sub-period, when the air-sea temperature difference is small, surface wind speeds decreasing, and heat flux and turbulence intensity are small.

3. A BROADER RANGE OF CONDITIONS: 30 JULY – 1 AUGUST

For a broader perspective, we present measurements from the three-day period 30 July – 1 August. During this time, the ship explored the Gulf of Maine between Cape Ann and mid-coastal Maine, with some excursions farther offshore (figure 5). The sea surface temperatures varied by up to 7 K. At the surface, the flow was offshore from the southwest. Transport times from the coast to the ship were 3-12 hours, based on surface wind speeds. Soundings during the period (figure 6) are again remarkably similar, with strong, shallow, surface-based statically stable layers. The surface-based stable layers are all approximately 100 m deep. The next layer above, the "intermediate layer," is also statically stable but much less so. In several soundings, more than one distinct layer can be seen below 2 km. Again, we note that the layer below the minimum height of the soundings is also statically stable, with sea-air temperature differences of 1-7 K (figure 7). The micrometeorological measurements in figure 7 show a range of wind speeds, turbulence intensities, and heat fluxes. The heat flux and vertical velocity variance are correlated with wind speed but not with the temperature difference. Heat flux magnitudes are in the range expected for well-developed stable boundary layers.

Selected wind profiles from 30 July – 1 August are shown in figure 8. Many of the profiles have pronounced low-level jets (wind speed maxima above the surface but below ~500 m). Such jets are ubiquitous in stable boundary layers, but the mechanisms contributing to their formation are still an active topic of research (Chimonas 2005; Lundquist 2003). For our purposes, it is sufficient to note that the wind speed at or below 100 m may be substantially faster than at slightly higher levels. There is almost always some directional shear between 6 m and 100 m (figure 9), although in the middle part of the period it is relatively small. Directional shear between 6 m and 500 m is, as expected, larger than in the shallower layer. Because of the common jet structure, the vector shear is sometimes less between 6 m and 500 m than between 6 m and 100 m.

4. DISCUSSION AND CONCLUSIONS

Various classification schemes have been advanced for stable boundary layers. For example, Mahrt et al. (1998) set forth three categories: weakly stable, transition, and very stable. The classification is based on the stability parameter z/L, where z is the measurement height and L is the Obukhov length. During the 15-16 July period, the boundary layer at the ship was always very stable, with z/L greater than 1 (based on the inertial dissipation flux measurements). On 30 July – 1 August, the boundary layer was very stable early and late in the period. In the middle of the period, the boundary layer was in a transitional stability regime, with $0.1<z/L<1$.

According to the stability classification, the very stable boundary layer ($z/L>1$) should be only intermittently turbulent. However, the boundary layers observed from the ship during these periods seem to be continuously (albeit weakly) turbulent. Richardson numbers (bulk or flux) calculated from the ship measurements are always less than 0.25, generally less than 0.1. In the absence of any clear guidance in the literature, we take 0.25 as a reasonable estimate of the critical value below which turbulence should be produced.

We find that the stable boundary layer forms very quickly in flow off the land during the day, as shown at 0100 UTC on 16 July. We see a temperature difference of 10 K between the sea surface and the air at 100 m. The transport time from land is only 20-30 minutes. Clearly the small local heat flux is insufficient to cool the layer so rapidly. To cool the layer by the measured amount in 30 minutes requires a downward heat flux of approximately 150 W m^{-2} . The observed profiles are strongly concave upward, that is, the surface layer is cooled much more than the rest of the new marine boundary layer. The only plausible source of the turbulence required to accomplish this cooling is advected turbulence (Mahrt et al. 2001; Vickers et al. 2001). Briefly stated, the vigorous convective turbulence over land continues for a few eddy turnover times (20-30 minutes) after the surface heating (and therefore turbulence production) has been cut off by the air's passage over the shoreline. This decaying turbulence works against the increasing static stability to provide the mixing required to cool the layer.

Wind profiles observed over the Gulf of Maine commonly show substantial directional and vector shear between the surface and 100 m, and even greater directional shear between the surface and 500 m. Directional shear was less in the moderately stable regime (31 July) than in the strongly stable regimes before and after, while vector shear between the surface and 100 m was greater in the moderately stable sub-period. The entire 15-16 July period was very stable, but the directional shear in the layer below 100 m was least when heat flux magnitude was greatest (even though the flux was small).

Pollutant transport in this boundary layer cannot be modeled or understood without capturing this vertical structure in the winds. Modeling at 2.5 km grid spacing with a fine vertical grid captures some, but not all, of the important effects (Angevine et al. 2006). The model developed a stable boundary layer, but not as quickly (not as close to shore) as in reality, and the modeled layer was less stable and deeper than observed. The wind shear was also less than observed. If chemical transport is being modeled, the less stable boundary layer in a model may result in decreased isolation of the layers aloft from the surface, and therefore less efficient long-range transport than that described by (Neuman et al. 2006).

Few or no clouds were present during the periods discussed here. During other periods of the ICARTT study, low clouds and fog were common. Fog and low clouds occurred primarily when the flow was not from the U.S. east coast. The boundary layer structure under those conditions is likely to be quite different than that described here.

REFERENCES

Angevine, W. M., M. Tjernstrom, and M. Zagar, 2006: Modeling of the coastal boundary layer and pollutant transport in New England. *Journal of Applied Meteorology and Climatology*, **45,** 137-154.

Angevine, W. M., C. J. Senff, A. B. White, E. J. Williams, J. Koermer, S. T. K. Miller, R. Talbot, P. E. Johnston, S. A. McKeen, and T. Downs, 2004: Coastal boundary layer influence on pollutant transport in New England. *J. Appl. Meteor.*, **43,** 1425-1437.

Chimonas, G., 2005: The nighttime accelerations of the wind in the boundary layer. *Bound.-Layer Meteor.*, **116,** 519-531.

Lundquist, J. K., 2003: Intermittent and elliptical inertial oscillations in the atmospheric boundary layer. *J. Atmos. Sci.*, **60,** 2661-2673.

Mahrt, L., J. Sun, W. Blumen, A. C. Delany, and S. Oncley, 1998: Nocturnal boundary-layer regimes. *Bound.-Layer Meteor.*, **88,** 255-278.

Mahrt, L., D. Vickers, J. Sun, T. L. Crawford, G. Crescenti, and P. Frederickson, 2001: Surface stress in offshore flow and quasi-frictional decoupling. *J. Geophys. Res.*, **106,** 20,629-20,639.

Neuman, J. A., D. D. Parrish, M. Trainer, T. B. Ryerson, J. S. Holloway, J. B. Nowak, A. Swanson, F. Flocke, J. M. Roberts, S. S. Brown, H. Stark, R. Sommariva, A. Stohl, R. Peltier, R. Weber, A. Wollny, D. T. Sueper, G. Huebler, and F. C. Fehsenfeld, 2006: Reactive nitrogen transport and photochemistry in urban plumes over the North Atlantic Ocean. *J. Geophys. Res.*, **submitted**.

Rogers, D. P., D. W. Johnson, and C. A. Friehe, 1995: The stable internal boundary layer over a coastal sea. Part I: Airborne measurements of the mean and turbulence structure. *J. Atmos. Sci.*, **52,** 667-683.

Smedman, A.-S., H. Bergstroem, and B. Grisogono, 1997a: Evolution of stable internal boundary layers over a cold sea. *J. Geophys. Res.*, **102,** 1091-1099.

Smedman, A.-S., U. Hoegstroem, and H. Bergstroem, 1997b: The turbulence regime of a very stable marine airflow with quasi-frictional decoupling. *J. Geophys. Res.*, **102,** 21,049-21,059.

Vickers, D., L. Mahrt, J. Sun, and T. L. Crawford, 2001: Structure of offshore flow. *Mon. Wea. Rev.*, **129,** 1251-1258.

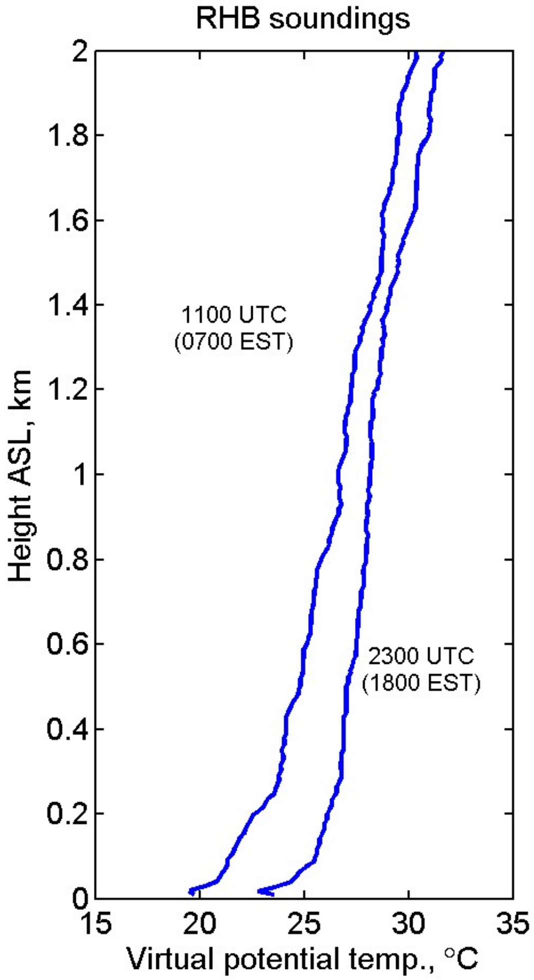

Figure 1: Soundings from the ship during the stationary period.

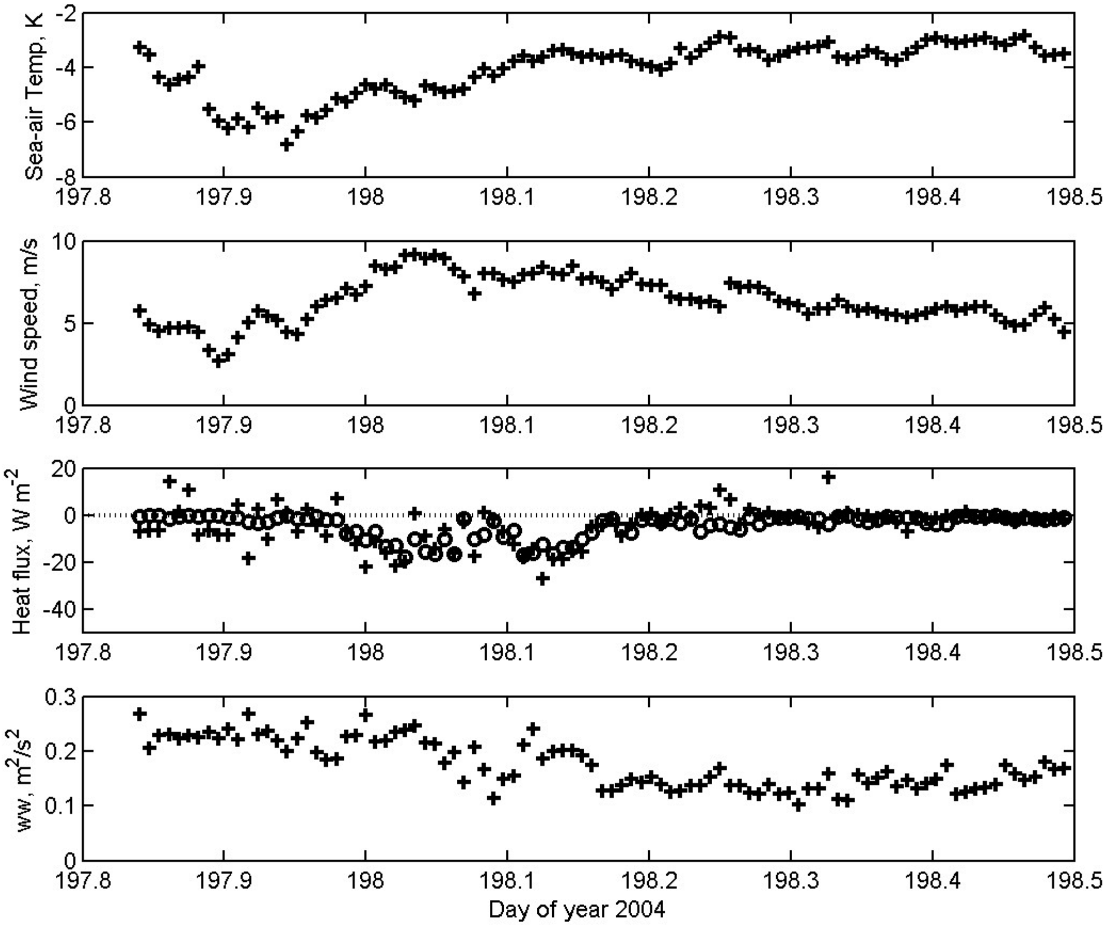

Figure 2: Micrometeorological measurements from the ship's flux package during the stationary period. Time is in UTC, day of year 198 is 16 July. Two heat fluxes are shown, eddy covariance method (plus signs) and inertial dissipation method (circles).

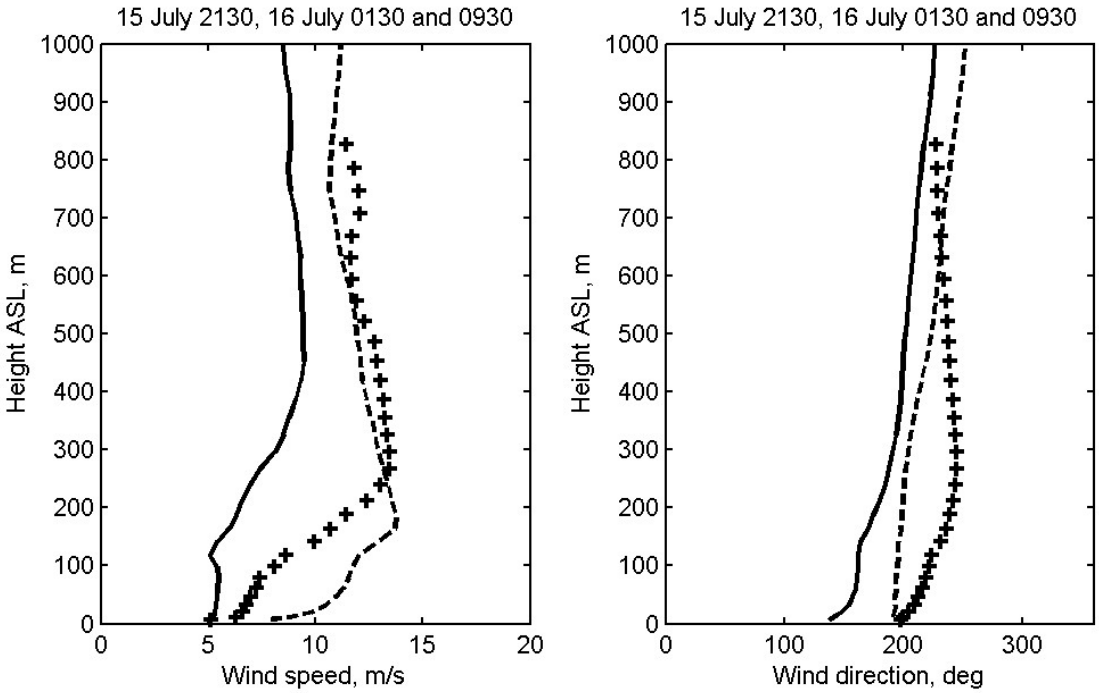

Figure 3: Wind profiles measured above the ship at 2130 UTC 15 July (solid), 0130 UTC 16 July (dashed), and 0930 UTC 16 July (plus symbols). Profiles are 1-hour averages centered at the specified time, using lidar measurements up to about 500 m and wind profiler data above.

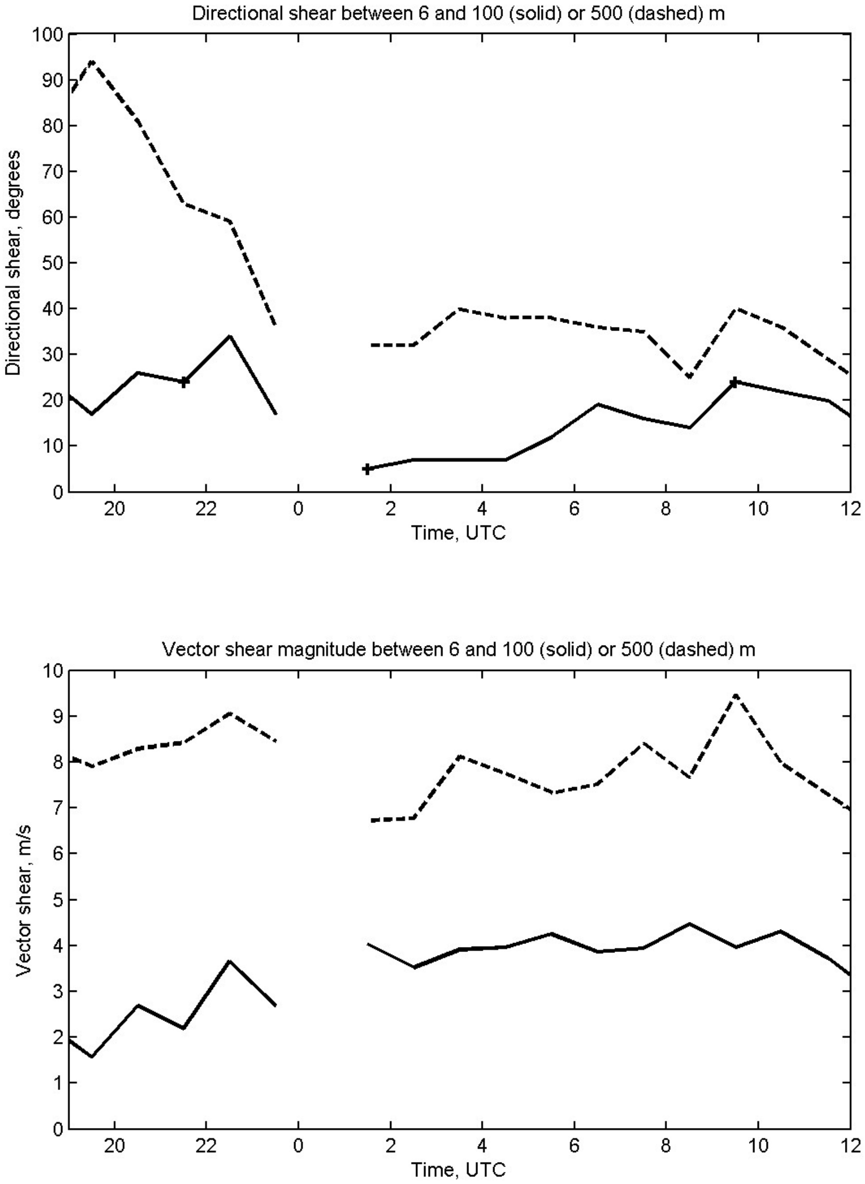

Figure 4: Two measures of wind shear above the ship starting at 1900 UTC 15 July. Solid lines are shear between 6 m and 100 m, dashed lines are shear between 6 m and 500 m. Upper panel shows directional shear (difference in wind direction, upper level minus lower level), lower panel shows the magnitude of the shear vector.

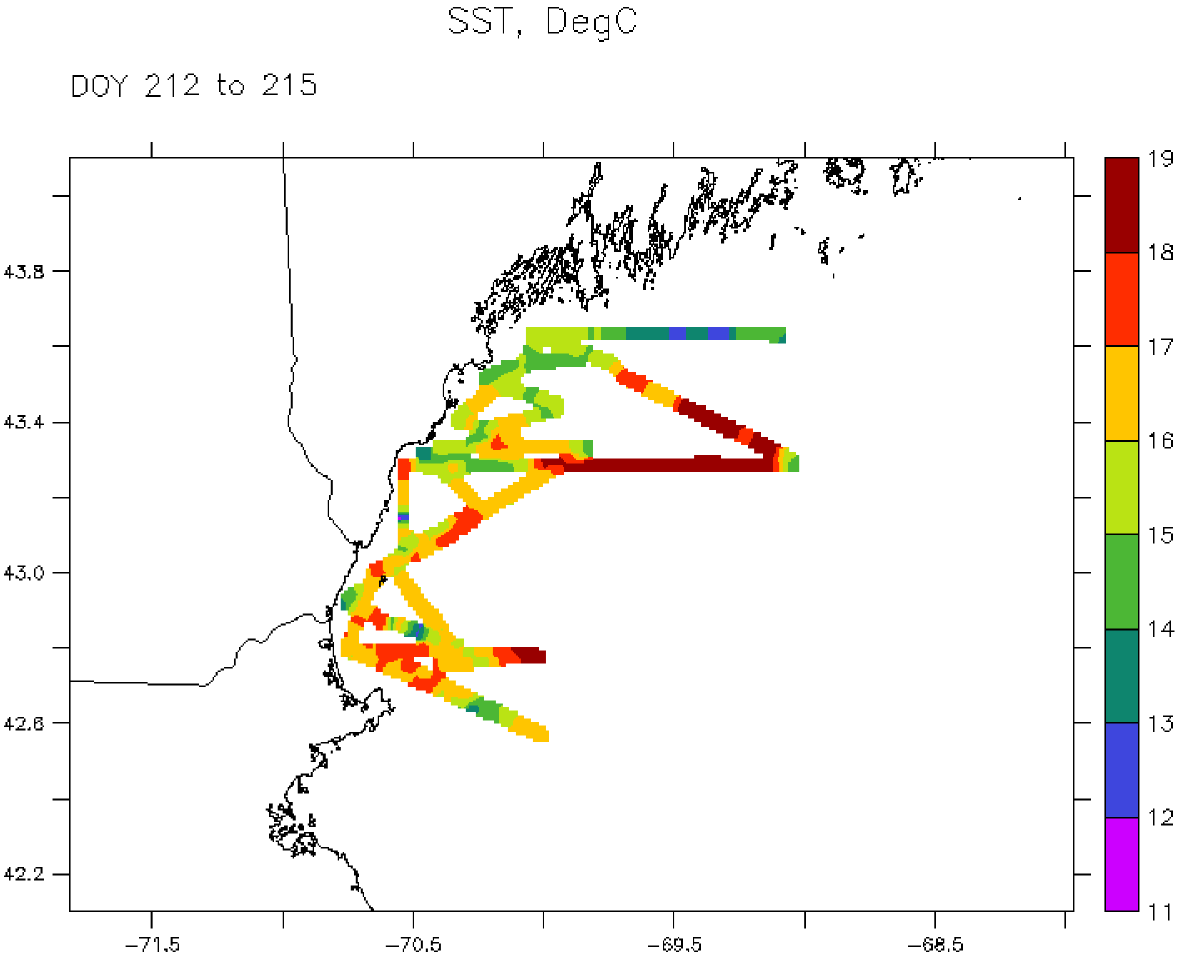

Figure 5: Sea surface temperature along the cruise tracks for 30 July-1 August 2004.

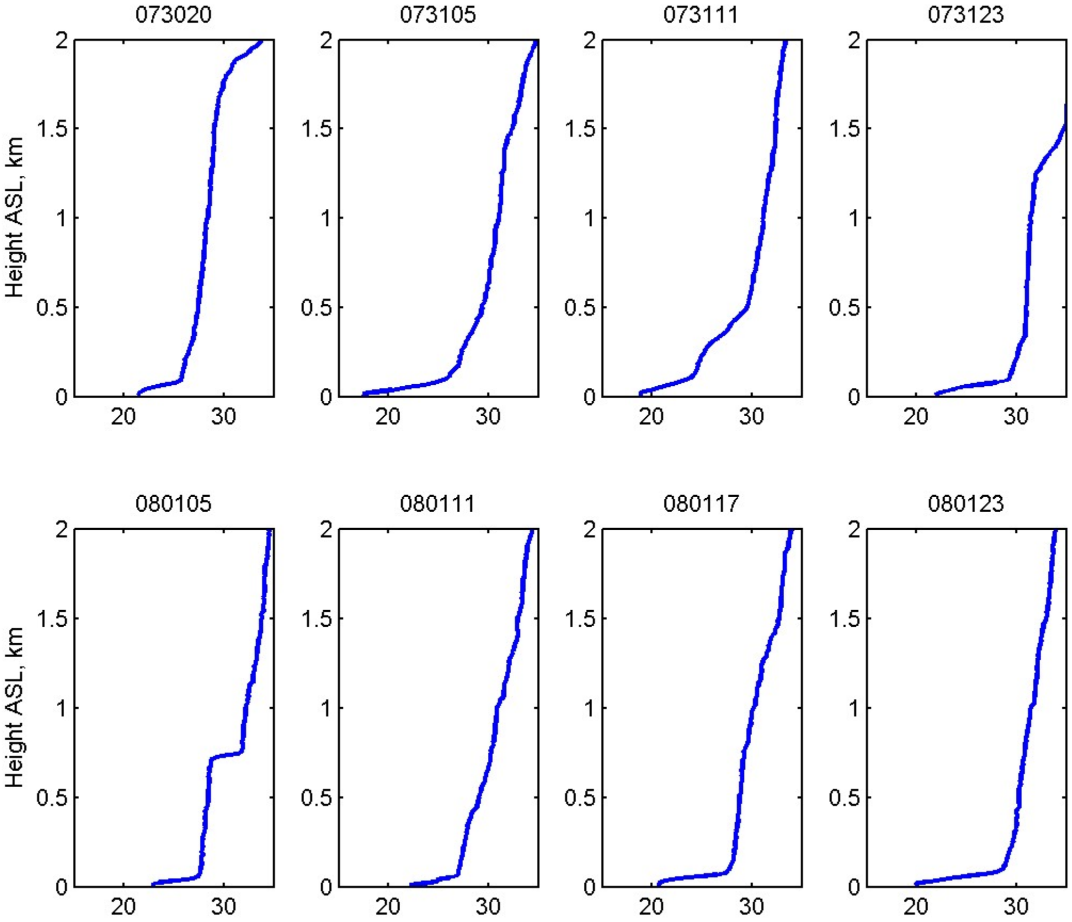

Figure 6: Virtual potential temperature soundings from the ship on 30 July - 1 August. From upper left to upper right, the sounding times are 2000 UTC 30 July, 0500, 1100, and 2300 UTC 31 July. From lower left to lower right, times are 0500, 1100, 1700, and 2300 UTC 1 August.

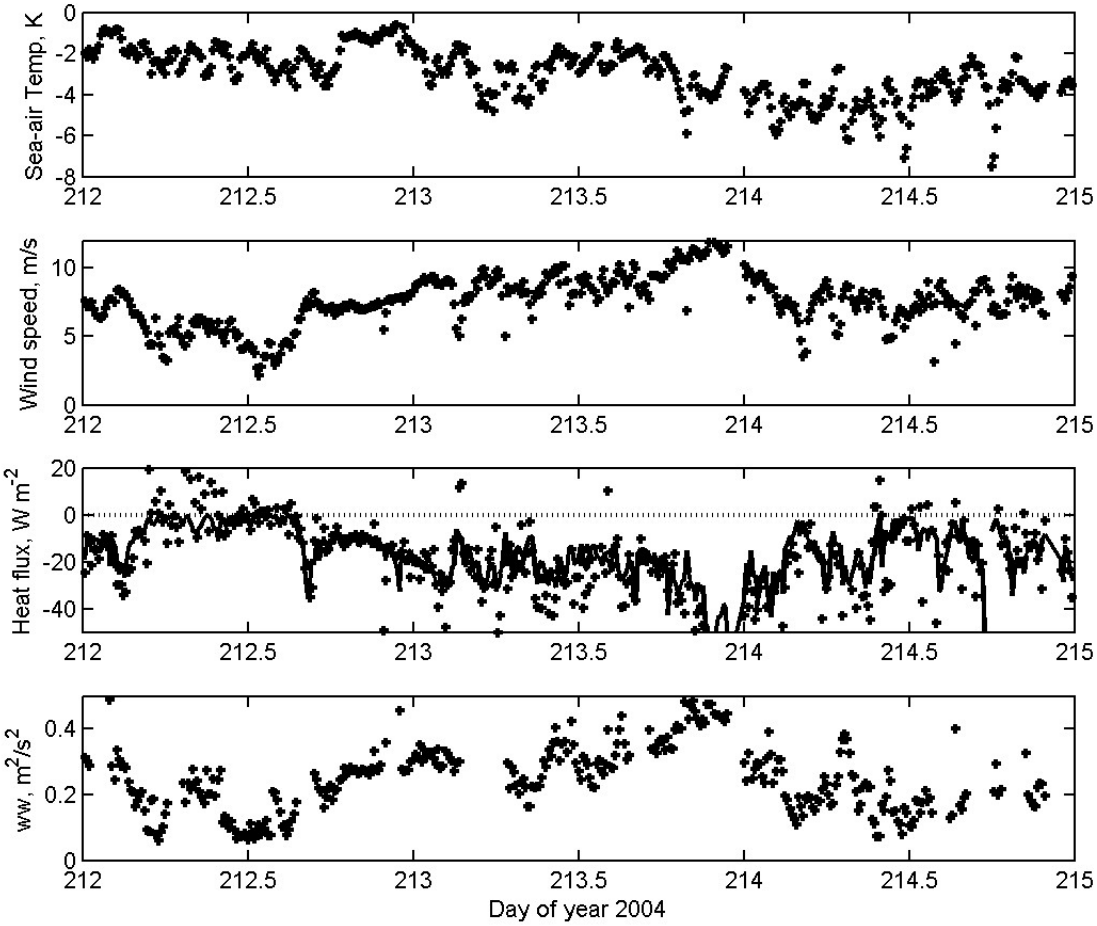

Figure 7: Micrometeorological measurements from the ship on 30 July - 1 August. Two heat fluxes are shown, eddy covariance method (plus signs) and inertial dissipation method (line).

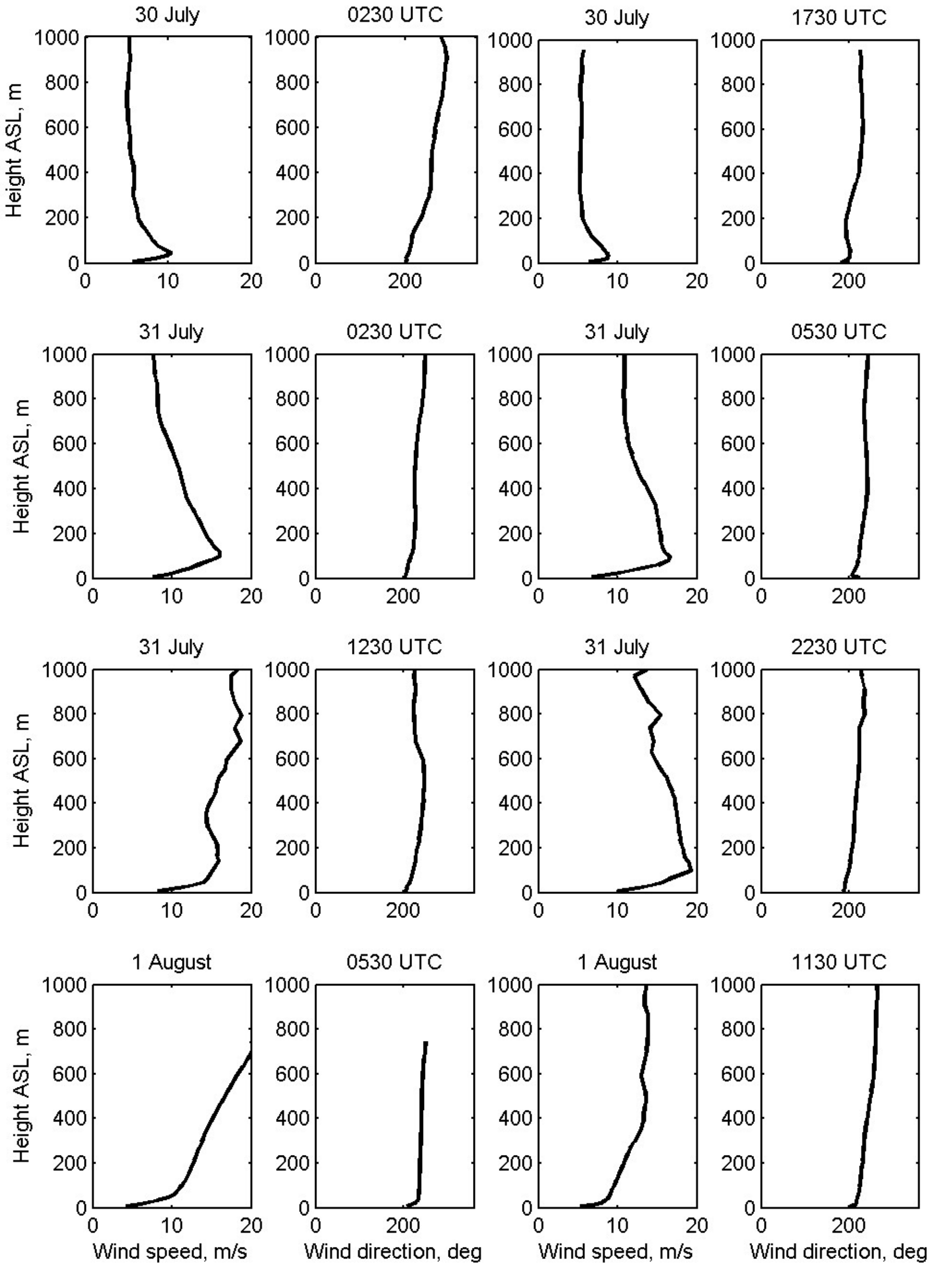

Figure 8: Wind speed and direction profiles at selected times during 30 July - 1 August.