6.6 MODIFICATION OF SURFACE AND BOUNDARY LAYER METEOROLOGY AND CHEMISTRY BY SEA BREEZE INCURSIONS DURING NE-OPS

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1. INTRODUCTION

Sea breeze circulations have the ability to significantly modify the atmospheric boundary layer by replacing the existing air mass with low level incursions of cool, moist air, elevated wind speed, and changes in wind direction that can either increase or diminish the concentrations of chemical constituents depending on the relative difference between the *in-situ* and upstream properties. The NE-OPS Philadelphia site is located near the western fringe of mid-Atlantic sea breeze intrusions (~ 200 km inland). Several sea breeze fronts propagated through the site during the 1999 and 2002 summer field intensives and were documented using a suite of instruments, including Raman lidar, tethersondes, profiler/RASS, and surface particulate and trace gas analyzers. Common to all sea breeze events is the sudden (~ 1-10 minutes) rise in relative humidity to saturation levels, and the concurrent increase in optical extinction (total and back scatter coefficients) with the formation of haze droplets on existing aerosols. Measurements show that temperatures declined by several degrees and wind speed increased by factors of 2-3 as the shallow (100 – 300 m) air mass propagated through the site. The effect on ozone and other trace gas concentrations depends on the relative differences between the two air masses. Sea breeze events have been observed where ozone concentrations were reduced by nearly a factor of two (e.g., 165 to 95 ppbv), and others where ozone increased as the sea breeze front replaced drier and/or cleaner air mass. Doppler radar reflectivity displays show that as the sea breeze continues westward, its length, intensity, and signature clear air return diminishes, eventually dissipating in the surrounding air mass. Meanwhile, conditions within the cool, moist air mass can remain for hours after passage. The depth, propagation speed, and timing of the sea breeze are crucial to prediction of pollution episodes. Operational numerical models are capable of simulating the sea breeze circulation, but generally fail to accurately capture the depth and timing of these events at locations well removed from coastal regions, where they still can exhibit a significant influence on the local meteorology and chemistry. Moreover, the sea breeze can be altered by interactions with meso-dynamic forcing (e.g., outflow boundaries).

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2. BACKGROUND

During summers 1998, 1999, 2001, and 2002, an intensive measurement campaign took place 18 km NNE of central Philadelphia at the Baxter Water Treatment Facility near the Delaware River (40^o 02.14' N 75^o 00.28' W). An extensive suite of instruments was deployed to investigate the processing controlling urban air pollution. The first three field campaigns (1998-2001) were sponsored by the U.S. E.P.A., while the summer 2002 intensive was conducted under the auspices of the Pennsylvania Department of Environmental Protection (PA-DEP). A detailed overview of the field projects, instruments, and measurements can be found in Philbrick et al. (2000, 2002).

In this paper, key measurements are used to describe the influence that the passage of sea breeze convergence zones have on the meteorological and chemical properties of the local air mass. These measurements were obtained at the surface and aloft using tethered balloons, Raman Lidar, trace gas analyzers, nephelometers, wind profilers with RASS, Doppler weather radar, and archived data from the NOAAport feed.

During the summer field campaigns of 1998 and 2001, no occurrences of sea breeze fronts were observed. The 1998 campaign was a short 3-week pilot study designed for testing the site and systems. July 2001 was influenced by a persistent long wave trough and attendant northwesterly flow, which is a directional orientation that typically suppresses the westward propagation of the sea breeze. However, during the summers of 1999 and 2002, five sea breeze events were fully documented. This paper will focus on two events as representative of the range of similarities and differences in sea breezes events observed at the Philadelphia site during NE-OPS.

3. SEA BREEZE CASE STUDIES

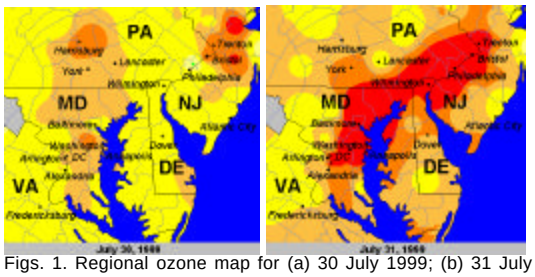
Two case studies are described which document the modification of surface and boundary layer meteorological and chemical properties. The 31 July 1999 and 20 July 2002 cases were chosen to highlight differences that can occur with only minor changes in the orientation of the regional wind direction, and its relation to the orientation of the propagating sea breeze front. The two case studies also capture the recurrent features associated with sea breeze incursions. Sea breezes can have a profound impact on air quality forecasts. By the time they reach the Philadelphia area, they are shallow air masses that can be readily influenced by even moderate meso-dynamic forcings, making the timing

and impact on local air quality often difficult to accurately predict.

3.1 The 31 JULY 1999 Case Study

The characteristics of the 31 July sea breeze have been reported in Clark et al. (2002). The approach taken here is intended as a comparison of similarities and differences observed between different sea breeze events.

The July 31 episode developed rapidly beginning with Code Orange ozone levels to the west and northeast of Philadelphia on July 30 (Fig. 1a).



Figs. 1. Regional ozone map for (a) 30 July 1999; (b) 31 July 1999 (EPA AIRNow, 2002).

Westerly transport aloft advected O_3 from the western boundary on 30 July, while downslope heating and differential heating along the coastal plain contributed to the emergence of a leeside trough along the I-95 corridor. The trough amplified on 31 July enhancing the convergence along the corridor, and retrogressed westward as the near-surface temperature gradients intensified in response to daytime heating (Fig. 2).

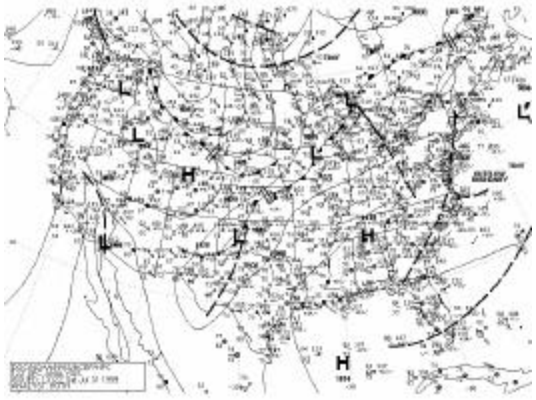


Fig. 2. Surface analysis for 12Z, 31 July 1999.

Wind direction shifted from NE in the morning to SE by early afternoon, with wind speeds less than 3 m/s over the period. The morning NE wind could have contributed to the transport of remnant O_3 from the Trenton, NJ into the Philadelphia area, adding to the *in-situ* production under light winds during the midday period on 31 July. This light wind condition would eventually allow the sea breeze to propagate a considerable distance inland. Mid-afternoon temperatures reached 38 C (100 F), and O_3 concentrations soared to 165 ppbv, the highest levels recorded in Philadelphia in 11 years. Code Red conditions extended from Washington DC to Trenton NJ by midday (Fig. 1b).

The clear-air reflectivity from the Fort Dix, NJ Doppler radar monitored at the site displayed the propagation of the sea breeze convergence zone. The sea breeze front passed the site at 1709 EDT, as indicated by the rapid increase in $PM_{2.5}$ as measured by the laser-diode nephelometers (Fig. 3). Note that the effects are more profound at the surface and 150 meters, yet are still evident at 75 and 225 m. This feature is also captured in the vertical profiles discussed later. A reflectivity display from 1906 EDT, almost two hours after the sea breeze front passed the site, shows a stationary line of convergence that eventually disappeared in the embedded air mass (Fig. 4). The area of reflectivity seen off the NJ coast identifies the remnant of a convective system that produced an outflow boundary that propagated westward. The outflow boundary was distinct from the sea breeze front (not seen in Fig. 4), but appeared to provide additional forcing that helped the sea breeze extend further inland.

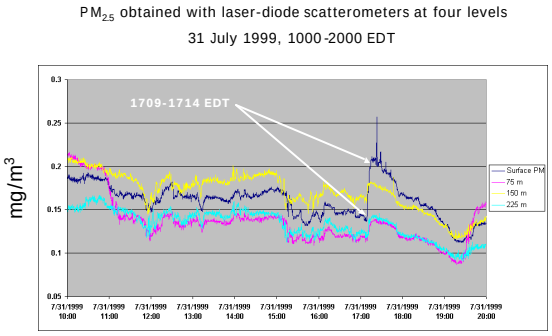


Fig. 3. $PM_{2.5}$ for July 31, 1999 obtained using a laser nephelometer attached to a tethered balloon as a proxy indicator of concentration. The sea breeze passed the site between 1709 and 1714 EDT. Time series are at the surface and 75, 150 and 225 m.

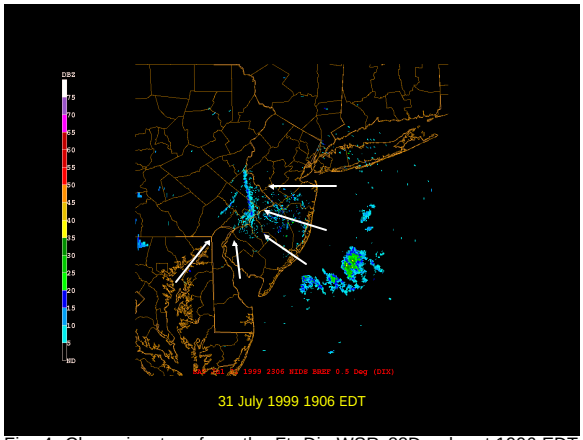
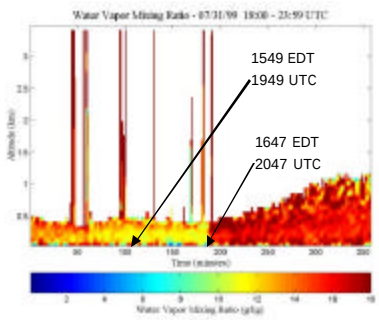


Fig. 4. Clear-air return from the Ft. Dix WSR-88D radar at 1906 EDT on 31 July 1999. The arrows indicate approximate wind direction.

The modifications to the boundary layer in the wake of its passage were dramatic. In a layer only 100 m deep, wind direction at the site backed more than 90 degrees, temperature decreased by 1.5 C, wind speed doubled, and [O_3] fell from 160 ppbv to 95 ppbv in 10 minutes. The $PM_{2.5}$ concentrations responded abruptly (see Fig. 3). At the surface, $PM_{2.5}$ concentration increased from 0.14 to 0.21 mg m^{-3} in 6 minutes, while aloft $PM_{2.5}$ concentrations exhibited a simultaneous step increase of about 30%. The increase in PM can be explained as an increase in scattering coefficient associated with the activation of aerosols, previously too small for detection (< 0.3 mm), by the increases in relative humidity accompanying the sea breeze. This sudden increase in water vapor content is captured in the Raman lidar time series shown in Fig. 5.



PSU Raman Lidar

Fig. 5. Times series of water vapor mixing ratio obtained using the PSU Raman lidar on 31 July 1999.

This dramatic change in the air mass was also observed in the two sets of vertical profiles, obtained immediately before (1549 EDT) and after (1647 EDT) the passage of the sea breeze (Fig. 6). (*Note: The times used to identify vertical profiles are start times. Vertical profiles take approximately 30 minutes to complete, hence the difference in the time reported for the onset of the sea breeze. The sea breeze passed the site at 1709 EDT, while the balloon was still on its ascent to 300 m, which began at 1647 EDT*). This set of profiles demonstrates the modification to the lower boundary layer that accompanies the passage of a sea breeze. In a shallow 100 m layer, air cools, specific humidity rises by 4 g/kg, wind speed doubles as the wind direction changes by from southwesterly to southeasterly, and O_3 concentration diminishes from 160 to 100 ppbv. This change occurred over about 10 minutes. With the increase in scattering came an attendant increase in haze and a decrease in visibility. The sea breeze continued to propagate inland for several more kilometers before becoming stationary and eventually dissipating. However, the air mass remained modified at the site for several hours after its passage.

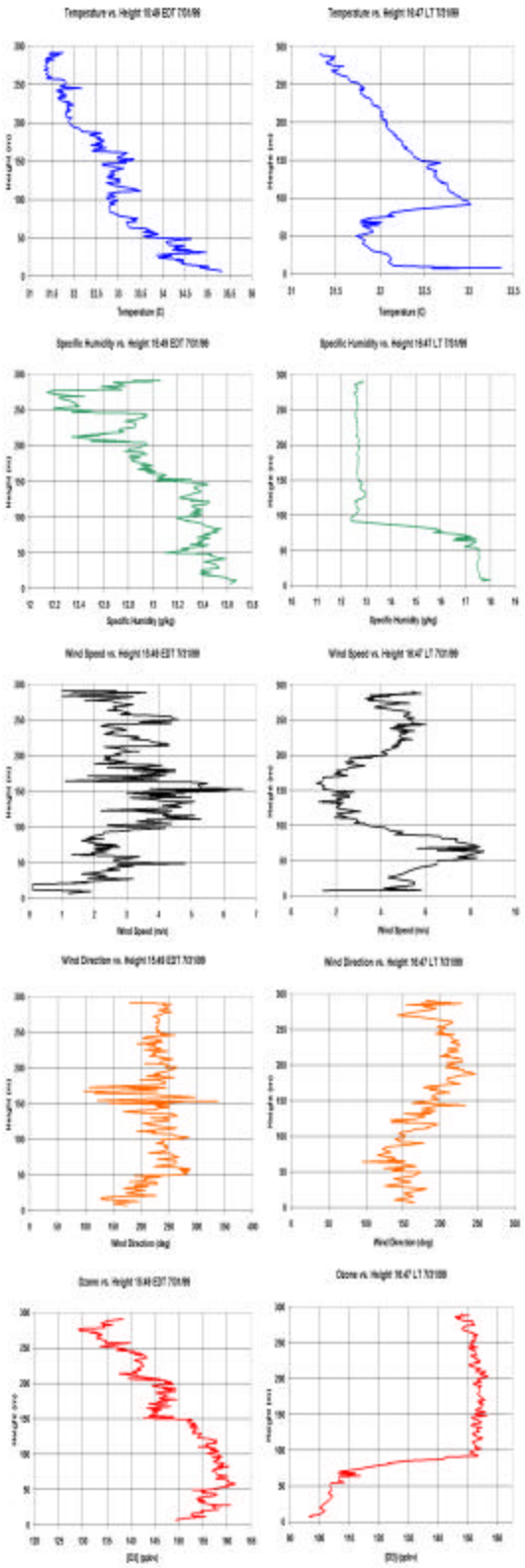


Fig. 6. Vertical profiles obtained using a tethersonde system on 31 July 1999. Left column is 1549 EDT; Right column is 1647 EDT. Top to bottom: Temperature (C), specific humidity (g/kg), wind speed (m/s), wind direction (deg), and O_3 concentration (ppbv).

3.2 The 20 JULY 2002 Case Study

The synoptic pattern on 20 July 2002 was distinctly different from that of 31 July 1999. A weak cold front passed over the site in the morning and was situated along the Mason-Dixon line by 12Z (Fig. 7).

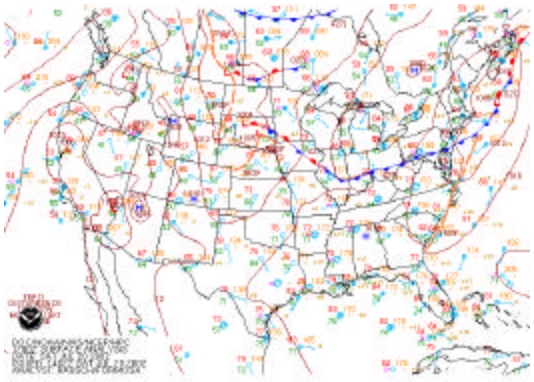


Fig. 7. Synoptic setting at 12Z, 20 July 2002.

A NNW wind at 3-4 m/s steadily veered to easterly throughout the day, and weakened to 1-2 m/s. The daylight hours remained clear but hazy with elevated relative humidity (T=26 C; T_d = 19 C; RH ~ 60%) at 18Z. The Fort Dix radar identified a sharp sea breeze convergence zone moving eastward across NJ at 6 m/s (Fig. 8). Favoring the propagation of the sea breeze was the light regional easterly wind.

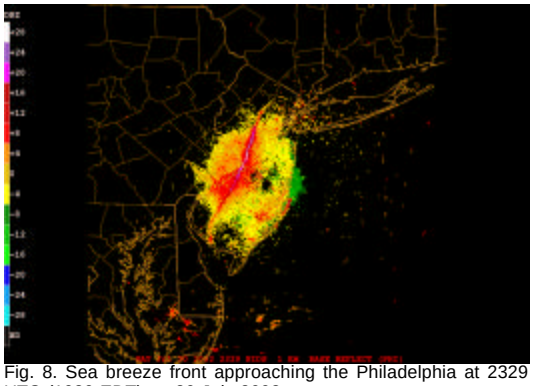


Fig. 8. Sea breeze front approaching the Philadelphia at 2329 UTC (1929 EDT) on 20 July 2002.

Prior to the intrusion of the sea breeze, concentrations of trace gases were characteristic of the clearer air mass advected in from the east over rural, non-industrial areas of NJ. However, conditions changed rapidly as the sea breeze approached the site. Convergence ahead of the sea breeze resulted in step-increases in the surface concentrations of CO, NO_X, and SO_2. b-scattering coefficient exhibited a similar rise as the leading edge of the sea breeze front approached, however O_3 did not respond until after the front passed the site. The time series of trace gases are shown in Fig 9. The sea breeze

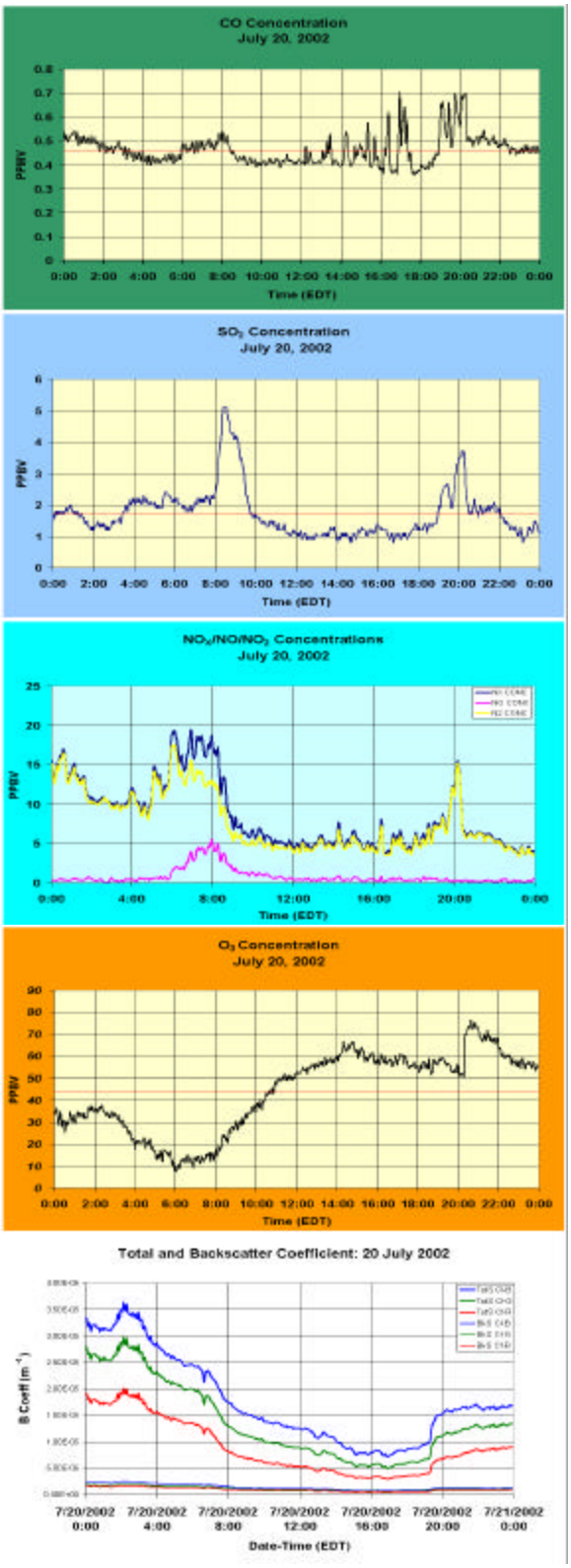
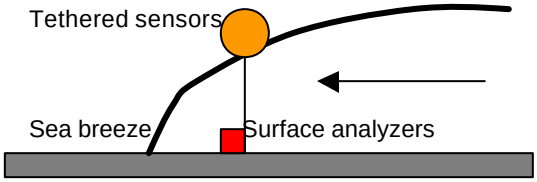


Fig. 9. Time traces of CO, SO_2, $NO/NO_2/NO_X$, O_3 and β-scattering coefficient on 20 July 2002. Note the jump in concentration and scattering around 2000 EDT corresponding to the passage of the sea breeze front.

front contributed to the jump in concentrations ahead of the front for CO, NO_X, and SO_2 and scattering coefficient, while the increase in O_3 immediately following the sea breeze front appears to be related to the shift in wind direction from E to SE, and the greater influence that a southerly wind component would have on the advection of O_3 from upwind urban environments. The increase in scattering is likely due to both an increase in the aerosol load in the convergence zone as well as the increase in scattering caused by the increase in water content.

Equally interesting are the vertical profiles obtained with the tethered balloon system (Figs. 10 & 11). In this particular case, the sea breeze front passed the site as the sensor packages reached 300 m. That is, the surface trace gas sensors first record the sea breeze, then minutes later at 300 m, as the air mass thickness increased behind the leading edge, the airborne sensors responded to the boundary layer modification, as depicted in the cartoon below. This is apparent in the descent sounding, which shows a boundary layer greatly enriched in moisture (Fig. 10) and newly activated $PM_{2.5}$ (Fig. 11).



One the most significant features of the 20 July 2002 sea breeze event is the observed increase in trace gas concentrations accompanying the intrusion of this air mass. Understandable are the increases in hydrated aerosols, b-scattering coefficient, and specific humidity as the marine air mass replaces the *in-situ* condition. But the increase in trace gases can only be a consequence of the change in wind direction from E to SE, and the attendant transport of pollutants from the urban areas to the south. And while the increases in concentration do not contribute to a serious degradation of air quality - after all, the marine air mass is relatively clean, the observations do show how a slight and abrupt change in wind direction can have a dramatic impact on local conditions.

4. CONCLUSIONS

This paper focused on the modification of the surface and lower boundary layer by sea breeze incursions, and the similarities and differences characteristic of this set of events. Only five sea breeze episodes were documented during NE-OPS, but in every case the modifications to the local conditions were dramatic. Mesoscale numerical models with high spatial resolution are

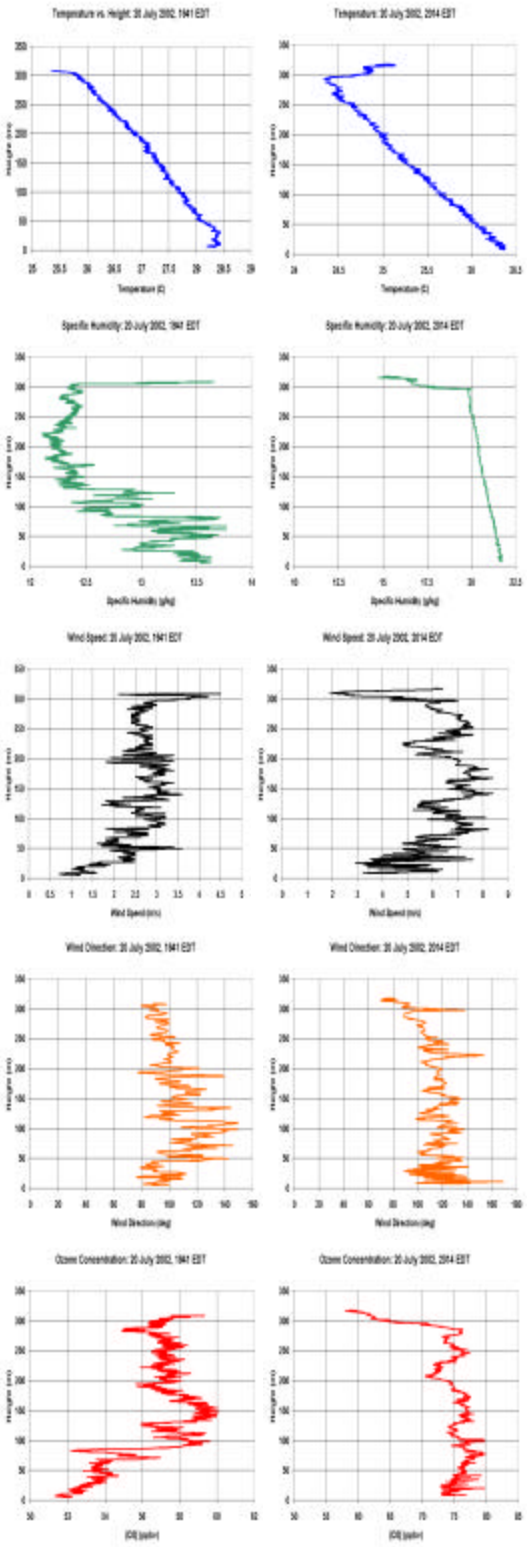


Fig. 10. Vertical profiles obtained using a tethersonde system on 20 July 2002. Left column is 1941 EDT; Right column is 2014 EDT. Top to bottom: Temperature (C), specific humidity (g/kg), wind speed (m/s), wind direction (deg), and O_3 concentration (ppbv).

capable of simulating the general characteristics of sea breezes. However, the 31 July 1999 case study

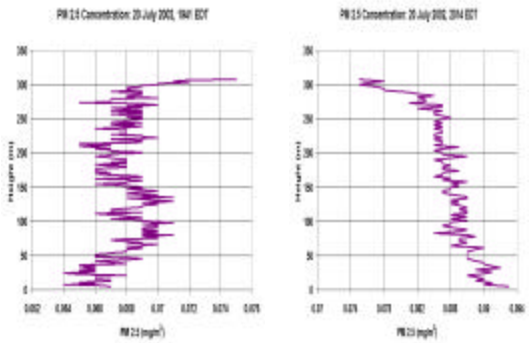


Fig. 11. Same as Fig. 10 except for PM2.5. Left is the ascent profile obtained immediately prior to sea breeze passage. Right profile obtained immediately after. Note evidence of change at 300 meters.

makes it apparent that sea breezes are shallow air masses whose initiation and propagation are not easy to predict. Moreover, the 20 July 2002 case study shows that the modification to the boundary layer is dependent to a large degree on the relative changes in wind direction. Doppler weather radar serves as a useful tool for now-casting such events. The NE-OPS data set may prove useful for model validation, and provide insights that may help in the development of sub-grid-scale parameterizations.

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