**10.5** FIRST OBSERVATIONS OF FOG AND LOW CEILING ENVIRONMENTS AT THE FAA NORTHEAST CEILING AND VISIBILITY FIELD SITE

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## 1. INTRODUCTION

An instrumented site has recently been set up in the northeastern United States to serve as the main facility for the study of ceiling and visibility (C&V) conditions. This initiative is taking place through a partnership among the National Ceiling and Visibility, Terminal Ceiling and Visibility and Winter Weather programs of the Federal Aviation Administration's Aviation Weather Research Program (AWRP) (Kulesa et al., 2003). Data from the instrumented site serves many purposes. The main objectives are documenting and gaining an improved understanding of the structure and evolution of low visibility (fog) and low ceilings affecting the NE region. The occurrence of such events lead to important disruptions in operations at the major air terminals in the New York City area (Allan et al., 2001) as well as leading to hazardous conditions for the overall general aviation, marine and road transportation activities in the region. Results from this field program will serve to support the further development and evaluation of various tools such as C&V expert systems as well as improved parameterizations and translation algorithms used by numerical forecast models (Herzegh et al., 2003).

In this paper, the suite of dedicated ground-based instrumentation and sensors installed on a 90-m tower at the C&V field site is described, along with other available datasets used to characterize the regional conditions during events of interest. Overall findings of a preliminary analysis of the first observations taken during fog events are then discussed and serve to illustrate the variable character of fog in the complex environment of the NE.

## 2. SITE LOCATION AND INSTRUMENTATION

Observational capabilities used to characterize fog and low ceiling environments in the NE include surface-based sensors and an instrumented 90-m tower located on the campus of the Brookhaven National Laboratory (BNL) in east-central Long Island, NY. Other data sources include the 12-hourly soundings from the National Weather Service office located on the BNL campus and from another sounding site in extreme southeastern Massachusetts, 1-min surface measurements obtained from the network of Automated Surface Observing System (ASOS) deployed at the major terminals and regional airports in the region. Hourly data from buoys located in the coastal waters around Long Island are also available. For the location of the main tower, ASOS sites and buoys, see Fig. 1. Furthermore, GOES-12 satellite imagery and radar reflectivity data from the Upton NEXRAD, also located on BNL campus, are used to track cloud and precipitation systems.

The central observing facility revolves around the presence of a 90-m meteorological tower located on BNL campus. The area is characterized by relatively flat terrain, with the land surface composed of mostly forested areas, as well as low to moderate density buildings and roadways typical of North American suburban areas. A transition toward more densely populated areas occurs on Long Island along the east-to-west transect. In the immediate vicinity of the tower, located in a grassy clearing, trees (mixed pine and deciduous) of about 15 m in height are found to the S, SW (most frequent wind direction at fog onset), W, NW and N. To the NE, E and SE, low industrial buildings are found within a radius of approximately 1 mile.

Tower instrumentation consists of 7 levels of temperature, humidity and wind measurements. Other tower instrumentation include three visibility/present weather sensors at the base, middle and top of the tower, an optical fog spectrometer providing measurements of drop size distribution in the 2 to 50 $\mu$m diameter range, two shortwave and longwave radiometers providing measurements of upwelling and downwelling radiation and two sets of fast response temperature and humidity flux measurement systems. Surface instrumentation includes an additional set of temperature/relative humidity sensors at 2 m, a barometric pressure probe and a GEONOR precipitation gauge. Soil temperature and moisture are measured at the site at five levels from near the ground surface down to a depth of 1 m. Remote sensing capabilities include a Vaisala laser ceilometer, providing measurements of cloud base heights up to 4 km every 30 seconds, and a 12-channel profiling microwave radiometer providing retrievals of temperature and humidity profiles as well as cloud water content every 6 minutes (Ware et al., 2003). Table I provides a complete list of instruments and their location.

To obtain a regional view of conditions during fog events, 1-min near-surface measurements of visibility, temperature, humidity, wind speed and direction from the network of ASOS stations are used. Cloud ceiling heights are also obtained from the ASOS' laser ceilometers with a temporal resolution of 30 seconds, while measurements of precipitation accumulation over 15 minutes are archived along with measurements of precipitation rate and type. Hourly observations of atmospheric pressure, air temperature, wind speed and

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Figure 1. Location of the instrumented C&V site (red square and arrow), main ASOS sites (white dots) and buoys (blue dots) from which data is used to characterize conditions during fog and low ceiling events.

Table I. List of sensors at the FAA NE C&V field site.

| Sensor | Location |
|---|---|
| Biral-HSS visibility / present weather | 4, 32, 70 m |
| Vaisala HMP45C Temperature/Relative humidity | 2, 10, 15, 20, 32, 45, 70, 85 m |
| RM Young wind monitor | 10, 15, 20, 32, 45, 70, 85 m |
| Kipp & Zonen CNR1 radiometer | 32, 70 m |
| Metek USA-1 sonic anemometer | 32, 70 m |
| Campbell Scientific $KH_2O$ fast-response hygrometer | 32, 70 m |
| Droplet Measurement Technologies optical fog spectrometer | 32 m |
| Campbell Scientific barometric pressure probe | surface |
| GEONOR precipitation gauge | surface |
| Campbell Scientific soil temperature | -3, -8, -15, -30, -45, -90 cm |
| Decagon volumetric soil moisture | -3, -8, -15, -30, -45, -90 cm |
| Vaisala CT12K ceilometer | surface |
| Radiometrics 12-channel profiling microwave radiometer | surface |

direction, as well as water temperature from buoys in the coastal waters of the Atlantic Ocean and in the Long Island Sound (see Fig.1) are also available through NOAA's National Data Buoy Center.

## 3. PRELIMINARY DATA ANALYSIS

During the period from October 2003 to June 2004, daily monitoring of conditions allowed the identification of a total of 27 events of interest, ranging from long-lived dense fog events, short-lived dense fog events, low ceiling/light fog events, along with "near fog" events, where conditions were conducive to radiation fog formation but dense fog was not observed. A preliminary data analysis of a subset of the identified events has been completed. The objectives of this analysis are the identification of the likely mechanisms leading to fog formation and subsequently influencing its evolution, as well as to assess the overall observational capabilities at our disposition. Here, a fog event is loosely defined as a period of one or more hours during which horizontal visibility is reduced below 1 km. A complete dataset was not always available during the fall as the installation of the site was ongoing during that time period. Nevertheless, the available data is analyzed as a first look into the character of fog in the region. Salient features observed during some of the events are discussed and main findings are summarized.

### 3.1 *October 10$^{th}$ 2003*

A low C&V event characterized by significant spatial and temporal variability took place over Long Island on October 10$^{th}$ 2003, as the NE was under the influence of a broad high-pressure system. Light surface winds prevailed early in the night; with radiation fog forming as cooling of the near-surface air occurred. Cooling was more rapid in the eastern portion of Long Island, leading to fog forming earlier at FOK when compared to stations located further west in more urbanized areas (Fig. 2a). At the C&V tower site on BNL campus, visibility measurements at various heights suggest the formation of an elevated fog layer as the period of reduced visibility began at 32 m several minutes before than the one at 4 m (Fig. 2b). Observations of humidity on the tower suggest dew deposition at the surface as the process responsible for the initial formation of fog aloft (Pilié et al., 1975), as an inversion in the humidity profile developed in the lowest 50 m of the atmosphere before the onset of fog (Fig. 3).

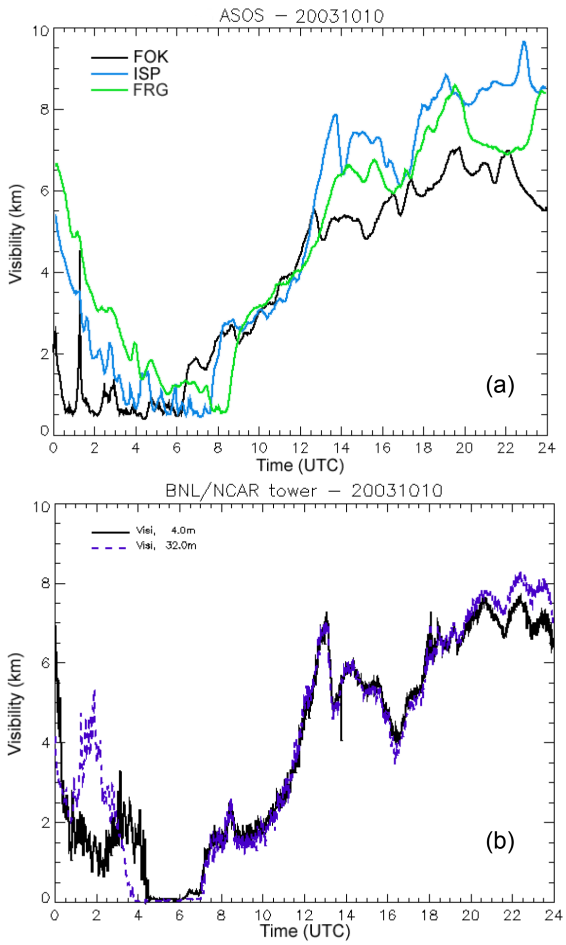


Figure 2. Horizontal visibility observed (a) at three ASOS stations and (b) at two heights (4m, solid line; 32m, dashed line) on the C&V tower, October 10th 2003.

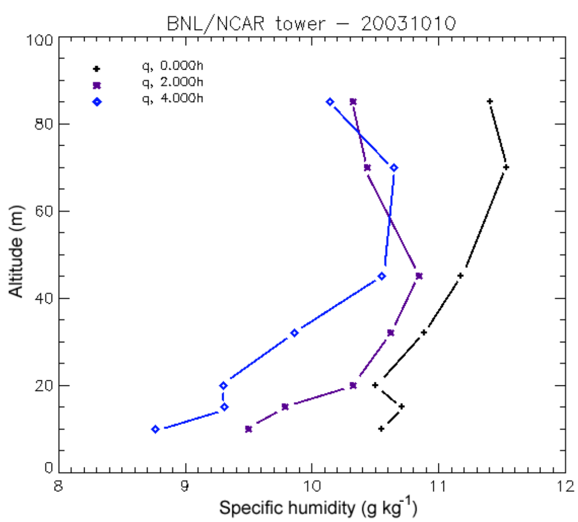


Figure 3. Profiles of observed specific humidity at 0000 UTC (✚), 0200 UTC (✖) and at 0400 UTC (◆), on November 10th 2003.

A rapid increase in visibility took place during the middle of the night, with a tendency for the increase to occur later at locations in the central and western parts of Long Island (Fig. 2). As data from the ceilometer at the C&V site was not available on that day, data from the ceilometer at HWV (located closest to the main tower site) indicate that the change in visibility was in fact associated with a rapid transition of the cloud base height (Fig. 4). The height at which backscattering from cloud droplets was observed experienced a sudden rise of 200 m in about 20 minutes around 0700 UTC. Some backscattering was also sporadically detected around 200 m during the fog event. Furthermore, stations that didn't report fog such as LGA, HPN and EWR, began reporting a low stratus cloud deck at 0700 UTC, 0830 UTC and 0845 UTC respectively, with ceiling heights detected between 200 m and 400 m. These facts, along with the very rapid transition in cloud base height, seem to support the hypothesis of a dissipating fog layer under the influence of a propagating marine stratus cloud deck.

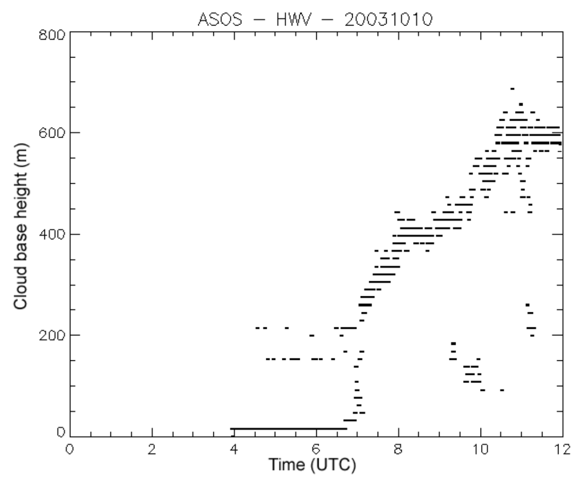


Figure 4. Ceilometer observation of cloud base height at Shirley (HWV) on October 10th 2003. Symbols indicate detection of cloud base at every 30 sec.

The 1200 UTC sounding launched at proximity to the tower site provides evidence of a low cloud deck with a cloud top at 700 m (not shown). The increase in downwelling longwave radiation associated with the presence of the boundary layer cloud deck above the fog reduces the radiative cooling at fog top, stopping the production of fog water. The gravitational settling of fog drops then depletes the fog layer of its water, leading to dissipation of the fog layer (Roach, 1995). Another plausible mechanism contributing to fog dissipation related to the appearance of an upper cloud deck may be that the net radiative cooling of the fog layer is replaced by warming from the surface under the influence of an upward soil heat flux (Choularton et al., 1981). Both mechanisms could in fact contribute to fog dissipation in this case. It is hard to conclude anything about the first mechanism as radiation sensors were not located above the fog. But measurements of soil temperature show profiles with which an upward diffusion of heat is expected (not shown).

### 3.2 *November 4th 2003*

A significant low C&V event, characterized by a short-lived period of dense fog, occurred on November 4th 2003. The ceilometer at the tower site detected patchy ground fog for 45 minutes beginning at 1000 UTC and a low cloud appearing just after 1100 UTC with a subsequent rapid lowering of cloud base (Fig. 5). The fog event resulting from the lowering of cloud base was confirmed by observations of visibility on the tower (not shown). After 1300 UTC, cloud base lifted at a rate of approximately 50 m $h^{-1}$ as drizzle and light rain developed. The appearance of the low clouds and subsequent cloud base lowering occurred as the wind shifted from the west-southwest to the east (Fig. 6). These events were related to the southwesterly propagation of a “backdoor” cold front associated with a developing high pressure system over eastern Canada (Fig. 7). Observations from the surface network provide evidence that cloud had formed earlier over southeastern Massachusetts, Rhode Island and southern Connecticut. So the likely scenario involved cloud formation in the colder air found upstream and subsequent advection over the site as the cold front propagated. Satellite imagery and surface observations suggest that cloud formation was associated with the frontal system (Fig. 7). For example, an elevated cloud layer could have formed as shallow convection developed over the water as the cold air from the NE was flowing over a warmer surface (Fig. 8). The resulting turbulent mixing of the relatively warm and moist surface marine air with the overlying colder air could have lead to cloud formation as previously pointed out by Pilié et al. (1979).

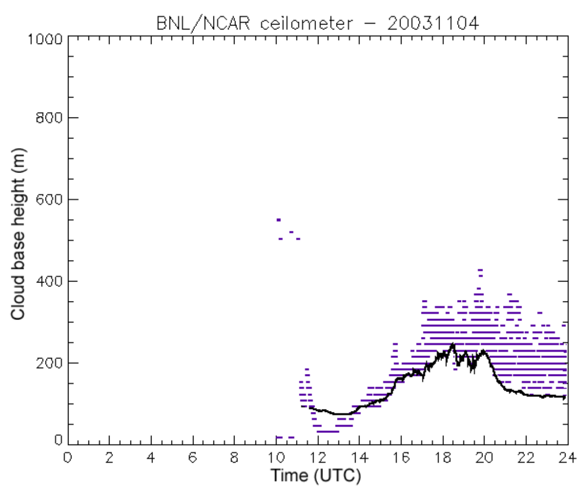


Figure 5. Ceilometer observation of cloud base height (symbols) and the calculated LCL from near-surface data (solid line) at the FAA C&V field site on November 4th 2003.

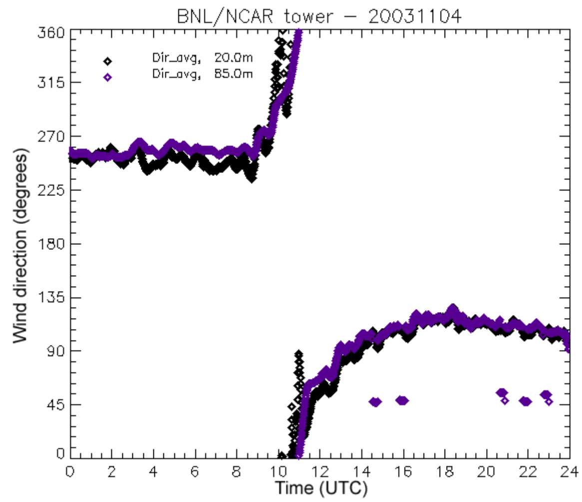


Figure 6. Temporal evolution of observed wind direction at 20 m and 85 m at the C&V field site, November 4th 2003.

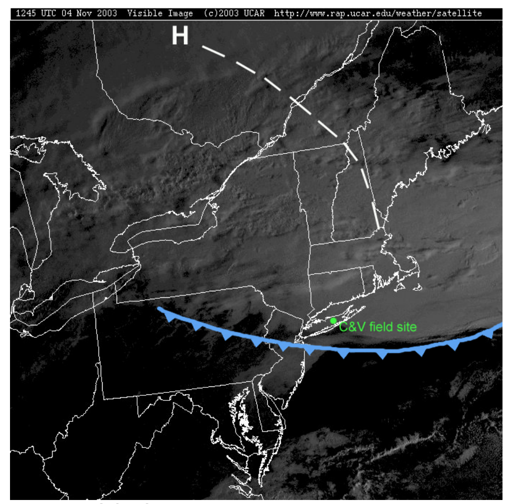


Figure 7. GOES-12 visible imagery at 1245 UTC on November 4th 2003. The location of the high-pressure center, axis of the ridge, and a cold front, analyzed by the NWS Hydrometeorological Prediction Center in the 1200 UTC surface analysis, are also shown.

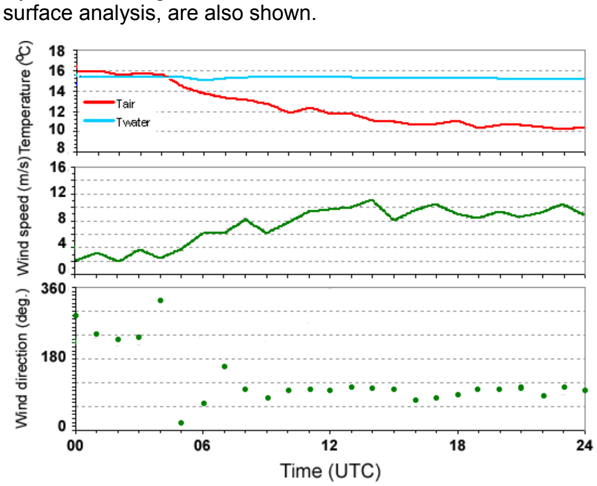


Figure 8. Evolution of air temperature (red line), water temperature (blue line), wind speed (green line) and wind direction (dots), at buoy 44039 on November 4th 2003.

At the C&V site, clouds initially appeared a few hundred meters above the ground at the same time as important cooling was observed at the upper levels of the tower (Fig. 9). Then, the combined effects of differential cold air advection and cloud top cooling lead to the destabilization of the boundary layer, as evidenced by the potential temperature profiles observed after 1200 UTC (see Fig. 9). During this transition, observations at the tower also indicated an increase in moisture close to the surface (Fig. 10), possibly related to the evaporation, at sunrise, of water deposited as dew and/or from ground fog earlier in the night. This evaporation provided enough moisture to counterbalance the warming near the surface as the destabilization occurred, so that an increase in relative humidity was observed (not shown). Thus, the combined influences from the continuing cold air advection aloft and the increase in moisture near the surface contributed to the apparent lowering of cloud base and subsequent fog.

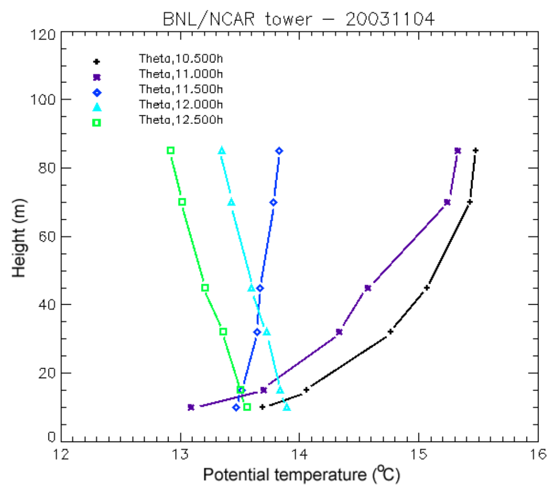


Figure 9. Profiles of potential temperature observed at the C&V tower site on November 4th 2003. ✚: 1030 UTC, ✱: 1100 UTC, ◇: 1130 UTC, △: 1200 UTC, □: 1230 UTC.

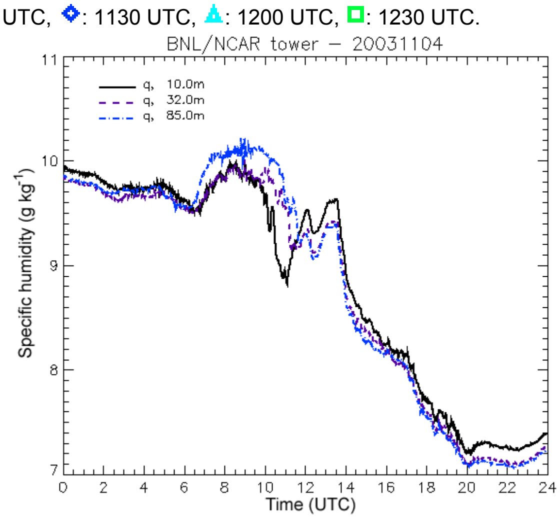


Figure 10. Temporal evolution of specific humidity at three levels on the C&V tower: 10 m (solid black line), 32 m (dashed magenta line) and 85 m (dot-dashed blue line).

The lifting of cloud base that took place after 1300 UTC (Fig. 5) occurred under the influences of continuing cold air advection, low level drying (Fig. 10) occurring under the likely influence of advection of dry air found further behind the front, and increased turbulent mixing associated with the destabilization mentioned above. The coupling of the cloud layer with the drying near-surface air is indicated by the rather good correspondence between the observed cloud base and the Lifting Condensation Level (LCL) calculated from the temperature and humidity observed at 10 m on the tower (Fig. 5).

### 3.3 *November 28th 2003*

Another low C&V event took place over Long Island on November 28th 2003. Ceilometer data indicated the presence of very low cloudiness during the night (sunrise is a little after 1200 UTC on this day), and a fog period later in the day (from 1530 UTC to some time after 2000 UTC) (Fig. 11). Clouds initially appeared over the site at 0000 UTC at an altitude of about 500 m. A little before 0200 UTC, a period of cloud base lowering began, leading to very low ceilings from 0400 UTC to 1100 UTC. A period during which low clouds dissipated was observed until a few minutes before 1400 UTC. A low ceiling reappeared just before 1400 UTC, leading to light fog at the site shortly thereafter. This period of fog occurred as onshore flow prevailed ahead of an approaching warm front (Fig. 12).

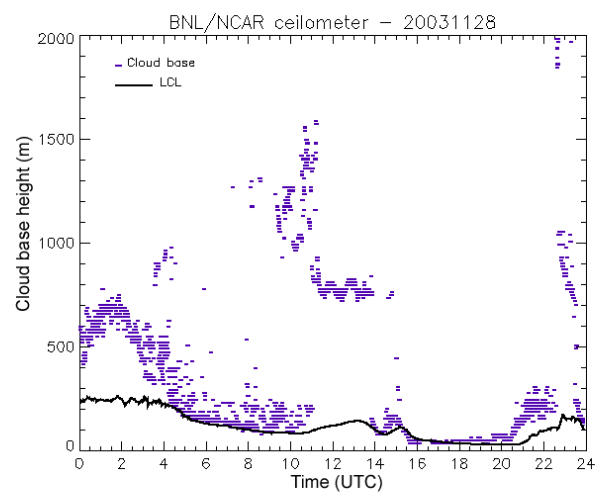


Figure 11. Ceilometer observation of cloud base height (symbols) and the calculated LCL from near-surface data (solid line) at the FAA C&V field site on November 28th 2003.

The initial appearance of low level clouds over the C&V field site seemed to be related to the marine environment. The 0000 UTC Upton NY (OKX) sounding shows a surface inversion superimposed by a moist well-mixed layer up to 700 m (Fig. 13). A strong and dry inversion is observed above the moist layer between

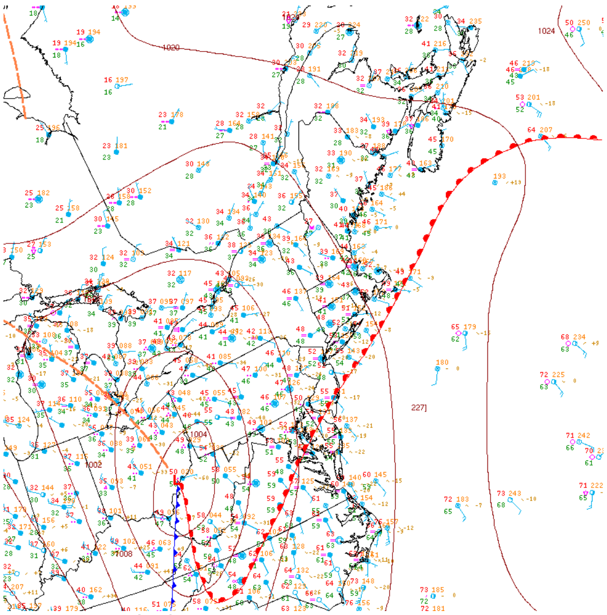

Figure 12. Surface weather observations and corresponding sea-level pressure and frontal analyses from the NWS Hydrometeorological Prediction Center, at 1200 UTC on November 28th 2003.

700 m and 1200 m. The moist layer was associated with southerly to south-southwesterly (onshore) flow. The presence of a surface inversion suggests that the stratiform cloud layer was decoupled from the surface at that time. This is further suggested by the poor correspondence between the calculated LCL from observations taken at 10 m and the observed cloud base during the first hours of the night (Fig. 11). Observations at the field site provide some clues on the mechanisms responsible for the cloud base lowering observed during the night. Measurements of temperature and dew point temperature taken at the top of the tower show an increasing temperature during the

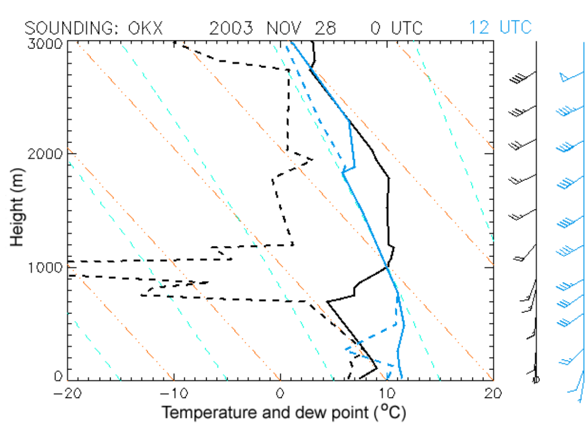


Figure 13. Profiles of temperature (solid lines), dew point temperature (dashed lines) and wind from radiosondes launched at Upton NY (OKX) on November 28th 2003, at 0000 UTC (black) and 1200 UTC (blue).

night, associated with the southerly flow ahead of the warm front (Fig. 14). An even more important increase of the dew point was observed after 0200 UTC, suggesting the significant influence of low level horizontal advection of moisture. As this was occurring, a gradual coupling between the near-surface air and the atmosphere aloft could be detected through the observed profiles of potential temperature and specific humidity on the tower. A gradual transition toward well-mixed profiles occurred between 0000 UTC and 0400 UTC (not shown). Furthermore, evidence of the developing turbulence was detected after 0200 UTC, as depicted by the variance of vertical wind fluctuations about 15-min running averages calculated from high-frequency wind measurements from sonic anemometers (Fig. 15). Further proof of the coupling between the cloud and the surface is provided by the rather good correspondence between the calculated LCL and the actual cloud base after 0400 UTC. Thus the influx of moisture from the marine boundary layer and the mixing associated to the developing turbulence in the cloud and sub-cloud layers lead to the thickening of the cloud layer through a lowering of cloud base.

A brief period of low cloud clearing was observed between 1100 UTC and 1345 UTC (Fig. 11). This time period was also characterized by a slight drying of the low level air. In fact, a subtle cooling of the temperature was detected at the top of the tower, along with a more important decrease in the dew point temperature (Fig. 14). A similar phenomenon was observed at the 44025 buoy earlier in the night, starting at 0700 UTC (Fig. 16). That period of drying of the near-surface air occurred as a slight change in wind direction was taking place at the buoy. The drying occurred as the wind veered from the south-southeast to the southwest. A similar behavior was observed at the tower site (not shown). The 1200 UTC OKX sounding provided evidence of a shallow dry layer, between 200 m and 500 m, within a moist lower troposphere (Fig. 13). These observations suggest the propagation of a low level mesoscale disturbance within the synoptic flow field and a significant horizontal variability of moisture in the coastal boundary layer. The slight shift of the wind to the southwest suggests the drying and associated cloud clearing could have been related to the advection of dry continental air. The distribution of coastal boundary layer cloudiness is often modulated by the variable origins of the airmass found upstream, as determined by contrasts between the continental and marine environments (Lewis et al., 2003). The presence of upper clouds on that day prevented the confirmation of the probable mesoscale variability in the low cloud field and the tracking of features over the coastal areas of the Atlantic through satellite imagery.

The return of a low ceiling at the tower site was observed at 1340 UTC (Fig. 11). This occurred as the near-surface temperature and moisture began rising again (Fig. 14), in association with an increase in wind speed and return to a southerly flow (not shown).

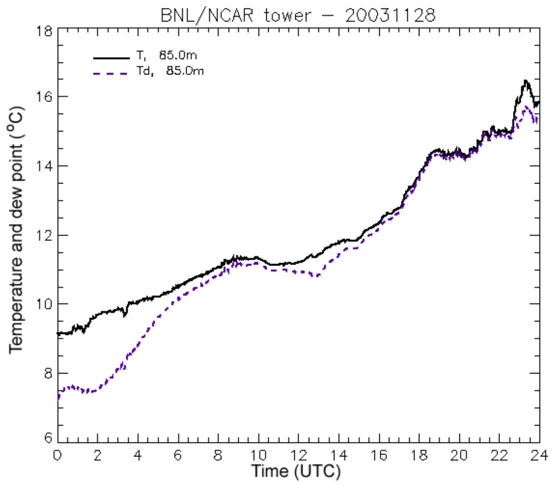


Figure 14. Observed evolution of temperature (solid black line) and dew point temperature (dashed magenta line) at 85 m on the C&V tower, November 28th 2003.

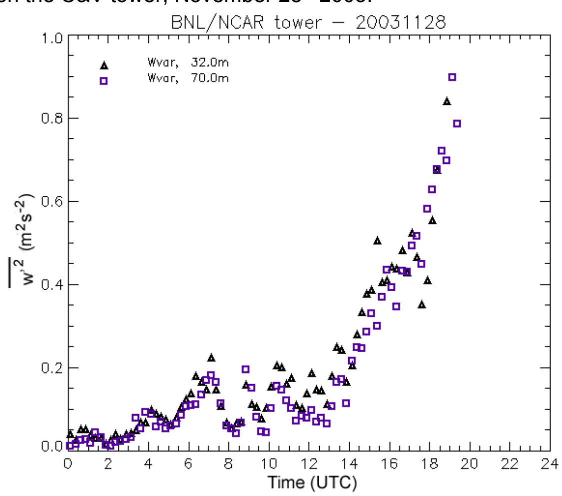


Figure 15. Temporal evolution of the variance of fluctuations of the vertical component of the wind calculated from 10 Hz sonic anemometer measurements at 32 m (▲) and 85 m (□), November 28th 2003.

Observations at the 44025 buoy indicated a similar behavior over the coastal waters, with the formation of sea fog (saturation at the surface) after 1200 UTC (Fig. 16). Thus the return of clouds over the site seemed to be related to the inland advection of marine fog. A ceiling at 150 m was initially detected, with variations in ceiling height observed thereafter. These variations were associated with variations in the near-surface temperature and humidity, as evidenced by the corresponding variability in the LCL (Fig. 11). Fog was subsequently observed at the tower site for about five hours. Variations in the ceiling height during the period leading to fog onset, and the variability in observations of visibility during fog (not shown), suggest the role of complex influences related to a possible mesoscale variability of the cloudy marine boundary layer and local scale interactions with the land surface during onshore flow.

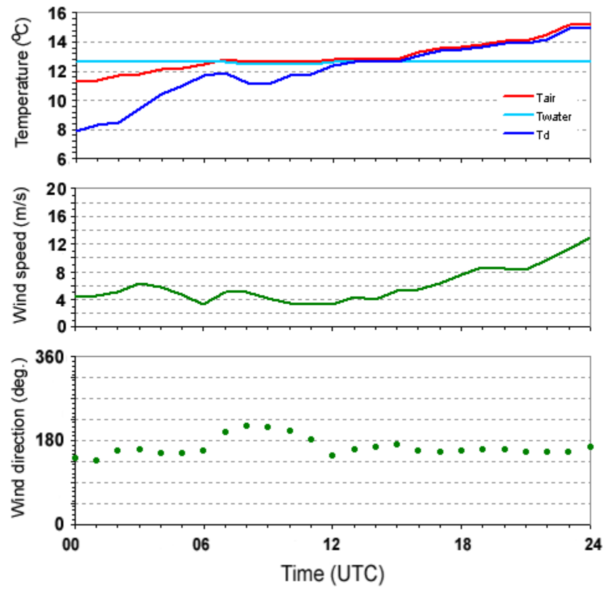


Figure 16. Evolution of air temperature (red line), dew point temperature (blue line), water temperature (light blue line), wind speed (green line) and wind direction (dots) at the 44025 buoy on November 28th 2003.

## 4. CONCLUSIONS AND PERSPECTIVES

Based on the results obtained from a preliminary analysis of conditions observed during a few low C&V events, it is shown that fog and low ceilings occur in the NE under a wide variety of influences. Of the events discussed, one was characterized by radiation fog forming in eastern Long Island, with surface visibility then increasing in the middle of the night as a low marine stratus cloud deck moved over the area. Also, the occurrence of a brief fog event was associated with a low cloud system propagating with a “backdoor” cold front, while fog was also observed during a day characterized by variable low ceiling conditions associated with onshore flow as an approaching warm front was located to the south of Long Island. Thus, the wide variety of scenarios leading to the occurrence of reduced visibility and low ceiling is already in evidence, pointing out to the challenge of providing accurate forecasts of such events. The important influence from the marine environment, where observations are sparse, is suggested from the results presented, as well as the role of mesoscale and local scale processes in the coastal zone.

To obtain a more complete view on the fog and low ceiling phenomena in the NE, a more in-depth analysis of data, including measurements from the more sophisticated instruments, will be performed. An analysis of microphysical data from the fog spectrometer located at the tower site will be performed to assess the possible variability in the microphysical structure of fog. Also, an analysis of data from fast-response sensors will be undertaken to assess the characteristics of turbulence during low C&V events. Results from detailed numerical simulations of chosen events will also be performed and analyzed in an effort to help unravel the mechanisms and interactions determining the behavior and variability of fog and other low cloud systems in the area. Finally, additional and updated information about the NE C&V field program can be found at the following web page: http://www.rap.ucar.edu/staff/tardif/fog/field_study.htm.

*Ackowledgments*

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