Meteorological Observations for U.S. East Coast Offshore Wind Power:
Improving the Mapping and Prediction of Offshore Wind Resources (IMPOWR)

*Corresponding author address:
Dr. Brian A. Colle
School of Marine and Atmospheric Sciences
Stony Brook University
Stony Brook, NY 11794-5000
brian.colle@stonybrook.edu
Abstract

The wind resource offshore of the East Coast of the United States is well known for its potential to provide abundant, clean, renewable, and domestic electricity. However, limited observations offshore of the East Coast are recorded at heights above the water that penetrate significantly into the planetary boundary layer (PBL). As a result, mesoscale models have been used to characterize the offshore wind resource in this region, but have not been evaluated fully within the PBL due to the scarcity of observations. This paper discusses the IMPOWR (Improving the Mapping and Prediction of Offshore Wind Resources) field study, conducted in the Nantucket Sound area in 2013–2014. The IMPOWR campaign provides a rich dataset of observations within the PBL from a variety of sources: high-frequency Long-EZ aircraft; a multi-level atmospheric and oceanic tower within Nantucket Sound; and LIDARs on the south shore of eastern Long Island and Block Island. In addition to new data for model validation and wind resource assessment, the IMPOWR field campaign provides new insights on meteorological features important for wind power development, such as the New York Bight jet and shallow marine layer.
1. Introduction

a. Background

The coastal waters of the northeast United States are an ideal for possible location offshore wind power developments given the combination of high population density, shallow coastal bathymetry, and potentially large wind resource (Kempton et al. 2007; Dvorak et al. 2012). Archer et al. (2013) addressed three main topics relevant to offshore wind farm development: (1) offshore wind resource assessment, (2) wind power forecasting, and (3) turbulent wake losses of wind farms. Wind resource assessment in coastal and offshore areas currently suffers from a lack of observations at turbine hub height, thus the need for more multi-level observations of wind and temperature on offshore platforms was identified. Improved understanding and realistic modeling of coastal processes are also necessary for accurate wind resource assessment and wind forecasting, yet current numerical weather prediction models and their parameterizations of the planetary boundary layer (PBL) have not been comprehensively evaluated in this offshore area. Since the power available in the wind is proportional to the cube of wind speed, small wind speed forecast errors can result in large errors in the prediction of the available power. Accurate representation of mesoscale and synoptic-scale processes are important for resource assessment and return on investment planning prior to construction, as well as operational forecasts such as hour-ahead and day-ahead power production forecasts, upon which unit commitment and scheduling decisions are based.

There are important diurnal circulations near the Northeast coast during the warm season, such as sea breezes (Veron and Hughes 2015; Novak and Colle 2006; Colby 2004) and low-level jets. Colle and Novak (2010) showed the existence of a diurnally-
forced low-level jet (LLJ) in the New York Bight region that often consisted of wind speeds in excess of 13 m s\(^{-1}\). Occurrences of the New York Bight Jet peak in the late spring time when the land-sea temperature contrast is the greatest, on days when the flow is primarily southwesterly around a Bermuda high-pressure system. The jet maxima, which were part of a larger scale coastal wind enhancement in the coastal southern New England region, were found to occur at ~150 m AMSL, just above hub height of a typical offshore wind turbine. Helmis et al. (2013) also confirmed the presence of several summertime LLJ structures above Nantucket, MA, using various observational datasets.

\textit{b. Motivation}

There have been limited observations of the marine boundary layer in the coastal marine environment of the northeast United States. This region, stretching from the south shore of Long Island to Georges Bank, has been identified by Dvorak et al. (2012) as an ideal location for an offshore wind energy grid based on regional energy demand, shallow water depth, and available wind resource. Although there have been significant advances in using mesoscale models, such as WRF, to characterize the wind resource, the capability of such models to accurately represent offshore winds is not yet fully established.

For extreme low wind speeds, the Coupled Boundary Layers Air-Sea Transfer (CBLAST; Edson et al. 2007) field experiment collected data around Nantucket Island during the mid-summer period of 2001–2003 in order to improve models. The CBLAST observational tower extended to 24 m, with additional turbulence, wind, and temperature data obtained by Long-EZ aircraft flights and SODAR. The field campaign reported on
here, IMPOWR (Improving the Mapping and Prediction of Offshore Wind Resources) addresses CBLAST deficiencies using analysis from a taller, 60-m tower. The Cape Wind meteorological tower, located within Nantucket Sound (Fig. 1) was operational from 2003 to 2011, and recorded data at multiple levels (20, 41, and 60 m).

The IMPOWR field program began in fall 2012 and continued through spring 2015, extending the analysis begun by CBLAST geographically and seasonally. This paper describes the IMPOWR experiment, as well as two illustrative case examples that further motivate the research. The cases are a coastally enhanced flow event near Nantucket Island and a New York Bight jet along the New Jersey coast.

2. IMPOWR: observations

A number of different in situ observational datasets were used during the IMPOWR experiment. Surface observations over the coastal waters were provided by the National Data Buoy Center’s moored buoys and Coastal Marine Automated Network stations, while surface land observations were available from National Weather Service (NWS) Automated Surface Observing System stations (Fig. 1a). Except for the NWS radiosondes over eastern Long Island (OKX) and coastal Massachusetts (CHH), which provided 12-hourly observations of temperature, moisture, and winds throughout the PBL, all the other datasets were at a single fixed height. Through a partnership with Cape Wind (CW), data were acquired from the CW meteorological mast (Fig. 1b,d), which consists of a continuous dataset of 10-minute observations of wind speed and direction at 20, 41 and 60 m, and temperature and pressure at 10 and 55 m above the sea surface over Nantucket Sound during 2003–2011. As depicted in Fig. 2, there is a strong
seasonal cycle in wind speed at CW, with the average winds gradually decreasing during the spring and early summer months, as diurnal circulations dominate over synoptically-driven systems, followed by a rapid increase of wind speed in October, as the synoptic pressure gradients increase. The winds at all three levels follow the same annual cycle, but the winds at 60-m are generally 10–20% larger than 20-m.

At the start of IMPOWR project, the CW instrumentation was no longer recording data, so the base of the CW tower (~12 m AMSL) was instrumented with wind, temperature, temperature and momentum flux, and relative humidity sensors on either side of the base to minimize wind-shadowing effects, along with a high-speed optical wave gauge. The data were recorded continuously at 20-Hz, and transmitted from the tower every ten minutes. Additional observations around 25 m were available at Buzzard’s Bay tower operated by the National Oceanic and Atmospheric Administration and from 24-m at the Air-Sea Interaction tower that had also been used in the CBLAST experiment (ASIT on Fig. 1a). Two LIDARs (from Deepwater Wind LLC) were deployed in the summer of 2014 at Southampton on Long Island and at the southwest corner of Block Island to get continuous wind measurements to 150 m above the surface.

Aircraft flights were conducted as part of the IMPOWR field campaign during the spring and summer of 2013 and 2014. A Long-EZ aircraft was used during 2013 (Fig. 1c), while a Cozy Mark IV aircraft was used after the fall of 2014 (not shown). Both aircrafts were fitted with the Aircraft-Integrated Meteorological Measurement System (AIMMS-20) instrument, which is capable of recording observations of three-dimensional winds, temperature, pressure, and relative humidity at a frequency up to 40 Hz. Flight operations were based out of Brookhaven Airport (KHWV on Fig. 1a) and
targeted the coastal areas of Nantucket Sound, Buzzard’s Bay, and Block Island Sound, as well as the New Jersey coast. Various flight maneuvers, such as constant-level flight legs, spiral soundings in the lowest 2 km, and slant-sounding flight legs below 1 km, were conducted in order to provide marine boundary layer profiles of momentum, thermal, and moisture fields, as well as turbulence and flux quantities. A typical flight period involved about an hour of transport to the location, around 2 hours of sampling, and then the return flight to Long Island.

3. IMPOWR: WRF simulations

This study utilized the Advanced Research WRF (Weather Research and Forecasting; Skamarock et al. 2008) model version 3.4.1. A series of short-term (30-h) WRF runs were completed for two separate evaluation periods: the Historical Period centered on the available data from the Cape Wind Meteorological Mast (2003–2011), and the IMPOWR aircraft flights conducted in 2013–2014. This paper focuses on IMPOWR flights, in which a large 4-km domain was used as the outer domain over the Northeast U.S., eastern Great Lakes, and Atlantic coastal waters, with a one-way nested inner 1.33-km domain (Fig. 1 region). The WRF runs used the Yonsei University (YSU; Hong et al. 2006), Unified NOAH land surface scheme (Tewari et al. 2004), RRTM longwave radiation (Iacono et al. 2000), Dudhia short-wave radiation (Dudhia 1989), Thompson microphysical parameterization (Thompson et al. 2004; Thompson et al. 2008), and no convective scheme on either domain. The initial and lateral boundary conditions were supplied by hourly analyses the National Center for Environmental Prediction’s Rapid Refresh (RAP; Benjamin et al. 2009). The RAP was chosen for the WRF simulations of the flight cases because of its higher spatial and temporal
resolutions, as well as improved data assimilation methods, over other available gridded analyses. The WRF domains were altered for the historical period to accommodate the smaller RAP spatial coverage. The 1/12\textsuperscript{th} degree daily gridded sea surface temperature (SST) product from the National Centers for Environmental Prediction was prescribed for all WRF runs. The model output interval for the 1.33-km domain was increased to 5 minutes in order to allow for interpolation of the model variables to the aircraft position in time and space.

3. Field Examples

As of early 2015, there have been 18 flights using the Long-EZ aircraft (Table 1). The goal was to sample a variety of different flow regimes, with a focus on the diurnal coastal flows during the warm season. There were several southwesterly flow cases, with enhanced flows and jets near the coast, but also two offshore (westerly) or northeasterly flow events. All events had limited low-cloud cover during the daytime (typically afternoon), which allowed more focus on the dry PBL processes during diurnal heating. The good visibility allowed the aircraft to descend to and sample 30–50 m above the sea surface.

Two example cases are discussed below to highlight some of the data collected as well as some preliminary comparisons with the WRF model. Both events have enhanced southerly or southwesterly flow, with one event around Nantucket Sound on 21 June 2013, and a New York Bight jet event on 23 July 2014.
a. 21 June 2013 Nantucket event

Three flights were conducted in the four day period of 20–23 June 2013, in the afternoons and evenings of 20, 21 and 23 June. The prevailing winds in the vicinity of Nantucket Sound during this period were predominantly south-southwesterly, with the presence of a high-pressure center to the south and east (Fig. 3a), which increased in intensity throughout the period (not shown). By early afternoon (1800 UTC 21 June), the air temperatures increased to 28–29 °C over the interior of New England, while the air temperatures over the coastal waters measured by the buoys were 18–19 °C. As a result, the strongest southerly surface flow was 5–7 m s\(^{-1}\) near the coast, while the winds were lighter and more variable over the interior land areas as well as further offshore.

The Long-EZ aircraft took off at 1730 UTC 21 June and ferried towards the Nantucket area while remaining nearly parallel to eastern Long Island (Fig 3b). It completed a series of short north-south stacks and a profile near the CW tower before returning back to Long Island following a similar track. Figure 3b shows the winds at ~50 m as the aircraft went towards Nantucket Sound. There was a steady increase in winds from 8–12 m s\(^{-1}\) towards the east, which is suggestive of coastal enhanced low-level southerly flow. Figure 4a shows an analysis of the winds and potential temperatures for the north-south stacks into and out of Nantucket Sound and the spiral at CW. The observed static stability (vertical potential temperature gradient) is largest to the south and strongest around 150 m; this elevated stable layer weakens and increases in height to the north. This is consistent with SST differences increasing from south to north, ranging from ~16 °C just south of Nantucket Sound to ~20 °C inside of the Sound (not shown). The observed marine layer in the observations is deeper over the northern half of the
cross section, which hydrostatically enhances the surface pressure difference between these coastal water locations and the interior land areas, thus resulting in enhanced flow (11 to 13 m s\(^{-1}\)) than locations to the south.

The WRF simulation with the YSU PBL is compared with the observations 18–21 h into the forecast at 1.33-km grid spacing. At 1800 UTC (Fig. 5), the WRF model diurnally warms the interior up to 28 °C at the surface; the surface winds are 5–8 m s\(^{-1}\) near the coast (Fig. 3a), while only 2–3 m s\(^{-1}\) south of Long Island, which is ~4 m s\(^{-1}\) weaker than the buoy observations. For the north-south cross section (Fig. 4b), the WRF isentropes are relatively flat at low-levels with no evidence of a well-defined marine layer, and as a result the winds are 2–3 m s\(^{-1}\) weaker than observed. The WRF model does develop a more defined stable layer eventually by 2100 UTC (Fig. 4c), but the layer is centered around 100 m, and the modeled winds are 1–2 m s\(^{-1}\) weaker than the 1800 UTC observations over the center part of the cross section. Overall, the WRF model developed the enhanced winds too slowly and the strongest winds are located too close to the coast.

\textit{b. 23 July 2014 New York Bight jet event}

Two flights occurred on 23 July 2014 to observe the development of the New York Bight jet along the New Jersey (NJ) coast towards western Long Island. At 1800 UTC 23 July, there was surface high pressure offshore of the U.S. East coast (Fig. 6a), and there was a cold front over central New York (NY) and Pennsylvania that was progressing eastward. The surface temperatures ahead of this front around New York City (NYC) were 32–33 °C, while it was 24–25°C over the coastal waters. The WRF
model simulates a similar large-scale pressure and surface temperature distribution across
the region (not shown). In the 1.33-km WRF domain the winds at 180 m AMSL are 14-
15 m s\(^{-1}\) along the NJ coast at 2100 UTC (Fig. 6b), and there were also enhanced
southerly winds just south of Long Island and along coastal southeast New England. This
wind enhancement is similar to the simulated NY Bight jet enhancement in the WRF
simulations presented by Colle and Novak (2010). This earlier study had limited
observations to show the evolution of the jet.

Figure 7 shows the two flight tracks for sampling the jet as well as the along track
winds plotted when the aircraft was between 100 and 225 m AMSL. During the first
flight between 1400 UTC and 1700 UTC 23 July (Fig. 7a), winds are 5–10 m s\(^{-1}\) from the
southwest along the NJ coast. There is a slight enhancement to 10–12 m s\(^{-1}\) in the NY
Bight region and just south of Long Island. A north-south cross section for the leg
parallel to the NJ coast shows a stable layer in the lowest 300 m (Fig. 8a), where there is
a 4–5 K increase in potential temperature from 150 m to 300 m; there is a mixed layer
(nearly constant potential temperature) above this stable layer. This mixed layer was
likely advected from the heated continental land areas (southern New Jersey). The winds
in the section are strongest near the surface (~10 m s\(^{-1}\)), with little evidence of enhanced
flow from south to north at this time.

During the second flight between 2000 and 2200 UTC 23 July, much stronger
winds were observed along the NJ and Long Island coasts (Fig. 7b). Winds were 12–15
m s\(^{-1}\) over much of the region, with the strongest winds (17–20 m s\(^{-1}\)) over parts of the
NY Bight. The south-north cross section (Figure 8b) shows that the marine layer had
increased in depth and was sloping down towards the north, with the strongest stability
around 200–250 m AMSL, especially in the northern part of the section. The winds had increased during the last few hours, with the strongest winds at 21 m s$^{-1}$ centered around 150 m AMSL. The winds increase 3–4 m s$^{-1}$ from south to north over a 60–70 km distance at this level, with most of the change in the first 30 km. Overall, the magnitude of these gale force winds were unexpected, especially considering they were 5-6 m s$^{-1}$ stronger than the models predicted (Fig. 6b).

4. Summary and Research Opportunities

The IMPOWR field study was motivated by the lack of thermodynamic and wind observations within the boundary layer over the Northeast U.S. coastal ocean. This has hindered the evaluation and improvement of planetary boundary layer parameterizations in these marine environments, which are important for wind resource assessment and forecasting in the coastal zone. The large number of days sampled with aircraft and other instruments during IMPOWR offer numerous scientific research opportunities.

One major question is whether mesoscale models (e.g., WRF) can accurately simulate the wind and temperature profiles in the marine boundary layer under different synoptic flow conditions. Preliminary results from IMPOWR, as shown above for the 21 June 2013 and 23 July 2014 events, among others not discussed here, suggest that the WRF underpredicts the amplitude of coastal low-level jets in this region and that these jets do not extend offshore enough and are too shallow in the model. There are several other IMPOWR jet events that can be evaluated to generalize these results (Table 1). In addition, several years (2003–2011) of wind observations at Cape Wind tower from 20 to 60 m have been collected and can be used to look at the wind profile from the surface to
about wind turbine hub height. Since summer 2014, two LIDARS have been collecting continuous measurements of the winds in the lowest 150-m over coastal Long Island and Block Island (Fig. 1), which also can be compared with the models. Over 90 WRF simulations have been completed using 5 different PBL parameterizations to construct a longer-term validation of WRF using these historical datasets. Preliminary results suggest that the WRF is more stable than observed (not shown), with temperatures often 2–3 °C too cold near the surface and with too little turbulent kinetic energy (TKE, a proxy for vertical momentum mixing).

Another important question is what factors may be leading to the wind and temperature biases in the model. The WRF model was rerun using several other PBL parameterizations for the two IMPOWR cases presented above as well as a few other events. Although there are some variations between the schemes, they all underpredict the warm season low-level jets, which suggest that there are other factors that may be limiting the jet magnitude than the turbulent closure assumptions in the PBL schemes. For example, the sea surface temperatures in WRF are fixed and based on a SST product that averages a few days of satellite-derived temperatures and buoys. In reality, the SSTs in Nantucket Sound can increase by 2–3 °C during afternoon heating and can exhibit significant spatial variability near the coast. As a result, the WRF SSTs tend to be too cool during the day, which may be leading to the cool bias in all PBLs, so additional experiments are needed to determine the role of these temporal and spatial SST variations on the simulated diurnal circulations.

IMPOWR also provides useful observations for mesoscale data assimilation in the coastal zone, where there are relatively sparse data to properly initialize the model. To
motivate this issue, we reran a few cases from the IMPOWR experiment using different initial and boundary conditions from the North American Mesoscale model analysis, Rapid Refresh analysis, Global Forecast System analysis, and North American Regional Reanalysis. The spread in low-level winds in WRF using these different analyses is larger than using different WRF PBLs for a single initialization, thus suggesting the importance of including relevant atmospheric small-scale structures at the start of the simulation (since these analyses all had a very similar synoptic patterns). The additional observations from IMPOWR can be ingested into WRF using an Ensemble Kalman Filter approach (Evensen 2003).

Lastly, the IMPOWR dataset is helping our understanding of important structures and processes associated with coastal diurnal flows that had only been modeled in previous studies (e.g., Novak and Colle 2010). For example, IMPOWR observations are yielding important knowledge on the small-scale variations in the marine boundary layer, such as localized pressure gradient and wind enhancements, similar to those observed in the 21 June and 23 July cases above. The derived TKE from these coastal flows suggests that there is significant vertical mixing even when the marine PBL is stratified with a relatively cool SST. The importance of vertical momentum transport was not highlighted in past studies using momentum budgets from WRF data (Colle and Novak 2010), since the model produced very little mixing.

The value of these IMPOWR observations, consisting of both in-situ aircraft and long-term in situ observations, will not only lead to improved boundary layer parameterizations over the coastal ocean, but also hopefully motivate additional field
campaigns along U.S. East coast. This is important given the relatively large wind resource in these areas and the general lack of model evaluations at hub height.

Acknowledgements

The project “Improving the Mapping and Prediction of Offshore Wind Resources” (IMPOWR) was funded under the DOE award # DE-EE0005377. The authors thank Energy Management, Inc, developer of Cape Wind, for providing access to its offshore meteorological tower for our instruments, and to the historical dataset from that tower. We also thank Deepwater Wind LLC for use of two LIDARs for this project.

References


**List of Tables**

Table 1: Flight days for the IMPOWR field experiment

**List of Figures**

Figure 1. (a) Map of the IMPOWR observations used in the region. Photos of: (b) the Cape Wind tower (green star in a); (c) Long-EZ aircraft that was deployed from near FOK on Long Island, and (d) a spiral of the Long-EZ over the Cape Wind tower. Photos credits: Dana Veron for (b), John Mak for (c), and Matthew Sienkiewicz for (d).

Figure 2. Wind speed climatology per month at the Cape Wind tower at 20, 41, and 60 m levels during 2003-2007, including count of valid 10-minute observations.

Figure 3. (a) Surface analysis over the Northeast U.S. and Mid-Atlantic from the NOAA-Weather Prediction Center at 1800 UTC 21 June 2013, with sea-level pressure contoured every 4 hPa. (b) Wind speed from the Long-EZ flight track at 40-50 m (colored in m s$^{-1}$). The box in (a) is the location of the flight level data in (a).

Figure 4. (a) Potential temperature (contoured every 1K), wind barbs (full barb = 10 kts using the color bar in Fig. 3) and wind speed (every 2 m s$^{-1}$) from the Long-EZ observations along AB shown in Fig 3. (b) Same as (a) except the 1.33-km WRF at 1800
UTC 21 June (forecast hour 18). (c) Same as (b) except for the 1.33-km WRF at 2100 UTC.

Figure 5. 1.33-km WRF surface (2-m) temperature (shaded in °C), sea-level pressure (solid every 1 hPa), and 50-m winds (full barb = 10 kts) valid at 1800 UTC 21 June 2013 (forecast hour 18).

Figure 6. (a) Surface analysis over the Northeast U.S. and Mid-Atlantic from the NOAA-Weather Prediction Center at 2100 UTC 21 July 2014, with sea-level pressure contoured every 4 hPa. (b) 1.33-km WRF wind speeds at 180 m (shaded in m s\(^{-1}\), and 1 full barb = 10 kts) at 2100 UTC 23 July (forecast hour 21).

Figure 7. Flight track and flight-level winds (colored in kts) between 100 and 225 m AMSL from the Long-EZ aircraft for (a) flight 1 from 1400-1700 UTC 23 July and (b) flight 2 from 2000-2200 UTC 23 July 2014.

Figure 8. (a) Potential temperature (contoured every 2K) and (b) wind speed (every 1 m s\(^{-1}\)) from the Long-EZ observations along track CD shown in Fig 7a from 1604–1623 UTC 23 July 2014. (c) Same as (a) except for flight 2 in Fig. 7b from 2123 UTC to 2141 UTC 23 July.

Table 1: Flight days for the IMPOWR field experiment

<table>
<thead>
<tr>
<th>Flight Day</th>
<th>Weather Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 November 2012</td>
<td>Cyclone warm sector with south winds</td>
</tr>
<tr>
<td>4 April 2013</td>
<td>Southwest flow around anticyclone</td>
</tr>
<tr>
<td>7 April 2013</td>
<td>Stable strong south flow ahead of warm front</td>
</tr>
<tr>
<td>Date</td>
<td>Weather Event</td>
</tr>
<tr>
<td>--------------------</td>
<td>----------------------------------------------------</td>
</tr>
<tr>
<td>9 April 2013</td>
<td>Southwest flow ahead of cold front</td>
</tr>
<tr>
<td>4 May 2013</td>
<td>Moderate northeast flow with a subsidence inversion at top of PBL</td>
</tr>
<tr>
<td>10 May 2013</td>
<td>Southwest flow with coastal sea breezes</td>
</tr>
<tr>
<td>16 May 2013</td>
<td>Southwest flow with coastal jet</td>
</tr>
<tr>
<td>20 June 2013</td>
<td>Coastal sea breeze with westerly flow aloft</td>
</tr>
<tr>
<td>21 June 2013</td>
<td>Coastal sea breeze with westerly flow aloft</td>
</tr>
<tr>
<td>23 June 2013</td>
<td>Southwesterly flow with coastal flow enhancement</td>
</tr>
<tr>
<td>24 June 2013</td>
<td>Weak NY Bight jet event</td>
</tr>
<tr>
<td>28 September 2013</td>
<td>Northeasterly flow around anticyclone</td>
</tr>
<tr>
<td>2 October 2013</td>
<td>Weak westerly flow</td>
</tr>
<tr>
<td>12 May 2014</td>
<td>Southwest flow with coastal jet</td>
</tr>
<tr>
<td>22 July 2014</td>
<td>New York Bight Jet</td>
</tr>
<tr>
<td>23 July 2014 (Flight 1)</td>
<td>New York Bight Jet (before jet)</td>
</tr>
<tr>
<td>23 July 2014 (Flight 2)</td>
<td>New York Bight Jet (after jet)</td>
</tr>
<tr>
<td>31 July 2014</td>
<td>Southwest flow with coastal jet</td>
</tr>
<tr>
<td>11 November 2014</td>
<td>Cold NW flow over warmer coastal waters</td>
</tr>
</tbody>
</table>
Figure 1. (a) Map of the IMPOWR observations used in the region. Photos of: (b) the Cape Wind tower (green star in a); (c) Long-EZ aircraft that was deployed from near FOK on Long Island, and (d) a spiral of the Long-EZ over the Cape Wind tower. Photos credits: Dana Veron for (b), John Mak for (c), and Matthew Sienkiewicz for (d).
Figure 2. Wind speed climatology per month at the Cape Wind tower at 20, 41, and 60 m levels during 2003-2007, including count of valid 10-minute observations.
Figure 3. (a) Surface analysis over the Northeast U.S. and Mid-Atlantic from the NOAA-Weather Prediction Center at 1800 UTC 21 June 2013, with sea-level pressure contoured every 4 hPa. (b) Wind speed from the Long-EZ flight track at 40-50 m (colored in m s$^{-1}$). The box in (a) is the location of the flight level data in (a).
Figure 4. (a) Potential temperature (contoured every 1K), wind barbs (full barb = 10 kts using the color bar in Fig. 3) and wind speed (every 2 m s\(^{-1}\)) from the Long-EZ observations along AB shown in Fig 3. (b) Same as (a) except the 1.33-km WRF at 1800 UTC 21 June (forecast hour 18). (c) Same as (b) except for the 1.33-km WRF at 2100 UTC.
Figure 5. 1.33-km WRF surface (2-m) temperature (shaded in °C), sea-level pressure (solid every 1 hPa), and 50-m winds (full barb = 10 kts) valid at 1800 UTC 21 June 2013 (forecast hour 18).
Figure 6. (a) Surface analysis over the Northeast U.S. and Mid-Atlantic from the NOAA-Weather Prediction Center at 2100 UTC 21 July 2014, with sea-level pressure contoured every 4 hPa. (b) 1.33-km WRF wind speeds at 180 m (shaded in m s\(^{-1}\), and 1 full barb = 10 kts) at 2100 UTC 23 July (forecast hour 21).
Figure 7. Flight track and flight-level winds (colored in kts) between 100 and 225 m AMSL from the Long-EZ aircraft for (a) flight 1 from 1400-1700 UTC 23 July and (b) flight 2 from 2000-2200 UTC 23 July 2014.
Figure 8. (a) Potential temperature (contoured every 2K) and (b) wind speed (every 1 m s$^{-1}$) from the Long-EZ observations along track CD shown in Fig 7a from 1604–1623 UTC 23 July 2014. (c) Same as (a) except for flight 2 in Fig. 7b from 2123 UTC to 2141 UTC 23 July.