Enhanced Northeast Winds in the Western Gulf of Maine:
A New Diagnostic Technique

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ABSTRACT

A recent study conducted by K. Apffel of the Gray, Maine National Weather Service (NWS) office found that strong northeasterly surface winds in the western Gulf of Maine are often under-forecasted by both numerical models and human forecasters (Apffel, 2005). This narrow wind core is frequently observed by the lighthouses and buoys of the Coastal/Marine Automated Network (C/MAN) stations in the near-shore region, while being simultaneously absent at adjacent land stations (ASOS/AWOS) and C/MAN sites nearer to the center of the Gulf. To investigate this phenomenon, wind events were identified from surface observation records over a five-year period (2000-2004) for three C/MAN locations in the western Gulf of Maine. Event selection criteria were determined in part from the results of the Apffel study, which found that the largest forecast errors, and the largest under-forecast wind speed biases, occurred when the wind direction was within the range between 15° and 75° true. Wind speeds of 6 m s⁻¹ (12 knots) or greater were chosen to isolate cases of operationally significant winds. An event was defined as beginning when the speed and direction criteria occurred simultaneously for three consecutive hours at three C/MAN stations: Matinicus Rock (MISM1), Portland Buoy (44007) and Isles of Shoals (IOSN3). From hourly observations taken on the identified event dates, mesoscale cross-shore and along-shore pressure and isentropic gradients were calculated. Similar calculations were performed using randomly selected hourly observations taken on non-event dates during the study period. Plotting the resulting cross-shore (\( \frac{\partial p}{\partial x'} \)) and along-shore (\( \frac{\partial p}{\partial y'} \)) pressure gradients for the entire period onto a rotated coordinate system produced significant separation between the events and the non-events. Plots isolating events occurring during each calendar month feature distinct patterns and groupings. Event frequencies demonstrate characteristic seasonal and diurnal patterns. Thus, refinement of this technique and its application on an operational basis represents a potentially valuable forecasting tool for NWS meteorologists responsible for this region. Further investigations of the larger scale synoptic features associated with enhanced wind events are in progress. Statistical studies to correlate the state of specific meteorological conditions with events using a larger data set are planned. Ultimately, the development of a practical, real-time computerized forecasting system and set of guidelines is envisioned.

1. Introduction

The New England climate is remarkable for rapidly changing weather conditions. On the synoptic scale, several major middle latitude climatological storm tracks from the south and west converge over the region, ensuring a regular supply of low-pressure systems and frontal activity to destabilize the atmosphere. Cold, dry continental air masses invading from the north routinely clash with relatively warm, moist air hailing from southern source regions. Tropical cyclones periodically threaten New Englanders with destructive winds, deadly coastal storm surges, and widespread inland flooding. These major synoptic-scale systems are obvious, revealed in routine surface analysis maps, radar loops, and satellite images. Forecasters generally do well in prognosticating the development,
intensification and track of these large systems.

However, the smaller mesoscale weather phenomena created by complex atmospheric interactions at the local level frequently wreak havoc in the New England region. These important events generally receive less recognition, and are perhaps more difficult to analyze and predict, than typical large systems. Moreover, these mesoscale features do not necessarily become obvious upon inspection of traditional synoptic charts, tending to hide beneath the inherently coarse resolution of broad area views. Fundamental meteorological changes occur on relatively small scales.

In eastern New England, no single topographical feature has more profound consequences than the Atlantic coastline (Fig. 1). Indeed, close proximity to the ocean does moderate the overall climate, minimizing the diurnal and average annual temperature ranges, for example. Conversely, atmospheric interactions at the land-sea interface can quickly affect conditions a large distance inland and seaward. A coastal zone has been defined as the 200 km region extending 100 km beyond each side of the coast, where conditions are “significantly affected, by sharp changes in heat, moisture, and momentum transfers and elevation that occur between land and water.” (National Research Council 1992) Moreover, greater than half of the United States population resides in coastal areas, and this number is projected to increase rapidly (NOAA 1998). Hence, volatile atmospheric conditions in the coastal zone continually affect great numbers of people who live, work and recreate there.

Wind forecasting in the western Gulf of Maine presents significant challenges to computer models and human forecasters responsible for this coastal region. Despite recent improvements to models, numerical guidance has performed poorly overall. A recent study conducted by K. Apffel of the Gray, Maine National Weather Service (NWS) office found that strong northeasterly surface winds occurring in the western Gulf of Maine (blue arrow, Fig. 1) are often under-forecasted by both numerical models and human forecasters (Apffel 2005). A persistent, narrow core of wind is observed periodically by the lighthouses and buoys of the Coastal/Marine Automated Network (C/MAN) in the near-shore region, while being simultaneously absent at adjacent land stations (ASOS/AWOS) and C/MAN sites nearer to the center of the Gulf. These unexpectedly high wind velocities represent a serious threat to maritime interests in the region.

Three primary categories of atmospheric forcing within the coastal zone are recognized (National Research Council 1992). The first category, thermally driven effects caused by sharp coastal zone temperature contrasts, was examined as a probable cause of these wind events. The existence of a coastal front in the near-shore region could produce enhanced flows along the coastline. A small-scale front would be incompletely determined due to the horizontal resolution of current operational
numerical models. Model parameterization schemes do not necessarily account correctly and completely for all conditions within the grid spaces over ocean areas, where minimal observational data are available for model initialization.

The second category, orographic effects forced by topographical features present on the landward side of the coastal zone, was also considered. Abrupt elevation changes and blocking by the coastal mountains of eastern Maine (Fig. 2) may force winds, with an initial component perpendicular to the coastline, to change course and move along this barrier. Coastal mountains can also lead to cold air damming under certain synoptic scenarios. Bell and Bosart (1988) established that cold air damming east of the Appalachians leads to a strong low-level wind maximum within the cold dome, having a significant northerly component parallel to the coastline. Miller and Keim (2003) define the sudden onset of the sea breeze circulation system (SBS) due to strong inland heating, and illustrate the confinement of the SBS to the coastal plain by inland barriers.

The third category, direct interaction with large-scale weather systems, was by definition excluded from this mesoscale investigation. A large system, such as a strong extratropical cyclone passing through the Gulf of Maine, creates high wind velocities over a broader area than the narrow core flow observed during the wind events seen in this study.

This paper focuses on the low level mesoscale environment in which this unexpectedly strong wind develops. Here we shall analyze surface observations taken during these unexplained enhanced wind events in the coastal marine zone, to reveal important features with the potential to improve wind forecasts. Current research is investigating the corresponding synoptic-scale conditions present during these events.

Future investigations will statistically correlate the state of specific meteorological conditions within the atmospheric boundary layer (ABL) coincident with event occurrences. Ultimately, a practical, real-time forecasting system and set of NWS operational guidelines is envisioned.

2. Data and Methods

To investigate the initial hypothesis that some type of frontal feature is involved, wind events were first identified using surface METAR observation records taken over a five-year period (2000-2004) at seven stations in the Gulf of Maine region (Table 1). Three coastal land-based stations (KPSM, KPWM, KRKD) were paired with three adjacent marine stations (IOSN3, 44007, MISM1) in the western Gulf.
Reference observations were taken from one station positioned nearer to the middle Gulf (44005). Parameters extracted include wind direction (deg), wind speed (ms\(^{-1}\)), sea level pressure (hPa), temperature (\(^\circ\)C), and potential temperature (\(\Theta\), \(^\circ\)C).

Event selection criteria were determined in part from the results of the Apffel study, which found that the largest forecast errors, and the largest under-forecast wind speed biases, occurred when the wind direction was within the range between 15\(^\circ\) and 75\(^\circ\) true (Apffel 2005). Wind speeds of 6 ms\(^{-1}\) (\(\approx\)12 knots) or greater were chosen to isolate cases of operationally significant winds. An event was defined as beginning when the speed and direction criteria were met for three consecutive hours simultaneously at three marine stations: Matinicus Rock, Casco Bay and Isles of Shoals. To qualify as an event, the high wind speeds must have occurred concurrently at all three marine stations, while being simultaneously absent from the adjacent land stations and the middle Gulf buoy (44005).

**Table 1.** Observing stations used in the Gulf of Maine wind study.

<table>
<thead>
<tr>
<th>STATION</th>
<th>LOCATION</th>
<th>TYPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>KPSM</td>
<td>Portsmouth, NH</td>
<td>ASOS</td>
</tr>
<tr>
<td>KPWM</td>
<td>Portland, ME</td>
<td>ASOS</td>
</tr>
<tr>
<td>KRKD</td>
<td>Rockland, ME</td>
<td>ASOS</td>
</tr>
<tr>
<td>IOSN3</td>
<td>Isle of Shoals, ME</td>
<td>C-MAN</td>
</tr>
<tr>
<td>MISM1</td>
<td>Matinicus Rock, ME</td>
<td>C-MAN</td>
</tr>
<tr>
<td>44007</td>
<td>Casco Bay, ME</td>
<td>NOAA Buoy</td>
</tr>
<tr>
<td>44005</td>
<td>Cashes Ledge</td>
<td>NOAA Buoy</td>
</tr>
</tbody>
</table>
From hourly observations taken on the identified event dates, cross-shore ($\delta p / \delta x'$) and along-shore ($\delta p / \delta y'$) pressure and isentropic gradients were calculated. For cross-shore gradient calculations, the land value was subtracted from the adjacent ocean value. For along-shore gradient calculations, the south value was subtracted from the north value. Observe that the Maine coastline runs at approximately a 60° angle to the east of true north (Fig. 3). Utilizing a coordinate system rotated accordingly to match the coastline, a positive cross-shore gradient indicates higher values detected toward the southeast, while a positive along-shore gradient indicates higher values toward the northeast (Table 2). Refer to Figures 4 and 5 showing the mathematical and directional gradient interpretations translated into the corresponding graphical quadrants.

All distances between stations have been calculated using the great circle method. The magnitudes are mesoscale following the Orlansky 1975 guidelines (Fujita 1986). In the cross-shore direction, distances are gamma-mesoscale ($\gamma$) at KPSM / IOSN3 (20.3 km) and KPWM / 44007 (18.5 km), while the KRKD / MISM1 distance (37.2 km) is consistent with beta-mesoscale ($\beta$).

The along-shore distance, calculated between stations IOSN3 and MISM1 (168.2 km), is also classified as beta-mesoscale. To maintain the integrity of the calculations, when an event hour contained missing or corrupted data for any station that entire hour was discarded for all stations. Matinicus Rock (MISM1) was a particular problem in this respect, with all data of the year 2003, as well as March and November 2004, being either missing or corrupted.
<table>
<thead>
<tr>
<th>MONTH</th>
<th>EVENT HOURS</th>
<th>EVENT %</th>
<th>NON-EVENT HOURS</th>
<th>NON-EVENT %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>27</td>
<td>5.0</td>
<td>90</td>
<td>8.3</td>
</tr>
<tr>
<td>Feb</td>
<td>14</td>
<td>2.6</td>
<td>90</td>
<td>8.3</td>
</tr>
<tr>
<td>Mar</td>
<td>48</td>
<td>9.0</td>
<td>45</td>
<td>4.2</td>
</tr>
<tr>
<td>Apr</td>
<td>96</td>
<td>17.9</td>
<td>100</td>
<td>9.3</td>
</tr>
<tr>
<td>May</td>
<td>23</td>
<td>4.3</td>
<td>93</td>
<td>8.6</td>
</tr>
<tr>
<td>Jun</td>
<td>44</td>
<td>8.2</td>
<td>92</td>
<td>8.5</td>
</tr>
<tr>
<td>Jul</td>
<td>21</td>
<td>3.9</td>
<td>91</td>
<td>8.4</td>
</tr>
<tr>
<td>Aug</td>
<td>19</td>
<td>3.6</td>
<td>90</td>
<td>8.3</td>
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<tr>
<td>Sep</td>
<td>67</td>
<td>12.5</td>
<td>96</td>
<td>8.9</td>
</tr>
<tr>
<td>Oct</td>
<td>91</td>
<td>17.0</td>
<td>95</td>
<td>8.8</td>
</tr>
<tr>
<td>Nov</td>
<td>59</td>
<td>11.0</td>
<td>99</td>
<td>9.2</td>
</tr>
<tr>
<td>Dec</td>
<td>26</td>
<td>4.9</td>
<td>100</td>
<td>9.3</td>
</tr>
</tbody>
</table>

**TOTALS:** 535 100.0 1081 100.0

| TABLE 3. Monthly distribution of wind events and random non-events. |

Therefore, the 14 flawed months were discarded for all stations, leaving a total 46 months of hourly observations for analysis. Out of 713 events initially identified from the original data set, 535 were analyzed. As anticipated, the exact distribution of events varied by calendar month (Table 3).

Similar gradient calculations were performed using randomly selected hourly observations taken on non-event dates during the study period. These observations serve to differentiate between conditions existing while events were and were not occurring. From the initial set containing 2400 random non-event hours, 1081 were analyzed. The results are equitably distributed across all calendar months (Table 3). Due to missing observational data, fewer nonevents were available for March; however, there appear to be sufficient nonevents for valid analysis and contrast.

### 3. Results

The resulting cross-shore ($\delta p/\delta x'$) and along-shore ($\delta p/\delta y'$) pressure gradient calculated for each location were plotted onto the rotated coordinate system. Plots of gradients for the entire study period produced an intriguing picture of the horizontal pressure field in the near-shore region during events and nonevents.

Significant separation is evident between the events (blue plots) and the non-events (red plots) in the KRKD / MISM1 graph (Fig. 6). The non-events tend to cluster near the origin, indicating relatively small gradient values. By contrast, the events tend to be positioned farther away from the origin, indicating higher gradient values. Events fall mostly into quadrant II, with far fewer found in the upper part of quadrant III. Virtually no events are located in quadrants I or IV (few exceptions).

From the graphical interpretation of plots located in each of the four quadrants (Figs. 4, 5), we conclude that for most wind events the pressure values were higher to the northwest and lower to the southeast. In relatively few cases, the pressure field was higher to the southwest and lower to the northeast. Recall that events plotted farther away from the graph origin represent proportionately larger mesoscale pressure gradient magnitudes. Observing the distinct
Fig. 6. Plot of cross-shore versus along-shore SLP gradient for all data at the KRKD / MISM1 location.

division between events and nonevents, a line has been subjectively drawn to mark the lower limit of event occurrences (Fig. 6). This line runs roughly west to east, defined by the approximate slope-intercept equation:

\[ \frac{\delta p}{\delta y'} = 0.66 \frac{\delta p}{\delta x'} + 0.01 \text{ hPa/km} \]

Generally speaking, above this line an event occurrence is more likely; while below the line we expect a lower probability of events. By this **event predictor guide line** we can also define the concept of false positives and false negatives. Any event located below the guide line is referred to as a **false negative**, while any nonevent positioned above the guide line is termed a **false positive**. Refinement of this procedure should increase the accuracy and reliability for operational applications. This technique would perhaps also be useful in measuring forecasting performance. Plots of forecasted events versus actual events could reveal any tendencies to under-predict or over-predict.

Additional plots isolating events occurring during each calendar month (Figs. 7 - 18) feature distinctive patterns and groupings. The identical event predictor guide line has been drawn on each graph to aid with consistent comparison of the results. As one might expect, warm season plots tend to be clustered more tightly around the origin, an indicator of the typical smaller pressure gradients seen during summer and fall. Conversely, the cold-season months display a broader distribution of events away from the origin, showing the general tendency toward larger gradient values during winter and spring.

Certain months display more distinct separation than others. July in particular (Fig. 13) demonstrates virtually complete
Figs. 7-9. Plots of cross-shore versus along-shore SLP gradient for months January-March at the KRKD / MISM1 location.
Figs. 10-12. Plots of cross-shore versus along-shore SLP gradient for months April-June at the KRKD / MISM1 location.
Figs. 13-15. Plots of cross-shore versus along-shore SLP gradient for months July-September at the KRKD / MISM1 location.
Fig. 16-18. Plots of cross-shore versus along-shore SLP gradient for months October-December at the KRKD / MISM1 location.
separation between events and nonevents, and contains no false negatives. Here we see that a vertical line drawn at approximately \[ x' = -0.03 \text{ hPa} \] cleanly delineates events. The along-shore pressure gradients are very small, and clustered tightly around the horizontal axis \[ y' = 0 \]. Evidently, during July enhanced wind events become more likely when the cross-shore pressure gradient exceeds 0.03-hPa in magnitude with higher pressure on shore.

The monthly plots also lead to the idea that it may be possible to create a unique event predictor guide line for each individual month. Further statistical analysis may reveal other periodicities, with event frequencies falling into characteristic seasonal and diurnal patterns. For example, the bar graphs of monthly frequency (Fig. 19) show distinct seasonal patterns. The greatest numbers of events occur during the months of April and October (35% combined). The top six months comprise 76% of events, leaving only 24% during the lowest six months. Therefore, NWS meteorologists should consider these facts before issuing wind forecasts for the western Gulf of Maine region.

![Gulf of Maine Wind Event Hours (All Data)](image)

Fig. 19. Monthly distribution and percentages of enhanced wind events in the western Gulf of Maine.
4. Conclusions

Among the variations of graphical analysis performed in this investigation, plots of the cross-shore pressure gradients versus the along-shore pressure gradients appear to have the best potential as an analytical and predictive tool for forecasting winds in the western Gulf of Maine. This type of analysis seems to be most reliable at the Rockland – Matinicus location (Figs. 6-18), and applies to events within this study area. One possible reason for the usefulness of Rockland is the longer cross-shore distance between KRKD and MISM1 (37 km vs. 18-20 km), allowing improved resolution of pressure gradients.

These results represent a significant step toward improved understanding and analysis of enhanced wind events in the region. Recognizing that the results are quite preliminary, further investigation in several related areas is recommended. First, rigorous statistical study of the results is necessary to quantify more exactly the correlation between specific conditions and event probabilities. Second, performance studies are required to establish the predictive reliability of this technique, when compared with the performance of numerical models and human forecasters under identical conditions. Third, the tendency of events to occur with higher cross-shore gradient magnitudes implies the potential to forecast actual wind velocities. This possibility should be investigated to ascertain whether the intuitive idea has merit.

Examination of the significant large-scale synoptic features present during wind events and nonevents is currently in progress at Judd Gregg Meteorology Institute by J. Moker (Moker 2006). Moker defines a quadrant system (Fig. 20), related to the mesoscale coordinate system described in this paper. Quadrant borders are defined such that the mesoscale axes align with the center of the synoptic quadrants. The Moker quadrants form a basis for classification of synoptic scenarios under which wind events become more probable. This work is geared toward identification of the synoptic conditions that NWS forecasters should consider when analyzing the potential for higher wind velocities in the region.

Fig. 20: The Moker synoptic-scale quadrant system (dashed blue lines). The superimposed mesoscale coordinate axes (black lines) align with the center of the synoptic quadrants. The Moker quadrants form the basis for classification of synoptic scenarios.

The ultimate goal of this cooperative project will be to develop a practical, real-time computerized forecasting system and set of guidelines. Given successful implementation in the Gulf of Maine, this technique might be applied, with modifications, to any similar coastal region.
Acknowledgements

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REFERENCES