Final Report:
COMET OUTREACH PARTNERS PROJECT

University: Plymouth State University (PSU)
University researcher preparing report: Samuel T.K. Miller

NWS Office: Center Weather Service Unit, Nashua, New Hampshire
NWS researcher preparing report: Scott Reynolds

Partners or Cooperative Project: Partners

Project title: Improved Sea Breeze Forecasting for Boston's General Edward Lawrence Logan International Airport

UCAR award number: S06-58394

Date: 02 April 2008

SECTION 1: SUMMARY OF PROJECT OBJECTIVES

Task 1 (University). Develop five-year database of sea breeze, marginal, and non-sea breeze events.

Task 2 (University). Stratification of all events into synoptic classes defined by Miller and Keim (2003).

Task 3 (University). Statistical analysis of event type by season and synoptic classes.

Task 4 (University). Calculation of mesoscale pressure and isentropic gradients for all events; determination of gradient thresholds separating event types.

Task 5 (University). Evolution of the wind field within the marine layer after onset of the sea breeze at Logan airport.

Task 5 (NWS). Evaluate mesoscale model guidance in sea breeze forecasting.

SECTION 2: PROJECT ACCOMPLISHMENTS AND FINDINGS

I have attached Ms. Thorp's final paper on the university's research, and Mr. Reynolds' draft summary of findings of the NWS' research. (Development of a more formal summary of the NWS' findings is currently underway.) Two Powerpoint presentations are also attached: One used by Ms. Thorp to discuss her research in several venues, including the 2007 Northeast Storm Conference (March 10, 2007) and the New England Regional Aviation Workshop (March 29, 2007). The other was used by Dr. Miller at a scientific colloquium at Plymouth State University in the Spring of 2007.

SECTION 3: BENEFITS AND LESSONS LEARNED – OPERATIONAL PARTNER PERSPECTIVE

Benefits to the Operational Partner:

- This project offered the CWSU meteorologists an opportunity to evaluate workstation WRF (wsWRF) model output generated by WFO Albany NY on a daily basis. The CWSU staff has not been exposed to many of the newer mesoscale models in the past.

- Collaboration between the CWSU and WFO Taunton has increased as a result of this project. There has always been an adequate level of collaboration between the two offices, but this increased coordination has resulted in a greatly increased level of situational awareness for all aviation-related weather impacts at both offices, and improved aviation forecast information provided by both offices. Based on anecdotal verification feedback from the WFO forecast and management staffs, this added collaboration has led to improved sea breeze forecast accuracy and lead times.

Lessons learned:

- There is still much work to be done in terms of introducing new forecast techniques and tools to the CWSU staff. There is also still much work to be done in educating all NWS forecasters (CWSU and WFO alike) on the impacts of weather on aviation operations.

- Technological limitations at the CWSU prevented archival of model output, thus limiting in-depth investigation of specific cases.

SECTION 4: BENEFITS AND LESSONS LEARNED – UNIVERSITY PARTNER PERSPECTIVE

Benefits to the university: This project enabled the student, Ms. J. Thorp, to work directly with meteorologists in the operational arena, and gain insight into their needs and methods, and demonstrate her abilities and research to the professional community. The university investigator (S.T.K. Miller) was able to learn more about the meteorological community involved in civil aviation.

Lessons learned: Regular, frequent communication and coordination between the university and NWS partners is necessary to maintain steady progress toward the project goals.

Major problems encountered: None.

SECTION 5: PUBLICATIONS AND PRESENTATIONS

Thorp, J, 2007: Improved Sea Breeze Forecasting for Boston's General Edward Lawrence Logan International Airport. (Paper *and* presentation; both attached.)

Miller, S.T.K.: Sea Breezes. (Powerpoint presentation; attached.)

Reynolds, S., 2007: Verification of Sea Breeze Technique and Numerical Model Guidance. (Informal paper; attached.)

SECTION 6: SUMMARY OF UNIVERSITY/OPERATIONAL PARTNER INTERACTIONS AND ROLES

University partner (Miller): Assisted university student Thorp with data acquisition, analysis, and interpretation. Maintained administrative control of grant expenses and funds. Assisted student with formulation and editing of final paper. Maintained contact for coordination with NWS partner.

NWS partner (Reynolds): Designed and carried out evaluation of sea breeze forecasting technique developed by Thorp and Miller, compared to sea breeze forecasts from operational numerical guidance, and formulated a summary of the results. Instructed the other meteorologists at the CWSU and ensured their participation in the verification piece of the project. Provided regular updates to WFO Taunton meteorologists on the project, including one training seminar presentation.

IMPROVED SEA BREEZE FORECASTING FOR BOSTON'S GENERAL EDWARD LAWRENCE LOGAN INTERNATIONAL AIRPORT

Jennifer Thorp
Plymouth State University

April, 2007

ABSTRACT

This study adapts the method of predicting sea-breeze events developed by Miller and Keim (2003) to Logan International Airport in Boston, Massachusetts (KBOS). A five-year dataset of hourly KBOS surface observations (2001-2005) was used to identify 565 days when the sea breeze occurred or was likely to occur at the airport. These days were classified into sea-breeze, marginal, or non-sea-breeze events. Sea-breeze events were further classified into fast and slow transitions, with a fast transition identified with a wind shift taking one hour or less, and a slow transition identified with a wind shift taking two hours or more. Morning United States surface analyses for each event were classified using the seven synoptic classes developed by Miller and Keim (2003), and statistics were developed to evaluate the distribution of synoptic classes amongst the different types of events and various seasons. Composite surface analyses of the different synoptic classes and types of events were then developed. There were significant differences between the composites of each event type within a synoptic class. The results of this study were then compared to the results of Miller and Keim (2003). The next stages of research will be to further examine the mesoscale pressure and isentropic gradients associated with all types of events and to investigate the effect of coastline shape upon the sea breeze.

Introduction

The sea breeze is a gravity current in which there is a landward flow of cool, moist marine air that develops when daytime heating results in a significant land-sea temperature difference (Miller et al., 2003). Boston's General Edward Lawrence Logan International Airport is located on the shore of the Gulf of Maine, and is therefore significantly impacted by sea breezes. Unexpected changes in wind direction and speed can result in passenger delays, wasted fuel, and added expense. An effective method is needed to predict sea-breeze events and behavior at Logan. This study adapts the method of predicting sea-breeze events developed by Miller and Keim (2003) to Logan Airport (KBOS).

Miller and Keim (2003) utilized a one-year data-set for Portsmouth, New Hampshire for 2001. Using the METARs from Portsmouth's Pease Air National Guard Base, 167 dates were identified as events. The study defined three types of events: sea-breeze event, marginal event, and non-sea-breeze event. Sea breezes were defined as insolation-driven local onshore winds. Marginal events were weak sea breezes. Non-sea-breeze events were those days when sufficient insolation was present but failed to produce a sea breeze at Portsmouth (Miller and Keim, 2003). Surface analyses for each date were obtained and classified using a synoptic class system developed for the study. Using standard surface observations, a cross-shore geostrophic wind component (u_G) and a cross-shore potential temperature gradient ($\delta\theta/\delta x$) were calculated for the hour of onset. The study found that in the presence of stronger positive u_G value, a stronger negative value of $\delta\theta/\delta x$ was needed to develop a sea breeze.

The objective of the current study is to develop a forecasting technique for the occurrence of a sea breeze at Logan International Airport. The technique would also be used to forecast the time of onset and the depth of the inland penetration of the sea breeze, and to forecast the time evolution of near-surface wind velocity after onset. A final goal of this research is to refine the synoptic classes created by Miller and Keim (2003) by using objectively-generated composite analyses.

Methods

It was first necessary to define a sea-breeze event at Logan International Airport. Using Miller and Keim (2003) as a reference, the following event types were defined for Logan:

1.) A *sea-breeze event* occurs when the surface wind in the study area is from some westerly direction at the beginning of the day, then shifts to a direction between 10° and 190° midday, and then returns to some westerly direction at the end of the day. This wind shift must not be associated with a synoptic-pressure system. The cloud cover must remain less than "broken" (BKN). The exception to this rule is when the ceiling height is equal to or greater than 18,000 feet. It was decided that any cloud cover above 18,000 feet would be high cirrus clouds and not significantly diminish daytime heating. The final stipulation was that no precipitation could occur in the study area within six hours of the onset and the end of the event.

  a.) A *fast transition* is when the wind shift to a direction between 10° and 190° occurs in an hour or less.

  b.) A *slow transition* is when the wind shift to a direction between 10° and 190° occurs in two or more hours.

2.) A *non-sea-breeze event* is an event in which the same conditions as a sea-breeze event exist, except no wind shift is observed at Logan Airport.

3.) A *marginal event* is one in which a sea-breeze event occurs but either is short lived (less than 2hrs), interrupted by periods of "calm" or "light and variable" winds, or has no clear start and/or finish.

After defining the different event types, a five-year data set (2001-2005) was obtained from the Plymouth State Weather Center (http://vortex.plymouth.edu). METAR observations from KBOS were examined in order to identify dates when sea-breeze events could occur based on the definitions noted above. The dates were then classified as fast, slow, marginal, or non-sea-breeze events. There were 97 fast sea-breeze events, 37 slow sea-breeze events, 44 marginal events, and 387 non-sea-breeze events for a total of 565 events over the five-year period.

The next step was to obtain the surface analysis for each date using the nearest analysis time to the time of onset (example, time of onset 1400 UTC, analysis time 1200 UTC). In the case of non-sea-breeze events, the average time of the onset for sea-breeze events was used, which is 1500 UTC. The surface analyses were obtained from the National Climatic Data Center's Service Records Retention System (SRRS). Two analyses were obtained from the Plymouth State Weather Center as they were missing from the SRRS. The surface charts were then stratified into the synoptic classes defined by Miller and Keim (2003).

Statistics were then generated for each event type and synoptic class to identify any trends and patterns.

After creating statistics, the individual surface charts were used to create composite analyses for each event type and synoptic class (example, fast transition sea-breeze synoptic class one). The composites were made using the National Climatic Data Center's North American Regional Reanalysis composite website (http://www.cdc.noaa.gov/Composites/Hour/).

Synoptic Classes

The synoptic classes used to classify each date were previously defined by Miller and Keim (2003). There are six synoptic classes and a seventh category for miscellaneous synoptic patterns. Synoptic classes one through three have a northwesterly boundary layer wind over the study area.

Class 1 (Fig. 1)—A large high is centered to the west of the study area creating anticyclonic northwesterly flow.

Class 2 (Fig. 2)—A weaker high pressure system is centered west or south of the study area and a low pressure system is centered east or north of the study area, creating neutral northwesterly wind flow (i.e., surface isobars showing neither cyclonic or anticyclonic curvature).

Class 3 (Fig. 3)—A strong low pressure system is centered to the northeast of the study area, creating cyclonic northwesterly flow.

Synoptic classes four and five were defined by southwesterly flow over the study area.

Class 4 (Fig. 4)—A large high pressure system is centered over the southeastern United States and a large low pressure can be found in central Canada, the Great Lakes region, or the northern Midwest of the United States. A surface cold front is located to the west of the study area.

Class 5 (Fig. 5)—A low pressure system is located west of the study area and a frontal system is located east or north the study area.

Synoptic class six has northeasterly flow over the study area.

Class 6 (Fig. 6)—A low pressure system is located to the southeast of the study area and a high pressure system is located to the northwest of the study area, creating a northeasterly flow over Logan International Airport.

Results

The occurrences of the synoptic classes are summarized in Table 1. The percentages represent each synoptic class versus the total number of events. Table 2 shows the comparison between the occurrences of each event type with each of the synoptic classes.

Table 1 shows that synoptic class four was the most common synoptic class for events overall. The results for Miller & Keim (2003) showed synoptic class two (30.5 percent) was the most common overall synoptic class. Another difference between the two studies is that significantly less synoptic class 6 events in the study of Boston (18.6 percent in Portsmouth). These differences may be attributed to the dissimilarity in the shape of the coastline between the two sites.

For fast transition sea-breeze events, 31% of the events occurred with synoptic class 4. Synoptic classes 1 and 2 each represented 22% of the fast transition sea-breeze events. Synoptic class 6, with shore-parallel winds, made up less than 10% of the total fast transition sea breeze events. For slow transition sea-breeze events, 38% of the events were with synoptic class 6. Slow transition sea-breeze events account for 39% of synoptic class 6 events. It can therefore be hypothesized that synoptic class 6 it is more likely to produce a slow transition sea-breeze event than a fast one. Marginal events occurred more often with synoptic classes 1 and 4. Non-sea-breeze events were more likely to occur with synoptic class 3 (27% of the events) than any other synoptic class. Synoptic classes 2 and 4 each represented 20% of the non-sea-breeze events.

The seasonal variations in event type (Fig 7.) show that when non-sea-breeze events are at their minimum, fast sea-breeze events are at their maximum. The distributions of fast sea-breeze events and non-sea-breeze events are mirror images of each other. Non-sea-breezes dominate throughout the year, but are at a relative minimum in the Spring. Fast-transition sea breezes reach a maximum in the Spring, and are at a relative minimum in the Winter.

Variations in Synoptic Class by Event Type

In order to compare the variation in synoptic class for classes one through three for each event type a conceptual schematic was created. The schematic (Fig. 8) shows the location of the composite high pressure center and measures the pressure gradient along the ridge axis over the study area. Composites were generated from a list of dates and times for each event as described above.

For synoptic class 1, the composite high center for fast, slow, and marginal events is almost collocated over eastern New York State (Fig. 9). The center of the composite high pressure system with the non-sea-breeze event is located further south over western Pennsylvania, creating a stronger gradient over the study area, and increasing the strength of the synoptically-driven offshore wind resisting the landward movement of the sea breeze.. The mean gradient for the non-sea-breeze events is also higher at 1.18 hPa/100km, which supports this reasoning (Table 3).

For synoptic class 2, the composite high pressure centers are somewhat more spread out; however the non-sea-breeze event's composite high center is the still farthest south (Fig. 10). The pressure gradient for the non-sea-breeze event is 1.12 hPa/100km (Table 4).

For synoptic class 3, the results were not as clear. Although non-sea-breeze events still have the strongest composite pressure gradient at 1.06 hPa/100km (Table 5), the composite high center is not the farthest south (Fig.11). The composite high center of the slow sea-breeze event is located farther south, and there are *two* high centers for the marginal events. These irregularities may be attributed to the small sample size. For synoptic class 3, there were only 4 fast sea-breeze events, 1 slow sea-breeze event, and 2 marginal events. A larger sample size is needed to get a more statistically-meaningful composite analysis of the sea-breeze with synoptic class 3.

A pattern can be found in the seasonal variation of each event type within these three synoptic classes (Fig. 12). Figure 12a (class 1) shows a peak in sea-breeze events occurring in late spring and early summer. It also shows that synoptic class 1 non-sea-breeze events happen least during the late spring and early summer. In Figure 12b (class 2), the peak of sea-breeze events occurs closer to midsummer than with synoptic class 1. Again, the minimum for non-sea-breeze events occurs at the same time as the sea-breeze event peak. And finally, in Figure 12c (class 3), there are no important seasonal variation for any of the event types.

Classes one through three behave as if they are along a single spectrum of class, with one and three at opposite extremes, and two in the middle. The same general trend for individual event types is evident in each class. Moreover, as you move along the continuum, the minima of non-sea-breeze events becomes greater; 20% for class 1, 40% for class 2, and 90% for class 3.

The composite analyses of synoptic class 4 for each event type (Fig. 13) show a noticeable increase in pressure gradient between fast sea-breeze events and non-sea-breeze events. There is also a clear rotation of the orientation of the isobars. For a fast sea-breeze event the flow at the top of the boundary layer is shore parallel, making it easier for the sea-breeze front to move inland. For the non-sea-breeze event, the isobars are oriented shore-perpendicular, causing a stronger wind component at the top of the planetary boundary layer opposing the landward movement of the sea-breeze. Further, the location of the low pressure system in Canada varies between the fast and slow sea-breeze events. For a fast sea-breeze event, the low is centered farther north into Hudson Bay. This causes the pressure gradient over the study area to be much weaker. For a slow sea-breeze event the low is centered farther south over James Bay, causing a slightly stronger pressure gradient over the study area.

For synoptic class 5, only non-sea-breeze events occurred, confirming the findings of Miller and Keim (2003).

The composite analyses for synoptic class 6 show no significant difference in the strength of the pressure gradient over the study area between fast sea-breeze events and non-sea-breeze events (Fig. 14). Moreover, the center of the high is located farthest east in the non-sea-breeze event which would create the weakest gradient over the study area. All these findings are counterintuitive, because it would be expected that the weakest pressure gradient would occur with the sea-breeze events. Since the pressure gradient is not a determining factor for synoptic class 6, it is necessary to look at more variables, such as the cross-shore temperature gradient. Another interesting point to note is that the seasonal variation of event type showed that each event had a peak in a different season (Fig.15). Non-sea-breeze events peak in the winter, fast sea-breeze events peak in the spring, marginal events peak in the summer, and slow sea-breeze events peak in the fall.

Mesoscale Calculations

A brief look at the cross-shore temperature gradient and geostrophic wind component for all event types allowed the determination of a relationship between these variables and the occurrence or non-occurrence of a sea breeze at Logan Airport. . Calculations were performed using observations recorded at four neighboring stations to estimate both parameters for Logan, at either the time of onset (for sea breeze and marginal events), or the mean time of onset (1500 UTC, for non-sea breeze events). The station north of Boston was Lawrence, Massachusetts (KLWM) and the southerly station was Taunton, Massachusetts (KTAN). Bedford, Massachusetts (KBED) was used as the western site and buoy 44013 was used as the eastern site. The results are shown in Figure 16, which is similar to the mesoscale results shown by Miller and Keim (2003) for Portsmouth, New Hampshire. 397 events are included in the diagram. There were missing data for 162 events and bad data for 6 of the non-events.. The area enclosed by lines A, B, and C represents a transition area in which any type of event may occur. All events to the right of line B are non-sea-breeze events. It can also be noted that area to the right of line C is also entirely non-sea-breeze events, as the resisting U_G component is too strong for a sea-breeze event to occur. In the area above line A, the cross-shore temperature gradient is too weak (and of the wrong sign) so that a sea-breeze event cannot occur. The area to the left of line D is in theory an area where only sea-breeze events can occur; however, there are no data to prove this theory.

Comparison of Results to Previous Work

Since this study is based on the work done in a prior study, a comparison of results was done. Table 6 shows the results from this study and the results from the study done by Miller and Keim (2003).

The results for synoptic classes two, four, five, and six are similar for the two studies. For synoptic class 1, the study for Boston showed that there is a greater chance of having a non-sea-breeze event than a sea-breeze event, which is the opposite of the result for Portsmouth. This distinction may be associated with the difference in the shape of the coastline between the two sites. The coastline near Boston has a concave shape, and Portsmouth's is more of a straight line. The Portsmouth observing site is also located about 5 miles inland, while Logan is right next to the water. The influence of coastline on the sea-breeze was studied numerically by McPherson (1970), and the results described here warrant further study

The study of Boston (a five-year dataset) showed that it is possible to have a sea-breeze event with synoptic class 3. The study of Portsmouth (using a one-year dataset) did not have any sea-breeze events with synoptic class 3, and therefore a larger dataset is needed to see if one would occur at that location.

From the overall totals, its can be hypothesized that a sea-breeze event and non-sea-breeze event are both more likely at Portsmouth than at Boston. The simple comparison of a total of 134 sea-breeze events in Boston over 5 years and 59 sea-breeze events in Portsmouth over 1-year (multiplied by 5, yielding an approximate total of 295 events for a five-year period), shows that it is more than twice as likely for a sea-breeze to occur at Portsmouth. Similarly, comparing the 387 non-sea-breeze events in Boston to the 167 non-sea-breeze events in Portsmouth (multiplied by 5, or approximately 490 for five years), shows that it is again more likely to have a non-sea-breeze event at Portsmouth. These results could be confirmed or disproved by further studies of Portsmouth using a full five-year data set.

Future Work

As part of continued research on the sea breeze at Logan International Airport, this study will look at the depth of the inland penetration and the time evolution of near-surface wind velocity after onset. The cross-shore geostrophic wind components and cross-shore temperature gradients will also be investigated in greater detail, using a more sophisticated calculation scheme.. The limits of variation of all synoptic and mesoscale quantitative parameters will be calculated. This study will also investigate the effect of coastline shape upon the sea breeze.

Acknowledgements. I would like to thank Dr. Samuel T. K. Miller (Plymouth State University) and Scott Reynolds (National Weather Service) for contributing to my research. This research was funded by a COMET Partners grant.

References

McPherson, R.D., A numerical study of the effect of a coastal bay on the sea breeze, *J. Appl. Meteorology*, 9, 767 – 777, 1970.

Miller, S. T.K., and B. D. Keim, Synoptic-Scale Controls on the Sea Breeze of the Central New England Coast. *Weather and Forecasting*, 18, 236-248, 2003.

Miller, S.T.K., B.D. Keim, R.W. Talbot, and H. Mao, Sea Breeze: Structure, Forecasting, and Impacts, *Rev. Geophys.*, 41 (3), 1011, doi: 10.1029/2003RG000124, 2003.

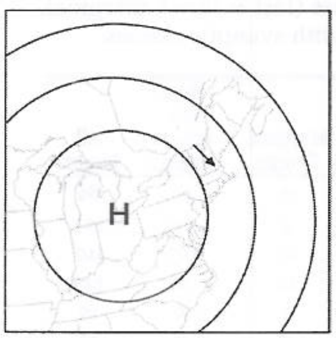


FIG. 1: "Synoptic class 1. Westerly to northerly geostrophic wind with a large high (or open ridge) dominates the region. Surface isobars are anticyclonically curved." (Miller and Keim, 2003)

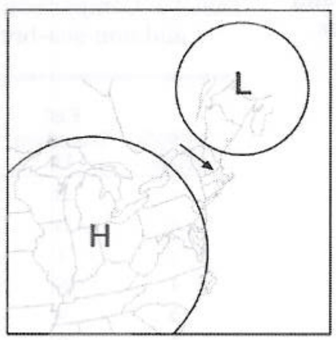


FIG. 2: "Synoptic class 2. Westerly to northerly geostrophic wind with a weak high (or open ridge) shares dominance of the region with a weak low (or open trough). Surface isobars have no significant curvature." (Miller and Keim, 2003)

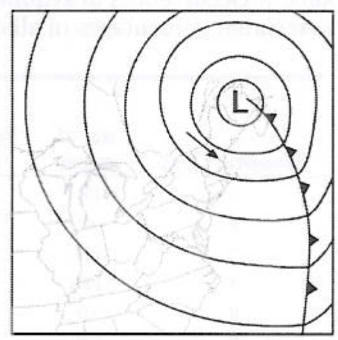


FIG. 3: "Synoptic class 3. Westerly to northerly geostrophic wind with a large low dominates the region. Surface isobars are cyclonically curved." (Miller and Keim, 2003)

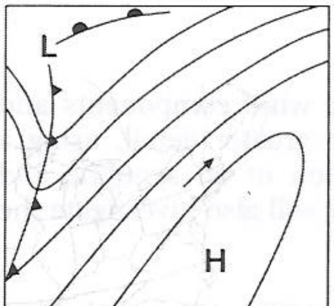


FIG. 4: "Synoptic class 4. Prefrontal southerly to westerly geostrophic wind with a high (or open ridge) located south of the study area, and a low with associated trough (or front) to the west. This class also includes the circumstance in which the isobar closest to the high center in the southeast does not wrap back around the eastern side of the high." (Miller and Keim, 2003)

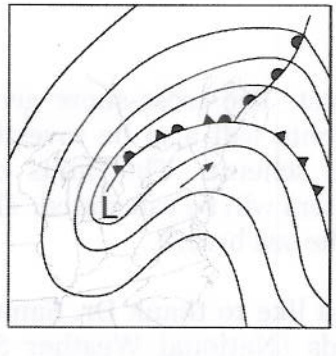


FIG. 5: "Synoptic class 5. Postfrontal southerly to westerly geostrophic wind, with a low with associated trough (or front) to the west, a weak ridge immediately to the east, and a front farther east." (Miller and Keim, 2003)

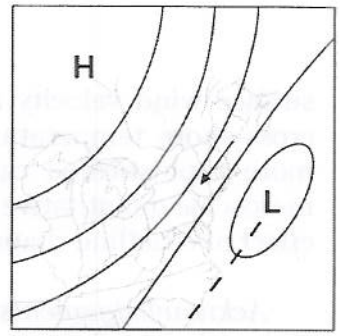


FIG. 6: "Synoptic class 6. Northerly to easterly geostrophic wind with a high (or northeastward-tilting open ridge) located to the northwest, and a low (or open trough) to the southeast." (Miller and Keim, 2003)

TABLE 1: Occurrences of synoptic classes and associated percentages of all occurrences.

Synoptic Class	No. of cases	Percentage of total
1	89	15.8
2	107	18.9
3	110	19.5
4	125	22.1
5	10	1.8
6	36	6.4
7	88	15.6
All	565	

TABLE 2: Comparison of sea-breeze (fast & slow), marginal, and non-sea-breeze events with synoptic classes.

Synoptic Class	Fast Transition SB	Slow Transition SB	Marginal Events	Non-sea-breeze events	All Events
1	21	10	16	42	89
2	21	6	4	76	107
3	4	1	2	103	110
4	30	5	14	76	125
5	0	0	0	10	10
6	9	14	6	7	36
7	12	1	2	73	88
	97	37	44	387	565

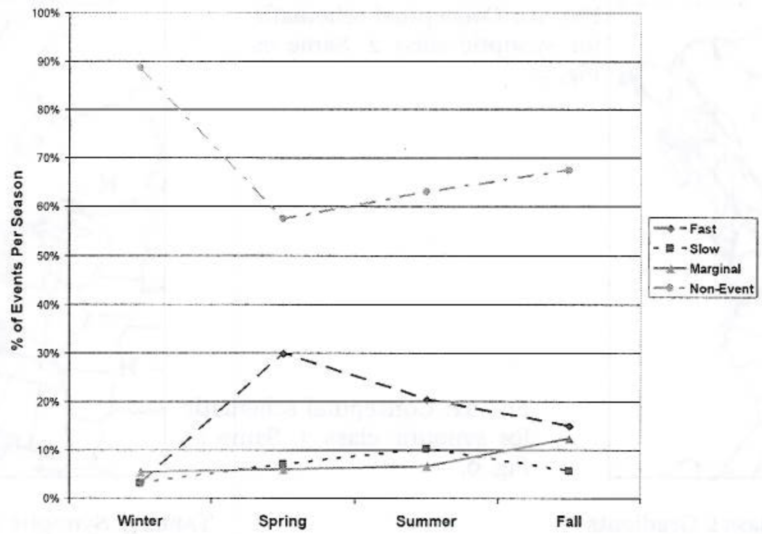


FIG. 7: Season distribution of event type. Winter is DJF, spring is MAM, summer is JJA, and fall is SON.

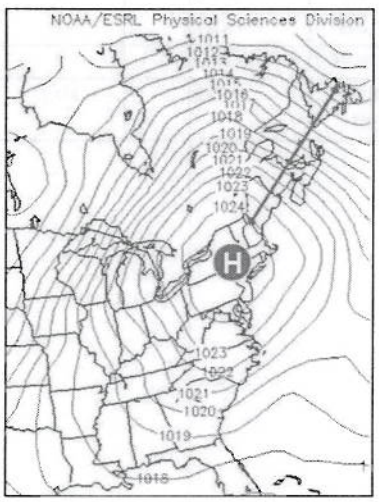


FIG. 8: Example of how the conceptual schematic was created using composite analyses. The schematic shows the pressure gradient along the ridge axis (line) and the location of the high center (symbol H). This example is of a fast transition sea-breeze event for synoptic class 1.

FIG. 9: Conceptual schematic for synoptic class 1. Dark blue represents fast sea-breeze events, light blue represents slow sea-breeze events, yellow represents marginal events, and red represents non-sea-breeze events.

TABLE 3: Synoptic Class 1 Gradients

Event Type	Gradient (hPa/100km)	n=No. of Events
Fast SB	0.81	21
Slow SB	0.72	10
Marginal	1.00	16
Non-Event	1.18	42

FIG. 10: Conceptual schematic for synoptic class 2. Same as Fig. 9.

FIG. 11: Conceptual schematic for synoptic class 3. Same as Fig. 9.

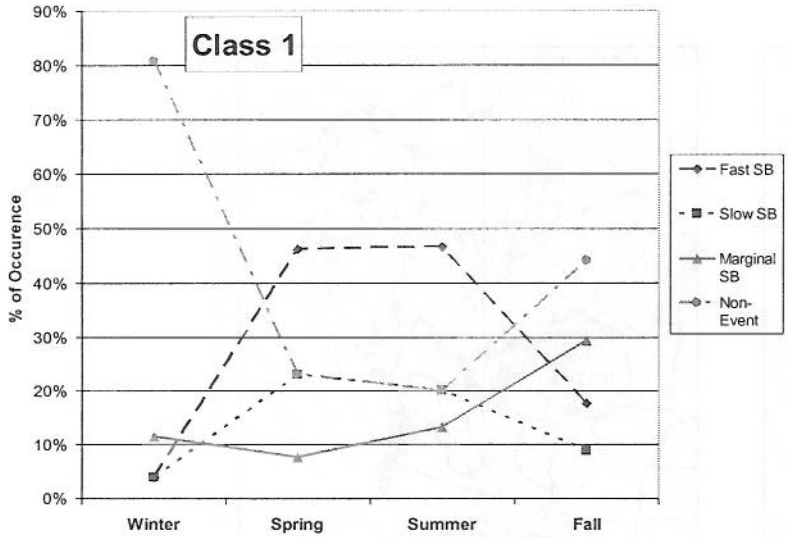
TABLE 4: Synoptic Class 2 Gradients

Event Type	Gradient (hPa/100km)	n=No. of Events
Fast SB	0.54	21
Slow SB	0.56	6
Marginal	0.72	4
Non-Event	1.12	76

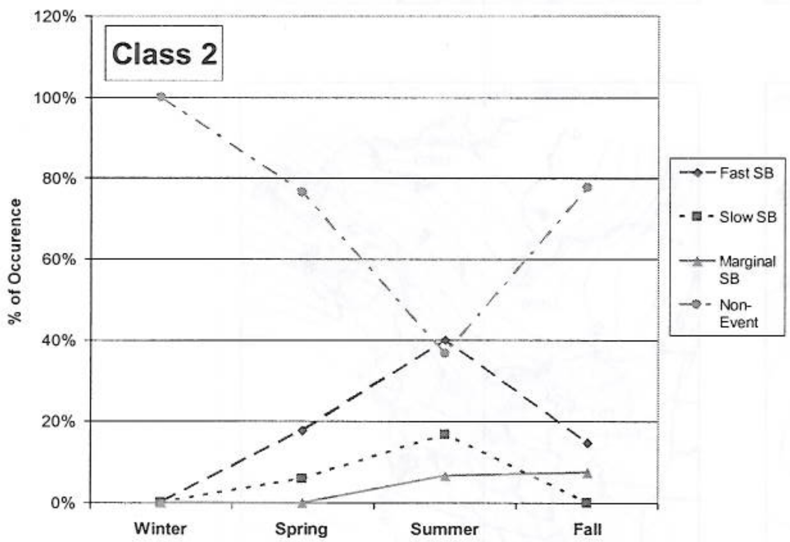
TABLE 5: Synoptic Class 3 Gradients

Event Type	Gradient (hPa/100km)	n=No. of Events
Fast SB	1.03	4
Slow SB	0.82	1
Marginal	0.81	2
Non-Event	1.06	103

a.)



b.)



c.)

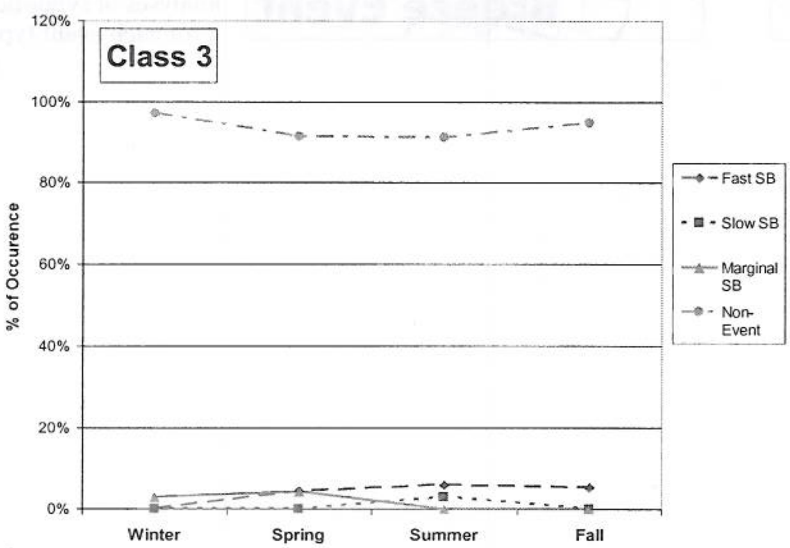


FIG. 12: Seasonal variation of event type occurrence for a.) synoptic class 1, b.) synoptic class 2, and c.) synoptic class 3.

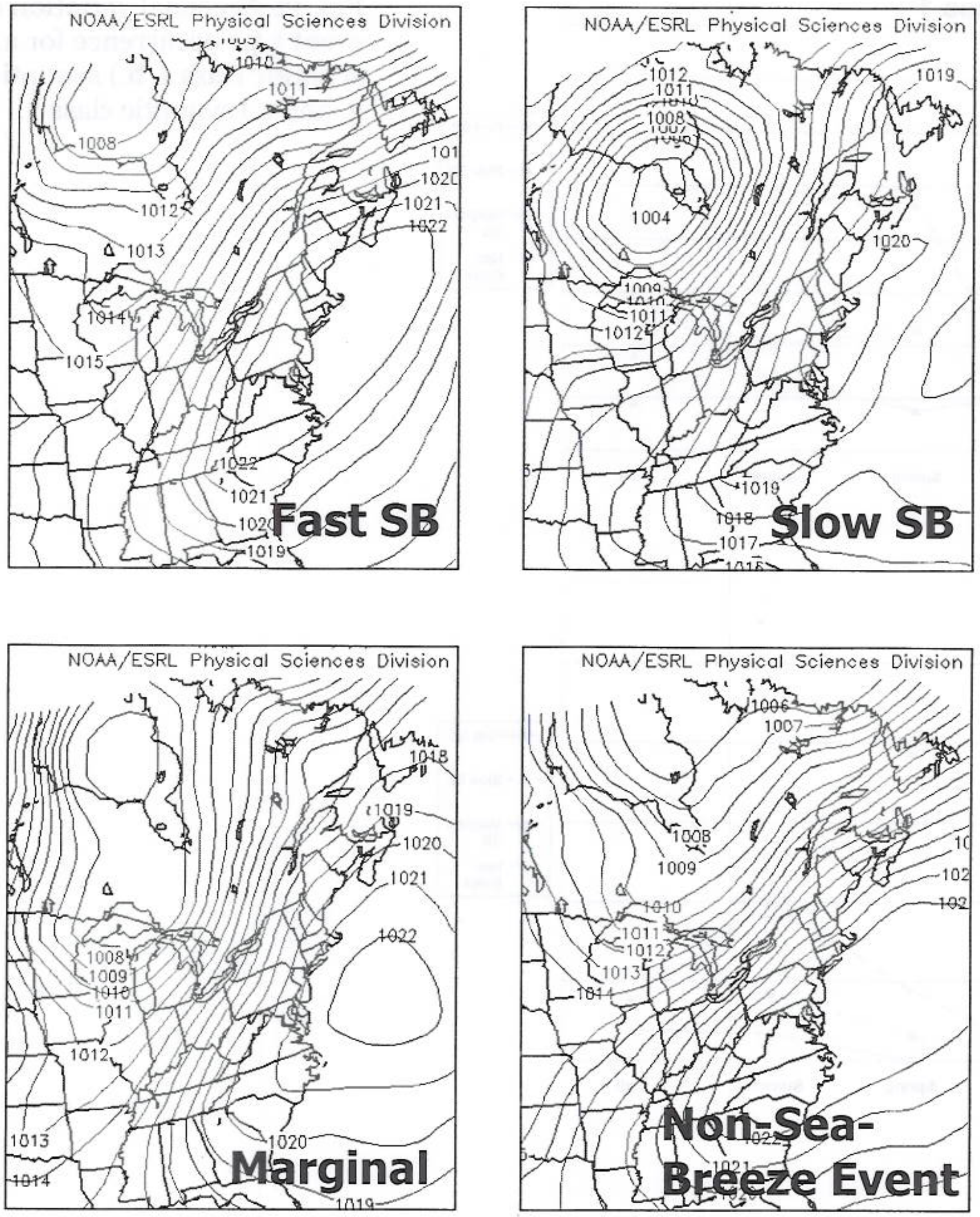


FIG. 13: Composite analyses of synoptic class 4 for each event type.

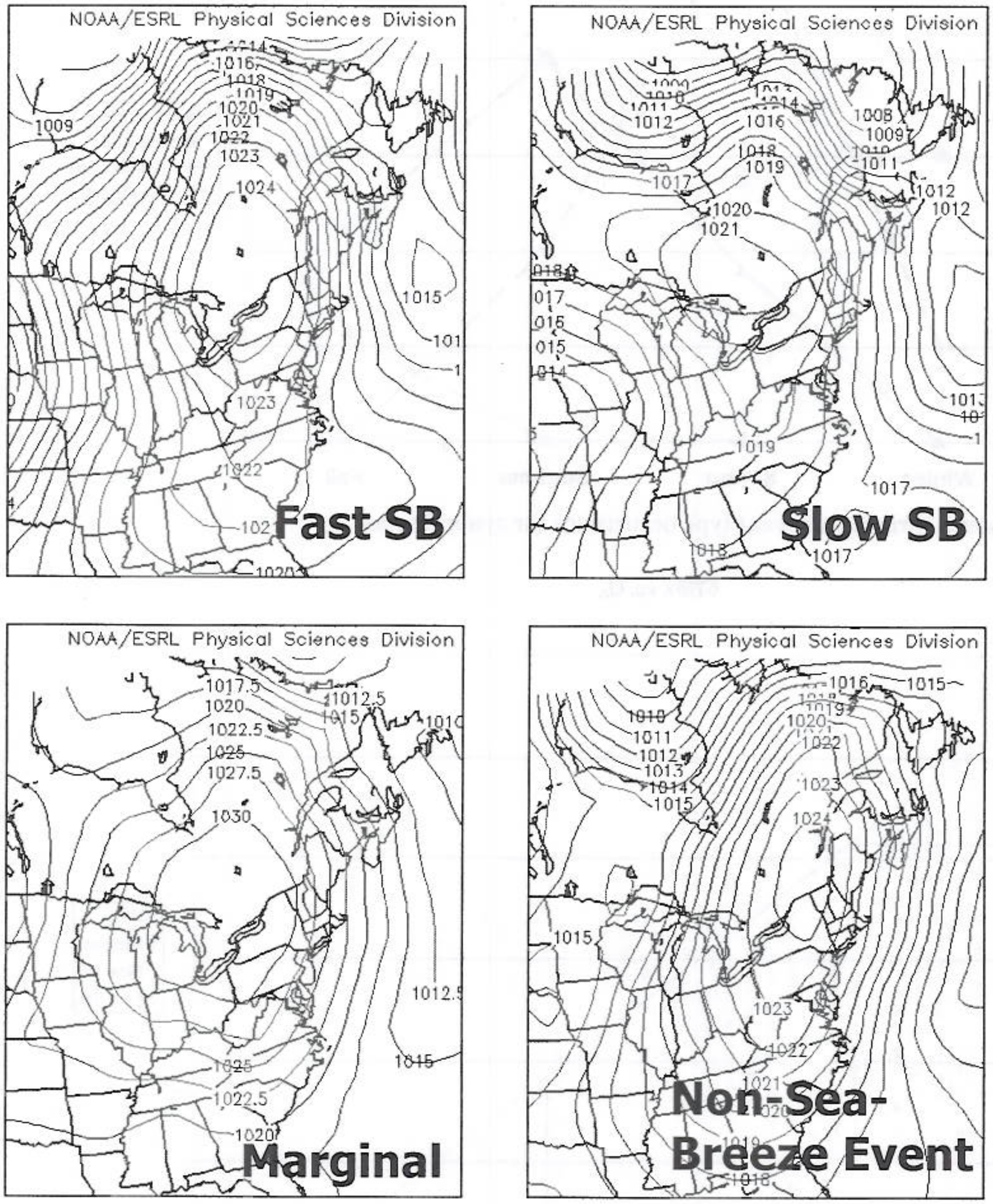


FIG. 14: Composite analyses of synoptic class 5 for each event type.

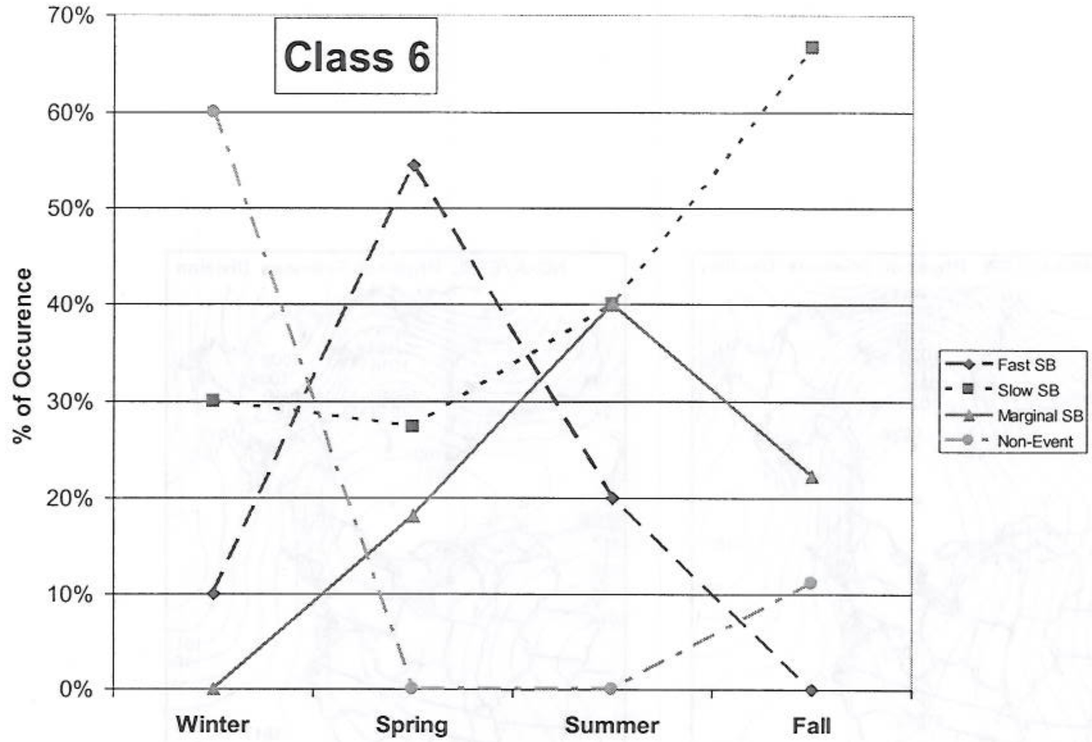


FIG. 15: Seasonal variation of event type occurrence for synoptic class 6.

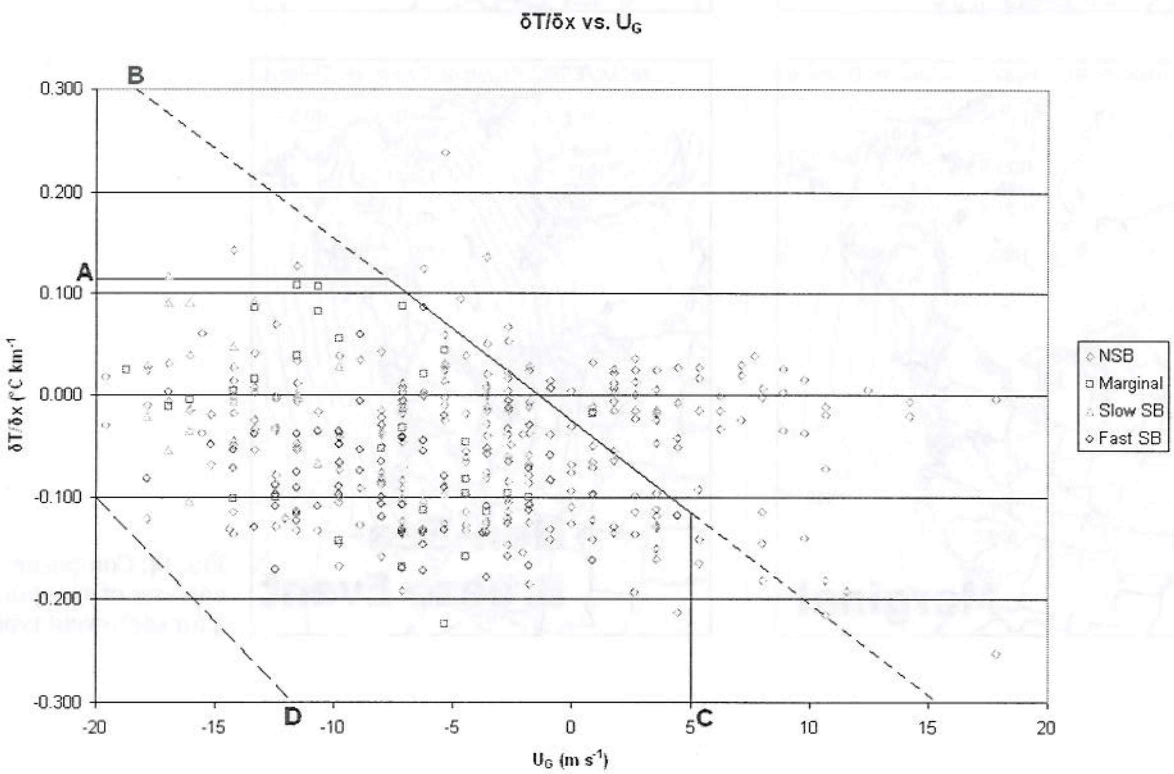


FIG. 16: Plot of 397 events with the cross-shore temperature gradient (°C km^{-1}) on the y-axis and the geostrophic wind component (m s^{-1}) on the x-axis.

Boston, MA

Synoptic Class	Sea-breeze events	Marginal events	Non-sea-breeze events	All Events
1	35%	18%	47%	89
2	25%	4%	71%	107
3	5%	2%	94%	110
4	28%	11%	61%	125
5	0%	0%	100%	10
6	64%	17%	19%	36
7	15%	2%	83%	88
No. of events	134	44	387	565

Portsmouth, NH

Synoptic Class	Sea-breeze events	Marginal Events	Non-sea-breeze events	All Events
1	60%	8%	32%	25
2	18%	6%	76%	51
3	0%	0%	100%	17
4	39%	6%	55%	31
5	0%	0%	100%	7
6	68%	10%	23%	31
7	40%	0%	60%	5
No. of events	59	10	98	167

TABLE 6: Results for similar studies on sea-breeze events for Boston, MA and Portsmouth, NH. Portsmouth uses a one-year data set from 2001 and was the focus of Miller and Keim (2003). Fast and slow transition sea-breeze events for this study have been combined for ease during comparison.

Verification of Sea Breeze Technique and Numerical Model Guidance

Period of Evaluation: 21 April 2007-15 October 2007

178 days in study period
65 days with an observed sea breeze
113 days with no observed sea breeze

Technique Evaluated	Sea Breeze POD	SB FAR	% Correct Forecasts
Thorp Technique	0.877	0.221	0.779
00Z GFS	0.521	0.048	0.764
06Z GFS	0.577	0.045	0.790
00Z NAM	0.571	0.091	0.768
06Z NAM	0.510	0.057	0.760
00Z GFS MOS	0.635	0.071	0.803
06Z GFS MOS	0.547	0.080	0.763
06Z ALY wsWRF	0.636	0.145	0.763
09Z ALY wsWRF	0.611	0.081	0.789

Key findings:

1) Simply using the Thorp technique's determination of a potential sea breeze day or no sea breeze (or an event day in the "non-event" subclass) outperformed each of the six (6) numerical models and two (2) statistical models evaluated.

2) Each of the 8 sea breezes not originally in the "yes" category for a sea breeze day can be accounted for with a minor modification of the Thorp criteria.

The CWSU ZBW forecast staff has a combined 70 years of experience at the ARTCC. Based on their observations of the KBOS sea breeze, a few minor "relaxations" of Thorp's criteria were considered in the forecast evaluation process. Sea breeze events can occur with ceilings below 18,000 feet, and sometimes with ceilings as low as 3000 feet. Sea breezes have also been observed with a starting wind direction slightly east of north (i.e. 010-030°). A look at the coastline to the north of KBOS (*need to add Fig. 1 here*) shows that a wind from 010-030° is actually a land-based wind versus an ocean-based breeze, as was originally calibrated from the Miller and Keim (2003) study.

Thus, after some discussion, the CWSU staff determined that starting wind directions of 010-030° would be allowable, as well as ceilings below 18,000 feet, provided that any cloud deck was in the Visual Flight Rules (VFR) category (i.e. ceiling greater than 3000 feet) and was not a solid overcast. After a careful reanalysis of borderline events in the database to ensure that a sea breeze did in fact occur on the dates in question, the above criteria modifications resulted in 9 additional sea breeze events to the database. This improved the Thorp technique POD to 1.000, the total number of correct forecasts to 0.800, and the SB FAR to 0.200.

Further study is needed to better delineate between fast, slow and marginal events, as well as improving onset time of the sea breeze at KBOS.