SHORT RANGE FORECASTING OF SEA BREEZE GENERATED THUNDERSTORMS AT THE KENNEDY SPACE CENTER: A REAL-TIME EXPERIMENT USING A PRIMITIVE EQUATION MESOSCALE NUMERICAL MODEL

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ABSTRACT

Thunderstorms pose a major threat to operations at the Kennedy Space Center (KSC), especially for Space Shuttle launches and landings. This paper summarizes the initial phases of a three year effort to assess the operational efficiency of using guidance from a mesoscale numerical model to improve sea breeze thunderstorm forecasts at and around the Shuttle landing strip. The redistribution of boundary layer moisture by the sea breeze has profound impacts on regional patterns of potential instability. Thunderstorm forecasting indices which combine model-predicted vertical motion fields with localized enhancements of the potential instability by sea breeze convergence appear to have considerable utility. Detailed case studies demonstrated the concept, which was then tested on a semi-operational basis during 1986. During the 1987 sea breeze season, daily forecast guidance generated by the numerical model will be provided to KSC forecasters.

Keywords: mesoscale numerical model, sea breeze, thunderstorms, Kennedy Space Center, short-term forecasting, lightning

1. INTRODUCTION

A three year effort is underway to develop improved operational techniques for forecasting sea breeze convection (SBC) thunderstorms at KSC. The Space Shuttle has extremely stringent weather requirements for both its launch and landing phase (Ref. 1). The orbiter itself can not be launched or landed through an atmosphere containing hydrometeors (due to the sensitivity of its heat shielding tiles). Lightning strikes are a threat to the system's avionics and computers. The orbiter's aerodynamic characteristics preclude a 7-8 m s⁻¹ cross wind at the Shuttle landing facility at KSC. Thus, thunderstorms at or near KSC are a major operational hazard.

Up to 40% of all Florida precipitation results from SBC storms during synoptically quiescent periods (Ref. 2). Thunderstorm forecasting techniques using routine synoptic data have been developed, but are not particularly applicable to Florida summertime convective storms. Forecasting techniques, largely using radiosonde data with statistical and pattern recognition schemes, are suggested by the results of Florida Area Cumulus Experiment (FACE) carried out during the 1970's (Ref. 3). These results, however, have not yet been widely translated into operational forecasting tools. Regional, or meso-alpha scale, numerical models (Ref. 4) bear promise for forecasting, out to two diurnal cycles, the environments in which convective storms develop. It quickly becomes apparent that shorter range forecasts (several hours) on the meso-beta scale are more difficult for a variety of reasons. However, substantial alterations in the thermal and moisture fields of the planetary boundary layer (PBL) are induced by the sea breeze (SB) even before the development of moist convection. These are suspected to play an important role in the initiation of SBC storms.

2. PRELIMINARY CASE STUDIES

During 1986, the Prognostic Three-Dimensional Mesoscale (P3DM) model and its two-dimensional counterpart, the P2DM, were configured to generate a variety of outputs relevant to operational forecasters. The model domain, (56 x 40, with 14 vertical levels to 6250 m) with an 11 km grid spacing (reduced to 7.5 km in 1986), was established to simulate flow over the entire peninsula, or if using the P2DM, in an east-west transect through KSC. The model was executed on a CYBER 205 supercomputer at Colorado State University (1985) or the University of Minnesota Supercomputer Institute (1986). The primary data input requirements for model initialization include the 1200 GMT radiosonde ascent, sea surface temperature (derived from satellite), an estimate of regional soil moisture, and the surface geostrophic wind at KSC (1200 GMT surface analysis). These versions of the model assume stationary and homogeneous synoptic conditions.

Standard output fields included the u, v, and w wind components, potential temperature, and mixing ratio. In order to generate information more familiar to operational forecasters, additional derived parameters include: the Lifted Index, the K stability index, the mean relative humidity, the mean relative humidity from the surface to 3000 m, and the precipitable water (surface to 500 mb), as well as the maximum upward vertical motion in each model grid cell.

In order to investigate the model's utility, detailed P3DM runs were made for three days in which the prevailing synoptic conditions were superficially similar (light south to southwest surface flow of unstable air) but which had distinctly different modes of SBC storms. These are described in considerable detail in Ref. 8. Only the first case study day will be illustrated here.

On 5 May 1984, southwesterly flow of moist, unstable air covered Florida, ideal for the development of thunderstorms at KSC (Ref. 5). The surface geostrophic wind was estimated at 200°, 2.0 m sec⁻¹, with light southwest winds extending to 500 mb. Surface sea temperatures averaged approximately 27°C. The average for the four south Florida radiosonde stations at 1200 GMT was -5 for the Lifted Index and 25 for the K Index. The east coast sea breeze (ECSB) and west coast sea breeze (WCSB) both onset at approximately 0630 LST. The ECSB penetrated westward only 55 km, but the WCSB moved eastward at least 130 km. Convection was monitored using surface reports, conventional radar, GOES satellite imagery, and lightning ground stroke data from the Florida LPATS (Lightning Position and Tracking System) network (Ref. 9). Widespread convection ensued, with over 25,600 lightning CG strokes monitored between 1000 and 1900 LST, with peak rates reaching 5,000 hr⁻¹ by late afternoon. Figure 1 is an enhanced GOES IR view at 1800 LST showing intense thunderstorms aligned several tens of kilometers inland from the east coast. The corresponding lightning CG display (Figure 2) reveals intense electrical activity in the zone of convergence created by the collision of the ECSB and the WCSB (Figure 3).
Extensive evaluations of the P3DM model output have been performed (Ref. 8). Figure 4 shows the excellent correlation between the predicted and observed positions of the sea breeze fronts. Figure 5 displays the predicted surface winds and associated maximum vertical motions (over 50 cm sec\(^{-1}\)). There is a clear correspondence between the predicted and observed fields, even several hours after the onset of convective scale interactions (CSI) between individual SBC storms. Most revealing is the deformation of the K stability index field (Figure 6). The values that were initially uniform at 1300 LST showed intense regional perturbations at 1800 LST. Figure 7, east-west cross sections at 1800 LST of the u (east-west) wind component, the w component, the potential temperature and the specific humidity, reveals the cause of the perturbations in the stability field. The dual sea breeze causes substantial vertical and horizontal redistribution of PBL moisture. At 2000 m, the specific humidity increased from 5 to 11 g kg\(^{-1}\) during the day. Comparable perturbations in the Lifted index (-1.5 to -6.5) were also found.

It has long been known that SB convergence provides a necessary, but not sufficient, condition for the development of SBC storms. Our other case studies revealed that on days with intense mid-level static stability, the sea breeze was less efficient in moistening the upper portion of the PBL. Thus, while intense surface convergence may occur, its destabilization of the atmosphere due to localized moisture convergence can often be far less efficient. In order to arrive at a simple and quantitative measure of the SB impact upon convective storm potential, a hybrid index was derived and tested. As shown in Table 1, the KLIW Index (a combination of the K, Lifted Index (LI), and vertical motion (w)) isolates those areas where vertical motions result in significantly greater destabilization of the local environment. Space-time sections (east-west through KSC) of the K Index and KLIW Index are shown in Figures 8 and 9. The KLIW Index, an arbitrary number from 0 to 12, tends to delineate more sharply the zones of preferred SBC storm potential. Limited experience suggests that with a KLIW = 1, widely scattered thundershowers become possible. Values above 5 indicate increasingly widespread and vigorous development. A similar combination of model-generated thermodynamic and vertical motion predictors has proven useful in estimating regions favorable to tornado genesis (Ref. 10). The 1985 case studies strongly suggested that even such a simplistic predictor as the KLIW Index might prove operationally useful.

### Table 1: The "KLIW" Index

<table>
<thead>
<tr>
<th>MAXIMUM W. (LOWEST 3000 M) CONTRIBUTIONS</th>
<th>0 - 3 cm/sec</th>
<th>4 cm/sec</th>
<th>5 - 10 cm/sec</th>
<th>11 - 19 cm/sec</th>
<th>20 - 29 cm/sec</th>
<th>30 - 39 cm/sec</th>
<th>40 - 49 cm/sec</th>
<th>50 + cm/sec</th>
</tr>
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<tbody>
<tr>
<td>K INDEX PERTURBATION (ABOVE MINIMUM VALUE)</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>LIFTED INDEX PERTURBATION (BELOW MAXIMUM VALUE)</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
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### Figure 1. GOES infrared image, MB curve, 1830 LST, 5 May 1984.

### Figure 2. Thirty minute summary of 2259 lightning cloud-to-ground (CG) strokes over Florida LPATS Network on 5 May 1984, 1800-1830 LST.

### Figure 3. Surface mesoanalysis showing wind streamlines and surface mesoscale frontal positions at 1800 LST, 5 May 1984.
Figure 4. (top) Observed and (bottom) P3DM-predicted two-hourly positions of the SB convergence zones for 5 May 1984.

Figure 5. (top) P3DM output, 1800 LST, 5 May 1984, showing surface (10 m) wind vectors and (bottom) maximum grid cell vertical motions (cm s⁻¹).
Figure 6. P3DM output, 1800 LST, 5 May 1984, showing the K stability index, with values ranging from 22 to 36.

Figure 7. East-west cross sections through KSC, surface to 3000 m, of P3DM predicted variables, at 1800 LST, 5 May 1984.

Figure 8. Space/time (XT) sections (0600 to 2200 LST) east-west across Florida at the latitude of KSC for the P3DM predicted values of the K index on 5 May 1984.

Figure 9. XT time section (0600 to 2200 LST) of the KLIW index along an east-west section through KSC, derived from the P3DM run for 5 May 1984. Contours at 1, 3, 5, 7, 9, and 11 units.
3. ONGOING OPERATIONAL FORECASTS

In order to further test the model, a series of 30 case studies using the P2DM were conducted during the 1986 season. Voluminous data sets have been collected and are presently undergoing detailed analysis as of this writing. Figure 10 reveals that 1986 was somewhat atypical, inasmuch as the convection (as indicated by total lightning CG stroke counts) was active at the beginning of June and gradually weakened as the summer progressed (Case Day 30 being 3 August). This general trend was clearly evident in the model's predicted maximum grid cell vertical motion within the domain.

The KLIW Index provided a useful guide to forecasters. Figure 11 reveals histograms of the values of the maximum Total KLIW Index (the highest value of the sum of the indices for the seven P2DM grid cells centered on X68, the Shuttle landing strip). Those days on which a thunderstorm was noted within 45 km of X68 clearly had a different profile (average 31) than those days with no SBC storm (average 12, and 8 if the single outlier is removed). Table 2 suggests that the KLIW Index contains useful guidance. During 1986, a series of blind tests were conducted to ascertain whether a skilled forecaster, when provided with P2DM model output, would generate improved local forecasts made for KSC. Preliminary results are highly encouraging. Forecasts of the onset time of the ECSB without the model averaged 1210 LST, versus the observed 1128 LST (42

<table>
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<tr>
<td>PROBABILITY OF A SEA BREEZE THUNDERSTORM WITHIN 45 KM OF X68 (11-19 LST)</td>
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<tr>
<td>MAX. TOTAL KLIW</td>
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<tr>
<td>-----------------</td>
</tr>
<tr>
<td>0 - 10</td>
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<tr>
<td>11 - 20</td>
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<tr>
<td>21 - 30</td>
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<td>31 - 40</td>
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<td>41 - 50</td>
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With the P2DM output as guidance, the average predicted onset time became 1120 LST (only 8 minutes early, with 13 too early, 11 too late, and one perfect). The observed inland penetration of the ECSB at 1700 LST was 64 km, versus 61 km as predicted by the P2DM.

The test forecaster consistently underestimated inland penetration by an average of 28 km without the model but only by 8 km with the model's guidance.

As for thunderstorms at X68 (defined as thunder heard), for 29 days the forecaster prepared a conditional (yes/no) forecast for the period 1100 LST to 1900 LST using only that information routinely available before 1000 LST. Then, a second forecast was made with the assistance of P2DM model guidance (including the KLIW). The percent correct increased from 62% to 72%. There were four days when both forecasts were incorrect, 14 when both were correct, seven in which the model allowed for a correction of an erroneous prediction, and four in which the model reversed a correct forecast. Expressed in alternate terms, the thunderstorm forecast probability of detection (POD) increased from 0.40 to 0.93 and the critical success index improved from 0.30 to 0.61. There was a tendency, however, to overforecast thunderstorms, as noted by the increment of the false alarm rate (FAR) from 0.37 to 0.57. Similar trends were found for forecasts of thunderstorm occurrences within 45 km of X68.

The KLIW Index, however, is a purely empirical formulation. Since 1986, a much more rigorous technique has been under development to ascertain the mesoscale probability of SBC storms. A one-dimensional cumulus scheme, based loosely on the Fritsch-Chappell parameterization, is executed at each model grid cell at hourly intervals. Outputs include maximum cloud top height, in-cloud updraft speeds, estimated radar reflectivity, peak downdraft speeds near the surface, and estimates of the probability of convective initiation. This Diagnostic Cloud Model (DCM), which does not result in feedback into the P3DM/P2DM, nonetheless appears to generate highly realistic convection patterns. It will be thoroughly tested during 1987 as a replacement or supplement to the KLIW.

The monitoring of mesoscale surface convergence patterns in the vicinity of KSC (Ref. 5) shows promise for short-term nowcasts (approximately 60 minutes). Yet there remains a significant gap between the nowcast and the guidance provided by synoptic scale models (limited though it be). Needed are mesoscale forecasting techniques for SBC storms in the one to 12 hour range. Preliminary research by Pielke (Ref. 6-7) strongly suggested that under synoptically non-disturbed conditions, the general location and onset time of SBC storms, plus some indications of their initial (first several hours) intensity and behavior, can be predicted by a dry (non-condensing) primitive equation mesoscale SB model. Such a model can explicitly generate mesoscale boundary layer convergence plus account for the ensuing modification of the low-level temperature and moisture environment. This paper summarizes the first two years of a three year effort funded by the NASA Kennedy Space Center. Its goal is to demonstrate that a currently available mesoscale numerical model can provide operational forecasters with improved guidance for the task of predicting the approximate time and location of the initial SBC thunderstorms over central Florida, and at least some indication of their character, before thunderstorms obscure the sea breeze circulation.

During the 1987 sea breeze season (June through August), the P2DM will be executed daily on a CYBER 205 (turn around 3-12 minutes), with output available by 0900 LST. A guidance package will be prepared by R"SCAN forecasters and transmitted to KSC. This package will include a narrative describing the predicted mesoscale regimes over central Florida, hourly forecasts of the conditions expected at the 500 ft meteorological tower at KSC, and several XT time sections describing the most relevant meteorological parameters (storm probability/intensity, vertical motion fields, etc.). This is believed to represent the first actual routine application of a mesoscale numerical model in an operational forecasting environment.

4. SUMMARY AND CONCLUSIONS

Sea breeze convection thunderstorms pose serious operational problems to the launching and landing of the Space Shuttle at the Kennedy Space Center and have proven exceptionally difficult to forecast. The Prognostic Three-Dimensional Mesoscale (P3DM) model, developed by Pielke as a Florida sea breeze model, reveals a strong correlation between regions of mesoscale convergence and the triggering of SBC thunderstorms. The P3DM was modified to generate stability parameters familiar to the operational forecaster. In addition to the mesoscale fields of wind, vertical motion, moisture, and temperature, a new stability indicator, the KLIW Index, a combination of model-predicted K and Lifted Indices and the maximum grid cell vertical motion, was proposed and tested. Results of blind tests during 1986 indicated that a forecaster, provided with guidance derived from model output, could improve local thunderstorm forecasts. During 1987, an improved diagnostic for SBC storms will be applied as part of a guidance package provided on sea breeze days to KSC forecasters.

5. ACKNOWLEDGEMENTS

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