Verification Analysis of the University of Virginia Three-Dimensional Mesoscale Model Prediction over South Florida for 1 July 1973

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ABSTRACT

An improved version of the mesoscale model, originally developed by Pielke (1974), is used to predict the sea breeze circulations over south Florida for a synoptically undisturbed day during the summer of 1973. Radar and surface observations are used to quantitatively verify the model results and to improve our understanding of the physical processes which occur over the region.

Among the improvements to the model are the incorporation of a surface heat budget, longwave and shortwave radiative fluxes, a prognostic equation for the depth of the planetary boundary layer, as well as a more accurate numerical representation of the advective and diffusive terms in the model. Despite these significant changes in the model, however, the predicted sea breeze circulation pattern is still quite similar to the earlier simulations.

Among the conclusions of this study are the following:

1) As shown in earlier experiments, the agreement between predicted convergence zones and shower distribution improves during most of the afternoon. Although the specific locations of shower occurrence cannot be predicted, the general regions of preferred convective rain activity are simulated with skill by the model.

2) The surface winds and temperature predictions have some skill except in or near regions of showers where local cumulonimbus circulations dominate.

3) Mesoscale moisture flux through the approximate cloud-base level is shown to precede the occurrence of rain in the NOAA south Florida cloud seeding area during the morning and early afternoon.

1. Introduction

The understanding of mesoscale meteorological phenomena is essential if we are going to solve some of society's most critical problems. Two trouble areas which need intensive mesometeorological work include the understanding of the effect on local weather of local and regional changes to terrain and vegetation (e.g., the urban effect), as well as the alterations in air quality due to man's activities. Both topics impact on regional and, perhaps, even global climatic changes, while the second subject deals with environmental health and the quality of life.

The mesoscale model discussed in this paper is a tool to examine alterations in the synoptic flow induced by inhomogeneities in the underlying terrain. The major purpose of this paper is to examine the quantitative accuracy of the model for a particular day over south Florida, 1 July 1973.

2. The model

Since it was originally developed by Pielke (1974), improvements to the model have been reported in Mahrrer and Pielke (1975, 1976, 1977a,b, 1978) and in Pielke and Mahrrer (1975). Only a brief summary of the model will be given here. (Symbols referred to are listed in the Appendix.)

a. Boundary layer

The surface layer fluxes of heat, moisture and momentum are based on the work of Businger et al. (1971) and Businger (1973), while the turbulent mixing in the remainder of the planetary boundary layer was parameterized using an exchange coefficient formulation as described by O'Brien (1970). The value of \( Z/L \) was limited between \(-25 \) and \(+5 \) because observations were not available to verify their formulations over all values of \( Z/L \). The value of
the friction velocity $U_*$ was also confined to a minimum value (half the initial value of the friction velocity) because $Z/L$ becomes difficult to define properly when $U_*$ becomes too small. In fact when $U_*$ becomes very small and $\theta_*$ is still significant, we have entered a regime where $U_*$ is not the appropriate scaling velocity as suggested by Businger (1973).1

The depth of the planetary boundary layer is predicted utilizing a formulation introduced by Deardorff (1974) and tested by Pielke and Mahler (1975).

b. Ground surface

The temperature at the soil-air interface is calculated using an energy budget where the longwave and shortwave radiation, the soil heat flux and the turbulent mixing of sensible and latent heat are used to calculate the equilibrium surface temperature. The temperature at the water-air interface is prescribed and assumed invariant in the calculation.

c. Radiation

The changes of air temperature due to shortwave and longwave radiative fluxes are parameterized following the methods of Atwater and Brown (1974). Heating of the atmosphere by shortwave radiation is confined to water vapor, while carbon dioxide and water vapor are considered in the longwave radiation heating/cooling algorithm. Mahler and Pielke (1977a,b) discuss the surface heat budget and radiative heating routines in detail.

d. Numerical scheme

The advective terms are evaluated by an upstream interpolation with a cubic spline. Purnell (1976) has shown this method to be at least as good as a fourth-order Arakawa scheme when the latter method is applied to a grid with half the spacing as the spline scheme. The vertical diffusion terms are represented by the method discussed in Paegle et al. (1976) which was shown to be extremely accurate even for long time steps.

The horizontal diffusion is represented by a highly selective low-pass filter developed by Paul Long (1977, personal communication). This filter, applied to control the spurious buildup of high-wavenumber energy due to aliasing, removes all $2\Delta X$ information each application but leaves wavelengths $6\Delta X$ and greater essentially unchanged. For the simulation presented in this paper, the filter is also applied in the vertical, ostensibly to remove $2\Delta Z$ noise. However, more recent work suggests that the vertical filter is not necessary. Future work will retain only the horizontal filter.

Mahler and Pielke (1978) give details regarding the numerical scheme as well as tests against an independent model. Mike McCumber (personal communication, 1977) has simulated a sea breeze using the two-dimensional version of the model and finds the kinetic energy is conserved to within 2% after 8 h.

e. Boundary and initial conditions

At the initial time, the potential temperature and specific humidity profiles are specified, while the velocity profile is determined through an Ekman-layer type balance equation in the planetary boundary layer (see Mahler and Pielke, 1976, p. 1394) and is specified in terms of the geostrophic shear above that layer.

At the lateral walls, the horizontal gradients of pressure and the prognostic variables ($Z$, $u$, $v$, $\theta$, $q$ and $h$) are set equal to zero.

3. The experiment

During the 1973 NOAA Florida Area Cumulus Experiment (FACE), surface mesoscale data was collected over a region of south Florida between 1 July and 15 August. Pielke and Cotton (1977) reported on the collection of the data and analyzed in detail the mesoscale structure over the region for one of the days. To perform the model verification, it was decided to choose a day in which the synoptic weather pattern was reasonably homogeneous over the area and the shower coverage appeared to be a minimum. These two criteria were required because the model, in its present form, cannot explicitly represent effects due to moist thermodynamics, nor simulate changeable or horizontally varying synoptic conditions. Of the days for which data were collected, 1 July seemed the best candidate and was chosen for this verification experiment. If the simulation performs well here, we can conclude with confidence that the basic physics are realistically represented, and we can thereby continue to generalize the physical framework of the model.

The geostrophic wind and geostrophic vertical wind shear used to initialize the model were estimated from the 0700 EST synoptic surface pressure (Fig. 1) and upper air (Fig. 2) analyses. The values, assumed temporally and spatially constant, are given as

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1 We have performed experiments prescribing a minimum permissible value to $U_*$ as well as letting it be freely calculated. When there is a synoptic flow, only at the locations where the wind reverses direction to become onshore it is small enough to be limited. In both cases the predicted fields are essentially identical.

2 Paul Long is a research meteorologist at the Techniques Development Laboratory of the National Weather Service in Silver Springs, MD.
which corresponds to a low-level geostrophic wind of 4.34 m s\(^{-1}\) from 120° with a geostrophic wind shear such that \(u_\theta\) and \(v_\theta\) are zero above 2.53 km.

The virtual potential temperature and specific humidity used to initialize the model were based on the Miami 0700 EST 1 July radiosonde ascent (Fig. 3) and are as follows:

\[
\begin{align*}
\hat{\theta}_d(Z_0) &= 299.9 \text{ K} \\
\hat{\theta}_d(10 \text{ m}) &= 299.9 \text{ K} \\
\hat{\theta}_d(57.5 \text{ m}) &= 301.2 \text{ K} \\
\hat{\theta}_d(200 \text{ m}) &= 301.6 \text{ K} \\
\hat{\theta}_d(500 \text{ m}) &= 302.2 \text{ K} \\
\hat{\theta}_d(950 \text{ m}) &= 303.3 \text{ K} \\
\hat{\theta}_d(1.6 \text{ km}) &= 305.0 \text{ K} \\
\hat{\theta}_d(2.5 \text{ km}) &= 310.0 \text{ K} \\
\hat{\theta}_d(3.5 \text{ km}) &= 314.5 \text{ K} \\
\hat{\theta}_d(4.5 \text{ km}) &= 318.6 \text{ K} \\
\hat{\theta}_d(5.5 \text{ km}) &= 323.0 \text{ K} \\
\hat{\theta}_d(6.0 \text{ km}) &= 325.0 \text{ K} \\
\end{align*}
\]

\[
\begin{align*}
\hat{q}(Z_0) &= 0.0180 \text{ g g}^{-1} \\
\hat{q}(10 \text{ m}) &= 0.0180 \text{ g g}^{-1} \\
\hat{q}(57.5 \text{ m}) &= 0.0166 \text{ g g}^{-1} \\
\hat{q}(200 \text{ m}) &= 0.0155 \text{ g g}^{-1} \\
\hat{q}(500 \text{ m}) &= 0.0138 \text{ g g}^{-1} \\
\hat{q}(950 \text{ m}) &= 0.0110 \text{ g g}^{-1} \\
\hat{q}(1.6 \text{ km}) &= 0.0076 \text{ g g}^{-1} \\
\hat{q}(2.5 \text{ km}) &= 0.0052 \text{ g g}^{-1} \\
\hat{q}(3.5 \text{ km}) &= 0.0035 \text{ g g}^{-1} \\
\hat{q}(4.5 \text{ km}) &= 0.0022 \text{ g g}^{-1} \\
\hat{q}(5.5 \text{ km}) &= 0.0013 \text{ g g}^{-1} \\
\hat{q}(6.0 \text{ km}) &= 0.0009 \text{ g g}^{-1}.
\end{align*}
\]

The levels were chosen so as to give added resolution near the ground along with a reasonably regular transition to the 1 km spacing used higher up.

The vertical distribution of the initial soil temperature, required in the surface heat budget equation, was prescribed assuming that at sunset the maximum amplitude would be somewhat below the surface with cooler temperatures deeper in the soil. Observed initial soil temperature profiles would be desirable in future observational programs. The values used are as follows:

\[
\begin{align*}
T_s(\text{sfc}) &= 301.0 \text{ K} \\
T_s(-30 \text{ cm}) &= 301.5 \text{ K} \\
T_s(-5 \text{ cm}) &= 301.8 \text{ K} \\
T_s(-35 \text{ cm}) &= 301.0 \text{ K} \\
T_s(-10 \text{ cm}) &= 302.3 \text{ K} \\
T_s(-40 \text{ cm}) &= 300.5 \text{ K} \\
T_s(-15 \text{ cm}) &= 302.5 \text{ K} \\
T_s(-45 \text{ cm}) &= 300.0 \text{ K} \\
T_s(-20 \text{ cm}) &= 302.4 \text{ K} \\
T_s(-50 \text{ cm}) &= 299.5 \text{ K}.
\end{align*}
\]

The soil characteristics used in the model correspond to a sandy, dry soil with the wetness of the soil weighted to 5% of the saturated value at the given temperature and to 95% of the specific humidity prescribed at the first model level above the ground. The surface albedo is assumed constant with a value of 0.2. The soil conductivity, density and heat capacity are 0.003 cm² s⁻¹, 1.5 g cm⁻³ and 0.32 cal g⁻¹ K⁻¹, respectively.

The model integrations were initiated at sunset on the evening of 30 June (1916 EST) and carried out for 24 h. The resultant circulations are due to the diurnal variations of solar input, the prevailing synoptic flow, and the resultant differential heating between land and water.

4. Verification

The observations on 1 July included surface wind and temperature observations supplemented with
Fig. 2. The 850, 700 and 500 mb analyses at 0700 and 1900 EST 1 July 1973. (Analyzed by Jose Fernandez-Partagas)

Fig. 3. The Miami radiosonde sounding at 0700 EST 1 July 1973.
spatial mappings of shower and cloud coverage as seen via the Miami National Weather Service WSR-57 10 cm radar, and the ATS-3 geostationary and DAPPS (Data Acquisition and Processing Program Satellite) earth orbiting satellites. Since most of the observations were confined to the period from early morning through late afternoon [see Pielke and Cotton (1977) for a brief description of the observations], the verification is presented for only that time frame.

a. Surface winds

The surface-layer wind data collected during the 1973 FACE Program are compared in Figs. 4–11 against predicted winds at 3 m at 2 h intervals from 0600 to 1800 EST\(^3\). The simulated winds at that level were diagnosed from

\[ (u_3^2 + v_3^2)^{1/2} = U_w k^{-1} \left[ \ln(3 \text{ m}Z_0^{-1}) - \Psi_1(\xi_{3m}) \right] , \]

where the direction of \(u_3\) and \(v_3\) were assumed parallel to the winds at the first model level above the ground (5 m). Since only a slight difference in height is involved, the wind speeds at 5 m are very close to those at 3 m. The variable \(\Psi_1\) is a function of stability \((\xi_{3m} = 3 \text{ m} L^{-1})\), as discussed by Businger (1973).

The early morning winds are predicted to be quite light over land, in good agreement with the observations, although the offshore winds at several coastal sites along the lower east coast of south Florida are not correctly simulated. A possible explanation for the failure of the model to predict the observed offshore winds could be because the area is urbanized, resulting in a more aerodynamically rough terrain which will mix the cool air higher when some mechanical turbulence is present. In the model this urbanization is not included.

As the surface becomes heated by the sun, the observed velocities increase throughout south Florida. Interestingly, along and slightly inland from the east coast, most of the observed winds develop a northerly component as surface heating is initiated, before veering to the east by about 1000 EST. This pattern has been found on other days analyzed from the 1973 FACE data. While the strengthening of the surface winds is well represented by the model, the veering is not. The observed veering is probably an inertial rotation due to the Coriolis effect, since the westerly component winds along the southeast coast are apparently decoupled from the synoptic pressure gradient. Once the offshore mesoscale pressure gradient and hence the land breeze decays, the winds will tend to rotate clockwise.

By 1200 EST both the observations and the predictions show a strengthening of the winds inland from the east coast with weaker velocities further west. In both the observations and the predictions

\(^3\) The time of output of the predictions displayed in this paper corresponds to 16 min after the hour.
significant onshore winds along the west coast began about 1100 EST.

By 1400 EST the agreement between the observed and predicted wind distributions was qualitatively quite good with onshore winds along both coasts with a region of comparatively weak winds in the interior. The eastern zone of onshore winds was situated further inland due to the superposition of the east-south easterly prevailing synoptic flow. The predicted directions along the east coast were slightly more southerly than observed, perhaps due to the inability to estimate the proper large-scale
pressure gradient during the initialization or to correctly specify the aerodynamic roughness of the ground surface in that region. In the latter case, larger roughness lengths over the urbanized area would turn the wind more toward lower pressure.

The agreement along the east coast was good all day, with both the simulation and the observations showing a decrease in wind speeds later in the day as cooling occurred. There were, however, substantial disagreements at a number of sites in the western half of the peninsula caused by the showers in the vicinity of the stations (see the radar mapping...
in Figs. 12–19 for corresponding times). As found by Pielke and Cotton (1977), the occurrence of rain substantially perturbs the wind field due to the inflow and outflow associated with the showers. After the rain, the surface layer winds tend to be decoupled from the air stream higher up as a result of the development of a surface layer which is stably stratified by such mechanisms as evaporative cooling.

The surface wind verification will be examined in more detail in Section 3c by using cross-section analyses.
b. Shower coverage

In Pielke (1974) and Cotton et al. (1976), the shower coverage was found to agree favorably with the predicted convergence zones. Figs. 12–19 illustrate the Miami WSR-57 10 cm radar depiction and predicted vertical motion at 1.2 km (approximate cloud-base height) at hourly intervals from 1200 to 1900 EST for 1 July (no significant rainfall occurred over land at earlier times). As found in the earlier papers and as seen in these figures, significant rain develops over land only after substantial sea-breeze-induced convergence occurs, with the shower pattern becoming better organized as the afternoon proceeds. The improved predictions with time are likely due to the sea breeze convergence of
moisture and heat, as well as the convergence of the cumulus clouds themselves. This latter process probably promotes cloud merger with its attendant increase in rainfall and cloud lifetime as discussed by Simpson and Dennis (1974) and Westcott (1977). For instance, the latter author found that although 66.8% of the echoes between 0830 and 1930 EST on July 1 were single during their entire lifetimes, they yielded only 16.1% of the total rainfall. She found that the bulk of the rain and the largest areal coverage were from showers which had merged twice with other systems.

The pattern of the convergence zone for this run also agrees closely with that found by Pielke and Mahrer (1976) for a simulation of 1 July 1973, using an older version of the model. In the 1976 run, the surface temperature variation over land was prescribed by a sinusoidal variation, upstream differencing of the advective terms was utilized and there was no shortwave or longwave radiational heating. Despite these and other less important changes, the results are remarkably similar, although the magnitudes of convergence in the more recent calculation are greater. This result implies...
that with comparatively simple physics, the general patterning of showers over south Florida (and in other comparable geographic regions) on synoptically undisturbed days can be obtained with comparatively little cost and, therefore, could be applied to operational forecasting situations.

At 1200 EST no substantial showers were observed by radar over land, while the model predicts the most significant regions of convergence both along the west coast and east of Lake Okeechobee. The largest upward motion is associated with the region of the coastline which is curved so as to accentuate the intensity of low-level horizontal convergence. During the afternoon as the magnitude of sea breeze convergence increases, the qualitative agreement with the shower pattern improves, although the observed showers appear to move inland less rapidly than in the predictions. This difference probably illustrates the uncertainty in properly specifying the initial synoptic velocity field and the soil characteristics. Previous model experiments have shown that either slightly slower speeds, or a somewhat

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**Fig. 15.** As in Fig. 12 except for 1500 EST.

**Fig. 16.** As in Fig. 12 except for 1600 EST.
Fig. 17. As in Fig. 12 except for 1700 EST.

cooler ground surface temperature (because of higher soil wetness, or different values of conductivity, density or heat capacity) would slow the inland movement of the eastern convergence zone. Weaker easterly synoptic flow would permit a greater inland penetration of the western convergence zone.

Even with these differences, however, it is clear from a comparison of the temporal variation of the predicted vertical motion field at the approximate cloud-base level and the observed showers, that the sea breeze convergence exerts a strong control on the locations of cumulonimbus development and movement. This conclusion was reached by Pielke (1974) when the model had a much simpler physical and mathematical framework. However, in order to evaluate the model more quantitatively, it was decided to investigate the following two questions:

- What fraction of the predicted convergence zones are covered by showers?
- What fraction of the showers which occur lie inside of the predicted convergence zones?

Ideally, one would also want the observed convergence zones, but this information was not available with sufficient resolution or quality for the en-

Fig. 18. As in Fig. 12 except for 1800 EST.
tire south Florida peninsula. Ulanski (1977) has shown for a subsection of the peninsula that low-level convergence precedes the onset of rainfall by a significant amount of time, and the results presented here suggest his observation is equally valid on the peninsula scale as well.

In order to examine these questions, the predicted vertical motion field at 1.2 km (contoured at 8 cm s\(^{-1}\) intervals) and the observed radar echo patterns were digitized and the intersections of the two fields compared. The results of this comparison are given in Table 1 where \(F_E\) is the fraction of echoes in convergence zones with values equal to or greater than the vertical velocities indicated at the bottom of the table; \(F_m\) is the fraction of the model domain covered by convergence equal to or greater than the vertical velocities indicated at the bottom of the table (for this analysis only the region of the model calculations where the predictions and the range of coverage of the radar are coincident are compared); \(F_c\) is the fraction of convergence zones, equal to or greater than the vertical velocities indicated at the bottom of the table, covered by echoes; \(A_p\) is the total area (km\(^2\)) of observed echoes (total possible area is 9157 km\(^2\)); and \(A_m\) is the total area (km\(^2\)) in which positive upward motion and observed echoes are coincident.

In Part I of the table, a ratio of \(F_E/F_m\) greater than unity indicates skill at predicting the locations of the showers. For 1900 EST, the contour intervals are twice the interval of those at the earlier times because of the sharp gradient of the convergence zones and the resultant difficulty in digitizing the data.

The information displayed in Table 1 illustrates that the best quantitative agreement between the simulated convergence and the observed rainfall occurred around 1600 and 1700 EST. Since the \(w > 0\) region covers a large fraction of the peninsula (which is where most of the showers occurred), the agreement with the convergence zones of 8 cm s\(^{-1}\) and greater is a more stringent test of the model since these zones cover a much smaller proportion of the land.

The calculated ratios of \(F_E/F_m\) (displayed in Table 2), which represent a type of skill score, show that the model has positive skill in 26 to 30 categories with values of 2.0 or greater in 20 of these. In the four categories with negative skill, these intense regions of convergence were very small and if the model were even slightly in error it would miss the accurate prediction. Indeed this points out a more general problem of the verification method as presented here, since a perfect forecast, except for a small displacement between predictions and observations, could show little or no skill. In future analyses of this sort, more sophisticated pattern recognition approaches should be used.

The information displayed in Part II of Table 1 examines the fractional coverage of a convergence zone by echoes. A value of 1.0 would indicate the convergence zone was totally covered by showers, while a value of zero would show that no echoes occurred inside of the convergence zone. As seen in the table, only a relatively small fraction of the convergence zones are covered by showers at any given time. Thus we can conclude that, although the sea breeze convergence strongly influences the region of showers, the precise locations of rainfall at a given time are determined by factors such as
small-scale surface temperature inhomogeneities, shower interactions, shadowing by middle and upper level clouds, etc., which the model is unable to simulate.

The limited evidence available also suggests that the sea breeze convergence and the regions of non-precipitating cumulus clouds are also closely correlated. Unfortunately, the 1973 FACE Program was held before the comparatively high-resolution of the Synchronous Meteorological Satellite (SMS-1) was available, so that on 1 July of that year, only one picture from the polar orbiting DAPPS and a series of relatively poor quality ATS-3 imagery were available to compare with the predictions. Even so, the satellite view from DAPPS for 1301 EST (see Fig. 20) depicts accentuated cumulus activity near regions predicted to have stronger convergence (cf. Fig. 13). The ATS-3 imagery (Fig. 21) (at least to the extent possible to see in the figure) also shows a good correlation between convergence and cumulus cloud activity over south Florida. Future work should quantitatively compare the model predictions against the high time and space resolution satellite imagery which is now available from the SMS-1.

Rainfall data estimated from radar and gauges in the 1973 FACE cloud seeding area can also be used to verify the model and to interpret its results.

<table>
<thead>
<tr>
<th>Time (EST)</th>
<th>( F_{e}/F_{m} ) (I)</th>
<th>( A_{p} )</th>
<th>( A_{p} )</th>
<th>( A_{0} )</th>
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<tr>
<td>1200</td>
<td>0.46/0.35</td>
<td>1.06/0.08</td>
<td>0.00/0.00</td>
<td>0.00/0.00</td>
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<tr>
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<td>0.38/0.12</td>
<td>0.003/0.015</td>
<td>0.00/0.00</td>
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<tr>
<td>1400</td>
<td>0.81/0.41</td>
<td>0.50/0.18</td>
<td>0.21/0.06</td>
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<tr>
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<td>0.41/0.16</td>
<td>0.23/0.07</td>
<td>0.06/0.01</td>
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<td>1600</td>
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<td>0.16/0.08</td>
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<tr>
<td>1700</td>
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<td>0.60/0.19</td>
<td>0.24/0.08</td>
<td>0.07/0.03</td>
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<tr>
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<td>0.30/0.08</td>
<td>0.15/0.04</td>
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<tr>
<td>1900</td>
<td>0.34/0.32</td>
<td>0.20/0.14</td>
<td>0.10/0.06</td>
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</table>

For 1200–1800 EST

(i) \( w > 0 \) cm s\(^{-1}\)
(ii) \( w > 8 \) cm s\(^{-1}\)
(iii) \( w > 16 \) cm s\(^{-1}\)

For 1900 EST

(iv) \( w > 24 \) cm s\(^{-1}\)

\( F_{e} \) (II)

<table>
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<tr>
<th>Time (EST)</th>
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<td>1900</td>
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<td>0.1205</td>
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<tr>
<th>Time (EST)</th>
<th>( F_{e}/F_{m} )</th>
</tr>
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<td>1600</td>
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<tr>
<td>1700</td>
<td>2.49</td>
</tr>
<tr>
<td>1800</td>
<td>2.19</td>
</tr>
<tr>
<td>1900</td>
<td>1.06</td>
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(10)
predicted sea breeze moisture flux in the EML Target Area, at the approximate cloud base level (1.2 km) is plotted in Fig. 22, along with the best estimates of observed rainfall (digitized radar adjusted by gage clusters; see Woodley et al. (1974)). Also plotted is the predicted moisture flux at 1.2 km from the older version of the model. As seen in the figure, there is a close correspondence in shape between the two simulations with the newer version having larger fluxes which develop somewhat earlier. The peak convergence over the Target Area with the newer version is approximately \(5 \times 10^{-5} \text{s}^{-1}\).

The time of maximum in predicted flux is almost coincident with the observed rainfall peak (\(\sim 1630\) EST), while the rate of increase of moisture flux in the morning and early afternoon is almost parallel with the rate of increase of rainfall. Up to about 1400, the flux of a given magnitude precedes the mean rainfall of equal value by about 4 h. Over a much smaller region, Ulanski (1977) finds that the low-level convergence associated with individual showers in the EML Target Area precedes the rainfall at the ground from 60 to 90 min. Over the larger scale of the entire EML Target Area, one would expect the lag to be greater; however, an independ-

c. Cross-section analyses

In order to investigate the properties of the sea breeze over south Florida in a different fashion, time
cross sections of temperature and winds were made from the observations on a line from Fort Lauderdale on the east coast to Naples on the west. These were compared against the equivalent predicted cross sections in the model. It is felt that evaluating the statistics for a cross section from the east to the west coast is a more stringent test than using all the observed winds over south Florida, since the latter are not equispaced over land but rather are concentrated along the east coastal region. As evident from a qualitative examination of the winds in that area (Figs. 4–11), the strengthening of the onshore winds during the morning and gradual reduction in speed late in the afternoon are well described by the model.

Due to an oversight, potential temperature rather than temperature was prepared for the model-derived cross-section analysis, which results in tem-
The two cross sections of surface wind (Fig. 23) show light winds speeds in the early morning due to the stably stratified surface layer. As heating occurs, the observations and predictions show the development of stronger easterly flow along and inland from the east coast. In the model, however, the winds only slowly increase in speed, with the direction essentially invariant. In reality the winds had veered to the east from a westerly and northerly direction. Along the west coast the winds became onshore at NOG about 1400 EST, while at the equivalent location the model predicted this would occur about 3 h earlier. Further inland at AA5, the agreement is better with the onset of westerly component winds agreeing within 1 h of the observation.

In the late afternoon, as surface heating decreases, the predictions show a gradual reduction of speed in the onshore wind flow along and inland from both coasts with the directions remaining relatively unchanged. Along and inland from the east coast, a similar pattern is found in the observations, apparently because the surface layer becomes more stably stratified. Along the west coast after 1700, in contrast to the model, the winds become irregular in speed and direction. This discrepancy between the predictions and reality appears due to easterly winds induced by the showers inland from the west coast as illustrated in the radar maps for these times.

Indeed, substantial disagreement at point locations in the south Florida surface wind maps (Figs. 4–11) can invariably be related to shower activity in the vicinity.

The predicted 3 m potential temperature cross section (Fig. 24) agrees favorably with the observations in showing a reasonably regular warming of the surface layer during the morning. The magnitude of the values, however, are quite different in the early morning with the real values being consider-
Fig. 23. Time cross section of observed (bottom) and predicted (top) surface winds along an east-west line from Fort Lauderdale to Naples (along the 18th grid line from the southern edge of the model).
Fig. 24. As in Fig. 23 except for observed (bottom) and predicted (top) temperature at the 17th grid line from the southern edge of the model.
ably cooler. This difference suggests another possible explanation (besides the urbanization along the east coast mentioned earlier) for the failure of the model to predict the observed land breeze along the east coast. The difference in temperatures could be explained as a result of the assumed soil characteristics used in the simulation, and this facet of the model must be studied in more detail.

The model predicts the warmest temperatures to occur around 1500 in the western two-thirds of the cross section. The observations show a qualitatively similar pattern with warmer temperatures skewed toward the western portion of the peninsula and a maximum at two of the sites in that region at 1500. Along the west coast, however, the maximum occurred earlier apparently because of the showers in the vicinity which caused the sharp cooling after 1300. By 1700, along the west coast, warming had occurred which is not predicted by the model, perhaps due to the advection of warmer air into the area from regions where showers did not occur.

Along and inland from the east coast, except for insufficient cooling in the early morning and evening which, as we said earlier, could be due to an incorrect specification of the soil characteristics, the magnitudes and trends of temperature are well simulated.

In order to study the temperature and wind forecasts more quantitatively, an error analysis was performed on the data, based on the method discussed in Keyser and Anthes (1977). The magnitudes of the errors in horizontal velocity and temperature were estimated from

$$E = \left\{ \sum_{r=1}^{T} \sum_{s=1}^{N} (\phi_{st} - \bar{\phi})^2 / TN \right\}^{1/2}, \quad \phi_{st}$$

$$E_{UB} = \left\{ \sum_{r=1}^{T} \sum_{s=1}^{N} \left( (\phi_{st} - \bar{\phi}) - (\phi_{st} - \bar{\phi}) \right)^2 / TN \right\}^{1/2}, \quad \phi$$

$$\sigma = \left\{ \sum_{r=1}^{T} \sum_{s=1}^{N} (\phi_{st} - \bar{\phi})^2 / TN \right\}^{1/2}, \quad \phi_{st}$$

$$\sigma = \left\{ \sum_{r=1}^{T} \sum_{s=1}^{N} (\phi_{st} - \bar{\phi})^2 / TN \right\}^{1/2}, \quad \phi_{st}$$

where $\phi$ refers to either $u$, $v$ or temperature. $N$ is the total number of stations (seven) and $T$ the hours of record used in this analysis (13 h from 0600 to 1900 EST 1 July). An overbar indicates the arithmetic average, while a caret over the variable refers to an observation. The absence of a caret indicates a prediction.

$E$ is the rms error, while $E_{UB}$ is a rms error after a bias is removed. As discussed by Keyser and Anthes, this bias can often account for a significant fraction of the rms error. Such bias could be due to an incorrect specification of the initial and/or the bottom or boundary conditions.

The standard deviations in the predictions and the observations are given as $\sigma$ and $\dot{\sigma}$. As described by Keyser and Anthes, an rms error which is less than the standard deviation of the observed field indicates skill in the predictions. Moreover, the values of $\sigma$ and $\dot{\sigma}$ should be close if the prediction is to be considered realistic.

These verification statistics for the cross section are given in Table 3. As seen in Table 3, the observed and predicted standard deviations for $v$ and temperature are very close, although the predicted standard deviation for $u$ is about half that observed, perhaps due to the effect of the irregular winds associated with the rain showers, as mentioned earlier in the text. A comparison of $E$ and $E_{UB}$ shows that there is a bias in the temperature and $v$ component predictions although no significant one in $u$. The systematic discrepancy in the $v$ component is evident in Fig. 23, where the more southeasterly winds inland and along the east coast in the predictions are likely related to an incorrect specification of the initial geostrophic wind and/or $z_0$ over land in the model. The bias in temperature could be related to our inability to precisely specify soil characteristics, as well as a result of the use of predicted potential temperature rather than temperature values in the comparison.

The value of $E_{UB}$ and $\dot{\sigma}$ for $u$ and $v$ are of the same order which, using the criteria of Keyser and Anthes, does not show skill in predicting these fields.

<table>
<thead>
<tr>
<th></th>
<th>$E_{UB}$</th>
<th>$\sigma$</th>
<th>$\dot{\sigma}$</th>
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</thead>
<tbody>
<tr>
<td>$u$ (m s$^{-1}$)</td>
<td>3.1</td>
<td>3.1</td>
<td>1.2</td>
</tr>
<tr>
<td>$v$ (m s$^{-1}$)</td>
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<tr>
<td>$T$ (K)</td>
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<td>3.9</td>
</tr>
<tr>
<td>$u$ (m s$^{-1}$)</td>
<td>1.9</td>
<td>2.1</td>
<td>1.2</td>
</tr>
<tr>
<td>$v$ (m s$^{-1}$)</td>
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<tr>
<td>$T$ (K)</td>
<td>3.6</td>
<td>2.9</td>
<td>2.7</td>
</tr>
</tbody>
</table>

An examination of the cross section, however, suggests that the major contribution to $E_{UB}$ occurs in those regions where showers had existed or were occurring, and thus where the model physics are inadequate. The values $E_{UB}$ and $\dot{\sigma}$ for temperature, on the other hand, indicate skill in predicting the low-level temperature.

The cross section in the older version of the model where surface temperature was prescribed rather than predicted was also verified using (1)–(4), and the results compared against those of the current version for the times in which data from both integrations were available (0600–1900). The results from the analysis are also tabulated in
Table 3. The verification statistics are quite similar to those found with the current version and, in fact, the $u$ prediction is superior with the older model. This result illustrates what is probably obvious. If observed surface temperatures are available, it is preferable to use them directly in the model as a lower boundary rather than predict surface temperature prognostically. On the other hand, however, if one is interested in studying the interactions between the atmosphere and the ground, it is necessary to include the surface heat budget. The result that the new version of the model predicts surface temperatures as well as it does encourages us to conclude that the parameterization of radiation and ground-air interactions used in the model are reasonably accurate.

5. Conclusion

This paper has quantitatively documented the degree of skill of a mesoscale model without moist thermodynamic feedbacks to simulate the weather patterns over the south Florida peninsula for a particular day in 1973. Several major conclusions are possible from these results.

- As found in previous mesoscale studies over south Florida (Pielke, 1974; Cotton et al., 1976), the dry sea breeze is a dominant control of shower patterning during synoptically undisturbed days. This degree of control is due to the convergence of heat and moisture, as well as of cumulus clouds themselves by the sea breeze for a good portion of the day before substantial cumulonimbus activity occurs. Considerable cumulonimbus convection over a period of time is required to deplete this sea breeze supply of latent and sensible energy.

- While most of the showers occur in the predicted convergence zones, much of the convergence region is not covered by precipitating clouds. This indicates that sea breeze convergence is a necessary but not a sufficient explanation for most of the shower clusters which occur on synoptically undisturbed days. The precise location of showers in the convergence zones must be caused by localized terrain inhomogeneities or shower interactions such as found by Holle and Maier (1974) and Ulanski (1977).

- The sea-breeze-induced moisture flux at the approximate cloud-base level exerts a dominant control on the resultant showers, at least through the peak of rainfall, indicating that most of the water supply for the clouds during that time period is on the mesoscale. This result is supported by observations by Cotton and Pielke (1978) in the 1973 FACE program which show a dominance of 11 km averaged moisture fluxes at 600 m relative to the fluctuating fluxes along flight tracks across south Florida. This conclusion suggests that the cumulus cloud response to the sea breeze circulation, for a large portion of the day, can be directly related to the mesoscale moisture flux at cloud base.

- The sea breeze circulation dominates the surface wind and temperature fields except in regions where shower activity is or had been occurring, in which case rain-induced and storm-scale dynamics dominate. The surface wind pattern away from shower areas can be explained straightforwardly as a combination of accelerations or decelerations due to differential heating and roughness, and to surface layer stability.

- The incorporation of a surface heat budget along with a parameterization of shortwave and longwave radiative fluxes resulted in a realistic calculation of the surface layer temperature across south Florida. This improvement to the model will permit evaluations of the influence of varying ground surface characteristics on the resultant mesoscale circulation.

Finally, this paper presents a set of mesoscale resolution data with which other modelers can use to test their simulations, as well as to compare against the model presented here. The quantitative comparison of model predictions with observations for particular case studies is needed to demonstrate the utility of mesoscale dynamic models.

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Arthur Mizzi performed an excellent job in reducing some of the data and Donna Hensley success-
fully undertook the difficult job of typing this manuscript. Kathy Ghazzawi performed the service of making the final corrections to the paper.

APPENDIX

List of Symbols

\[ Z \] height
\[ U_* \] friction velocity \([= \rho \tau^{1/2}]\), where \( \rho \) is air density and \( \tau \) surface shearing stress
\[ \theta_* \] scaling temperature which is proportional to heat flux
\[ u_g \] east-west geostrophic velocity component
\[ v_g \] north-south geostrophic velocity component
\[ u \] east-west velocity component
\[ v \] north-south velocity component
\[ \bar{Z}_t \] top of the planetary boundary layer at the initial time
\[ \hat{\theta} \] potential temperature at the initial time
\[ \hat{q} \] specific humidity at the initial time
\[ Z_0 \] aerodynamic roughness parameter
\[ T_s \] temperature of the soil
\[ \kappa \] von Kármán’s constant (=0.35)
\[ \xi \] nondimensional height \([= Z/L]\), where \( L = \theta U_*^2/\kappa g \theta_* \); \( \theta \) is the mean potential temperature in the surface layer and \( g \) the gravitational acceleration

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