

Numerical Experiments on the Influence of the Mesoscale Circulation on the Cumulus Scale

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ABSTRACT

The EML mesoscale model developed by Pielke (1974) was used to simulate the sea breeze circulation over South Florida with its modification of the thermal and moisture structure of the synoptic air mass over South Florida. The numerical experiment was performed for a case study day (16 May 1968) during which extensive cloud observations were performed. To examine the response of the cumulus scale, the one-dimensional time-dependent cumulus model developed by Cotton (1975) was initiated with the theoretical soundings predicted by the mesoscale model, along with cloud scales and cloud areal coverage observed on the case study day. The mesoscale model results demonstrated that the sea breeze over South Florida alters the synoptic environment by 1) substantially perturbing the vertical thermodynamic profile, 2) increasing the depth of the planetary boundary layer, 3) inducing larger surface fluxes of momentum, heat, and moisture, 4) changing the vertical shear of the horizontal wind in lower levels of the atmosphere, and 5) developing intense, horizontal convergence regions of heat, moisture and momentum, and cloud material.

The cumulus-scale model responded by developing a significantly deeper, longer lifetime, precipitating cloud under the forcing of the perturbed sounding. The cloud-scale model consistently underpredicted cloud top height or overpredicted rainfall. This behavior may be attributed to the inadequacy of the nonlinear eddy viscosity model of eddy transport, to the inability of the one-dimensional cumulus cloud model to incorporate vertical wind shear and strong boundary layer fluxes of heat, momentum and moisture induced by the mesoscale circulation, and/or to the fact that the mesoscale model without a convective parameterization scheme predicted soundings which might be too dry and too stable aloft.

1. Introduction

It has long been known that the synoptic environment has a profound impact on the depth of growth, intensity of development, and rainfall rates of cumulus clouds. The synoptic atmosphere may even be such that no cumulus cloud can develop. Concepts such as convective instability, conditional instability, lifting condensation level, and convective condensation level were all developed with the idea of determining the cumulus cloud response to the synoptic environment.

Recently there has been evidence that intensive cumulus cloud activity, such as areas of cumulus congestus and cumulonimbus, requires initiation and sustenance by mesoscale systems. Such systems are larger than individual cumulus clouds, but smaller than such synoptic features as cyclones, hurricanes or fronts. Matsumoto *et al.* (1967) and Uccellini (1975) have independently found over the Sea of Japan and in

the Midwest of the United States that significant cumulus activity occurred only when initiated by mesoscale systems and dissipated when the mesoscale system became inoperative. Pielke (1974) similarly found over South Florida that the typical dominant mesoscale system, the sea breeze, was the primary control of thunderstorm location and movement on days with low vertical wind shear.

In this paper we will use the model developed by Pielke (1974) to examine the alteration of the synoptic environment over South Florida by the sea breeze, and discuss what influence this could be expected to have on cumulus development. To examine the response of the cumulus scale, we shall employ the one-dimensional time-dependent cumulus model developed by Cotton (1975). These experiments represent a first step in the examination of the complex interaction between deep precipitating cumulus clouds and mesoscale circulations.

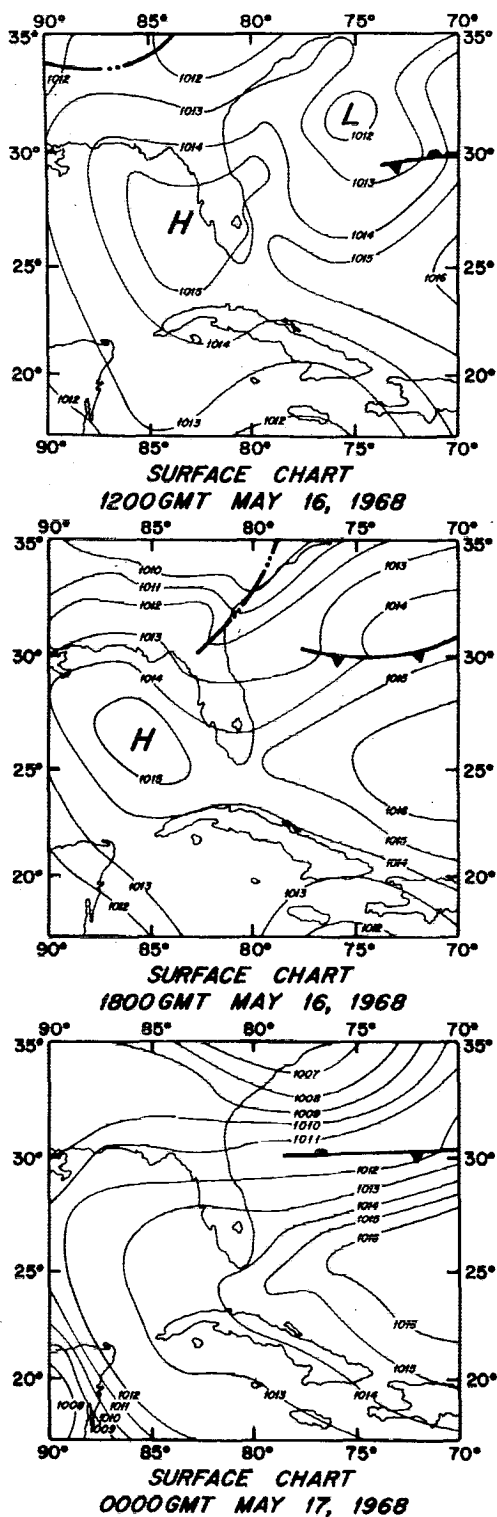


FIG. 1. Surface pressure fields on 16 May 1968 at 0700, 1300 and 1900 EST.

2. Case study

NOAA's Experimental Meteorology Laboratory (EML) performed single-cloud cumulus experiments

in 1968 and 1970, during which considerable cloud observations as well as synoptic analyses were made. The data for one case study day during the single-cloud experiments, namely 16 May 1968, was chosen to predict the sea breeze circulations as a function of the initial synoptic state and to determine the response of cumulus clouds to the mesoscale altered environment.

This date was chosen as a particularly good day to integrate the mesoscale model because the vertical shear of the synoptic wind and its spatial variation across most of South Florida was small.

The synoptic surface pressure fields on 16 May 1968, at 0700, 1300 and 1900 EST, are illustrated in Fig. 1. As evident in the figure, a ridge axis running through South Florida drifted south during the day so that the surface geostrophic winds for a large portion of the day over most of South Florida were light from the southwest. From these analyses, a low-level geostrophic wind from the southwest at 3 m s^{-1} was used to initialize the mesoscale model. The 0700 EST Miami, Key West and Tampa radiosonde soundings were used to initialize the thermodynamic profile. The surface temperature over land was assumed to have a sinusoidal function of time with a maximum amplitude of 10°C and a half-period corresponding to the length of daylight at Miami on 16 May.

The agreement between model predictions and observations was quite good, although only surface meteorological observations at regular reporting stations and shower coverage as viewed by the Miami WSR-57 10 cm radar were available for verification of the model predictions. The predicted horizontal motion field at 50 m, predicted vertical velocity field at 1.22 km, and observed shower coverage and surface winds at 6, 8 and 10 h after sunrise are illustrated in Figs. 2-4.

By 6 h after sunrise (Fig. 2), the predicted and observed winds agree reasonably well, except at Key West which was apparently south of the synoptic ridge axis, along the west coast where the coastline is more irregular than simulated in the mesoscale model, and at two stations on the middle eastern coast which have showers at or near the observation site. Shower activity had increased slightly over that observed a few hours earlier.

By 8 h after sunrise, the shower activity was located primarily in the southern tip of the peninsula which is where the model predicts the largest vertical motions. Along the east coast, there is excellent agreement between observed surface winds and the predicted winds at 50 m. From Flamingo in the extreme tip of the peninsula to Vero Beach along the upper east coast in the figure, the winds back from southwest through south to east-southeast.

After 10 h, the agreement between the predicted convergence and observed showers becomes quite good especially inland along the west coast and over the southern portion of the region, although the predicted

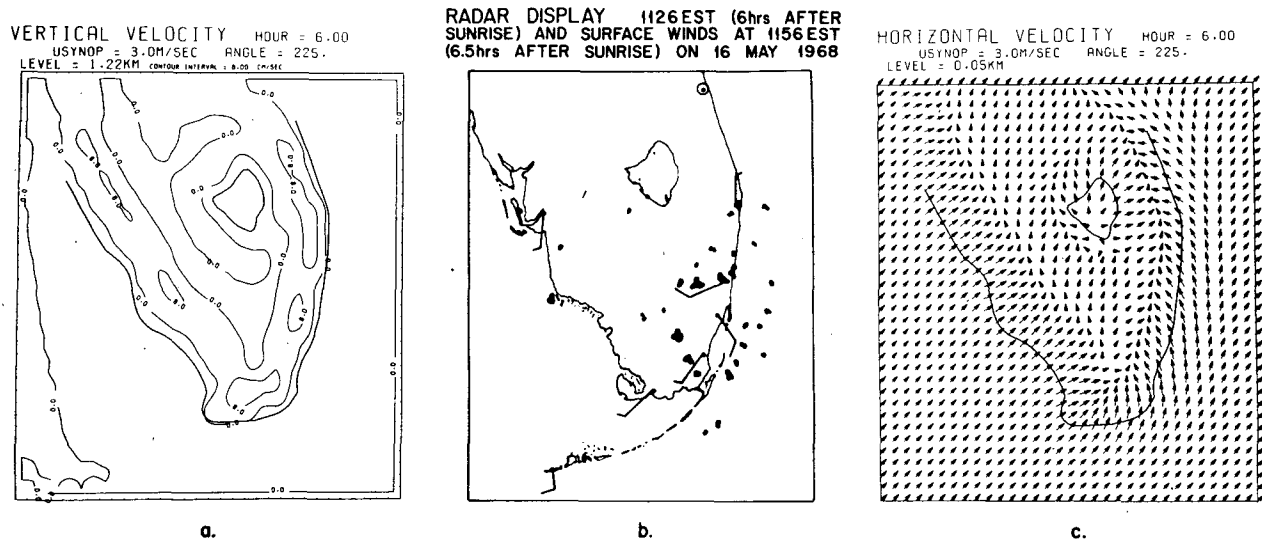


FIG. 2. Predicted and observed fields at 6 h after sunrise: predicted vertical motion field (a), radar-observed shower coverage (b), and predicted surface wind field (c).

convergence zone is somewhat further inland than the observed shower zone. Possibly this indicates that the prescribed geostrophic wind speed was too high or that the dynamic and thermodynamic effects of convection significantly altered the mesoscale circulation. The minimum convergence region predicted by the model inland along the west coast is well represented by a minimum in shower coverage in roughly the same area. Along the east coast the shower area was more amorphous, and even though there is a correlation between convergence zones and rain areas, the actual patterning of showers is not as linear as predicted by the model.

The predicted horizontal winds at 50 m illustrated in Fig. 4c also agrees favorably with the observed

wind field at 1526 EST, given in Fig. 4b. As seen in Fig. 4b, the observed winds were southwesterly on the south coast of the peninsula and became progressively more easterly further north along the Florida east coast, which is in excellent agreement with the predicted winds.

Overall, the model performs quite well in describing the preferred locations of showers and in predicting the time evolution of the horizontal wind field. For these reasons it is a useful vehicle to describe the potential alterations of the synoptic thermodynamic profile by the sea breeze, and to investigate the effect of the perturbed thermodynamic soundings on cumulus cloud development.

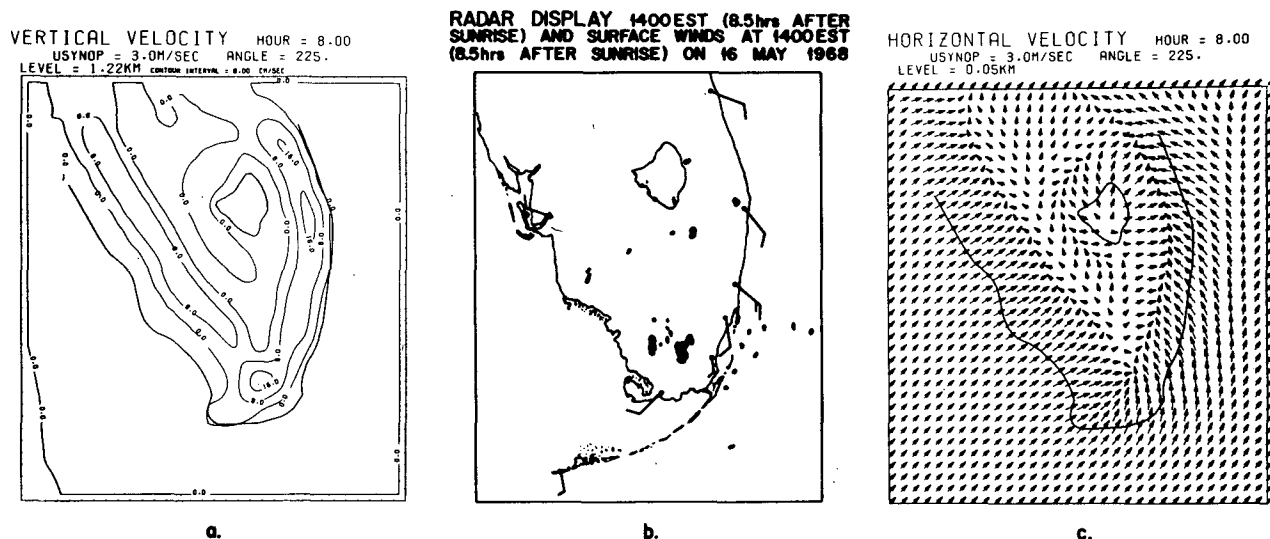


FIG. 3. As in Fig. 2 except at 8 h after sunrise.

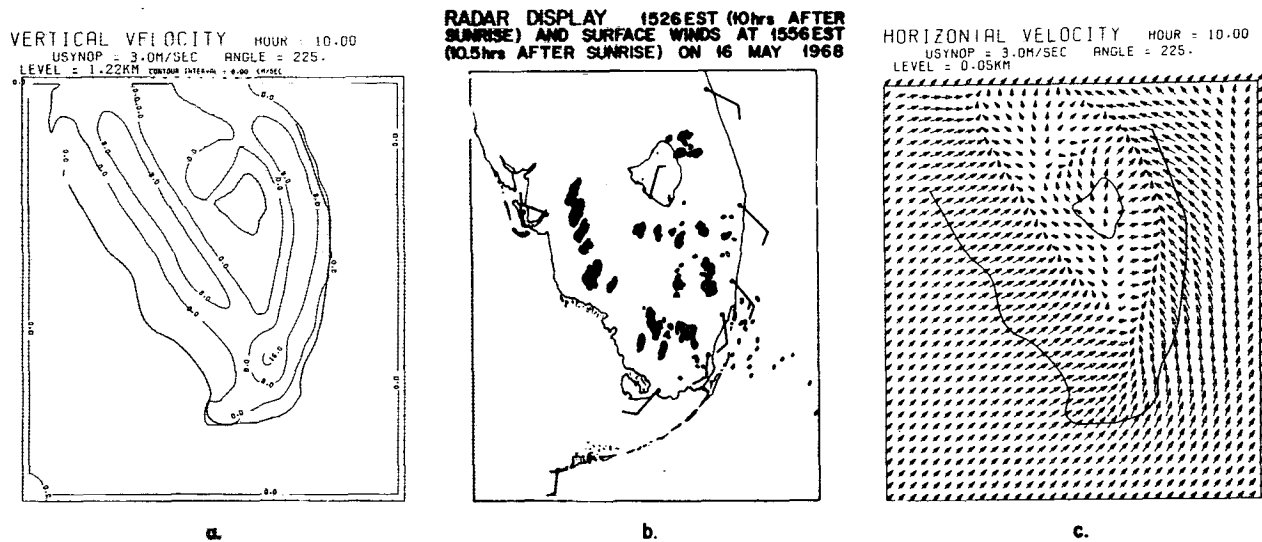


FIG. 4. As in Fig. 2 except at 10 h after sunrise.

3. Influence of the mesoscale on the cumulus environment

As mentioned in Section 2, the Miami, Tampa and Key West soundings for 0700 EST 16 May were used to obtain an average thermodynamic sounding to initialize the model. Deviations from this sounding during the course of the model integration should indicate the influence of the sea breeze on the thermodynamic structure over South Florida.

Verification of the predicted sounding changes is limited, with only Miami making a radiosonde observation at nonstandard time. The sounding at 1300 and the regular sounding taken at 0700, given in

Fig. 5, illustrate a marked warming from the surface up to above 500 mb, and the development of a super-adiabatic layer from 1000 to about 940 mb, or through a depth of about 500 m. There was little change in the moisture structure below 800 mb, but substantial drying above that level to 400 mb was evident.

The predicted soundings over Miami, at about the equivalent times as the actual soundings, showed a similar trend in the lower levels with the development of a superadiabatic layer up to 600 m and warming up to around 1.5 km. In contrast to the observed sounding, however, there is little temperature change above that level. The predicted moisture sounding is also different than the observed with moistening up

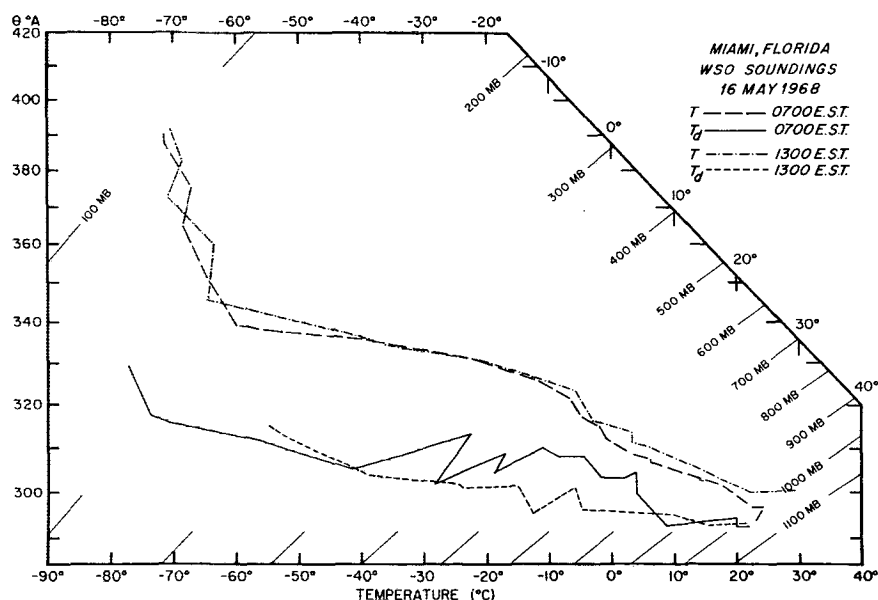


FIG. 5. Radiosonde soundings at 0700 and 1300 EST 16 May 1968 from Miami.

to about 800 mb with little change above that. Moreover, the prescribed surface temperature in the model is higher than observed, although the surface temperature in the model is at the roughness height which is essentially at ground level, while the observed surface temperature was measured at a height of ~ 1 m. In an unstable atmosphere the temperature at the roughness level would be significantly higher.

There are two likely explanations of the differences between the observed and the predicted thermodynamic soundings aloft. The synoptic environment could be changing with time, and/or the drying and warming aloft could be a result of cumulus-induced subsidence. Neither process is described by the model.

Nonetheless, despite these differences, the model does a reasonable job of describing the trend in the thermodynamic profile in the lower levels of the troposphere during the day, and will be useful in examining the impact of these changes on cumulus cloud response over the South Florida peninsula. Since the thermodynamic structure simulated by the mesoscale model has not been fully verified, the following experiments with the cumulus model must be viewed as sensitivity tests of that influence of the mesoscale on cumulus development.

Finally, the mesoscale model predicts alterations from the synoptic environment other than changes in the vertical thermodynamic structure, or the creation of convergence regions of heat, moisture and momentum. In the development of the sea breeze, the vertical profile of the horizontal winds are substantially changed from the synoptic profile along with the creation of a deeper planetary boundary layer and a corresponding increase of vertical fluxes of heat, momentum and moisture. While these effects undoubtedly influence cumulus cloud development, they cannot be examined in the context of a one-dimensional cloud model.

4. Response of the cumulus model

The one-dimensional cumulus model discussed by Cotton (1975) is an extension of the model developed by Asai and Kasahara (1967). The system of equations is closed with a nonlinear eddy viscosity approximation based on the Smagorinsky (1963) concept. A generalized form of the buoyancy enhancement model developed by Lilly (1962) is employed. It is of the form¹

$$K_m = (k_2 \Delta)^2 2^{-1/3} |D_{ij}| [1 - (K_H/K_m) Ri]^{1/3}, \quad (1)$$

where Δ is a characteristic turbulent length scale, here chosen to be the cube root of the averaging volume and k_2 is a coefficient assumed to be 0.165. In the original form discussed by Cotton, the ratio of eddy heat flux to momentum flux (K_H/K_m) in (1) was held fixed at values of 1-3 throughout the numerical experiment. It was found, however, that values

as large as 10 were needed to prevent the development of nonlinear instability when the model was run with the theoretical soundings discussed in this section. That is, the superadiabatic subcloud layer predicted by the mesoscale model resulted in strong accelerations in vertical velocity in the subcloud layer with considerably smaller accelerations in the immediate moist layer above. The resultant energy cascade created a pile-up of momentum and scalar properties on the grid scale. To overcome this difficulty, only in the regions where needed, a variable form of K_H/K_m proposed by Smagorinsky and employed by Drake *et al.* (1974) was adopted. It is of the form

$$\frac{K_H}{K_m} = (3 - 3.Ri + Ri^2) / [1 + (1 - Ri)^{1.5}],$$

$$0 < \frac{K_H}{K_m} < 10. \quad (2)$$

In addition to modification (2), a precipitation model based on the work of Cotton (1972) was also employed. The resultant continuity equation for precipitation mixing ratio Q_H is

$$\frac{\partial \bar{Q}_H}{\partial t} = \bar{Q}_H \frac{\partial w'}{\partial z} - \frac{\partial}{\partial z} \left[(w' + \bar{V}_T) Q_H - \bar{V}_T \frac{\bar{Q}_H}{\rho_0} \frac{\partial \rho_0}{\partial z} \right]$$

$$- \frac{\overline{2w'Q_H''}}{R} + \frac{\partial}{\partial z} \left[\overline{(w''Q_H'')} \right] + S_1(\bar{Q}_H) + S_2(\bar{Q}_H) + S_3(\bar{Q}_H), \quad (3)$$

where the average and fluctuation quantity are defined in Cotton (1975). The vertical and horizontal eddy transport of precipitation is approximated with the above eddy viscosity model assuming that

$$K_{Q_H} = K_H. \quad (4)$$

The source terms $S_1(\bar{Q}_H)$ and $S_2(\bar{Q}_H)$ represent the respective source of rainwater by autoconversion and accretion as defined by Cotton (1972), for a cloud having an initial droplet concentration of 100 cm^{-3} and a radius dispersion of 0.25. The time dependence in the Cotton autoconversion formulation is approximated by the average time it takes a parcel to move from cloud base to level Z . The last term on the right-hand side of (3) represents the evaporation of rainwater in a subsaturated environment. Rainwater is partially evaporated similar to Orville and Sloan (1970). The terminal velocity \bar{V}_T of precipitation is approximated by a water-content-weighted mean also similar to Orville and Sloan (1970).

Beginning with a saturated moisture perturbation from the observed cloud base through a depth of twice the cloud radius, the model was run with the Miami 0700 EST (Fig. 5) sounding and the three

¹ All terms are defined in an appendix.

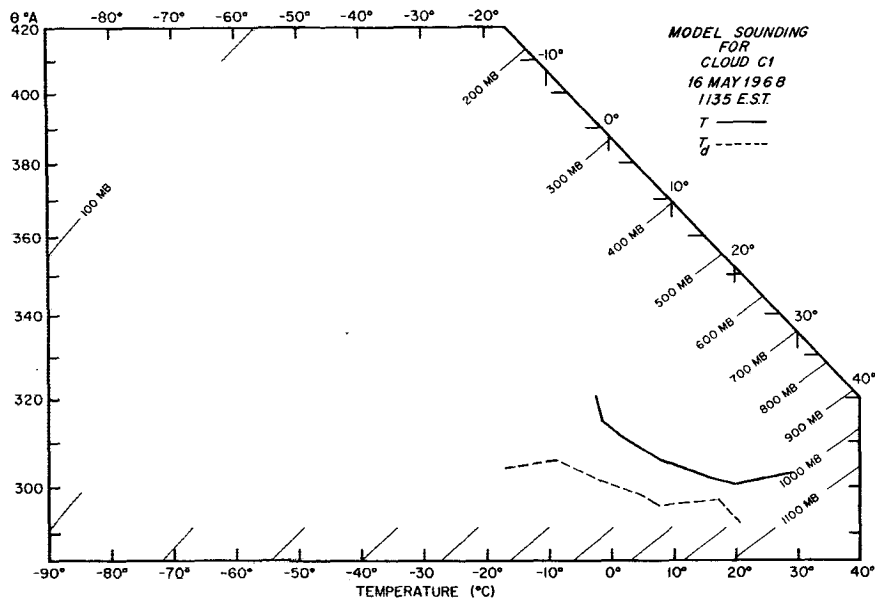


FIG. 6. Theoretical sounding predicted by the mesoscale model corresponding to 1135 EST in the vicinity of the observed cloud C₁.

theoretical soundings (C₁, C₂, C₃) illustrated in Figs. 6-8 predicted by the Pielke model near in space and in time to the observed cumuli.

Fig. 9 shows that the response of the cloud model to the Miami 1200 GMT sounding was the formation of a simple non-precipitating cloud puff with a rising cloud base. The total simulated cloud lifetime was only 6½ min with a cloud top of only 2.0 km.

Fig. 10 shows that the model responded to sounding C₁ by first forming a cloud puff followed by a rapidly rising tower with a stable cloud base. The assigned

cloud areal coverage of 3.5% was estimated from the case study which resulted in a compensating subsidence of sufficient magnitude to lead to the decay of the cell after 35 min. Only a trace of precipitation was predicted at the ground 45 min after cloud formation. This is in spite of the fact that over 1.5 g kg⁻¹ of precipitation formed 30 min after cloud formation at a height of 3.2 km. Most of the precipitation evaporated either in the subcloud layer or during the decay of the cell.

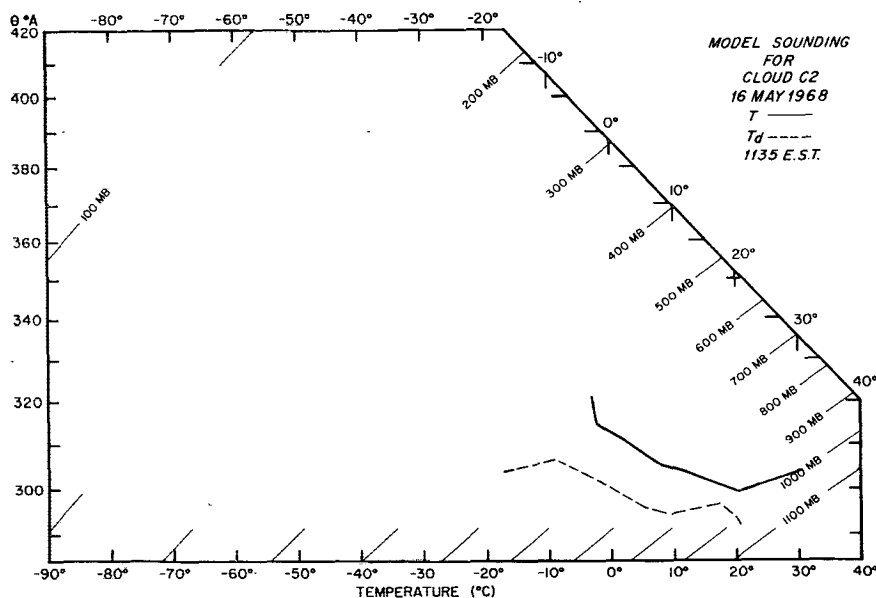


FIG. 7. As in Fig. 6 except for cloud C₂.

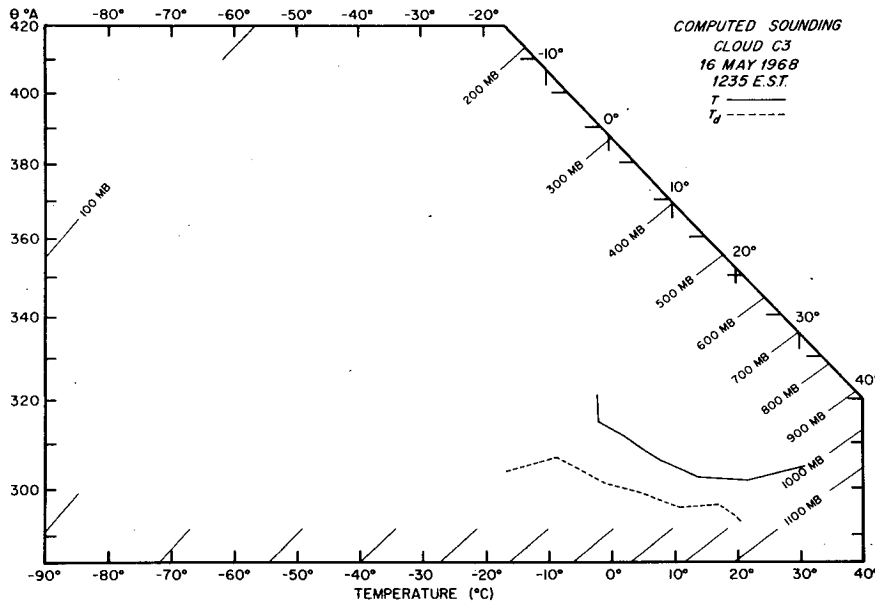


FIG. 8. As in Fig. 6 except for cloud C₃ at 1235 EST.

As illustrated in Fig. 11, a somewhat more vigorous cloud was predicted with sounding C₂. Even though precipitation water contents were as high as 4.0 g kg⁻¹ at a height of 3.2 km, only a trace of surface precipitation was predicted. The model underpredicted the height of the observed clouds C₁ and C₂ by approximately 500 m.

As illustrated in Fig. 12, the model responded to sounding C₃ even more vigorously, but was found to underpredict cloud top height and rainfall. A rather intense shower developed in the cloud but it was again largely evaporated in the subcloud layer. This moistening, however, was able to assist in the forma-

tion of a secondary cloud between 45 and 60 min. In an attempt to increase the predicted cloud top height, the eddy exchange coefficient K_2 was adjusted from 0.2 to 0.1. This resulted in an increase in height but still below the observed height of 14 km, while at the same time, a ridiculous rainfall of 8 inches was predicted.

In an earlier analysis of the one-dimensional, time-dependent, model-predicted data, Cotton (1975) found that the model had a tendency to either underpredict cloud top height or overpredict liquid water content. It was asked whether this tendency might become worse or lessen as the depth of convection increased

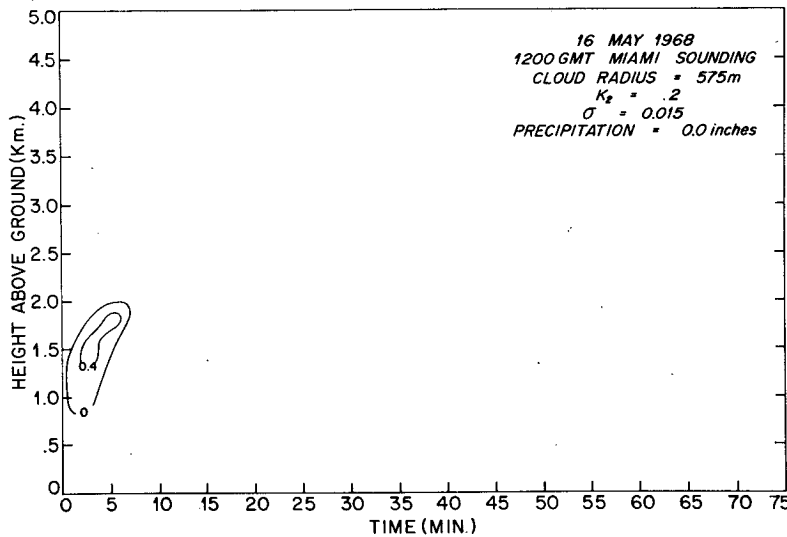


FIG. 9. Cloud liquid water content field predicted by the model using the Miami 1200 GMT sounding (contour interval 0.4 g kg⁻¹).

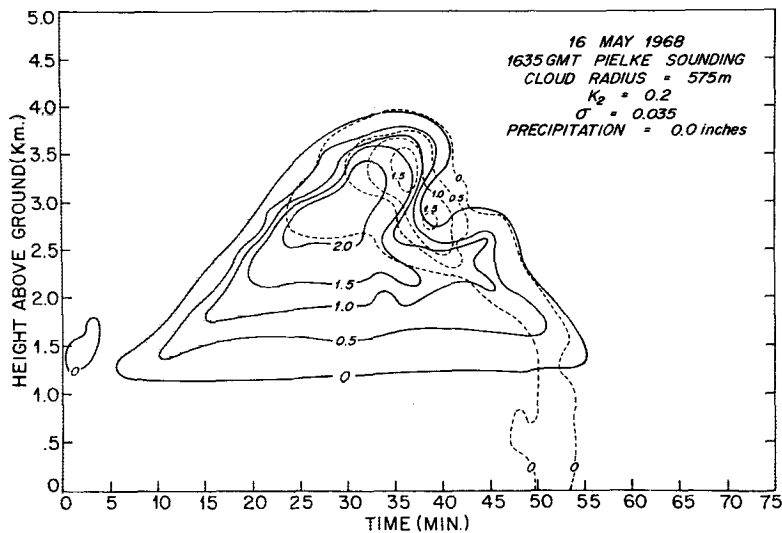


FIG. 10. Cloud liquid water content (solid lines) and precipitation water content (dashed lines) predicted by the model using the theoretical sounding C_1 (contour interval 0.5 g kg^{-1} .)

and the system evolved into a precipitating system. The results of this study suggest that the former is the case. That is, as the observed depth of convection increases, the tendency of the model to underpredict cloud-top height or overpredict liquid water content increases. This result further supports the conclusion made by Cotton (1975) that the eddy viscosity model is an inadequate model for turbulent transport in cumulus clouds since the turbulence in cumulus clouds can transfer energy into the mean flow while the eddy viscosity model and, furthermore, the entrainment model only extracts energy from the mean flow.

This conclusion must be qualified to some degree, however, since these numerical experiments have been performed with theoretical soundings which have not been verified. Since the theoretical soundings are drier aloft than the observed and are perhaps more stable, this could reinforce the tendency for the model to underpredict cloud-top height. In addition, cloud C_3 was part of an extremely complex, multi-cell, small cumulonimbus. It would thus be quite surprising that a single-cell model such as the one-dimensional time-dependent model, could well represent such a system.

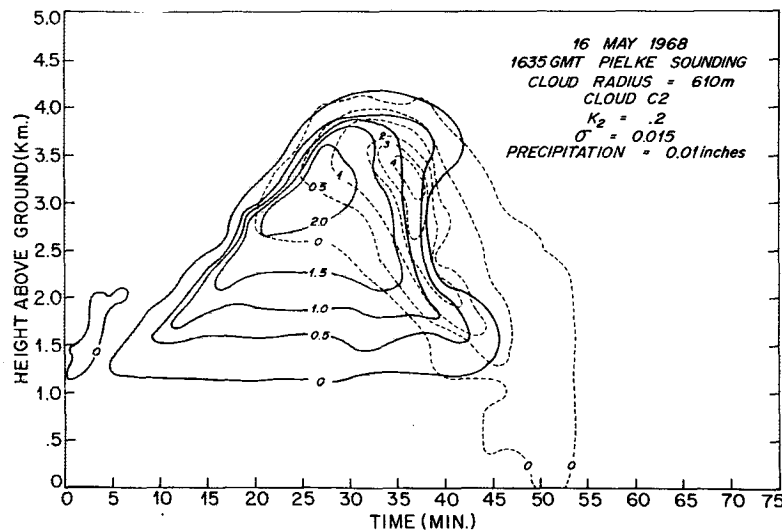


FIG. 11. As in Fig. 10 except for the theoretical sounding C_2 (contour interval for cloud liquid water content 0.5 g kg^{-1} and precipitation 1.0 g kg^{-1} .)

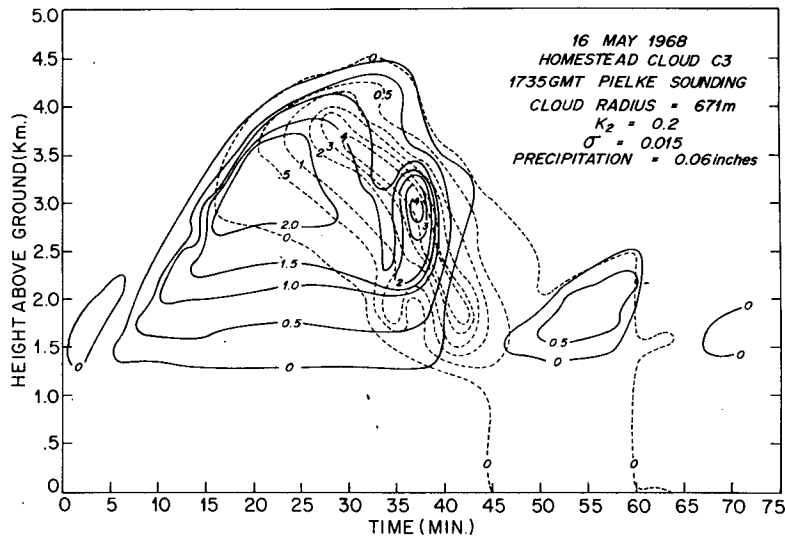


FIG. 12. As in Fig. 10 except for the theoretical sounding C_3 (contour interval for cloud liquid water content 0.5 g kg^{-1} and precipitation 1.0 g kg^{-1} .)

5. Summary and conclusions

The EML mesoscale model results for 16 May 1968 illustrate that the sea breeze over South Florida alters the synoptic environment by:

- 1) Substantially perturbing the vertical thermodynamic profile.
- 2) Increasing the depth of the planetary boundary layer.
- 3) Inducing larger surface fluxes of momentum, heat and moisture.
- 4) Changing the vertical shear of the horizontal wind in lower levels of the atmosphere.
- 5) Developing intense, horizontal convergence regions of heat, moisture, momentum and cloud material.

The response of the cumulus scale to the perturbed thermodynamic profile was illustrated with the one-dimensional cumulus model which developed a significantly deeper, longer lifetime, precipitating cloud under the forcing of the perturbed sounding. The importance of the alteration of the environment by the mesoscale circulation on the prediction of convective precipitation was dramatically illustrated. Of equal importance was the sensitivity of the precipitation forecast to the formulation of eddy transport. These results further support the conclusion that the nonlinear eddy viscosity model is an inappropriate model for parameterizing turbulent transport in cumulus clouds.

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APPENDIX

List of Symbols

$ D_{ij} $	magnitude of deformation tensor
K_H	eddy viscosity for heat
K_{QH}	eddy viscosity for precipitation
K_m	eddy viscosity for momentum
Q_H	average mixing ratio of precipitation
Q_H''	fluctuation in mixing ratio of precipitation
Ri	generalized gradient Richardson number
t	cloud lifetime
u''	radial velocity fluctuation
V_T	terminal velocity of precipitation
w'	average cloud vertical velocity
w''	vertical velocity fluctuation
Z	height above surface
ρ_0	basic state density

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