Specification of the Scale and Magnitude of Thermals Used to Initiate Convection in Cloud Models

RICHARD T. McNIDER
Department of Mathematics and Statistics, University of Alabama in Huntsville, Huntsville, Alabama

FRED J. KOPP
Institute of Atmospheric Sciences, South Dakota School of Mines, Rapid City, South Dakota
8 December 1988 and 5 June 1989

ABSTRACT
Boundary layer similarity techniques are employed to specify the scale and intensity of a thermal perturbation used to initialize a cloud in a numerical cloud model. Techniques are outlined to specify the needed similarity variables from external information. Finally, the cloud model response using the similarity scaled thermal is analyzed employing variations in the similarity variables giving an indication of the importance of the correct specification of the initiating thermal.

1. Introduction
Many cloud models impose a temperature perturbation in order to initiate moist convection (e.g., Orville and Kopp 1977; Klemp and Wilhelmson 1978; and Miller and Pearce 1974). This perturbation is variously meant to represent either characteristic inhomogeneities arising in a convective boundary layer, variations in surface thermal properties or the influence of pre-existing cumuli. In practice, however, the choice for both the magnitude and scale for this perturbation has in most instances been ad hoc with little physical guidance being used. Unfortunately, the selection of the magnitude and scale of the perturbation can condition the subsequent convective response in that too large a perturbation can initiate moist convection which might not naturally occur. Conversely, too small a perturbation will not produce a natural response. Tripoli and Cotton (1980) provide a short discussion of the weaknesses in thermal specification and offered an alternative specification of a saturated bubble based on radar information.

If the role of the cloud model is restricted to understanding mature cloud dynamics or cloud microphysics (such as in some of the studies mentioned above), then an ad hoc perturbation is generally sufficient. However, as cloud models have become sophisticated, some model studies are beginning to examine the initiation of convection as a forecast problem. For such an investigation the magnitude of the thermal perturbation is critical.

One alternative to specifying a perturbation is to provide a surface heat flux to the cloud model and carry out a large eddy simulation (LES) so that thermal and velocity perturbations of the proper scale naturally develop. Recently Balaji and Clark (1988) using an LES approach indicated that subsequent deep convection is in fact conditioned by the initial convection. The LES procedure, however, is computationally expensive in that the cloud model may have to run for several hours prior to the period of moist convective interest in order to develop the proper spectral response. Also, with the LES method, there is no assurance that the clouds of interest will form near the center of the domain, away from the effects of lateral boundaries.

In the present study it is proposed that the scale and intensity of the perturbation used to initialize a cloud model be determined using boundary layer similarity. While other scales may be operating to alter the convective potential (mesoscale or synoptic-scale lifting), the magnitude of the vertical velocities on the mesoscale and synoptic scale is generally one to two orders of magnitude less than the magnitude of boundary-layer scale eddies. Over the last decade there have also been great strides in developing similarity expressions for turbulent statistics in the convective boundary layer (e.g., Kaimal et al. 1976; Caughey 1981) which makes this specification possible.

In the following, similarity expressions are utilized to specify a characteristic scale and intensity of a thermal perturbation used in a two-dimensional cloud model. The length scale is selected based on the peak wavelength in the temperature fluctuation spectrum, while the magnitude of the perturbation is based upon the upper tail of the distribution of thermal boundary layer fluctuations. Two methods are also proposed for...
choosing the realistic magnitudes of the characteristic similarity variables which determine the scale and intensity of the perturbation. Finally, the comparative response of the cloud model to the specified perturbation versus the response to the heated spinup of a large eddy approach is given. Additional examples are given of the differential cloud model response to mesoscale variations in boundary layer attributes.

The specification of the scale and intensity of the thermal boundary layer similarity provides some of the scale selection demonstrated to be important in the work of Balaji and Clark (1988). It should also be noted that the scale and intensity of the thermal based on planetary boundary attributes taken from a specific sounding also provides implicit incorporation of effects such as inhomogeneities in surface properties and/or the presence of a preexisting field of cumuli.

2. Perturbation parameterization

In the following, the thermal perturbation is specified only in two dimensions (the horizontal dimension, \(x\), and vertical dimension, \(z\)) but can easily be extended to three dimensions assuming horizontal symmetry in the second horizontal dimension. The functional form of the thermal perturbation, \(\theta'\), from a base state is assumed to be Gaussian and given by

\[
\theta'(x, z) = A \sigma_\theta(z) \exp\left[-\frac{(x-x_c)^2}{0.5 \lambda_m}\right]
\]

where \(x_c\) is the center of the model domain, \(\sigma_\theta(z)\) is the standard deviation of thermal fluctuations in the boundary layer and \(\lambda_m\) is a characteristic length scale of the thermal fluctuations. The parameter \(A\) determines the part of the \(\sigma_\theta\) distribution selected. For example, for \(A = 2\), a thermal perturbation is chosen which would be two standard deviations above the mean of the distribution so that for a normal distribution, the magnitude of the fluctuation would be in the top \(2\%\) of all fluctuations.

In a cloud model, it is normally desired that the perturbation be specified in the center of the model domain to avoid boundary effects. Thus (1) gives a thermal perturbation centered in the domain whose size and intensity is dependent upon two physical parameters, \(\sigma_\theta\) and \(\lambda_m\) which will now be specified from boundary layer similarity.

The horizontal length scale, \(\lambda_m\), is taken to be the wavelength having the maximum spectral density in the temperature fluctuation spectrum. In a convective boundary layer this scales with the boundary layer height, \(z_i\), (Kaimal et al. 1976); and most of the convective boundary layer can be approximated by

\[
\lambda_m = 1.5z_i.
\]

From boundary layer similarity, the standard deviation of thermal fluctuations, \(\sigma_\theta\), scales with both the convective velocity scale, \(w_*\), and \(z_i\) and is given by Caughey (1981) as

\[
\sigma_\theta^2(z) = 1.8 \left(\frac{z}{z_i}\right)^{-2/3} T_*^2
\]

where

\[
T_* = \frac{w'\theta_i}{w_*}
\]

and

\[
w_* = \left(\frac{z_i g}{\theta} w'\theta_i^2\right)^{1/3}.
\]

The quantity, \(w'\theta_i\), is related to the surface heat flux and \(g\) is gravity. Note that \(w'\theta_i\) is related to the surface heat flux, \(H_0\), by \(H_0 = \rho c_p w'\theta_i\), where \(\rho\) is the air density and \(c_p\) is the specific heat capacity. Combining (4) and (5) into (3) yields

\[
\sigma_\theta(z) = 1.34 z^{-1/3} \left(\frac{w'\theta_i}{\theta g}\right)^{2/3} \left(\frac{\theta}{g}\right)^{1/3}.
\]

In order to utilize (1)–(5) two external physical parameters, \(z\), and \(w'\theta_i\), have to be specified. The planetary boundary layer height can generally be estimated from the sounding used to initialize the cloud model as the height of the nearly adiabatic layer; i.e., the height to which \(d\theta/dz \approx 0\). The surface flux, however, is not normally directly available from routine observations. A boundary layer model with a surface energy budget can provide estimates of the surface heat flux as a function of external information such as surface roughness, latitude, day of the year etc. (see McCumber and Pielke 1981). This is the method employed in the examples used in this paper.

An alternative, which is gaining acceptance in the air pollution community, is an estimate based on routine observations such as cloud cover, wind speed and auxiliary information such as sun angle and surface roughness. Van Ulden and Holtslag (1983) provide methodologies for these estimates. Perhaps easier to utilize are a set of nomograms developed by F. B. Smith in Pasquill and Smith (1983). The nomograms give surface heat flux, friction velocity and Monin–Obukov length from data on surface roughness, wind speed and vertical variation in potential temperature which can be obtained from the sounding.

As an example of the dependence of \(\sigma_\theta\) on heat flux, Table 1 gives \(\sigma_\theta\) for various values of the surface heat flux. For this table, \(z\) was taken to be 100 meters. Thus, for \(A = 3\) the maximum magnitude of the perturbation in (1) would range upward to 1.3 degrees. At a height of 10 meters the maximum fluctuation would be over 3 degrees.

3. Examples of perturbation parameterization

A cloud model developed by investigators at the Institute of Atmospheric Sciences at the South Dakota
Table 1. Characteristic values of $\sigma_{\theta}$ as a function of heat flux from Eq. (6). The height, $z$, was taken to be 100 meters and $\theta = 300$ K.

<table>
<thead>
<tr>
<th>Surface heat flux $H_{0}$ (W m$^{-2}$)</th>
<th>Small</th>
<th>Moderate</th>
<th>Relatively large</th>
</tr>
</thead>
<tbody>
<tr>
<td>60.0</td>
<td>120.0</td>
<td>180.0</td>
<td>240.0</td>
</tr>
<tr>
<td>240.0</td>
<td>300.0</td>
<td>360.0</td>
<td>420.0</td>
</tr>
<tr>
<td>360.0</td>
<td>420.0</td>
<td>480.0</td>
<td></td>
</tr>
</tbody>
</table>

School of Mines is used to demonstrate the application of the similarity scaled perturbations. The model is a two-dimensional, slab-symmetric model; i.e., no variations are allowed in the second horizontal dimension. The reader should refer to Orville and Kopp (1977) or Chen and Orville (1980) for a description of the cloud model.

In the following demonstrations the planetary boundary layer height, $z_{b}$, and surface heat flux, $\rho c_{p} w \theta_{b}$, are taken from a mesoscale boundary-layer model with a surface energy budget. See Pielke and Mahrer (1975) or McNider and Pielke (1981) for a description of the mesoscale model. Figure 1 shows an example of the mesoscale variation of the heat flux and $z_{b}$ from a two-dimensional mesoscale simulation over west Texas in which cloud cover to the east suppressed surface heating and boundary layer development (see Fig. 2 for a satellite image and schematic of the model domain). Figure 3 shows the model-simulated temperature field indicating a deep mixed layer to the west and a shallower more stable environment to the east. Figure 4 shows corresponding variations in $\lambda_{m}$ and $\sigma_{\theta}$ from (2) and (3). As can be seen, substantial variation in the intensity and scale of a perturbation exists.

To demonstrate the application of the scaled perturbation versus a LES heated spinup simulation, the cloud model is integrated for two cases. Both cases use the 1700 UTC sounding taken from the mesoscale model at the approximate location of Amarillo, Texas. In the first case, the cloud model is initialized using the similarity scaled perturbation applicable at Amarillo, i.e., with a heat flux of approximately 420 W m$^{-2}$ and a boundary layer height of 3300 meters. For comparison, a second case was run in which the cloud model was not initialized with a perturbation, but, the model was heated at the surface using the surface heat flux applicable at Amarillo (420 W m$^{-2}$). Figure 5 shows the cloud moist convective response for both cases in terms of maximum vertical velocity over the period of integration. For the case without perturbation, the model atmosphere remains horizontally homogeneous and individual convective elements cannot appear. After 30 minutes, however, the case with no imposed perturbation shows a stronger response to the heating. The transition occurs as roundoff error gradually produces a computational homogeneity. Unnaturally, however, the air next to the ground has become very unstable and when computational inhomogeneities finally develop they tap this overly strong source of buoyant energy to produce a very strong thermal and associated vertical motion at 36 min. This thermal is also inconsistent with the planetary boundary layer depth which is an attribute of the sounding. This experiment is perhaps somewhat artificial in that LES modelers normally impose some perturbations near the surface. For example, Balaji and Clark (1988) impose a random white noise at the surface in their LES simulations. It does, however, show that heated spinup must be treated carefully.

Fig. 1. Variation in (a) heat flux across the model domain and (b) planetary boundary layer height across the model domain. Height is in meters and horizontal distance is in kilometers. AMA stands for Amarillo and CRO stands for Crowell, Texas.
The response of the cloud model to the imposed scaled-thermal seems more reasonable. This is based on the fact that as heating continues, the subsequent velocity response of the model at longer integration times is more in line with the initial response to the imposed perturbation than to the overly large initial response to the homogeneous heating. This is as it should be, since the specified perturbation is supposed to be compatible with the planetary boundary layer depth and heat flux imposed. The initial response is, in fact, slightly larger which may be due to the choice

**FIG. 2.** Satellite view of the region over which the mesoscale model simulation was carried out. Large variations in the surface heat flux occurred across the domain between the clear and cloudy areas. The dashed line shows the two-dimensional cross section employed by the mesoscale model.

**FIG. 3.** Potential temperature field and wind field output of a mesoscale model simulation for 24 April 1982 used as input information for the cloud simulations in this study.

**FIG. 4.** Variations in the scale and magnitude of thermal perturbations due to varying $H_{0}$ and $z_{c}$ across the model domain. Variations in $\lambda_{m}$ are solid; variations in $\sigma_{Z}$ are dashed. Variations in $\sigma_{Z}$ were calculated at a height of 100 m.
of $A = 3$ in the simulation, which corresponds to a perturbation with a magnitude in the top 0.1% of all thermals.

The second example of the similarity scaled thermal examines the comparative cloud model response to variations in the scale and intensity of the thermal across the mesoscale region described in Figs. 1–4. In the first comparative case the cloud model was initialized using the sounding near Amarillo. Using this sounding the model was run first using the heat flux and boundary layer height applicable at the same location, i.e., $H_0 = 420 \text{ W m}^{-2}$ and $z_i = 3300$ meters. Using the same sounding, the cloud model was then rerun using the heat flux and boundary layer height applicable at Crowell, i.e., $H_0 = 12 \text{ W m}^{-2}$ and $z_i = 2200$ meters. Using $A = 3$ in (1) yields a maximum amplitude of the perturbation of nearly 3 degrees near the surface for the first run and approximately 0.3 degrees for the second run. As would be expected the cloud model response given in Fig. 6 is quite different in the two runs. Assuming that the first run is the true response, it demonstrates that pick-

of $A = 3$ in the simulation, which corresponds to a perturbation with a magnitude in the top 0.1% of all thermals.

The second example of the similarity scaled thermal examines the comparative cloud model response to variations in the scale and intensity of the thermal across the mesoscale region described in Figs. 1–4. In the first comparative case the cloud model was initialized using the sounding near Amarillo. Using this sounding the model was run first using the heat flux and boundary layer height applicable at the same location, i.e., $H_0 = 420 \text{ W m}^{-2}$ and $z_i = 3300$ meters. Using the same sounding, the cloud model was then rerun using the heat flux and boundary layer height applicable at Crowell, i.e., $H_0 = 12 \text{ W m}^{-2}$ and $z_i = 2200$ meters. Using $A = 3$ in (1) yields a maximum amplitude of the perturbation of nearly 3 degrees near the surface for the first run and approximately 0.3 degrees for the second run. As would be expected the cloud model response given in Fig. 6 is quite different in the two runs. Assuming that the first run is the true response, it demonstrates that pick-

of $A = 3$ in the simulation, which corresponds to a perturbation with a magnitude in the top 0.1% of all thermals.

The second example of the similarity scaled thermal examines the comparative cloud model response to variations in the scale and intensity of the thermal across the mesoscale region described in Figs. 1–4. In the first comparative case the cloud model was initialized using the sounding near Amarillo. Using this sounding the model was run first using the heat flux and boundary layer height applicable at the same location, i.e., $H_0 = 420 \text{ W m}^{-2}$ and $z_i = 3300$ meters. Using the same sounding, the cloud model was then rerun using the heat flux and boundary layer height applicable at Crowell, i.e., $H_0 = 12 \text{ W m}^{-2}$ and $z_i = 2200$ meters. Using $A = 3$ in (1) yields a maximum amplitude of the perturbation of nearly 3 degrees near the surface for the first run and approximately 0.3 degrees for the second run. As would be expected the cloud model response given in Fig. 6 is quite different in the two runs. Assuming that the first run is the true response, it demonstrates that pick-

of $A = 3$ in the simulation, which corresponds to a perturbation with a magnitude in the top 0.1% of all thermals.

The second example of the similarity scaled thermal examines the comparative cloud model response to variations in the scale and intensity of the thermal across the mesoscale region described in Figs. 1–4. In the first comparative case the cloud model was initialized using the sounding near Amarillo. Using this sounding the model was run first using the heat flux and boundary layer height applicable at the same location, i.e., $H_0 = 420 \text{ W m}^{-2}$ and $z_i = 3300$ meters. Using the same sounding, the cloud model was then rerun using the heat flux and boundary layer height applicable at Crowell, i.e., $H_0 = 12 \text{ W m}^{-2}$ and $z_i = 2200$ meters. Using $A = 3$ in (1) yields a maximum amplitude of the perturbation of nearly 3 degrees near the surface for the first run and approximately 0.3 degrees for the second run. As would be expected the cloud model response given in Fig. 6 is quite different in the two runs. Assuming that the first run is the true response, it demonstrates that pick-

of $A = 3$ in the simulation, which corresponds to a perturbation with a magnitude in the top 0.1% of all thermals.

The second example of the similarity scaled thermal examines the comparative cloud model response to variations in the scale and intensity of the thermal across the mesoscale region described in Figs. 1–4. In the first comparative case the cloud model was initialized using the sounding near Amarillo. Using this sounding the model was run first using the heat flux and boundary layer height applicable at the same location, i.e., $H_0 = 420 \text{ W m}^{-2}$ and $z_i = 3300$ meters. Using the same sounding, the cloud model was then rerun using the heat flux and boundary layer height applicable at Crowell, i.e., $H_0 = 12 \text{ W m}^{-2}$ and $z_i = 2200$ meters. Using $A = 3$ in (1) yields a maximum amplitude of the perturbation of nearly 3 degrees near the surface for the first run and approximately 0.3 degrees for the second run. As would be expected the cloud model response given in Fig. 6 is quite different in the two runs. Assuming that the first run is the true response, it demonstrates that pick-

of $A = 3$ in the simulation, which corresponds to a perturbation with a magnitude in the top 0.1% of all thermals.

The second example of the similarity scaled thermal examines the comparative cloud model response to variations in the scale and intensity of the thermal across the mesoscale region described in Figs. 1–4. In the first comparative case the cloud model was initialized using the sounding near Amarillo. Using this sounding the model was run first using the heat flux and boundary layer height applicable at the same location, i.e., $H_0 = 420 \text{ W m}^{-2}$ and $z_i = 3300$ meters. Using the same sounding, the cloud model was then rerun using the heat flux and boundary layer height applicable at Crowell, i.e., $H_0 = 12 \text{ W m}^{-2}$ and $z_i = 2200$ meters. Using $A = 3$ in (1) yields a maximum amplitude of the perturbation of nearly 3 degrees near the surface for the first run and approximately 0.3 degrees for the second run. As would be expected the cloud model response given in Fig. 6 is quite different in the two runs. Assuming that the first run is the true response, it demonstrates that pick-
ing a perturbation too large may cause an overestimate to the convective response.

4. Conclusions

A simple methodology is given for specifying a thermal perturbation in a cloud model consistent with dry planetary boundary attributes. While other scales may be applicable for some studies such as cumulus dominated boundary layers, it is felt if boundary layer thermals are assumed to be the triggering mechanism that this methodology at least gives an objective method for choosing the magnitude and scale of a thermal perturbation. Even where cumulus dominated layers exist, if the sounding is applicable to this situation and the boundary layer depth is chosen from this sounding, then part of the proper scaling for the thermal is included. The technique described here has advantages over a LES initialization in that it is computationally more efficient and ensures that the dominant moist convection will initially occur in the center of the domain. It should be noted, however, that the LES method, where computer resources permit, provides a more realistic selection of the proper spectral response.

Acknowledgments. The authors would like to thank F. R. Robertson, M. Kalb and G. Wilson for their comments and suggestions. This study was sponsored by the National Aeronautics and Space Administration Contract NAS8-36479. The second author was a University Space Research Associate Visiting Scientist at Marshall Space Flight Center during this study, supported under NASA Contract NAS8-35830.

REFERENCES


