Application of a Convective Plume Model to Prediction of Thunderstorms

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ABSTRACT

The numerically calculated height of a steady-state model of a convective plume, which relies on the entire sounding of temperature and humidity above the assumed cloud base, is considered to be a measure of the thermodynamic predisposition of the atmosphere to convective overturning. The plume height is evaluated as a predictor of summer thunderstorms at Tampa, Fla., and is found to contain more forecast skill than a combination of two simpler and more familiar predictors, the Showalter Index and the precipitable water depth. In absolute terms, however, the skill is modest. Skill is somewhat improved when a simple measure of the zonal geostrophic flow over the Florida penninsula is considered as a predictor together with the height of the model plume, but it is suggested that a major portion of skill, not yet within reach, resides in prediction of the mesoscale systems in which convection is organized.

1. Introduction

Synoptic meteorologists generally agree that two kinds of considerations must be kept in mind in the prediction of thunderstorms. These are, broadly, thermodynamic and hydrodynamic in character.

Evaluation of the thermodynamic aspect requires a measure of the susceptibility of the atmospheric temperature and moisture stratification to deep buoyant convection, according to the physical rationale first provided by the traditional "parcel method" of assessment of stability, and later much extended and elaborated by Bjerknes (1938) and many others. Forecasting practice has been to rely on simple convective indices obtained from sounding data at two or three levels, guided by implicit considerations of thermal buoyancy and environmental entrainment, but with little explicit physical basis. A numerically calculated model convective plume of the type proposed by Squires and Turner (1962), on the other hand, is physically explicit and relies on the sounding data at many levels through the entire depth of the troposphere. Thus, the properties of such a model can be regarded as a stability index, admittedly more complex than conventional indices, but more satisfying physically. As a practical matter it is difficult to see how the purely thermodynamical aspect of thunderstorm prediction could be more exhaustively exploited. The primary concern of this paper is to present the results of an initial attempt to explore the forecasting usefulness of such a model.

There is no satisfactory understanding of how the hydrodynamic influence works, aside from a general appreciation that thunderstorms are relatively likely when the vertical motion is upward on some scale substantially larger than that of the cumulonimbus updraft. The connection with synoptic-scale ascent is elusive, but it is reasonable to argue that the cumulonimbus can sense the mesoscale vertical motions since the disparity in updraft speeds is not so large. There can be little doubt, moreover, that virtually all thunderstorm activity displays some degree of mesoscale organization. Such circulations, however, are enormously varied and little understood. Some are so intimately related to the convection itself that little can be predicted prior to the onset of convection. Others, however, are evidently directly forced by a fixed geographical feature, such as a coastline or a range of mountains and are therefore easier to deal with. We will be concerned incidentally with an effect of this sort.

Our results refer to summer conditions at Tampa, Fla., a location of high thunderstorm frequency in a region in which air-mass changes are slow, so that a sounding may be taken to represent the temperature and moisture stratification of a longer subsequent period than for a location in higher latitudes, where air-mass changes are more rapid and more dramatic.

2. The plume model

The model used as a basis for prediction is a modification by Phillips (1970) of a one-dimensional, steady-state model proposed by Squires and Turner (1962). Cloud properties are assumed to be horizontally uniform. The rate of lateral entrainment of environmental air into the rising plume is given by

$$\frac{1}{M}\frac{dM}{dz}=\frac{2\alpha}{R}$$

where M is the upward mass flux within the cloud, R is the cloud radius (a function of height), and α is a constant, taken as 0.1. It is necessary to specify conditions at cloud base. We assumed that the virtual temperatures are identical at a 900 mb cloud base and in the laterally adjacent environment, and that the updraft speed and cloud radius are 2 m/s and 2 km, respectively. This choice assures the prediction of clouds reaching the upper troposphere when the potential instability is large. The budgets of momentum, entropy, and water substance are then used to derive detailed vertical profiles of the cloud parameters.

The model is unrealistic for deep convection, particularly in its assumptions that the vertical pressure distributions are identical in the cloud and in the environment, and that there is no downdraft or other internal cloud structure and that the condensate does not fall relative to the updraft. It does not appear, however, that this lack of realism will vitiate the usefulness of the results for forecasting, because our aim is to derive from the results a probability of thunderstorm occurrence, on the basis of the thermal and moisture stratification, not to model the actual cloud faithfully. It seems unlikely that a more complex and accurate cloud calculation, whatever its other virtues, would reveal more information about the effects of stratification.

3. Predictions based upon the model

We chose to relate the pressure at the top of the plume calculated from the 1200 GMT Tampa sounding to the relative frequency of occurrence of thunder at the same station during the six-hour period beginning at 1800 GMT. Other results of the calculation such as maximum updraft speed or maximum water load did not seem to represent as well the overall character of the cloud, although we did not attempt to explore the matter systematically. Our dependent sample was 136 such calculations, for periods during the summers of 1970 and 1972 when real-time subjective thunderstorm forecasts were being made in the Department of Meteorology. The results are shown in Fig. 1. In the 13 instances in which the computed top failed to reach above the 600 mb level, only one thunderstorm was subsequently observed. Unfortunately, in the single instance of a computed top above the 200 mb level, no thunderstorm occurred, an example of the fickleness of nature to which the experienced forecaster becomes inured. Within these limits, however, there is a systematic increase of frequency with cloud depth.

The REEP equation (Miller, 1964) derived from this set of results is shown as a dashed line in Fig. 1. It is given by

$$Y_1 = 111 - 0.16X_1, \quad 700 < X < 70$$

where Y_1 is the estimated percent probability of thunderstorm occurrence and X_1 is the plume top in millibars. For a plume top lower than the 700 mb level the probability is taken as zero. The probability forecasts produced by this algorithm were evaluated by computing for each one the Brier score and summing the scores over all forecasts. This total is given by

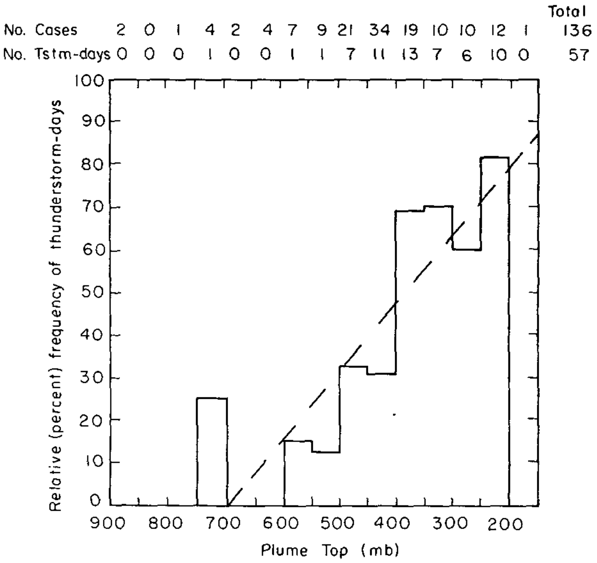

FIG. 1. Histogram of percent frequency of occurrence of thunderstorm days at Tampa vs pressure-level of the top of the plume calculated from the 1200 GMT sounding. The sample is taken from the summers of 1970 to 1972. The dashed line represents the REEP equation derived from the data (see text).

$$S = \frac{1}{136} \sum_{i=1}^{136} (Y_i - O_i)^2$$

where Y_i is the forecast probability given by the REEP equation in the ith instance and O_i is the corresponding "observed" probability, taken as 100% if thunder occurs and zero if not. To evaluate skill, we formed a corresponding control score given by

$$C = \frac{1}{136} \sum_{i=1}^{136} (\bar{O} - O_i)^2,$$

where $\bar{O}$ in this instance is 42%, the relative frequency of thunderstorms in the dependent sample. A modest skill was shown, S being 19.4% smaller than C.

In a test on independent data, for 74 days during June, July, and August, 1973, the forecast score was 15.7% smaller than the control score derived from the relative frequency in the dependent sample. Since in the independent sample the relative frequency of thunderstorms was substantially higher (41 occurrences in 74 instances), the appropriateness of our control could be mooted. We take the position that a control forecast must be known ahead of time and that a control derived after the fact from the independent relative frequency is therefore inappropriate.

We conclude that these predictions based on the plume model show skill, albeit not in overwhelming amounts.

4. Operational significance of the plume-model skill

Though the plume calculation is performed very quickly on a computer, it requires more resources than does the computation of simpler indices, such as the Showalter Index (Showalter, 1953), the Lifted Index (Galway, 1956) and the *K* Index (George, 1960). These can be obtained by simple manipulation of temperature and dew-point values at a smaller number of levels. We are not aware of extensive comparisons of skill of these various indices, but our experience suggests that the differences are not large. We derived, for comparative purposes, a forecast equation based on simpler measures.

The Showalter Index and Lifted Index have physical appeal because their computation simulates the lifting of an air parcel and assessment of consequent thermal buoyancy in the middle troposphere. The Lifted Index, however, appears to be too indiscriminate, yielding good potential wherever absolute humidity is high in the boundary layer, regardless of the moisture stratification aloft. The importance of high humidity aloft in preventing erosion of cumulus clouds by entrainment of environmental air is clear from model plume calculations, and was established empirically long ago by Chalker (1949) among others. The Showalter Index is the excess of the 500 mb temperature over the temperature achieved at the level by a sounding parcel lifted hypothetically from an initial elevation of about 1.5 km, dry-adiabatically to its lifting condensation level, then moist adiabatically. Since it defines regions of likely convection more sharply, we chose it in preference to the Lifted Index.

As an additional predictor which is sensitive to moisture in the middle as well as the lower troposphere, as is the *K* Index, we chose the precipitable water depth as calculated by the National Meteorological Center. This quantity is a measure of the total mass of water vapor in the layer from the surface to the 500 mb level.

The REEP equation for these two predictors developed from 1200 GMT data on 154 days[1] during the summers of 1970–1972 is

$$Y_2 = 33 - 3.6X_2 + 4.0X_3$$

where X_2 is Showalter Index plus 10°C and X_3 is category of precipitable water, chosen so that category one includes values from 0.21 to 0.30 inch, category two represents values from 0.31 to 0.40 inch, and so forth.

Values of *S* and *C* were obtained from the dependent sample for this equation and for the 44% relative frequency of thunderstorm days in this sample. The amount of skill was substantially smaller than that yielded by the plume model, since *S* was only 6.6% smaller than *C*. When the equation was applied to the 74-day period of independent data in the summer of 1973, the percentage improvement increased to 8.5. Since the forecasts for these same days based on the plume model yielded a percentage improvement of 15.7, it appears that more information is contained in the results of the plume calculation. We suggest that such calculations might be profitably employed in appropriate operational situations.

5. The effect of the double sea-breeze

Since the absolute skill of the forecasts based on plume calculations is so slight, we were led to consider as an additional predictor a factor related to the kinematics of the larger-scale flow. If has long been appreciated (e.g., Byers and Rodebush, 1948) that thunderstorm activity over the Florida peninsula is generally greater on days when a westerly sea-breeze along the west coast combines with sea-breeze enhancement of the normal easterly along the east coast to produce large-scale convergence. Pielke (1974) has shown, both observationally and by mesoscale numerical experiments, that convection in the vicinity of Tampa is enhanced on days when the westerly sea-breeze impinges on an easterly geostrophic flow of modest strength across the peninsula, and is suppressed when westerly geostrophic flow prevails over Florida.

As an initial assessment of the effect of zonal geostrophic flow on the sea-breeze and convection, we categorized 206 days during the summers of 1970–1973 according to sea-level pressure difference between Jacksonville (JAX) and Key West (EYW) at 1200 GMT. Days when this difference was one millibar or more positive, less than one millibar, or one millibar or more negative, were denoted easterly, neutral, or westerly days, respectively. Corresponding thunderstorm-day frequencies in the 1800–2400 GMT period, are given in Table 1. The reason for particularly high thunderstorm frequency on neutral days is not clear, and the sharp drop from this to the westerly category is no doubt fortuitous in part, but the strong suppression of convection on westerly days indicates the desirability of using this pressure difference as a predictor.

Accordingly, and in the anticipation that the pressure difference and the calculated plume top were not highly

TABLE 1. Thunderstorm frequencies at Tampa for categories of geostrophic zonal flow.

Type of flow	No. of days	Number of thunderstorm days	Percent frequency of thunderstorm days
Easterly	129	71	55
Neutral	36	21	58
Westerly	41	4	10
All	206	96	47

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[1] The dates more or less coincide with the 136 dates chosen for plume calculations. The number is larger because it includes a number of instances in which garbling of teletype data precluded a plume calculation, though the Showalter Index was obtained.

correlated, we obtained a REEP equation from 133 days in the 1970–1972 developmental period, with these two quantities as predictors. It is

$$Y_3=-120+4.1X_4+7.6X_5$$

where Y_3 is the percent probability of a thunderstorm day, X_4 is the sea-level pressure difference (Jacksonville minus Key West) plus 20 mb, and X_5 is the plume top in 50 mb categories with the value one assigned to the layer from 900 mb to 851 mb, ranging upward to 15 for the layer from 200 mb to 151 mb. As with Y_2, any computed values of Y_3 less than zero or greater than 100 were replaced by those limiting values. On the basis of the Brier score, this equation yielded a 27.4% improvement over the climatological forecast (a probability of 43%) in the dependent period. In the same independent 74-day period in the summer of 1973 used for testing forecasts based on the other REEP equations, the Y_3 forecasts represented an improvement of 22.8% over the climatological forecast. In both instances substantial additional skill results from the addition of the second predictor, but the absolute skill remains modest.

6. Concluding discussion

We have made a pilot study of the effectiveness of the calculated height of a hypothetical steady-state convective plume as a predictor of summer thunderstorms at Tampa. We find a modest degree of skill, relative to climatological forecasts based on a pair of simpler and more familiar predictors. We find that skill is enhanced by joint consideration of calculated plume top and a measure of the zonal geostrophic flow across the Florida peninsula, presumably because of its association with the sea-breeze regime, which has an important effect on convection apart from its association with variations in air-mass stability.

The question arises whether this skill can lead to improvement in the present state of the art in thunderstorm forecasting. Since we are not aware of any reliable measures of this state, we undertook to make real-time forecasts of thunderstorms during the summer of 1973 at Tampa, among a number of locations. Details of this effort are provided by Garrett (1974). It suffices here to say that the predictand was the same as that used in our studies, namely, the probability of occurrence of audible thunder in the period from 1800 GMT to 2400 GMT, that the forecasts were completed (by the authors and by a number of other students) at the beginning of this period, and that the forecasts based on any and all information available up to this time on the National Facsimile Circuit and on Service A and C teletype.

A consensus forecast is made each day by averaging the individual forecasters' probability forecasts. These consensus forecasts for Tampa, verified by the Brier score, represented an improvement over the climatological forecast of 34% in a 47-day sample, while the Y_3-forecasts yielded a 25% improvement for the same sample. The Y_3-value was not available to the forecaster. It seemed clear, therefore, that solely the radar and surface observations received immediately prior to 1800 GMT, the beginning of the forecast period, were at least as informative as the Y_3-value determined from 1200 GMT observations, but it is likely that the availability of the latter could have affected an improvement in skill, since it surely represents at least partially independent information. The Y_3-value, of course, has the advantage of being available well before the initial appearance of showers and thunderstorms in the normal diurnal cycle, and would be particularly valuable for forecast decisions made during the morning.

We did not attempt to calculate plumes from predicted soundings, though we appreciate that this possibility should be explored. Contemporary operational numerical-prediction models probably lack sufficient vertical resolution and precision to make such calculations effective now. Alternatively, the plume model might yield greater skill at other locations where air-mass variability is more dramatic. Our experience suggests that much of the skill in thunderstorm prediction resides in skill, now almost entirely lacking, in predicting the mesoscale patterns of organization of convection. Extension of the work reported here may help to establish that the quantitative limit of predictability of thunderstorms on the basis of thermodynamic considerations alone is not high.

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