Forecasting

A CONCEPTUAL APPROACH TO THUNDERSTORM FORECASTING

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ABSTRACT

A conceptual approach to thunderstorm forecasting is described in terms of the four basic ingredients needed to produce significant convection. These ingredients are: instability or a source of destabilization, moisture, synoptic scale lift aloft, and low level convergence. The role of each parameter is discussed in some detail. When all four of these ingredients occur in the same place at the same time, the probability of occurrence of significant thunderstorms increases dramatically.

1. INTRODUCTION

Convective weather phenomena occupy a very important part of a Weather Service office's forecast and warning responsibilities. Severe thunderstorms require a critical response in the form of watches and warnings. (A severe thunderstorm by National Weather Service definition is one that produces wind gusts of 50 knots or greater, hail of 3/4 inch diameter or larger, and/or tornadoes.) Nevertheless, intense thunderstorms, those just below severe intensity or those producing copious rainfall, also require a certain degree of response in the form of statements and often staffing. (These include thunderstorms that produce hail of any size and/or wind gusts of 35 knots or greater, or storms producing sufficiently intense rainfall to possess a potential for flash flooding.) Intense thunderstorms can have as much or more impact on the public, and require as much action by a forecast office, as do severe thunderstorms. For the purpose of this paper the term "significant convection" will refer to a combination of these two thunderstorm classes.

It is the premise of this paper that significant convection, whether intense or severe, develops from similar atmospheric situations. For effective operations, forecasters must be familiar with factors that produce significant convection.

The purpose of this paper is to describe several basic elements of thunderstorm forecasting, including mesoanalysis. Discussion will center on four specific topics and is not intended to be an in-depth dissertation on convection forcasting. What is presented here is a realistic and operationally feasible approach to the forecasting of significant convection.

The four basic elements discussed below descibe a conceptual approach to forecasting significant convection. This approach provides the forecaster with a listing of physical parameters important to the occurrence of the event. It also provides a basic understanding of why these parameters are important, and how they fit together to produce the event. It then becomes the responsibility of the forecaster to use his/her analytical abilities to determine where these parameters will occur simultaneously in time and space. This will indicate the most likely area and time frame for intense thunderstorm occurrence. The conceptual approach provides a wide degree of flexibility and understanding in the forecast decision process. By recognizing the needed parameters in both current analyses and numerical guidance, a forecaster can better anticipate intense thunderstorm occurrence, particularly events that do not have a high degree of correlation to a set of forecast models or typical conditions.

2. CONCEPTUAL ELEMENTS OF THUNDERSTORM FORECASTING

From a basic point of view, four parameters are necessary for the occurrence of significant convection:

(1) unstable air or a source of destabilization

(2) moisture

(3) synoptic scale lift aloft

(4) low level convergence.

2a. INSTABILITY OR DESTABILIZATION

Convective weather systems rely to a high degree on the thermal and moisture structure of the atmospheric column in which they develop. Specifically, accelerations attained by the convective core significantly depend upon thermal buoyancy. The potential of an atmospheric column to produce this buoyancy is commonly measured in terms of the column's convective stability. Two basic operational approaches are used to determine convective stability, stability indices and sounding analysis.

There are many measures of convective stability. Numerous indices have been developed over the years to aid the forecasting of severe weather and thunderstorms in general. All provide a means of gaging the convective potential of the atmospheric column. Some indices work better for severe weather (e.g., SWEAT); others work better for non-severe convection (e.g., K index). It is beyond the scope of this paper to go into detail on any of these indices. (See, for example, the index comparison of David and Smith (2).) Several of these indices are routinely produced. They provide a quick measure of the atmosphere's convective potential.

Due to the varied nature of the vertical thermal and moisture structure, sounding analysis often provides an informative measure of convective potential. Sounding analysis allows the forecaster/analyst to integrate all levels of data into the stability measuring process. For example, the effects of negative buoyancy due to a warm, mid-level cap can be assessed by this approach. The destabilization effects of nearby or approaching air can also be examined. An initially stable environment can be destabilized within a few hours by advective or a diabatic heating processes. Sounding analysis combined with standard surface or upper air charts often provide clues to this destabilization.

Remember, an unstable atmospheric column by itself will not produce thunderstorms. Other factors must be present; they are discussed below.

2b. MOISTURE

Thunderstorms need sufficient moisture in the lower layer to develop and grow. Williams (3) showed that surface dewpoints greater than 55°F were most favorable for the occurrence of severe convection. Generally, enough moisture must be present so that any lifting of the inflowing air goes above the level of free convection (LFC).

Dewpoint temperature analyses are the best method of recognizing moisture patterns in both surface and upper level charts. It is common practice among forecasters to shade areas of upper level charts with dewpoint depressions of five Celsius degrees or less. This highlights areas of high relative humidity and possible clouds, but does not give a good measure of absolute moisture. Dewpoint analyses provide this measure. With the proliferation of computer power in forecast offices it is easy to produce charts with dewpoint instead of dewpoint depression.

The surface aviation (SA) observing network provides sufficient data for analysis of subsynoptic scale features (4). Areas of strong moisture gradient, or tongues of moisture intruding into relatively dry regions, become obvious via dewpoint analysis; these are features favorable to thunderstorm occurrence. When these dewpoint analyses are combined with wind data, areas of moist inflow or moisture convergence can be inferred. Hudson (5) showed that moisture convergence tends to lead development of significant convection by several hours. Moisture convergence $(\nabla \cdot r\mathbf{V})$ (where r is mixing ratio and $\mathbf{V}$ is vector velocity) mathematically combines mass convergence $(r\nabla \cdot \mathbf{V})$ and moisture advection $(\mathbf{V} \cdot \nabla r)$. It maximizes where convergence and moist inflow are best. Convergence and moist inflow also make an important contribution to the low level forcing discussed in section 2d. Several numerical analysis programs are available to calculate this quantity.

Satellite infrared (IR) and visual imagery can often provide qualitative pictures of moisture locations on a mesoscale level, such as dark (warm) moist tongues in IR imagery or cumulus fields in visual pictures. Cumulus fields also imply something about low level instability. Numerous techniques have been developed for using satellite features in forecasting convection.

In addition to the need for low level moisture to feed the thunderstorms, the vertical distribution of moisture can be important. Forecasters look for intrusions of dry air at 700 mb as an indicator of severe potential. On the other hand, a deep layer of moisture has been associated with storms that produce copious rainfall (flash flood potential). Thus both the horizontal and vertical distribution of moisture should be examined for a complete picture.

2c. SYNOPTIC SCALE LIFT ALOFT

Studies of upper tropospheric divergence (6) and warm advection (7) lead to the conclusion that synoptic scale upward motion is a factor favorable for the development of significant convection. This lift, by itself, will not generate convection but will produce an environment conducive to the development of significant convection. Synoptic scale lift aloft can also act as a destabilizing mechanism, if allowed to act long enough on certain types of vertical thermal and moisture structure.

Synoptic studies have shown that synoptic scale lift can be attributed to both dynamic and thermodynamic factors. Dynamic factors include positive vorticity advection (PVA) increasing with height and/or upper tropospheric divergence. Thermodynamic factors include warm advection, primarily at the 850 to 700 mb level.

The importance of warm advection to the development of intense convection was demonstrated by Maddox and Doswell (7). Three cases were used to illustrate situations where convection developed in areas of warm advection. Dynamic factors in these situations were weak or absent. Warm advection appears to be a major factor in the development of flash flood producing convection.

In other situations warm advection is weak or non-existent, and dynamic factors produce the required mid-tropospheric lift. McNulty (6) showed that synoptic scale divergence predominated in the 200-300 mb layer in cases of severe weather. This divergence, when properly coupled with low level convergence, can create areas of upward vertical motion.

Studies have related thunderstorm occurrence to divergence aloft; their findings show:

(1) Strong convergence aloft tends to suppress significant convection.

(2) Weak convergence aloft can often be overcome by highly unstable air forcing its way upward from the lower troposphere.

(3) Weak to moderate upper divergence appears to create the most favorable environment for significant convection.

(4) Strong upper divergence favors stratiform rather than cumuliform development due to the widespread large scale vertical motion.

These results can be extended to the intensity of mid-tropospheric lift without too much loss of generality. Specifically, result (1) applies to moderate to strong subsidence, a situation unfavorable for the occurrence of significant convection. Result (2) can be associated with weak subsidence. If conditions are very unstable and strong, low level forcing exists, and isolated thunderstorms can sometimes push upward despite the inhibiting effects of weak subsidence. Result (3), weak to moderate lift, when combined with the other three parameters discussed here, creates a vertical structure most receptive to development of significant convection. Most important thunderstorm events occur in this type of environment. Result (4) implies strong lift; this favors stratiform clouds.

It may be more realistic to think of synoptic scale lift as a spectrum of values rather than four distinct categories. For example, as lift increases from moderate to strong, situations will arise in which both cumuliform and stratiform clouds occur, such as embedded thunderstorms. The cut-off or change-over point from one type of convection to the next will not depend upon lift intensity alone, but upon the combined effect of all four of the factors being discussed here.

Some researchers have emphasized warm advection as the major lift producing mechanism while others have stressed the importance of upper divergence. Operational experience points to the more general concept of synoptic scale lift aloft as a better description of the required physics. In some situations, warm advection is the dominant lift mechanism; in other situations dynamic factors predominate. During the summer, when dynamics are typically weak, thermodynamic lift is a key. During the spring dynamics are strong and can be the dominating lift mechanism. Severe weather forecasters use the "no change line" (the 700 mb dividing line between upstream cold advection and downstream warm advection) as an indicator of where severe thunderstorms will occur. The "no change line" indicates where cold advection will reduce the middle level cap and release the low level air. Since cold advection is associated with subsidence, dynamics are the predominant lift mechanism, not thermodynamics. However, in most situations both dynamic and thermodynamic factors crease lift. Forecasters need to look for both sources of lift and not key on only one source.

In practice forecasters can determine dynamic and thermodynamic factors from analyses and numerical prognoses. Dynamic lift mechanisms include PVA increasing with height and upper divergence sources. Upper tropospheric divergence can be inferred from short wave troughs (divergence downstream from the trough) and jet maxima (divergence in the left front and right rear quadarant, depending upon curvature). Lift due to warm advection can be inferred from 850 and 700 mb contours/winds and isotherms. For short term forecasts (less than 12 hours) areas of lift can be determined from routine analyses. For the longer term (12-36 hours), numerical model fields, including vertical motion, are available. In either case the lift mechanism must be combined with the presence of the other three parameters discussed here for a successful forecast.

Satellite imagery has introduced a new dimension to lift identification. Clouds, which by their presence imply upward moving air somewhere in the vertical column, are routinely associated with short wave troughs, jet maxima and axes, and areas of differential vorticity advection. Satellite aloud patterns have enhanced the ideas associated with synoptic scale forecasting, and have also allowed forecasters to identify systems previously buried between rawinsonde stations. Satellite imagery has, at least qualitatively, opened the door to mesoscale analysis of upper tropospheric systems. The result has been significant improvement in short term forecasting, especially regarding convection. Satellite imagery will probably be the only type of upper level, mesoscale data available operationally until satellite sounding techniques become routine.

2d. LOW LEVEL CONVERGENCE

The fourth element required for significant convection is low level convergence. In some ways, this may be the most important of the four parameters. Without low level convergence to start and focus the forcing from the bottom, significant convection usually does not occur. An area, zone or line of convergence provides the mesoscale mechanical lift needed to get the air beyond the LFC.

The two main sources of low level forcing are terrain features and boundaries. Terrain, combined with a particular surface wind flow, can enhance convergence in local areas. The Big Thompson Canyon flash flood is an excellent example of terrain induced convection (8). Terrain effects are something that have not been extensively researched. As a result the forecaster must be familiar with the topographic features of his/her particular forecast area. Experience will dictate where local covergence effects occur. These effects should be part of a local forecasters handbook or similar reference source. Terrain effects can also combine with other convergence mechanisms, but must not be overlooked as a singular source of significant low level forcing.

In general, low level forcing is best identified from the surface (SA) observing network. Mesoanalysis of surface data provides the means to identify convergence areas. Boundaries are the most important features found via mesoanalysis. A boundary is a characteristic feature common to many mesoscale systems. A boundary refers to any low level, quasilinear discontinuity characterized by cyclonic shear and convergence. A main premise of the concept described here is that significant convection occurs along boundaries, and that these boundaries can be identified from surface data with the aid of satellite imagery. Boundaries are important because they tend to maximize geostrophic relative vorticity and moisture convergence. Both quantities are related to the localized low level upward vertical motion.

Boundaries can be subdivided into several types: deep boundaries; shallow boundaries; and convectively induced boundaries.

Deep boundaries include cold fronts, warm fronts, and stationary fronts. These are familiar to meteorologists and need not be discussed in detail here. They are easy to identify and have been associated with thunderstorms for many years. The "classic squall line" is a type of significant convection often associated with deep boundaries.

Shallow boundaries are those that do not extend upward through a significant depth of the atmosphere. One of the best examples is the dry line (9). It is best analysed on surface charts along the 45°F isodrosotherm (10). It is most common over the High Plains and is a known source of significant convection. Sea breeze "fronts" also fall into this category (11).

Convectively induced boundaries refer to lines of temperature, moisture and/or wind discontinuity produced by the cold outflow from thunderstorms. These act as excellent low level forcing surfaces for further convective development. These boundaries are often referred to as "bubble" boundaries. A boundary produced by yesterday's thunderstorms is often the low level forcing mechanism for today's convection. Boundary identification and forecast application, with examples, are covered in more detail in McNulty (12).

Up to this point the low level forcing mechanisms have been discussed in terms of surface data. However, in some cases forcing occurs above the surface. The best example of off-the-surface low level convergence is overrunning thunderstorms. Overrunning thunderstorms occur when moist unstable are is forced upward along a relatively shallow frontal boundary. The air flows upward along an isentropic (constant potential temperature) surface. Often a low level jet (LLJ) acts as the major forcing mechanism. In such situations the thunderstorms do not form along the surface boundary, but in the vicinity of the 850 mb front, several hundred miles to the cool side of the surface front.

In summary the fourth and perhaps most important element of convective forecasting is low level convergence. This convergence provides a mechanism for lifting the moist unstable low level air beyond the LFC and into a thermally buoyant environment. Terrain and boundaries provide a means to produce the required lift.

3. FORECAST IMPLICATIONS

The four parameters discussed above are occurring somewhere in the atmosphere most of the time. It is only when they occur over the same geographical area at the same time that significant convection results.

When the four parameters are derived from synoptic scale data (analyses or prognoses), relatively broad areas can be defined where thunderstorm occurrence is possible. This is done routinely for severe weather occurrence by SELS in the Convective Outlook (ACUS or SWO on AFOS). In order to reduce this area in both space and time, surface data must be examined. This is where mesoanalysis becomes important. Mesoanalysis allows the forecaster to identify the low level forcing mechanisms, e.g., boundaries, thus localizing the area for potential thunderstorm occurrence. This process is used in laying out SELS severe weather watches, but will also identify the area with the best potential for non-severe thunderstorms.

During this process a forecaster must examine all available data, identifying areas of instability, moisture and synoptic scale lift aloft, and then decide if all factors will occur in the presence of a low level forcing mechanism. Sometimes this process is easy. At other times, timing is critical, or something will be missing. This synthesis of the four necessary ingredients is what makes convective forecasting a challenge.

4. CONCLUSION

A brief discussion of the four basic ingredients needed to produce significant convection has been presented. These are: a) instability or a source of destabilization, b) moisture, c) synoptic scale lift aloft, and d) low level convergence. Synoptic scale lift aloft is associated with short wave troughs and jet maxima (sources of upper tropospheric divergence), increasing PVA with height, warm advection, or, as in most situations, a combination of these factors. Low level convergence refers to mechanical lift produced along boundaries, by terrain, or above the surface by the LLJ. When all four of these ingredients occur in the same place at the same time, the probability of occurrence of significant thunderstorms increases significantly.

The discussion presented in this paper describes a conceptual approach to forecasting significant convection. It has been successfully used operationally. The proper understanding and application of this concept should enhance and improve the forecasting of significant convection.

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FOOTNOTES AND REFERENCES

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