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AN AUTOMATED "3-ELEMENT" ALGORITHM FOR FORECASTING SEVERE WEATHER USING AFWA MM5 MODEL OUTPUT DATA

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1. INTRODUCTION

Forecasting severe weather continues to be a daunting challenge even in the 21st Century. Severe weather forecasters ponder dozens of surface and upper air, observed and model forecast parameters. According to Miller (1972), "It is extremely difficult to weigh these parameters and to assign them an order of relative importance. They are essentially interdependent and vary in relations to each other in different situations." According to the Storm Prediction Center (SPC) (http://www.spc.noaa.gov/faq/tornado/#Forecasting, 2004) discussing the software used to view the "enormous number of (parameters)", "…the most important software in the tornado forecast process is within the human brain. The forecaster must use it to sort all that information, toss out what is not needed, (and) properly interpret what is needed". The use of the hand-drawn severe weather composite chart is still taught within the SPC, and members of the SPC still teach the composite chart to forecasters across the Continental United States (CONUS).

A few automated forecasts of severe weather exist. The Air Force Weather Agency (AFWA) uses a regression equation that relates model lifted index, K index, and SWEAT index to severe weather (Knapp and Brooks 2000). The Meteorological Development Laboratory produces a Model Output Statistics forecast of severe weather (Hughes 2002). Colquhoun (1987) and Mills and Colquhoun (1998) created a thunderstorm and severe thunderstorm decision-tree system, and tested it using Australian numerical prediction model output data. The latter technique was not fully automated at the time of publication.

There is therefore ample opportunity to develop automated outlooks of severe weather, similar to the "AC" (area convection) product produced operationally by SPC forecasters. One such algorithm, the 3-Element severe algorithm, is described here. Data used for this algorithm are described in section 2, the algorithm development methodology is briefly summarized in section 3, and the three "elements" composing the severe weather algorithm are explained in section 4. Finally, two case studies are presented in section 5, strengths and weaknesses of the 3-Element algorithm are listed in section 6, and a summary with potential future work is presented in section 7.

2. DATA

The AFWA MM5 (Grell et al. 1995) outputs gridded data at 3-h intervals through 72 h. MM5 45 km runs are made every 6 h, and these grids were used as raw input to the severe storm forecast algorithm. GrADS (Gridded Analysis and Display System) software (Institute of Global Environment and Society 2004 http://grads.iges.org/home.html) was used to display raw model variables and to create new parameterizations as combinations of the raw variables. The corresponding SPC outlooks and real-time receipt of reports were used as targets for the algorithm forecast. The algorithm first ran in the warm season of the year 2000.

3. ALGORITHM DEVELOPMENT

The 3-Element (3-E) algorithm was developed using an "ad-hoc" methodology. A manuscript has been submitted to the National Weather Digest describing the algorithm development methodology. In summary, interactive visualization and analysis software was used to display and algebraically manipulate gridded model data as potential predictors of severe weather. The corresponding SPC outlooks and near-real-time receipt of reports were used as targets for the algorithm forecast. Raw predictors were selected, new predictors were parameterized, and sometimes removed in an iterative process. Algorithm predictor thresholds were also adjusted in near-real time. After the algorithm was fully developed, a statistical process was used to optimize thresholds of individual parameters. The optimization revealed that the human-selected thresholds were already close to optimal.

4. 3-ELEMENT ALGORITHM

Using the iterative development approach above, the severe storm algorithm reached a satisfactory level of skill after it had three "elements": instability, dynamically oriented forcings, and weak capping. The name "3-Element Severe" was therefore applied to the algorithm.

Each of the three elements must be present for

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severe weather to be forecast. The presence of the instability element can be satisfied when threshold values of any of three stability indices are met. Likewise, the forcing element can be satisfied when any of three separate dynamic process indicators exceed thresholds. The weak cap element consists of two cap indices, either of which can "veto" severe weather if the index indicates a cap is present. The high-level algorithm can be depicted as follows:

IF (unstable) AND (forcing) AND (weakly capped)
THEN (forecast severe)

The instability element can be satisfied when threshold values of any of the following indices are exceeded: CAPE, lifted index, or total totals. The CAPE index is useful east of the Rockies where high values of CAPE correlate consistently with severe weather. The lifted index is found to be useful in the winter when severe weather occurs with lifted index values as weak as -2 ºC, and CAPE well under 500 J kg^{-1}. High values of Total Totals are useful in the Rockies, where CAPE and lifted indices are often less unstable than are typical in the rest of the CONUS.

The forcing element can be satisfied when any of three different forcing mechanisms exceed threshold values. The mechanisms are 850 hPa warm air advection, model 700 hPa upward vertical velocity, and boundary layer average convergence.

There are two capping indices output by the MM5 post-processor: Convective inhibition, and the AFWA lid strength index. Experimentation showed that both indices should be under threshold values (both weakly capped) before severe weather would occur. That is, if either cap index were over a threshold value, severe weather was unlikely.

So far, the 3-E algorithm is similar to Colquhoun's method (1987) or Mills and Colquhoun (1998). The 3-E goes beyond the flow-chart, if-then methodology of Colquhoun by allowing any of three different stability indices to satisfy the instability element, and by allowing any of three forcing mechanisms to satisfy the forcing element. Also, a variation to the 3-E was added so that it would work well in the wintertime, because it was unrealistic to expect that single threshold values of stability would work in all cases. The 3-E was developed in the warm season, when instability is high and dynamic forcings are often weak. In the winter season, it was found that weak values of instability were adequate if the forcing was strong. Thus, weaker thresholds of instability parameters were established that allow severe weather to be forecast as long as forcing parameters were present with stronger threshold values. Also, moderate values of both forcing and instability parameters existing together lead to a forecast of severe weather. The balance of forcing and instability can often be seen in a single case. Frequently the northern part of a storm system is forecast to be severe due to stronger forcing elements, and the southern part of a storm is forecast to be severe due to stronger instability.

Two filters are currently being tested to reduce false alarms, and appear to do so without missing severe events. The first filter rules out severe weather where the MM5 post-processor value of storm-relative helicity is under +20 J Kg^{-1}, and another filter rules out severe weather if the zero to six km shear is under 10 m s^{-1}.

5. CASE STUDIES

5.1 *Case Study: 30 May 2004*

A large area of severe weather occurred on this day with a very high density of reports (Fig 1a). The SPC 1300 UTC outlook (valid from 1300 UTC until 1200 UTC the next morning) and the 3-E forecast (from the 0600 UTC MM5 run valid 2100 UTC) (Figs. 1b and 1c) were very similar, and nearly all verifying reports were included in the areal coverage of both forecasts. 3-E forecasts valid later in the day included more area to the east than that shown in Fig. 1c.

In Fig. 1b, the SPC correctly issued a "high" risk of severe storms, which means that a high density of reports was expected. In Fig. 1c, the 3-E forecast is shaded dark blue where the instability is high (and the forcing parameters are either high or low). The 3-E forecast is shaded light blue when the instability values are low and the forcing parameters have high values. In Figs. 1b and 1c, light blue shading in the north indicates the "dynamic" part of the storm system, where the 3-E forcing terms exceeded high thresholds, and the dark blue shading to the south indicates that the instability terms exceed strong thresholds. There should be no expectation of high or low report density associated with the 3-E forecasts of either color. In addition to the dark and light-blue shadings where 3-E forecasts severe weather, contours of each element are shown on the output image: a green contour where there is instability, a red line delineates the weakly capped area, and a purple line surrounds areas with a forcing element. With this information, forecasters can choose to alter the 3-E forecast if they disagree with the MM5 forecast of a particular element.

Later in the evening, the 3-E algorithm forecast severe weather that did not occur. By 0600 UTC May 31, the 3-E forecast severe weather from Ohio and West Virginia, southwestward through northern Alabama to the

Texas Gulf Coast (Fig 1d). The 3-E typically over-forecasts during the nocturnal hours, and over-forecasts somewhat in the Gulf Coast states. In the Texas Gulf Coast area, Rapid Update Cycle analyses showed a trough in the Plains states through all levels of the atmosphere. The 300 hPa jet was 25 m s^{-1} almost to the Gulf Coast, and moderate wind shear existed as far south as central Texas. 3-E forcing parameters were present: 700 hPa upward velocity, boundary layer convergence, and 850 hPa warm advection. Since all three elements were present: instability, weak capping, and forcing mechanisms, the 3-E algorithm forecast severe weather. Understanding the lack of severe thunderstorms in the Gulf Coast states, in spite of the forecast and observed presence of each of the algorithm's three severe weather elements, is one weakness of the 3-E algorithm that needs to be addressed.

5.2 *Case: 27 July 2004*

Seasonally cool air had pushed into much of the CONUS. Near the edges of the cold air severe weather was possible. The SPC and 3-E forecast severe weather to occur in the Northern Plains and southwestern CONUS. The 27 July 0000 UTC 3-E run additionally forecast severe storms to occur in the Atlantic Coast states, with less severe forecast in that region from the 1200 UTC 3-E run.

While the SPC never formally forecast severe weather for the Mid-Atlantic states, they did issue a mesoscale convective discussion for Virginia and Maryland early in the day at 1749 UTC, stating that the "*THREAT WILL REMAIN LIMITED ENOUGH THAT A WATCH IS NOT LIKELY.*" The forecaster stated that "*THE PARALLEL NATURE OF UNIDIRECTIONAL SHEAR PROFILES WITH ORIENTATION OF DIFFERENTIAL HEATING/CONVECTIVE GENESIS BOUNDARY EXTENDING FROM SOUTHERN MARYLAND INTO SOUTH-CENTRAL VIRGINIA SUGGESTS THAT IT WILL TAKE A FEW MORE HOURS FOR CONVECTION TO ALIGN ITSELF FAVORABLY TO DEEP SHEAR VECTOR AND BEGIN POSING A THREAT FOR ISOLATED DAMAGING WINDS*." Recall that the 3-E forcing element consists of either 850 hPa warm advection, 700 hPa model upward vertical velocity, or average boundary layer convergence. It does not yet take into account any form of wind shear: vertical, speed, or directional. The lack of wind shear would therefore be a valid reason to second-guess the 3-E forecast of severe in this area.

In the Mid-Atlantic region, a tornado occurred in New Jersey and three wind reports occurred in southeastern Pennsylvania between 2100 and 0000 UTC (Fig. 2a), where no outlook or watch was issued by the SPC (Fig 2b). The 3-E algorithm did have limited success in the area, depending on the model run-time. The 27 July 0000 UTC 3-E run valid 2100 UTC forecast these events with great accuracy, with a bit of over-forecasting further south (Fig. 2c). The 3-E forcing element (highlighted in Fig. 2d) corresponds fairly well to the area north of the warm front. A forecaster viewing the 3-E forecast should have assumed the severe weather, if it occurred, would be very near the warm front where surface convergence probably was occurring in a locally concentrated area. This is another valid way to second-guess the 3-E algorithm, since it uses only an average boundary layer convergence as a forcing mechanism, which as can be seen in Fig. 2d only corresponds loosely with the location of the surface warm front. The 0600 UTC run valid 2100 UTC (not shown) had severe weather in the area, but not at the exact locations of the severe reports. The 1200 UTC 3-E run decreased the severe forecast to only a few isolated locations, located along the warm front near the location where severe reports occurred (Fig 2e). It is often the case that when the SPC and 3-E forecasts have differences, the verification seems to fall somewhere between the forecasts. That was the case on 27 July, when the SPC under-forecast severe weather in the area, and the 3-E algorithm over-forecast.

Both forecasts had only moderate success in the Four Corners region, where both forecasts changed somewhat during the day. Various runs of the 3-E algorithm suggested that scattered severe weather would occur over an area larger than the SPC's forecast. However, the area of concentrated reports in Utah was not well indicated by the 3-E forecast. The general location of the SPC severe forecast was good, but the SPC found it necessary to make the area larger during the day. Overall, the SPC and 3-E forecasts were both partly right and partly incorrect.

Severe storms occurred in the late afternoon and evening in the Dakotas and Nebraska. The SPC forecast later in the day removed Nebraska from the outlook area, which was unfortunately incorrect. The 3-E forecast did not forecast severe weather in Nebraska due to the lack of a forcing element. One of the weaknesses of the 3-E algorithm during the summer months has been the lack of a forcing element when severe weather occurs.

6. 3-ELEMENT ALGORITHM STRENGTHS AND WEAKNESSES

A lengthy list of 3-E algorithm strengths and weaknesses has been compiled during the four and one-half years that it has been running. One obvious advantage is that the 3-E program forecasts a snapshot of severe weather every 3 h (at every output time of the AFWA MM5). Highlights of other 3-E algorithm tendencies are listed here.

6.1 *3-E Algorithm Strengths*

Some of the known strengths of the 3-E algorithm are as follows:

- Parameters making up the three elements are well forecast spatially and temporally by the MM5. Therefore, severe weather areas forecast by the 3-E algorithm generally move smoothly and consistently across the country
- If one of the three elements is missing, severe weather will probably not occur due to the lack of that element. In other words, the stability, weak cap, and forcing elements are weighted well relative to each other
- Generally over-forecasts with current thresholds, but is mostly consistent in areal coverage with SPC out looks
- Quite good at forecasting location of isolated severe events (the three elements overlap in the correct location)

6.2 *3-E Algorithm Weaknesses*

Some of the known 3-E algorithm weaknesses include:

- Over-forecasts during the diurnal minimum time of severe weather (valid 0600, 0900, 1200, 1500 UTC)
- Over-forecasts in the Pacific Northwest and Rockies
- Severe weather reports are often further to the northeast than forecast by the algorithm
- Time of initiation is not a strong point
- Does not have surface T, Td, or explicit terrain effects

7. SUMMARY AND FUTURE WORK

The 3-Element severe weather algorithm has been running automatically at AFWA since the summer of the year 2000. Currently, the 3-E forecast is posted in near-real time to http://wxforecasting.org/keller/3e.html. According to the 3-E algorithm, three weather elements are needed for severe weather: instability, forcing, and weak capping. If the complex skill of severe storm forecasting can be described by three elements, the 3-E algorithm appears to be the best description to date of three basic components necessary for severe weather. It is hoped that the 3-E algorithm is a good framework from which to develop more sophisticated automated forecasts of severe weather.

In the future it will be necessary to determine if additional information added to the algorithm can fit into the "3-Element" methodology. Perhaps there should be 4 or 5 elements or many more. Keller (2004) describes a corresponding program that forecasts lightning with good skill. It is likely that lessons learned from that algorithm can be applied to the severe forecasting problem. One straightforward experiment would be to compare the lightning forecast to the severe weather forecast. If the lightning forecast can be trusted, then severe weather could be ruled out where lightning is not forecast.

8. REFERENCES

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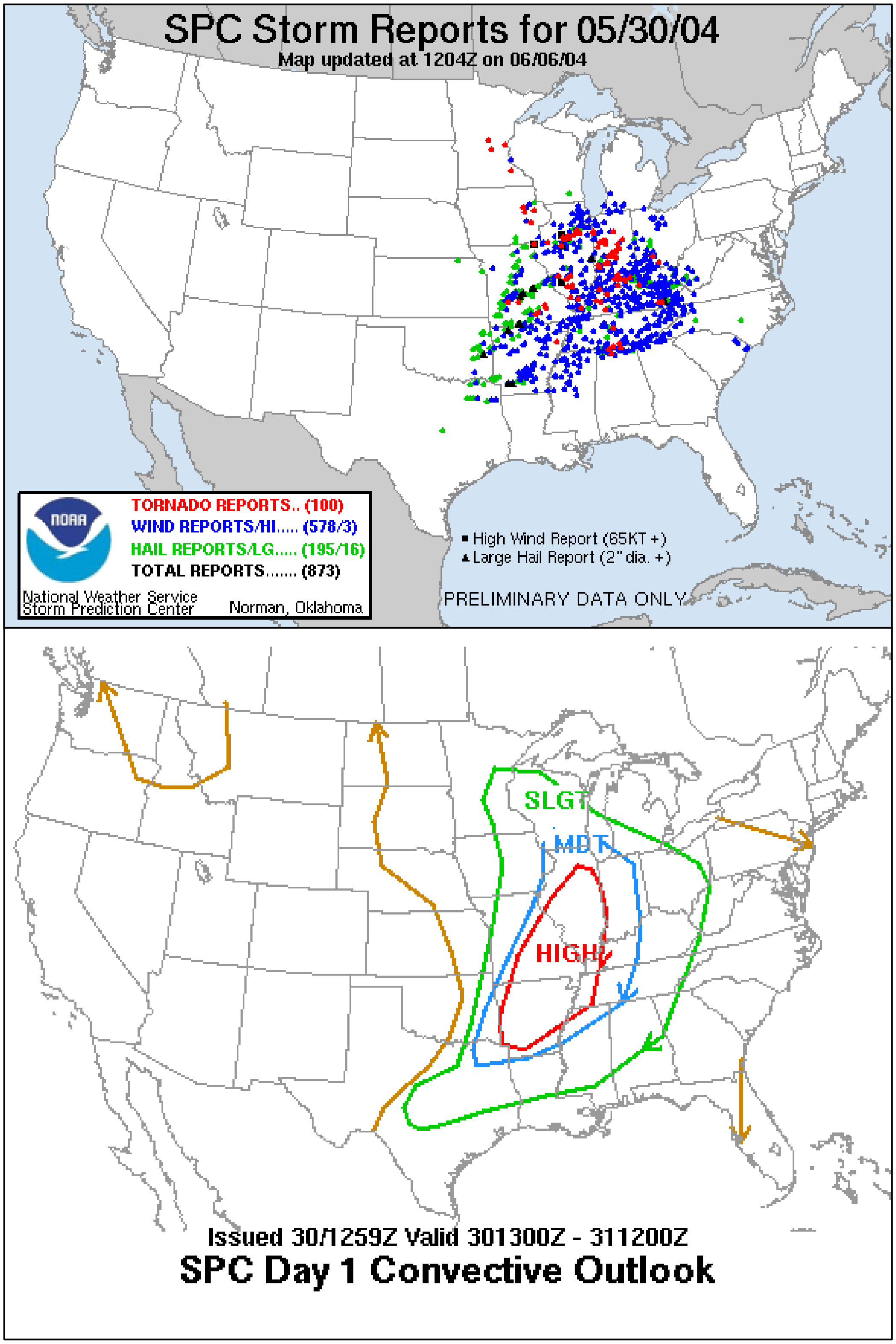

Fig 1. a) May 30, 2004 Storm Reports; b) SPC 1300 UTC outlook; c) 3-E 0000 UTC run valid 21 UTC. Severe area shaded, the three elements are contoured; d) 3-E 0000 UTC run valid 0600 UTC the next day.

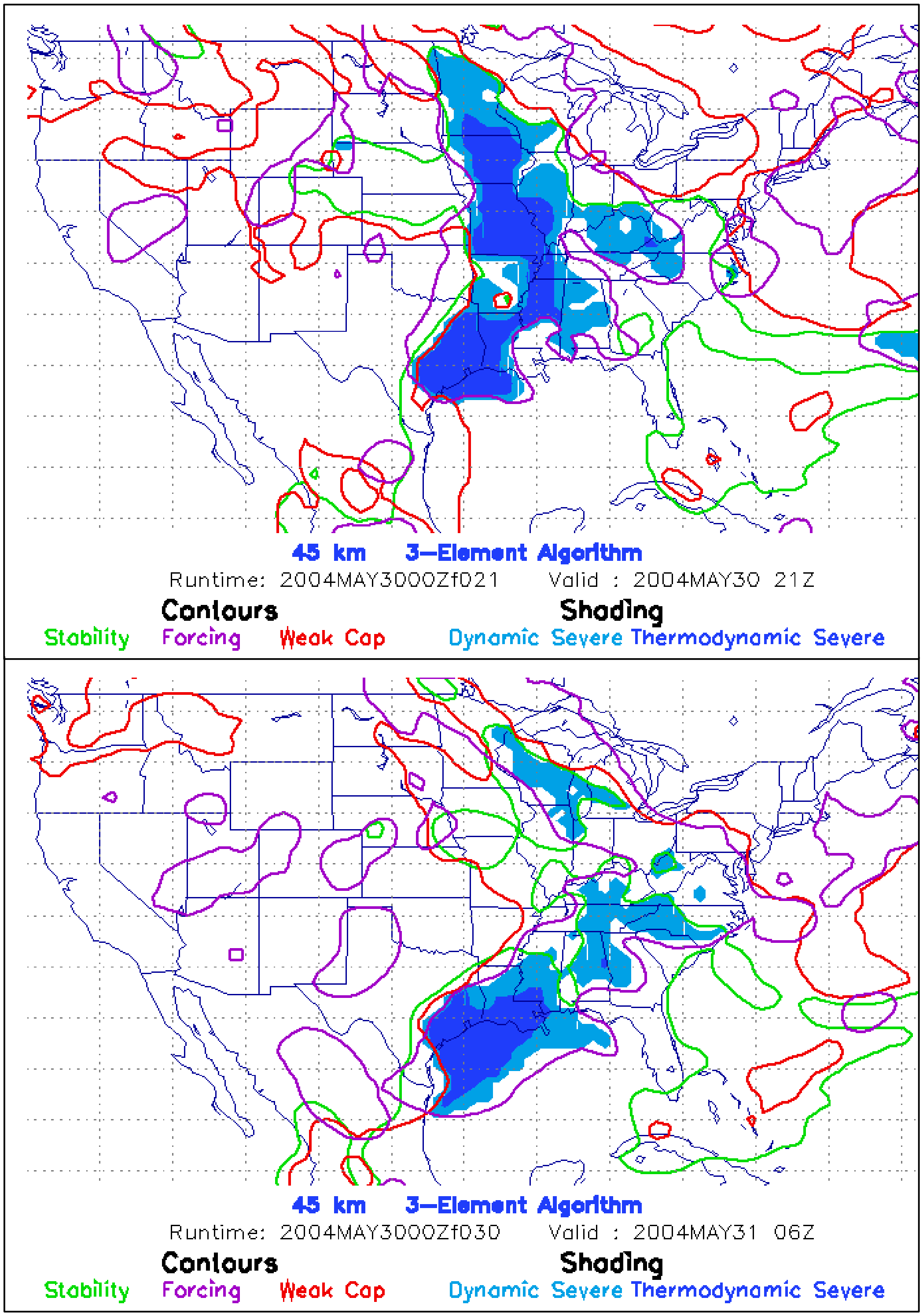

Fig. 1. (continued)

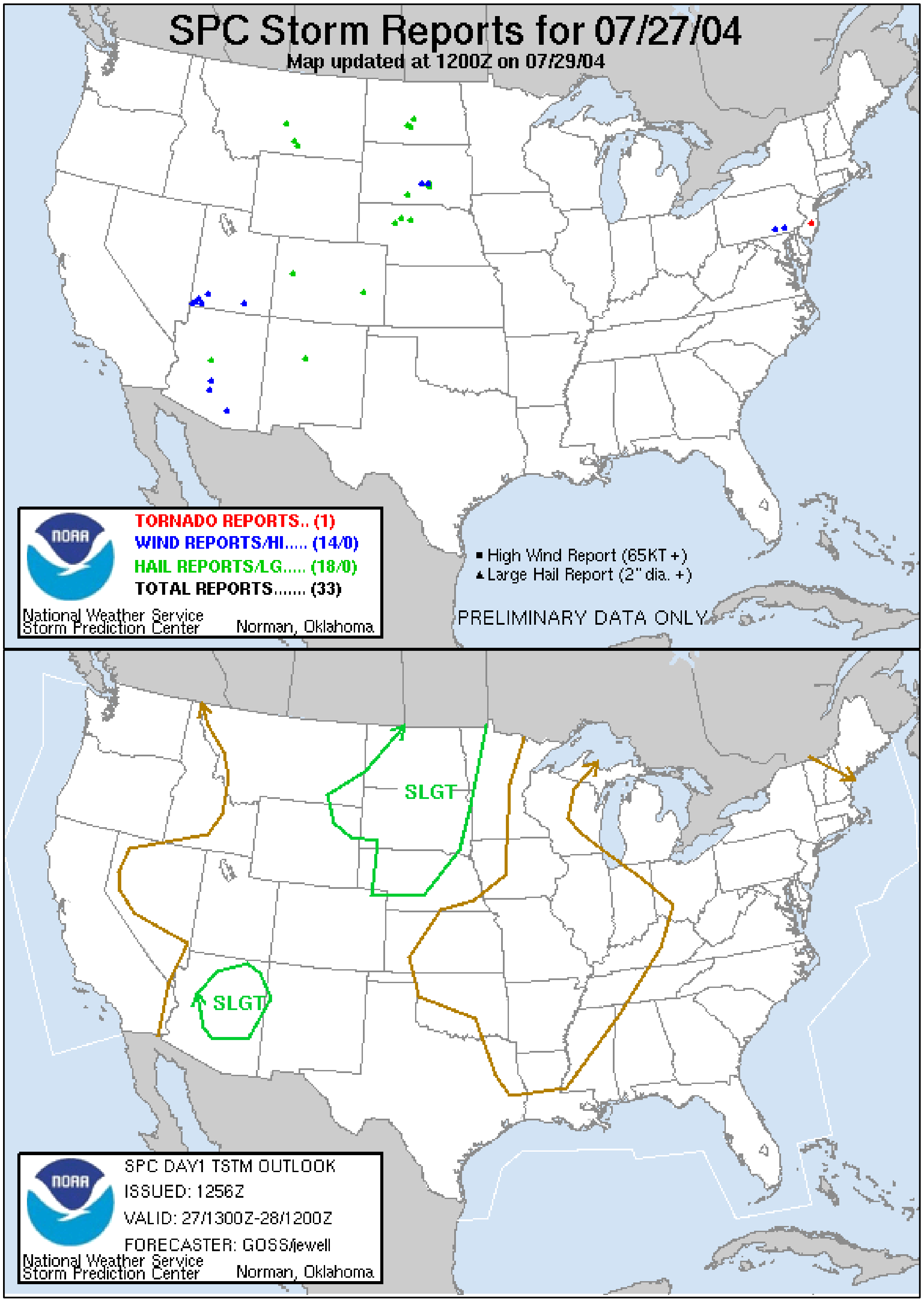

Fig 2. a) July 27, 2004 Storm Reports; b) SPC 1300 UTC outlook; c) 3-E 0600 UTC run valid 2100 UTC. Severe forecast is shaded, the three elements are contoured; d) 3-E close-up of PA/NJ area, with forcing element (purple line) emphasized; e) 3-E 1200 UTC forecast valid 2100 UTC, close-up of PA/NJ area

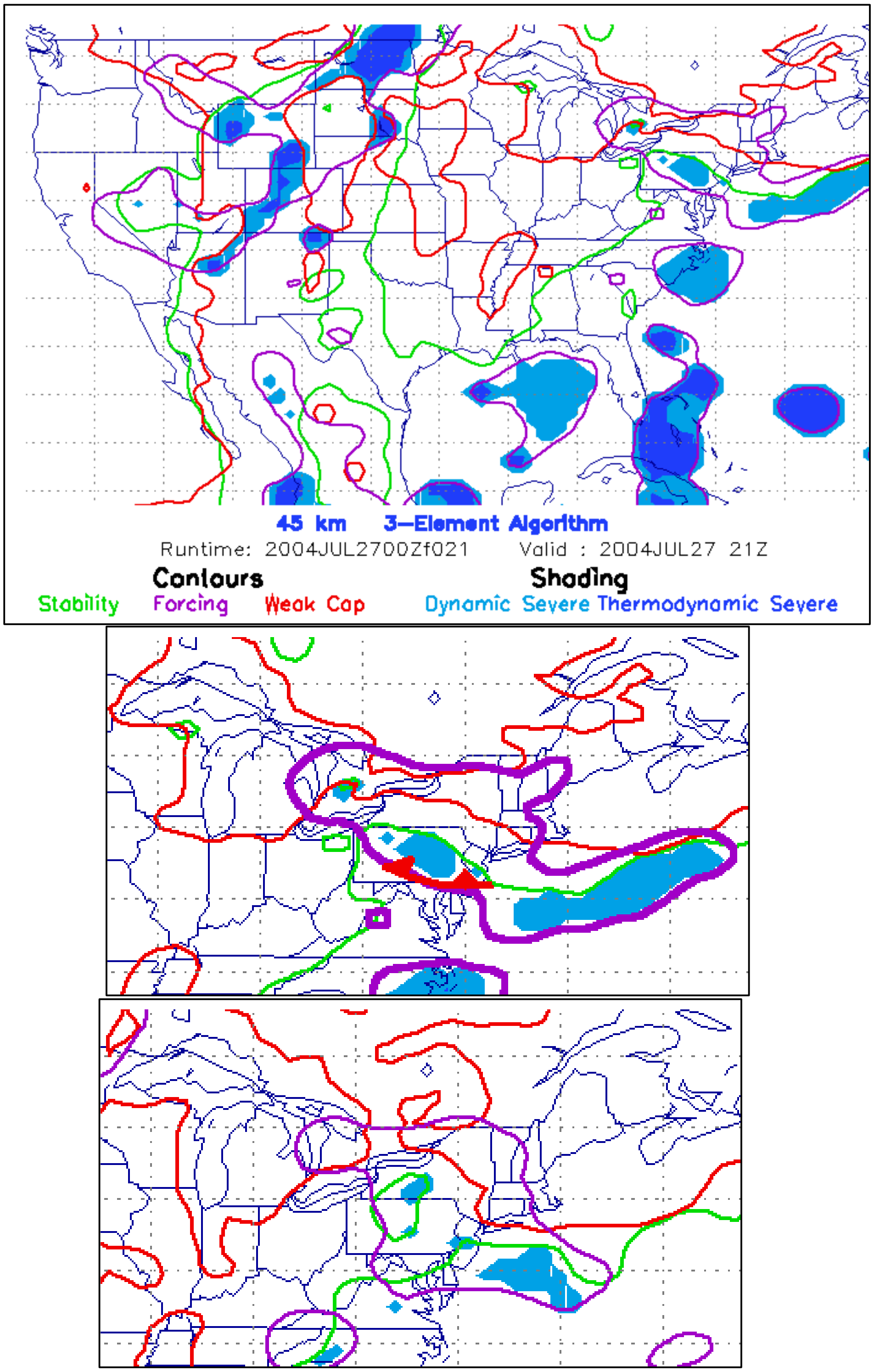

Fig. 2. (continued)