P7.1 A COMPARATIVE VERIFICATION OF TWO “CAP” INDICES IN FORECASTING THUNDERSTORMS

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1. INTRODUCTION

The forecasting of non-severe and severe thunderstorms in the continental United States (CONUS) for military customers is the responsibility of the Air Force Weather Agency (AFWA) CONUS Severe Weather Operations (CONUS OPS), and of the Storm Prediction Center (SPC) for the civilian government. Severe weather is defined by both of these organizations as the occurrence of a tornado, hail larger than 19 mm, wind speed of 25.7 m/s, or wind damage. These agencies produce ‘outlooks’ denoting areas where non-severe and severe thunderstorms are expected. Outlooks are issued for the current day, for ‘tomorrow’ and the day following. The ‘day 1’ forecast is normally issued 3 to 5 times per day, the ‘day 2’ and ‘day 3’ forecasts less frequently.

The forecasting of severe weather has been well documented, for example by Miller (1972). The forecaster considers dozens of meteorological parameters, such as instability, moisture, boundaries, ‘triggering mechanisms’, low and upper-level jets, and many others. The individual presence of any of these parameters is generally a favorable indicator of severe weather. In general, the likelihood and intensity of thunderstorms increases as the number of parameters and their strength increases.

Forecasters lean heavily upon computer model forecasts of severe weather parameters. AFWA uses the MM5 model operationally, and outputs digital forecast data and graphics every 3 hours for 72 hours. Over the CONUS, the model is run 4 times daily. The MM5 post-processor derives many of the severe weather ‘indices’ used by forecasters.

One commonly used stability index is the Lifted Index (LI). The LI is based on a boundary layer air parcel lifted to 500 mb. The difference between the actual temperature and the parcel temperature is the Lifted Index. The Best Lifted Index (BLI) uses the ‘most-unstable’ parcel in the boundary layer (defined later).

One severe weather parameter, the ‘cap’, is instead an inhibitor of convection. The cap is a temperature inversion, which separates relatively warm temperatures above the boundary layer from the cooler boundary layer. During the day, the boundary layer generally warms, becoming more buoyant or unstable. If sufficient warming occurs, the temperature inversion weakens, perhaps disappearing entirely. Boundary layer parcels are then sufficiently buoyant to rise to the Level of Free Convection (LFC), resulting in convection and possibly thunderstorms. In many cases dynamic forcing such as low-level convergence, low-level warm advection, or positive vorticity advection provide additional force to mechanically lift boundary layer parcels through the inversion.

In the morning hours, one of the biggest challenges in severe weather forecasting is to determine not only *if*, but also *where* the cap will break later in the day. Model forecasts help determine future soundings. Based on the model data, severe storm indices can be calculated that help measure the predicted dynamic forcing, instability, and the future state of the capping inversion.

One measure of the cap is the Convective Inhibition (CIN) (Colby, 1984). CIN is an index that is physically based on parcel theory. It is a measure of the ‘negative’ buoyant energy that a low-level parcel needs to overcome in order to reach the Level of Free Convection. Currently, maps from many organizations contour CIN values at intervals of 50 J/kg, for example, the SPC’s ‘Composite Chart’ (http://www.spc.noaa.gov/compmap). Recent publications have suggested lower values are appropriate. Ziegler et al. (1997) shows convection near the dryline occurs with CIN values “near zero” based on modeled soundings. The AFWA CONUS OPS severe weather checklist, revised in 1999, states that low, moderate, and high values of CIN are <13, 13 to 43, and >43 J/kg, respectively.

The AFWA MM5 uses the most-unstable parcel in calculating CIN and BLI. The most-unstable parcel is the model level in the lowest 150 mb that has the highest wet-bulb potential temperature.

Another measure of the capping inversion is the Lid Strength Index (LSI) (Graziano and Carlson, 1987). The LSI also is based on parcel theory, but its measure of the cap is somewhat arbitrary.

The AFWA MM5 LSI closely follows the specifications of Graziano and Carlson (1987). The LSI is the difference (ºC) of two wet-bulb potential temperatures. The first temperature is that of the most-unstable parcel lifted to the Lifted Condensation Level (LCL). This temperature represents the ‘parcel’ temperature. The second temperature is the sounding’s highest wet-bulb potential temperature excluding the lowest 10% of the atmosphere, where 10% is in millibars. This represents the ‘capping’ temperature. The capping temperature minus the parcel temperature is the Lid Strength Index.

In this paper, the generic wording ‘cap indices’ will be used to refer to CIN and LSI.

One problem in using CIN to forecast thunderstorms is that it often implies that much of the

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continental United States (CONUS) is uncapped on summer afternoons. Figure 1 is an example from the AFWA MM5 model. The Eta model also indicated an equally large portion of the country with low CIN values (between 0 and –10 J/kg, not shown). According to this example, the atmosphere is free to auto-convect, if one assumes that the vast areas with values of CIN smaller than -50 J/kg are uncapped. In fact, the contours indicate there are large areas smaller than -10 J/kg.

The motivation for this work was to help in forecasting *severe weather*. In this work, lightning data was collected and used as the validation of ‘convection’. Post-processor values of LSI and CIN from the AFWA MM5 were used as predictors of lightning strikes. Since *lightning* was used as the verification, it is technically more correct to say that this work assists in describing the initiation of *convection,* rather than severe weather. Since the initiation of convection is an integral part of severe weather forecasting, this work should be of practical use in severe weather forecasting.

The goal of this work was to quantitatively compare the skill of two cap indices, CIN and LSI, that are produced by the AFWA MM5 model.

2. DATA

The following data were collected for the CONUS at similar times: lightning strikes, and AFWA MM5 model output parameters: LSI, CIN, and the Best Lifted Index (BLI). Lightning strikes and MM5 model CIN, LSI, and BLI were collected from February through August 2001. Forecasts were collected for both ‘day 1’ and ‘day 2’ forecasts.

Lightning strikes were collected from the National Lightning Detection Network files at AFWA. A description of this data is found in Cummins et al. (1998). Individual strikes were collected and placed into MM5 grid point bins. One hour of lightning strikes were put into each bin; for example, strikes from 20:31 through 21:29 were put into the hour ’21 UTC’. For this study, 1 or more lightning strikes in a grid point bin was defined as convection.

3. EXPERIMENTS AND METHODOLOGY

AFWA MM5 model LSI and CIN were used as forecasts of convection. In this paper, convection is defined by lightning strikes. Model grid values of LSI and CIN were compared to equivalent grids of lightning strikes, and skill scores were calculated.

Calculations of the cap are meaningless unless there is instability. If there is no instability, there will be no convection. Therefore, forecasts of convection were made only where BLI values were +3 degrees or less. Visual examination of large numbers of maps indicated that +3 BLI is a very appropriate threshold value for lightning.

The MM5 domain is much larger than the area of detectable lightning strikes. To avoid forecasting over large expanses of oceans, where verifying lightning strikes were not available, all datasets were limited to MM5 grid points that lie within the CONUS boundaries.

Forecasts of convection using the model output cap indices were evaluated with the Critical Success Index (CSI) (also known as the Threat Score) (Wilks, 1995).

As a check on the CSI score, the correlation coefficients were calculated for LSI vs. lightning, and CIN vs. lightning. It should be noted that these coefficients measure only the linear relationship between these indices and convection. The relationship between these indices and convection may be highly non-linear. It is nevertheless informative to calculate the correlation coefficient, as it is a well-understood metric.

In order to compare the skill of CIN and LSI, it was necessary to find the threshold value for each that optimized the CSI score. Therefore many threshold values of CIN and LSI were tested with a computer program. A forecast of ‘convection’ was made wherever the cap index was forecast to be less than the threshold value, and the BLI forecast to be less than +3 degrees. The highest CSI score was selected, and the threshold value noted.

Thresholds for the cap indices were determined as follows: given a trial threshold value of the cap index, the hits, misses, and false alarms were tallied for all forecasts. The CSI score was then calculated. The trial threshold giving the highest CSI score was noted. That cap index threshold value is the threshold that should be used in forecasting. This is based on the assumption that the best forecast of convection is that which maximizes the CSI score.

Since the AFWA MM5 is run 4 times daily, there are many scores that can be calculated. CSI scores can be calculated for forecast projections from 0 to 72 hours for every 3 hours. CSI scores can also be calculated for each of the 4 daily AFWA MM5 model runs. Scores can also be stratified into months, which allows seasonal trends to be seen.

To assist in forecasting ‘day 1’ convection, CSI scores were calculated using the 9 hour forecast of the 12 UTC run of the AFWA MM5 valid at 21 UTC. To check the dependence of the skill scores on the model projection, forecasts of 3 hours and 27 hours were compared. Use of the 3-hour projection negates the dependence of skill scores on model timing and model accuracy, which may be a problem in 27-hour forecasts.

4. RESULTS

Table 1 shows scores relevant to forecasting ‘day 1’ convection. In the month of June, LSI was 50% better than CIN, with CSI scores of 16.7 to 11.7. In July and August, LSI is only slightly better than CIN. It is therefore one of the important suggestions of this work that LSI be used in addition to CIN to forecast the location of afternoon convection during the warm season.

Scores for 3 and 27-hour forecasts were compared to see if model run time had an effect on the relative skill of the indices. The 27-hour forecast naturally had less skill. Apart from that difference, tables similar to Table 1 showed little difference in the relative performance of LSI versus CIN in forecasting convection.

Table 1 also reveals that very few generalizations can be made about cap indices and convection. Table 1b shows the 9-hour forecast for the 00 UTC run of the AFWA MM5. The relative skill of the indices changes, with CIN generally the better index for convection valid at 09 UTC. As the season varies, the skill of both LSI and CIN change, and so do the optimal threshold values. One cannot therefore say that either LSI or CIN is the better index without taking these seasonal and diurnal factors into account.

Many combinations of model run time, forecast projection time, valid time, and month were considered. The author can provide the full set of tables.

The correlation coefficients between the cap indices and convection are shown in Table 2. The correlations provided an alternate statistical measure to the CSI score. It is seen that in general, CIN has a higher correlation to convection than LSI.

5. DISCUSSION

One surprising result of this work is the discovery that extremely small threshold values of CIN are skillful in the cold season. It is important to note that this conclusion is based upon the AFWA MM5, and its post-processor definition of CIN. In the month of February, threshold values of CIN very near zero showed surprising skill (not shown). Traditionally, CIN values of -50 or -100 J/kg have been considered as thresholds, where values larger (less than) –100 indicate a ‘strong’ capping inversion. For LSI, the optimal threshold was 1.0, smaller than the value of 2.0 typically used in the warm season.

It is acknowledged that CIN values smaller than 1 J/kg are extremely small. Looking at a sounding, a forecaster cannot distinguish 1 J/kg from 0 or 2 J/kg. The value of 1 J/kg is less than the accuracy measurable by rawinsondes.

Nevertheless, in the winter months, areas of CIN smaller than -1 J/kg are displayable from AFWA MM5 model output. Contours outlining the areas of 0.1 J/kg CIN are readily distinguishable from contours of 0.2 J/kg CIN. This, and the fact that the 0.1 J/kg areas yield better CSI scores, means that the 0.1 J/kg value of CIN contains information that helps forecast convection.

The cause and physical meaning of these very low values of CIN is uncertain at this time. In the winter, values of Convective Available Potential Energy (CAPE) are extremely low, implying that values of CIN would be low. Map contours of both fields showed that this is not the case. While values of both CAPE and CIN are low, it is not the case that CIN is being ‘limited’ by low CAPE values. One might expect that the model’s sub-grid scale convective parameterization is the cause of these extremely low values of CIN. However, contours of both of these fields show that convection and near-zero areas of CIN are not identical. Neither parameter is the cause of the other. Examination of model soundings in low-CIN areas tended to be moist adiabatic. This suggests a physical reason as to why model CIN values might tend to cluster near zero.

MM5 Model soundings were examined in locations where the LSI and CIN differed greatly. LSI and CIN often differ in the relatively dry air in the Southwestern CONUS. In many cases there is a deep, nearly adiabatic layer, extending from the surface to as high as 600 mb (see Figure 2). The dew point line in this sounding indicates a mostly dry atmosphere. Since the sounding is nearly dry-adiabatic, the CIN is quite low, suggesting convection. In contrast, the LSI is high, i.e., capped.

In these deep layer dry-adiabatic cases, the LCL occurs at a very high level, perhaps 200 or 300 mb above the surface. The LSI’s ‘cap’ level, at 10% of the atmosphere above the ground, therefore has a wet-bulb temperature that is much higher than the LCL wet-bulb temperature. Bothwell (2002) pointed out that the capping temperature of the AFWA formulation is often found at a level that is below the LCL. A drawback of this formulation is that it lacks physical meaning. Bothwell also hypothesized that thunderstorms in dry-adiabatic environments do not necessarily initiate from surface or boundary layer parcels. Where adiabatic lapse rates occur in a deep layer, the AFWA formulation of LSI correctly categorizes this kind of sounding as capped, while CIN is near zero and uncapped.

Much more work needs to be done to understand the LSI and CIN indices. Analysis of the differences should lead to an understanding of the ‘parcel’ that is actually lifted: surface, lowest 50 or 100 mb, most unstable, etc. When cap indices are different, why is one better than the other? Many forecasters believe that low CIN values by themselves are not enough to initiate convection. Why not? What does this imply about real-world thunderstorm initiation?

6. SUMMARY AND RECOMMENDATIONS

Two measures of the ‘cap’ were compared for use in forecasting convection: the Lid Strength Index and Convective Inhibition

From the findings of this study it is recommended that:

- CIN values of -1, -10, -25, and -50 J/kg should be contoured on model output charts, rather than -50 and -100.
- Use LSI, rather than CIN, as guidance in forecasting the breaking of the cap in the afternoon hours of the warm season.
- The skill of LSI and CIN varies with season and time of day. Tables similar to Table 1 should be studied by thunderstorm forecasters for appropriate combinations of season and time of day.
- Low wintertime values of CIN should be studied in other models, such as the Eta model.

- Cases of low AFWA MM5 model CIN should be examined in more detail.
- The differences between LSI and CIN should be studied. One promising area would be to understand how low or high LCL heights affect the use and skill of LSI and CIN.

7. Acknowledgements

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8. References

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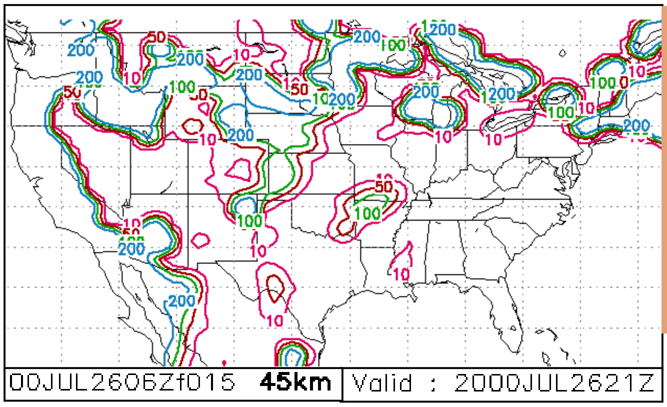

Figure 1. CIN from MM5 forecast valid at 21 UTC, showing much of the CONUS 'uncapped' with CIN < 50 J/Kg.

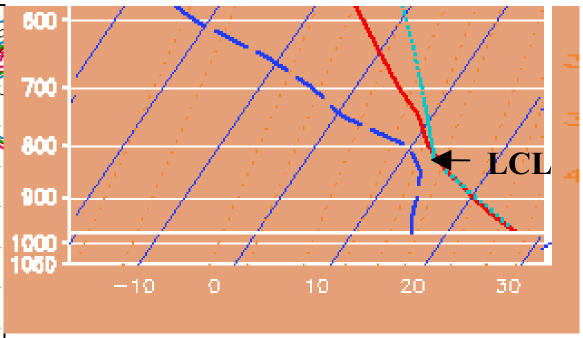

Figure 2. Example of high LCL with nearly dry adiabatic lower atmosphere. T, Td and a lifted surface parcel are shown. CIN is near zero (uncapped), while LSI=2.3 (more capped).

12Z RUN, PROJECTION=9 hrs (valid 21Z)							
	Feb-01	**Mar-01**	(not avail)	**May-01**	**Jun-01**	**Jul-01**	**Aug-01**
LSI: CSI*100	2.3 (1.0)	5.2 (1.0)		12.4 (2.0)	16.7 (2.0)	14.0 (1.5)	16.3 (2.0)
CIN: CSI*100	4.0 (-.1)	5.8 (-200)		8.5 (-50)	11.7 (-50)	13.4 (-50)	14.5 (-20)
00Z RUN, PROJECTION=9 hrs (valid 09Z)							
LSI: CSI*100	1.5	3.0		6.4	6.1	5.4	4.2
CIN: CSI*100	2.4	5.5		7.7	5.7	5.8	5.2

Table 1. a) CSI scores for LSI and CIN by month, from AFWA MM5 model run at 12UTC, 9 hour forecast valid 21UTC. Optimal threshold values of the cap indices are in parentheses. b). Same, except from 00UTC model run, valid 09UTC.

Correlation with convection	**Feb**	**Mar**		**May**	**Jun**	**Jul**	**Aug**
LSI	+.019	-.057		-.108	-.092	-.052	-.076
CIN	+.086	+.127		+.125	+.116	+.107	+.131

Table 2. Correlation of LSI and CIN with lightning strikes for various months. All MM5 runs (00, 06, 12, 18UTC).