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AN INVESTIGATION OF ISENTROPIC VERTICAL MOTION FIELDS AND THEIR RELATIONSHIP TO OBSERVED PRECIPITATION PATTERNS OVER THE SOUTHEAST UNITED STATES DURING THE WINTER OF 1993-1994

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1. Introduction

The precise prediction of vertical motion in space and time is the holy grail of all operational meteorologists. In concert with reliable moisture prognoses, accurate forecasts of atmospheric ascent usually provide good indications of where precipitation - the sensible weather element people care about the most - is going to occur at some future time.

Vertical motion on the synoptic scale can be deduced in a number of ways. One simple option is to *blindly accept* the forecasts of vertical motion which are generated directly from the numerical models' primitive equations. Fortunately, most conscientious meteorologists eschew this method, and instead *critically assess* the model output using the principles of modern meteorological analysis.

The most common approach is to analyze the models' fields in a quasi-geostrophic (QG) framework, diagnosing regions of differential vorticity and thermal advection (or preferably, Q-vector divergence) to infer areas of synoptic-scale ascent/descent. Since the 1970s, this has been the traditional method of analyzing vertical motion, and is very widely accepted (Dunn, 1992). However, another technique, *isentropic analysis*, is enjoying increasing popularity in the operational community. Originally the de-facto coordinate system for assessing meteorological data prior to World War II, isentropic analysis languished in the shadows of its isobaric counterpart for decades before being re-discovered in the late 1980s. This revival was fostered by the advent of powerful desktop computers and gridded display systems such as **P**ersonal **C**omputer-based **G**ridded **I**nteractive **D**isplay and **D**iagnostic **S**ystem (PCGRIDDS), which together have greatly facilitated the creation and presentation of isentropic datasets.

This paper summarizes a 1995 study conducted at WSFO Birmingham, in which model-derived isentropic vertical motion fields were compared with observed precipitation patterns over the south-central and southeast United States during the winter months of 1993-1994. Specifically, for a large number of events, the locations and magnitudes of model forecast *ground-relative* (GR) and *system-relative* (SR) isentropic vertical motion features were identified at multiple levels of the lower and middle troposphere. The accuracy of these fields was subjectively appraised through a comparison with observed radar summary charts valid at the forecast time. The primary goal of this investigation was to evaluate the claim, first advanced by Saucier (1955), that *system-relative* isentropic lift better emulates true vertical motion than does its ground-relative counterpart. A secondary goal was to determine, if possible, the optimal levels for assessing isentropic vertical motion fields. Through case study analysis, other investigators (*e.g.*, Gerard (1992); Baumgardt (1993)) have addressed the potential role of GR and/or SR isentropic lift in the development and enhancement of synoptic-scale precipitation areas. However, this study is believed to be unique in its direct comparison of GR and SR fields for a large sample of precipitation regimes.

2. Methodology

Isentropic analysis, as most forecasters know, is the evaluation of meteorological variables on surfaces of equal potential temperature (θ), known as *isentropes*. Assessing data in this reference frame is attractive, since in the absence of diabatic effects an unsaturated air parcel will follow an individual isentrope more faithfully than a constant pressure surface. A wide array of fields can be analyzed in isentropic coordinates, and a comprehensive discussion of the advantages or pitfalls of these techniques is well beyond the scope of this paper. The cause of isentropic analysis has been passionately and eloquently promoted by Dr. James Moore of St. Louis University, and the reader is referred to any of his articles (*e.g.*, Moore, 1986; Moore, 1992) for a thorough treatment of the subject. The following section briefly summarizes the technique for determining *adiabatic vertical motion* along isentropes.

a. fundamentals of isentropic vertical motion

As noted by Moore (1986; 1992), vertical motion in isentropic coordinates can be expressed as follows:

$$\omega = \underbrace{\left[\frac{\partial P}{\partial t}\right]_\theta}_{\mathbf{A}} + \underbrace{\vec{V}\cdot\vec{\nabla}_\theta P}_{\mathbf{B}} + \underbrace{\frac{\partial P}{\partial \theta}\frac{d\theta}{dt}}_{\mathbf{C}} \qquad (1)$$

where term **A** represents the local pressure tendency, term **B** is the advection of pressure by the wind along an isentropic surface, and term **C** is the contribution of diabatic heating or cooling.

In practical terms, the local pressure tendency (term **A**) reflects the degree to which an isentropic surface will move up or down with time. This quantity, a time-derivative, is difficult to measure operationally (although the recent availability of gridded data at 3-hr and 6-hr time steps is alleviating this problem), but is usually smaller and of opposite sign to the pressure advection term (**B**), particularly in regions of strong wind. Diabatic heating or cooling (term **C**) likewise is usually small compared with term **B**, and can be neglected for non-saturated, synoptic-scale flow. Moreover, terms **A** and **C** are always of opposite sign, and therefore act to cancel each other, at least partially (Hohman and Uccellini, 1987). However, as noted by Moore (1986), diabatic heating can become tremendously important in the presence of saturated ascent, particularly during episodes of convection. Latent heat release (diabatic heating) forces a parcel away from adiabatic, or along-isentrope motion, and sends it on a trajectory *across* potential temperature surfaces, thereby invalidating the fundamental assumptions of isentropic analysis. For this reason, forecasters need to be extremely wary when evaluating (or at least over-emphasizing) isentropic vertical motion fields in the presence of saturated or convective ascent. Unfortunately, these are the very regimes under which the accurate prognosis of vertical motion is most critical.

If we neglect terms **A** and **C**, then unsaturated, adiabatic vertical motion ($\omega_{adiabatic}$) can be described solely in terms of the advection of pressure by wind along an isentrope, as follows:

$$\omega_{adiabatic} \approx \vec{V} \cdot \vec{\nabla}_{\theta} P \qquad (2)$$

This relationship forms the basis for the simple technique most operational meteorologists use to evaluate isentropic vertical motion: wind barbs and isobars are overlaid on an isentropic surface, and rising (sinking) motion is inferred in those regions where wind is blowing from higher (lower) to lower (higher) values of pressure.

However, as discussed by Saucier (1955), and more recently by Moore (1992), it is the *system-relative* component of the wind, not the total wind vector itself, that is most relevant when evaluating adiabatic vertical motion. It must be remembered that while individual air parcels are traveling along isentropes, the θ "sheets" themselves are moving horizontally (and to some extent, vertically) with respect to the ground. Just as a thunderstorm's motion can significantly affect a storm-relative helicity calculation, an isentropic surface's horizontal movement <u>can in many instances</u> impact a true estimate of $\omega_{adiabatic}$. Therefore, determining the motion vector of the θ surface should be considered an essential part of the process of estimating isentropic vertical motion .

As noted by Moore (1992), if **C** is defined as the horizontal system motion of the isentropic surface, then (2) can be expressed as:

$$\omega_{adiabatic} \approx (\vec{V} - \vec{C}) \cdot \vec{\nabla}_{\theta} P \qquad (3)$$

where **V** - **C** is the component of the total wind vector blowing across isobars as the θ surface itself moves through space. Unfortunately, the determination of **C** can be problematic, depending on the synoptic regime. One methodology, suggested by Moore (1992) and adopted in this study, is to track the movement of upper level troughs or vorticity features for several hours through the time period of the isentropic analysis. This procedure, discussed in greater detail in the next section, is a useful indicator of θ-surface motion, and is often employed by forecasters at WSFO Birmingham.

b. study methodology

1) Overview and description of data

In the southern portion of the United States, isentropic analysis is most applicable during the cool months of the year, when pressure advection patterns are usually strongest, and widespread convection is less frequent. This investigation focused on precipitation events that occurred in the south central and southeast U.S. from 1 November, 1993 through 31 March, 1994. National composite radar summary charts, valid at 0000 UTC, were examined for each day during this five month period. From these charts, 36 separate precipitation events from throughout the study domain were chosen for investigation. The locations of these events are displayed in Fig. 1. The average spatial scale of these precipitation areas was about 65,000 km^2, although it must be remembered that radar summary charts tend to exaggerate the true areal extent of precipitation patterns.

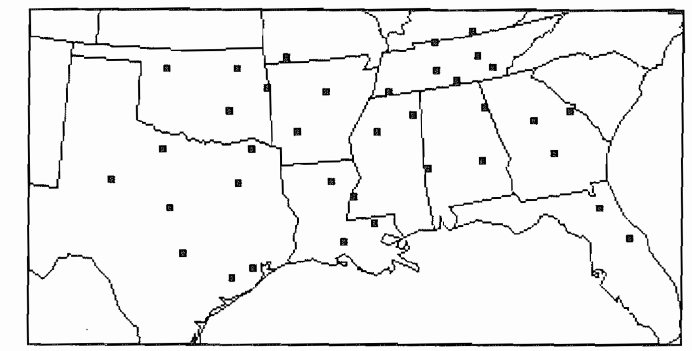

FIG. 1. Locations of precipitation events used in study. Boxes denote the centroids of precipitation areas.

The location and areal coverage of each of the precipitation events was compared with 24-hr forecasts of isentropic vertical motion derived from Nested Grid Model (NGM) gridded data. These fields were created using the December 1993 version of PCGRIDDS, employing the techniques described in the following section. For each case, the GR and SR $\omega_{adiabatic}$ fields were qualitatively compared with the precipitation areas, using a rating scale from 1 (poor) to 5 (excellent). The vertical motion fields were judged on their ability to capture the geographic location, areal coverage, and intensity of the precipitation regions. As a rule, a high degree of spatial agreement, coupled with a strong correspondence between the magnitude of the vertical motion and the degree of coverage or intensity usually merited a 4 or 5 in the evaluation. Conversely, those isentropic fields which agreed poorly in location and magnitude with the precipitation areas were typically awarded a score of either 1 or 2. For consistency, only one of the authors (KWB) performed all of the evaluations.

2) Creation of isentropic vertical motion fields in the PCGRIDDS system

One of the major advantages of PCGRIDDS (particularly the 1993 version utilized in this study) is its ability to easily generate and display isentropic data sets. This capability has led to a recent surge in the use of these fields by many National Weather Service forecasters. However, the *full* benefits of assessing vertical motion from the isentropic perspective can be achieved only if the analyst is willing to invest the extra time and effort required to ensure the proper selection of levels and system motions. This investigation employed the following four-step process to create the pertinent GR and SR isentropic vertical motion fields:

1) Choose a range of isentropic surfaces appropriate for the weather regime of interest
2) Generate the isentropic surfaces
3) Determine the proper system motion
4) Execute a special macro which will depict GR and SR $\omega_{adiabatic}$ fields over the area of interest

The initial step of selecting the proper isentropic surfaces is crucial to the ultimate success of the analysis. If the θ surfaces are too low, they may intersect the ground or lower boundary layer, where convection and diabatic effects can render an isentropic analysis suspect. On the other hand, layers that are chosen too high may fail to capture critical low-level moisture features, or may not provide an adequate representation of the vertical motion that is being forced by lower level processes. One goal of this study was to determine the optimal regions of the atmosphere for assessing isentropic vertical motion. To accomplish this, θ surfaces were selected and examined from each of the following layers: 1000-850 mb, 850-700 mb, and 700-500 mb. A cross-section of θ was taken through the center of each precipitation area at the 24-hr forecast time in order to identify the proper range of isentropes occurring within each layer. From these ranges, three individual θ surfaces were selected for each precipitation event, and their isentropic datasets were generated using the PCGRIDDS (version 12/93) "MTHT" command (**Note:** The process of creating isentropic surfaces has changed significantly in the 1996 version of PCGRIDDS. For information on how to create these datasets with this new PCGRIDDS version, please refer to the PCGRIDDS 96 documentation that accompanied your software package).

The determination of system motion (Step 3 above) is a difficult but important element in the process of evaluating isentropic vertical motion. A technique described by Moore (1992) was employed to obtain an estimate of the horizontal motion of the isentropic surfaces for each event. Following this methodology, 500 mb and 700 mb height and vorticity fields were examined at the 12 and 24-hr forecast time steps; by tracking those vorticity or height features that possessed temporal continuity through the twelve hour period, a qualitative estimate of system motion could be deduced. The efficacy of this procedure is highly dependent on the synoptic-scale pattern. As might be expected, accurate motion vectors are more difficult to obtain in weak flow regimes, because vorticity features are harder to track through time. However, a reliable estimate of system motion can *usually* be acquired if the analyst is patient and willing to invest the time to adequately assess the temporal trends of height and vorticity fields through several levels of the atmosphere.

After determining a system motion, GR and SR $\omega_{adiabatic}$ fields were generated for each of the 36 cases using a DOS "variable input macro creation" program similar to those described by Bradshaw and Westland (1995). This executable PASCAL program, which is accessed from within PCGRIDDS via the "DOS" command, accepts a system motion entered by the user, then creates a PCGRIDDS macro which will display both SR and GR isentropic vertical motion via equations (2) and (3). Examples of this program's user interface are shown in Figs. 2 and 3. It should be noted that the SR $\omega_{adiabatic}$ fields created by this program are valid only for the immediate area of interest. The accuracy of these estimates likely suffers as one moves into other regions of the country where system motions are different from that used to generate the SR field.

This program accepts a user-defined storm (or system) motion, then creates a macro to display storm-relative isentropic vertical motion.

To execute this program, you can either enter a storm motion vector in
degrees/knots, or input the beginning and ending lat/lon points of a
storm feature over a 12 hour period...

Enter:

(1) to enter a storm motion in degrees/knots
(2) to enter beginning/ending lat/lon
(3) to exit

Welllll...what is it gonna be? 2

?

A macro named "SRVV" has been created which will display storm-relative vertical motion on an isentropic surface. In addition, isobars and ground relative winds will also be plotted.

To execute this macro, simply type "SRVV." at the command line.
However, before you run this macro, make sure you have created
and set your isentropic surface.

FIG. 2. User interface of "MAKIVV.EXE" program, which creates a PCGRIDDS macro called "SRVV.CMD" to plot SR and GR isentropic vertical motion fields according to user-specified system motions.

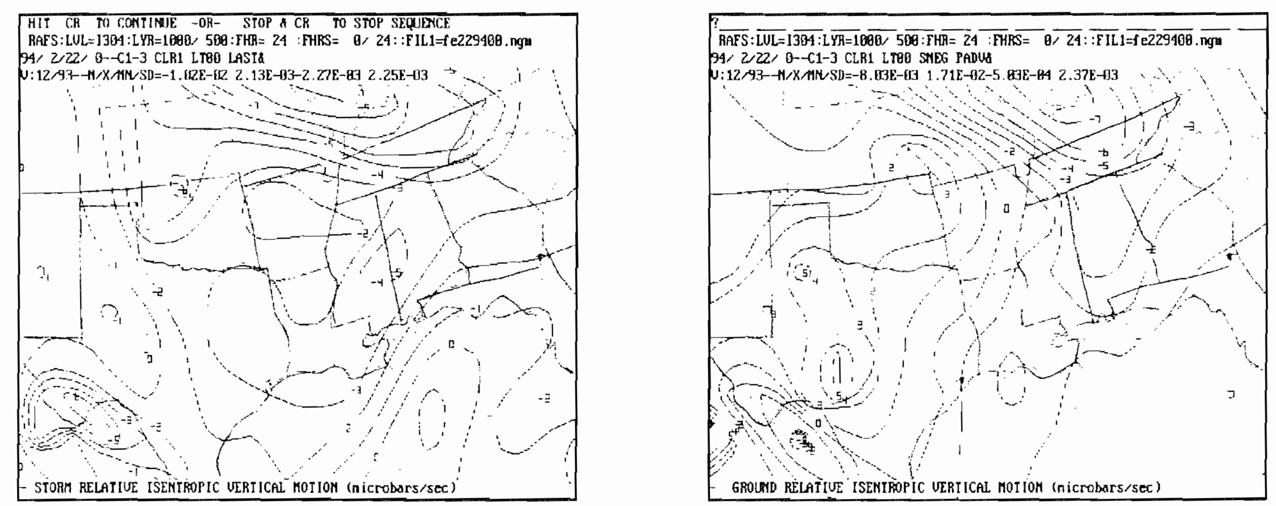

FIG. 3. Example of GR and SR isentropic fields created using the PCGRIDDS macro "SRVV.CMD".

3. Results

a. relative accuracy of GR and SR fields

One way to gauge the relative abilities of the GR and SR isentropic fields is to perform a side-by-side comparison of "best scores" for both types of vertical motion. Recall that three separate isentropic levels were analyzed and scored for each of the 36 cases. The best score for each event is defined as the highest score achieved among the three levels evaluated.

Figure 4 depicts a histogram of best scores for both the GR and SR vertical motion fields. A pronounced skewness toward the lower (poorer) end of the scoring range is apparent in the GR results. The majority of GR scores (61%) lie near the center of the scale, in the scoring categories 2, 3, or 4. However, a significant percentage of cases (39%) fall in the poor (score=1) category, while only one case merits an excellent rating (score=5). By comparison, the system-relative fields performed well. As shown in Fig. 4, 61% of the SR cases were categorized as very good or excellent (score= 4, 5) in their ability to predict the precipitation regions, compared with only 19% of the GR fields. At the other end of the spectrum, the SR fields garnered poor or relatively poor (score=1,2) ratings only 28% of the time; GR quantities were more than twice as likely to fall into one of these two categories. These findings illustrate the decisive advantage SR vertical motion fields have over their GR counterparts in the accurate depiction of future precipitation.

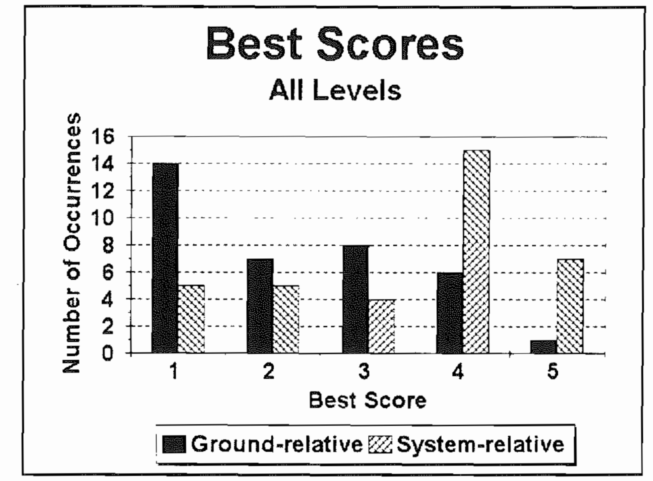

FIG. 4. Frequency distribution of GR (solid) and SR (cross-hatched) best scores for all levels.

b. simultaneous comparison of ground-relative and system-relative fields

A second method of assessing the relative utility of GR and SR vertical motion is to evaluate the performance of both fields "head to head" during each precipitation event. Table 1 displays a two-dimensional frequency distribution of best scores for both vertical motion types. Each box within the table represents a unique combination of GR and SR best scores (*e.g.*, GR=3 and SR=4); the values in each box indicate the number of events in which that combination occurred. The superiority of the SR fields is again readily apparent. A clear majority of cases (25 of 36) lie in the upper left half of the diagram, representing instances in which the SR fields were rated at least one point better than the GR quantities. Indeed, in nearly half the cases (16 of 36), the SR fields were judged *two or more* points better than the GR fields in their ability to capture the precipitation areas.

TABLE 1. Two-dimensional frequency distribution of best scores among all levels for each of the 36 events. Each box in table represents total number of times that a given SR and GR score combination occurred. Boxes lying in upper left half of diagram represent total occurrences in which SR outperformed GR; those in lower right half of diagram represent events in which GR outperformed SR. Shaded boxes represent tie events.

	GR Score=1	GR Score=2	GR Score=3	GR Score=4	GR Score=5
SR Score=5	**3**	**1**	**2**	**1**	**0**
SR Score=4	**5**	**3**	**4**	**2**	**1**
SR Score=3	**2**	**1**	**0**	**1**	**0**
SR Score=2	**3**	**1**	**1**	**0**	**0**
SR Score=1	**1**	**1**	**1**	**2**	**0**

Ground and system-relative $\omega_{adiabatic}$ accuracy can also be assessed within each of the three layers. Tables 2, 3 and 4 depict two-dimensional frequency tables for the 1000-850 mb, 850-700 mb, and 700-500 mb layers, respectively. The value in each box represents the frequency with which a GR/SR score combination occurred at each level. Consistent with the "best score" results shown in Table 1, the SR vertical motion fields decisively outperformed their GR counterparts in each layer. The SR fields in the 1000-850 mb layer were rated as good or better than the GR fields in 84% of the cases; comparable results were observed in the other two layers. Conversely, there were very few instances within any layer where the GR $\omega_{adiabatic}$ estimates did a *better* job of capturing the precipitation areas than did the SR fields. Taken together with the results presented in section 3*a*, the findings here underscore the importance of evaluating isentropic vertical motion *in a system-relative sense*, and should give pause to those forecasters fond of simply overlaying isobars and wind barbs at isentropic levels, without regard for the motion of the θ surface itself.

c. optimal isentropic levels for the diagnosis of vertical motion

One problem that forecasters often face is the decision of which isentropic levels to evaluate. It has been suggested that the ideal levels are those located 50 to 100 mb above the boundary layer, since this represents a region where low-level moisture transport can be optimally diagnosed. While the extreme lower troposphere (below 850 mb) may be an ideal choice for evaluating moisture, there is some question as to whether vertical motion in this region is well correlated with precipitation, as opposed to lift occurring at higher levels (*e.g.*, between 850 and 500 mb). This study tried to resolve this uncertainty by comparing isentropic vertical motion fields throughout the depth of the lower and middle troposphere.

TABLE 2. Same as TABLE 1, except for 1000-850 mb layer only.

	GR Score=1	GR Score=2	GR Score=3	GR Score=4	GR Score=5
SR Score=5	3	1	1	0	0
SR Score=4	4	2	1	2	0
SR Score=3	2	2	1	2	0
SR Score=2	3	1	1	0	0
SR Score=1	4	1	0	1	0

TABLE 3. Same as TABLE 1, except for 850-700 mb layer only.

	GR Score=1	GR Score=2	GR Score=3	GR Score=4	GR Score=5
SR Score=5	1	0	0	1	0
SR Score=4	4	2	3	0	0
SR Score=3	6	1	1	1	1
SR Score=2	4	1	1	1	0
SR Score=1	2	3	2	1	0

TABLE 4. Same as TABLE 1 except for 700-500 mb layer only.

	GR Score=1	GR Score=2	GR Score=3	GR Score=4	GR Score=5
SR Score=5	1	0	0	0	0
SR Score=4	6	2	2	0	0
SR Score=3	2	1	2	0	0
SR Score=2	7	1	2	0	0
SR Score=1	5	4	1	0	0

Frequency distributions of SR scores at each layer are displayed in Fig. 5. While the results are not clear-cut, there does appear to be a decline in the correlation between the vertical motion fields and precipitation areas as one ascends through the atmosphere. At the lowest layer (1000-850 mb), a majority of the cases (21 of 36) were rated as average to excellent (score=3,4,5). Twenty-one cases were also awarded comparable ratings within the next layer (850-700 mb). On the other hand, nearly half the cases within this layer were judged as poor or relatively poor (score=1,2). The reliability of the SR $\omega_{adiabatic}$ fields diminishes further still at the highest layer (700-500 mb). Here, over half of the cases (20 of 36) were evaluated as sub-par, almost twice as many as those recorded for the 1000-850 mb layer.

These results appear to demonstrate the importance of considering low-level vertical motion when forecasting the development of wintertime precipitation. However, prudence suggests that the interrogation of the data not end at this point. In only a small number of cases (7 of 36) did a very good or excellent score occur *only* in the lowest layer. To the contrary, for the majority of the events where overall best scores of 4 or 5 occurred, the high scores were observed at two or three of the layers simultaneously. This finding demonstrates the importance of examining isentropic vertical motion (or quasi-geostrophic vertical motion for that matter) at several levels of the atmosphere when preparing a forecast.

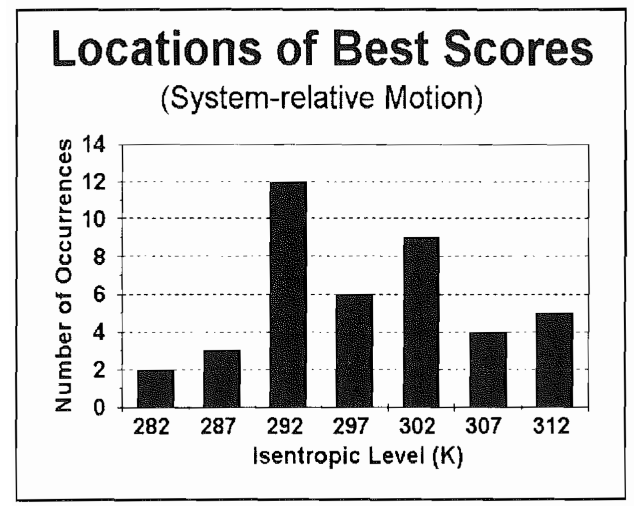

FIG. 6. Frequency distribution of SR best scores by isentropic level. Each bin on the horizontal axis represents the sum of occurrences in a 5K range centered at the labeled level.

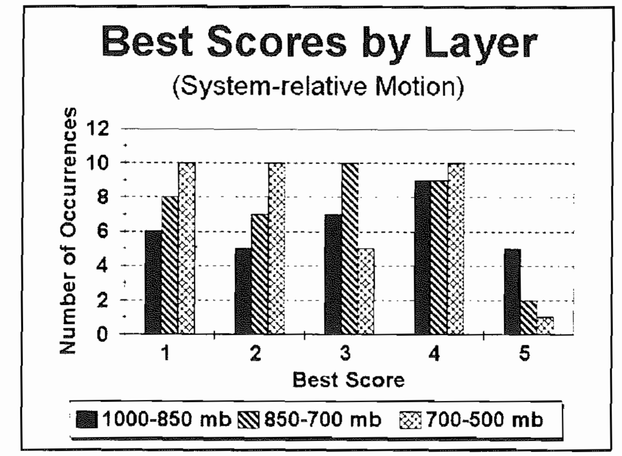

Fig. 5. Frequency distribution of SR best scores for the 1000-850 mb layer (solid), 850-700 mb layer (hatched), and 700-500 mb layer (cross-hatched).

To gain further insight regarding the choice of isentropic levels, a distribution of best scores vs. individual isentropic levels is shown in Fig. 6. The bulk of the best scores fall within the range between 290 K and 304 K; in most cases, these isentropic surfaces are located below 700 mb. These results are similar to those presented in Fig. 5, which suggest that the best layers for diagnosing vertical motion are those in the lowest 200-300 mb of the atmosphere. Based on these findings, it may be tempting to establish this range of levels as a "default set" for use throughout the winter months. However, it should be remembered that these cases were distributed throughout the southern United States, and occurred during a wide variety of weather regimes. Obviously, forecasters should select their isentropic surfaces on a case by case basis, following a careful consideration of the meteorological situation at hand.

5. Summary and Conclusions

This study examined isentropic vertical motion patterns during 36 precipitation events which occurred across the southern United States during the winter of 1993-1994. For each event, ground and system-relative isentropic vertical velocity fields were subjectively ranked from 1 to 5 for their ability to capture the essence of the precipitation areas. Isentropic surfaces were assessed within three separate layers of the lower and middle atmosphere: 1000-850 mb, 850-700 mb, and 700-500 mb. Two goals were pursued in this investigation: evaluate the relative usefulness of the GR and SR isentropic vertical motion fields (as depicted by the NGM), and determine the optimal levels for employing isentropic vertical motion. Several key conclusions can be drawn from the findings:

- In the majority of cases, the storm-relative vertical motion fields did a good to excellent job of depicting the location and magnitude of the precipitation areas, thereby confirming the utility of this parameter as a forecast tool.

- In the majority of cases, the system-relative vertical motion fields were better able to capture the location and magnitude of the precipitation areas than were the ground-relative fields. In fact, in a significant number of instances, the SR fields were substantially better. This trend was observed throughout the lower and middle troposphere.

- The system-relative vertical motion fields performed best in the two lowest layers of the atmosphere: 1000-850 mb, and 850-700 mb. The majority of these θ surfaces occurred within the range between 290 and 304 K. The accuracy of the SR fields gradually declined as one ascended into the 700-500 mb layer.

The consistent superiority of the system-relative fields over their ground-relative counterparts is the primary finding of this study. The results presented here should dispel any uncertainties that may exist regarding the relative merits of the two fields. In certain instances, system motion can be ignored without an appreciable degradation in the quality of the vertical motion estimate. At other times, however, this streamlining of terms can result in a significant misrepresentation of isentropic ω, both with regard to the location and magnitude of the ascent maxima and minima. **Clearly, any meteorologist who utilizes isentropic analysis on a regular basis is best served by examining vertical motion fields in a system-relative framework.**

Taken in isolation, the system-relative isentropic fields provided an accurate depiction of the precipitation regions in a large number of cases. This performance is encouraging, particularly when one considers that precipitation is not only a function of lift, but also of moisture, a parameter not evaluated in this study. What is not clear, however, is how the isentropic estimates would have fared against other representations of vertical motion, specifically QG diagnostics, or the model's own vertical motion fields derived from its primitive equations. With the advent of gridded model output, each of these quantities is now easily accessible to the forecasting community. However, each type of field has its own advantages and pitfalls, and with the time constraints placed on the typical line forecaster, it is imperative that he or she have a clear idea of which products are most applicable to the given meteorological situation. In this regard, additional inter-comparative studies should be undertaken to determine the relative merits of these vertical motion fields.

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