COMPOSITE MEANS AND ANOMALIES OF METEOROLOGICAL PARAMETERS FOR SUMMERTIME FLASH FLOODING IN THE NATIONAL WEATHER SERVICE EASTERN REGION

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1. Introduction

The purpose of this study was to identify weather parameters associated with summertime flash flooding in the eastern United States, and more specifically, to investigate how these parameters may be similar or different across different parts of the Eastern Region of the National Weather Service (NWS-ER). Flash flooding in the NWS-ER is a very serious forecast and warning challenge. Over the past 10 years there were 99 flash flood events, or about 10 per year on average, that resulted in at least one fatality in NWS-ER (from *Storm Data*, 1997-2006). In the same period there were 387 events, or nearly 40 per year, resulting in at least $1M damage.

Flash flooding in the eastern U.S. can be produced by a variety of weather systems, both synoptic scale and meso-scale, as noted by Lapenta, et.al. (1995). Giordano and Fritsch (1991) examined warm-season flash-flood producing storms over an eight-state "Mid-Atlantic" area, and found significant differences between the East Coast and the Ohio Valley. Other studies have examined heavy rainfall events over various parts of the eastern U.S. For example, Konrad (1997) looked at synoptic patterns associated with heavy rainfall over the southern Appalachian region and vicinity, while Harnack, et.al. (1999) examined upper-air parameters before and during heavy rainfall events over New Jersey.

Since many of those studies were published, two important new data sets have become available, namely the NCEP/NCAR global reanalysis (GR; Kalnay, et.al., 1996), and the North American Regional Reanalysis (NARR; Mesinger, et.al., 2006). These analyses greatly facilitate examination of weather parameters and patterns associated with specific phenomena or groups of related events. In particular, they allow for ready development of composite mean and anomaly charts of many different parameters at various levels throughout the atmosphere.

The goal of this study was to use NARR and GR data to produce charts showing mean conditions associated with flash flood days over different parts of the NWS-ER and corresponding charts showing the departure from long-term means (anomalies). Section 2 describes the methods and criteria used to identify days with representative flash flood events. Section 3 describes the resulting mean and anomaly charts. Section 4 discusses similarities and differences among different parts of NWS-ER, and finally section 5 suggests some further avenues of research.

2. Data and Methodology

2.1 Heavy Rain and Flash Flooding

This study is based on examination of flash flood (FF) events, whereas many previous studies have looked at cases based on heavy or intense rainfall reports. There is no universally accepted definition of a "flash flood"; however, the usual implication is that flooding occurs within six hours of the causative rainfall. It is recognized the flash flooding is not a purely meteorological event; hydrologic factors such as soil type, soil moisture and land use are very much in play. Thus the FF reports are something like a proxy for short-term heavy/intense rainfall. However, it is reasonable to believe that most warm-season flash flooding results from intense rainfall associated with deep moist convection (Doswell, et.al., 1996). Moreover, one might say that a flash flood effectively "measures" the area-wide rainfall much better than any rain gage network, and integrates the combined effects of total rainfall amount and instantaneous rainfall intensity. Finally, FF events are the direct cause for loss of life and property, and it is for these events specifically that operational NWS meteorologists must issue timely and accurate watches and warnings.

2.2 Selection of Cases

For this study, the NWS Eastern Region (NWS-ER) was divided up into four sub-regions: "New England", "Mid-Atlantic", Ohio Valley" and "South-Atlantic" (see Fig. 1.) The sub-region boundaries were based on NWS local office County Warning Areas (CWAs) and were chosen to be approximately equal in size, although they include anywhere from four CWAs ("Ohio Valley") to eight CWAs ("South-Atlantic"). The sub-region names do not quite correspond to traditional geographic regions; for example, Albany, NY (ALY) and Upton, NY (OKX) were included in the "New England" sub-region, because FF reports over the traditional New England area were relatively scarce. Orographically, the "Ohio Valley" sub-region is mainly west of the Appalachian Mountains, while the other sub-regions are mostly within or east of the mountains and closer to the Atlantic Ocean. These sub-regions correspond approximately to the regions in Lapenta, et.al. (1995), although they were looking primarily at synoptic-scale flooding.

To identify significant flash flood days for each sub-region, all flash flood (FF) reports from June through August, 1986-2006, for all 23 NWS-ER offices, were obtained from the internal NWS verification web site. These reports were entered into a spreadsheet, and sorted by day, office and sub-region. Days with at least five FF reports in any sub-region were identified. The number of reports on each of those days was plotted on a map by CWA, to get a rough distribution of reports with the sub-region.

From the days identified above, the most representative FF days were then selected according to the following criteria. First, for any sub-region, days with the most FF reports were selected, provided that the number of reports in that sub-region on the given day was greater than the combined total reports in the other three sub-regions. In other words, larger FF events focused on one sub-region were preferred. Hence, no FF day could be used for more than one sub-region. As a result of this criterion, numerous days with many FF reports in NWS-ER were omitted from the study, because the reports were more or less evenly distributed over two or more sub-regions. It was felt that inclusion of such days would tend to blur any possible distinctions in meteorological parameters among the sub-regions, thus defeating the main purpose. (From the local forecast and warning viewpoint, it is a relatively minor concern whether or not flash floods occur in other areas, so this criterion is likely not ideal for a local study.) Also, this method may tend to focus more on progressive systems that affect primarily one region on a given day, and another downstream region on the following day.

Second, FF days for any sub-region could not be consecutive; a separation of one day or more was required between FF days. This was meant to provide some degree of independence among the sample days. Some multi-day events are represented in this study, by selection of one day from the event. In the final selection, most events were at least one week apart (see Appendix).

Third, most days with FF reports in only one CWA were discarded. This was meant to avoid more localized FF events. However, a couple of single-CWA events were allowed for the "New England" sub-region because of the relative scarcity of reports there.

Finally, days with a named tropical system in or near NWS-ER were discarded. Tropical systems were identified by examining 1200 UTC surface charts from the "Daily Weather Map" series. In a few cases there was a named storm over the Gulf of Mexico or over the offshore waters of the Atlantic Ocean. This criterion does not guarantee that all tropical influences were eliminated; in a few cases a tropical storm may have recently traversed an area leaving behind enhanced moisture. Furthermore, moisture plumes extending pole-ward from tropical systems may sometimes enhance flash flooding far ahead of the main center. Of course, some of the worst flooding in NWS-ER occurs with tropical systems. However, an approaching tropical storm often seems to "trump" other forecast considerations, and may be considered as a separate type of event (LaPenta, et.al., 1995).

The end result of this process was four sets of flash-flood days representing the four sub-regions. These dates are listed in the appendix, and summary information for each set of FF days is given in Table 1. The dates in each list, taken together, are intended to represent the conditions associated with active flash flooding days in each sub-region. Note that the "Ohio Valley" sub-region, with the fewest CWAs, had the greatest number of FF days (25), and the greatest average number of reports per FF day (23.3). "New England" ended up with the fewest FF days (21) and the lowest average number of reports per day (9.3).

2.3 Creation of Composite Charts

Average meteorological conditions based on the dates in each list were examined using the GR and NARR re-analysis data sets. For general information on the GR data, see Kalnay, et.al. (1996); for more information about the NARR, see Mesinger, et.al. (2006). For this study, GR and NARR daily-mean data were accessed via web-based interfaces maintained by NOAA/ Earth System Research Laboratory (ESRL). NARR data is provided on a 32-km resolution grid at 25-mb pressure intervals from 1000 to 100 mb. However, daily composites from the NARR data were limited to basic fields: geo-potential height, temperature, specific humidity, zonal and meridional winds, vertical motion, and precipitation. The GR data is on a much coarser grid (about 210 km) and is available mainly at standard pressure levels. The GR data daily composites included the same basic fields as the NARR, but also certain derived fields such as precipitable water and lifted index, as well as the total vector wind.

The NARR daily composite means are averages of three-hourly NARR data at 00, 03, 06, 09, 12, 15, 18 and 21 hours UTC, while the GR daily composites are averages of 00, 06, 12 and 18 UTC data. The NARR daily composite anomalies are based on long-term means from 1979 to 2001; the GR anomalies are based on means from 1968 to 1996. Composite anomalies are obtained by subtracting the long-term mean from each daily mean, and then averaging these daily anomalies. The long-term mean for each sub-region is based only on the dates in the list for that sub-region, so the means show minor differences from one sub-region to another. As an example, for long-term means of 850 mb temperature, the maximum difference among the four sub-regions is about 0.5 deg C at any point.

The lists of FF days for each of the four sub-regions were supplied individually as input to web-based interfaces for the GR and the NARR data sets. From these web sites, composite daily mean and anomaly charts for each sub-region were created for geo-potential height, temperature, specific humidity, total vector wind, zonal wind, meridional wind, moisture transport and omega at 1000, 925, 850, 700, 500 and 250mb (moisture omitted at 250mb). Charts for mean sea-level pressure (MSLP), total precipitable water and lifted index were also generated. Total wind, MSLP, moisture transport and lifted index were based on GR data; all other fields were based on the NARR.

3. Results

Figure 2a shows daily composite means for mean sea level pressure, while figure 2b shows the corresponding composite anomalies. Each sub-region has a unique pattern, but an MSLP anomaly minimum is found to the west or southwest in all four. The strongest negative anomaly is associated with the New England events, while the weakest occurs with events in the South-Atlantic. The 1000mb height patterns (not shown) showed negative anomalies similar to MSLP, as would be expected.

The negative height anomalies persist upward through mid and high levels, but tend to shift west or northwest and away from the sub-region. The exception is the Ohio Valley sub-region, where the anomaly switches completely from negative to positive between 850 and 700 mb. Figures 3a and 3b show daily composite means and anomalies of 500mb height. Again, mean troughs and anomaly minimums are found west of each sub-region, except the Ohio Valley, which is under a positive height anomaly, with the maximum over the East Coast.

925mb temperature, daily composite means and anomalies, are shown in figs 4a and 4b. In general, the mean charts show a thermal ridge axis south or west of each sub-region, but the Ohio ridge has a more west-east orientation. The anomaly charts show positive (warm) anomalies over New England and the Ohio Valley, but negative (cool) anomalies over the South-Atlantic and near neutral anomalies over the Mid-Atlantic sub-region. Temperature composite charts for other levels (not shown) indicate similar patterns through the lower half of the troposphere.

Figures 5a shows daily composite means of specific humidity at 925 mb. The means show a moist axis over or near each sub-region, similar to the low-level thermal axis pattern. Higher up, e.g., at 500 mb (Fig. 6a), the moist axes become distinct moisture maxima centered over each sub-region. The corresponding daily composite anomaly charts (Figs. 5b and 6b) indicate distinct moist anomalies over at least part of each sub-region, tending to shift slightly toward the sub-region center with height. In the South-Atlantic, the low-level positive anomaly is relatively weak, but at mid levels, e.g., 700mb (not shown) and 500mb (Fig. 6b), it becomes comparable with the other sub-regions.

The wind patterns associated with flash flood days in each sub-region tend to agree qualitatively with the height patterns, as might be expected. Height troughs to the west result in southwesterly mean flow over the sub-region, except more westerly to slightly north of west over the Ohio Valley sub-region. Figure 7 shows daily composite means for the 250mb total vector wind. Each sub-region is in the right entrance region of an anti-cyclonically curved speed maximum, though the curvature is less pronounced for the Ohio Valley events. Composite *anomalies* for the total wind showed cyclonic circulations centered west of each sub-region through all levels, except becoming anti-cyclonic above 700 mb over the Ohio Valley with the circulation center to the east. Figure 8 shows daily composite anomalies for the total vector wind at 850 mb. The circulation at 850mb is weaker over the South-Atlantic and Ohio Valley, and elongated east-to-west over the Ohio Valley.

The 850mb wind anomalies are broken into their zonal and meridional components in figures 9a and 9b. The zonal wind anomalies (fig 9a) show a relatively sharp gradient from positive to negative over the southern part of each sub-region (except north from the Ohio Valley), suggesting a wind shift line or possibly a low-level boundary. The meridional wind anomalies (fig 9b) are positive for each sub-region, with stronger maxima over New England and the Mid-Atlantic. This pattern is evident at all levels. In fact, the meridional wind composite *means* (not shown) are also positive at all levels, except slightly negative (northerly) at mid levels over the Ohio Valley sub-region.

Figures 10a and 10b show 850mb moisture transport, daily composite means and anomalies. Moisture transport is defined as the product of the vector wind with specific humidity; units are (g/kg)*(m/s). Maxima in the composite means tend to lie over or along the southern or western fringes of each sub-region. The composite anomalies (fig 10b) show the same circulation patterns as the 850mb vector wind anomalies (fig 7), but with maxima somewhat better focused over New England and the Mid-Atlantic, and a weaker maximum over the South-Atlantic. The anomaly maximum for the Ohio Valley is slightly upstream, to the southwest.

Finally, daily composite means and anomalies for surface-based lifted index (LI) are shown in figures 11a and 11b. Each sub-region tends to be on the more unstable (or less stable) side of the strongest stability gradient, with more unstable air (LI = 0 to -3) to the south or west. Negative (more unstable) lifted index *anomalies* are located over or near each sub-region (fig 11b), and are roughly equal in magnitude except weaker over the South-Atlantic. It should be noted that the daily composite values shown here are likely not indicative of the most unstable conditions that typically occur with afternoon heating of low levels during the summer.

4. Discussion

4.1 Similarities among sub-regions

The daily composites showed negative anomalies in geo-potential height up to the 850mb level (and MSLP) for the FF cases from all four NWS-ER sub-regions. The anomalies were located generally west of the sub-region centers. The sub-region centers tended to be located in strong height-anomaly gradients, especially at higher levels. With cyclonic winds around the negative height anomalies, a southerly wind component resulted over each sub-region at low levels. At high levels (around 250 mb) an anti-cyclonically curved jet streak of 25-30 m/s was located down wind and poleward from each sub-region. Thus each sub-region was in the right entrance region relative to the jet streak, a location well known to be favorable for large-scale upward motion and de-stabilization.

Positive moisture anomalies of varying strengths were noted over each sub-region, from 1000 up to 500 mb. It is not clear whether this is a cause or an effect of deep moist convection; however, the NARR daily composites are an average of conditions from 00 UTC the prior evening through 21 UTC in the afternoon, the latter time being about the beginning of the diurnal FF maximum in summertime over the eastern U.S (Giordano and Fritsch, 1991). Thus the daily means should in general represent conditions prior to occurrence of most flash flooding. Finally, the MSLP anomalies, U-wind anomalies and LI composite means all suggest the presence of a low-level boundary to serve as a focusing mechanism for convection, although the orientation of the boundary (e.g., north-to-south or east-to-west) is unclear and no doubt varies from case to case.

4.2 Differences between sub-regions

In regard to height and wind fields, the Ohio Valley sub-region tends to stand apart from the others, with a weaker and more elongated pattern at low levels, and a ridge axis (anti-cyclonic flow) instead of a trough (cyclonic flow) at mid to high levels. The flow at mid levels tends to be slightly north of west rather than southwest as with the other sub-regions. This is consistent with the results of Giordano and Fritsch (1991), who found that strong convective events over the upper Ohio Valley during summer occur predominantly with northwest flow aloft, which results from long-wave ridging over the central U.S.

New England FF cases tended to occur with stronger negative height anomalies upstream and stronger positive meridional wind anomalies directly over the area. Examination of time-lagged anomaly charts (not shown) for days just before and after the FF events suggest that the New England events in this study were associated with progressive weather systems that resulted mainly in single-day FF events. This seems reasonable, since New England is the northernmost of the four sub-regions and closest to the mean summer position of the westerlies across the northern U.S. and southern Canada.

Low-level moisture and instability associated with flash floods in the South-Atlantic seem to be less of an anomaly than for the other sub-regions. This suggests that sufficient moisture and instability for flash floods are typically present on any given day in the South-Atlantic, and the key to flooding there may be the presence of a focusing mechanism, possibly a stationary front or surface trough to enhance low-level convergence. The temperature anomalies are actually negative for the South-Atlantic compared to positive elsewhere. This deep cool anomaly, centered west of the Appalachians, results in increasingly negative height anomalies at mid to high levels, and ultimately stronger winds near the tropopause.

Overall, the Mid-Atlantic sub-region seems to be a hybrid of the two sub-regions to its north and south. It shares negative height anomaly patterns (though weaker) with New England and the South-Atlantic. Temperature anomalies tend toward neutral or negative like the South-Atlantic, but low-level positive moisture anomalies are intermediate in strength between the South-Atlantic (weaker) and New England (stronger). Total wind and meridional wind component anomalies at low to mid levels for the Mid-Atlantic tend to be as strong as over New England.

4.3 Moisture Sources

The two major bodies of water that supply moisture for the NWS-ER are the Gulf of Mexico and the Atlantic Ocean. From figure 10a, 850mb moisture for the Ohio Valley sub-region appears to be transported entirely from the Gulf of Mexico (but perhaps by multiple trajectories), while the moisture source for the other regions is likely a combination of the Gulf and the Atlantic. The anomalies in figure 10b indicate that the moisture contribution from the Atlantic is significantly greater than normal during FF events in the three sub-regions east of the Appalachians.

5. Conclusions

The results of this study rely on a relatively small number of days (21 to 25) when FF events occurred in each of the defined NWS-ER sub-regions. Even with these small samples, it is apparent from the individual surface and upper-air charts that significant FF events affecting multiple NWS local offices can occur with a variety of synoptic-scale patterns. The results from this study should be interpreted as atmospheric tendencies rather than necessary conditions for flash flooding.

This study has looked at only a limited number of basic parameters at a few selected levels. Many additional derived parameters, including hydrologic variable, are available from the GR and NARR datasets. Vertical cross-sections and additional time-lag charts could also be created. Composite mean and anomaly charts for specific times, rather than daily means, could show more detail and perhaps reveal some diurnal trends leading up to flash floods.

6. Acknowledgments

Very helpful reviews of this paper were provided by Frank Alsheimer, Science and Operations Officer (SOO) at NWS Charleston, SC, and by Michael Evans, the SOO at NWS Binghamton, NY.

The re-analysis images shown in this paper were and provided by the NOAA/ESRL Physical Sciences Division, Boulder Colorado, from their Web site at "http://www.cdc.noaa.gov/".
The specific web sites used to create the composite charts were
http://www.cdc.noaa.gov/ Composites/Day for the GR data, and
http://www.cdc.noaa.gov/cgi-bin/NARR/plotday.pl for the NARR data.

Surface and 500mb maps from the "Daily Weather Map" series were obtained from the web sites
http://docs.lib.noaa.gov/rescue/dwm/data_rescue_daily_weather_maps.html and
http://www.hpc.ncep.noaa.gov/dailywxmap/frame.html.

7. References

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Appendix

Flash flood event dates used for each sub-region (year/month/day).

Ohio Valley	New England	Mid-Atlantic	South-Atlantic
1990/06/08	1986/07/29	1989/06/20	1986/08/19
1990/06/14	1990/08/07	1989/06/22	1989/07/04
1992/07/13	1991/06/03	1989/07/05	1989/08/18
1992/07/24	1992/08/09	1990/06/18	1995/06/22
1992/07/30	1996/06/13	1992/07/31	1995/07/03
1992/08/08	1996/07/03	1994/06/13	1996/08/03
1993/07/01	1997/07/09	1994/07/14	1996/08/12
1994/07/29	1997/07/15	1994/08/25	1999/07/24
1994/08/13	1998/06/13	1996/06/17	2000/07/24
1995/06/03	1998/06/17	1998/06/23	2000/08/04
1995/06/21	1998/07/01	1998/07/08	2001/06/01
1995/07/15	1998/08/11	1999/08/20	2001/06/25
1995/08/05	2000/07/16	1999/08/26	2001/07/04
1995/08/11	2002/08/16	2000/07/14	2002/08/28
1996/06/24	2004/08/21	2000/07/31	2003/06/08
1996/07/19	2005/06/16	2000/08/12	2003/06/18
1997/06/01	2005/06/29	2001/06/22	2003/07/13
1998/06/15	2005/07/06	2001/08/11	2003/07/29
1998/06/28	2005/07/18	2003/06/13	2004/07/11
2000/08/09	2005/08/14	2003/06/21	2005/06/07
2001/06/06	2006/06/29	2004/07/12	2005/07/07
2003/06/14		2004/07/14	2005/07/19
2003/07/08		2004/07/27	2005/08/09
2003/07/27		2006/06/25	2006/06/23
2004/06/15			

Table 1. Summary of flash-flood (FF) days in the study. All numbers refer to FF reports *within* each sub-region.

NWS-ER Sub-Region	OhVly	NewEng	Mid-Atl	South-Atl
Number of WFO CWAs	4	6	5	8
Number of FF Days	25	21	24	24
Avg. No. FF Reports per Day	23.3	9.3	15.8	11.7
Max No. FF Reports, Any Day	71	30	39	28
Min No. FF Reports, Any Day	10	5	8	7
Fraction of Total NWS-ER FF Reports In sub-region (all days)	.88	.80	.79	.89

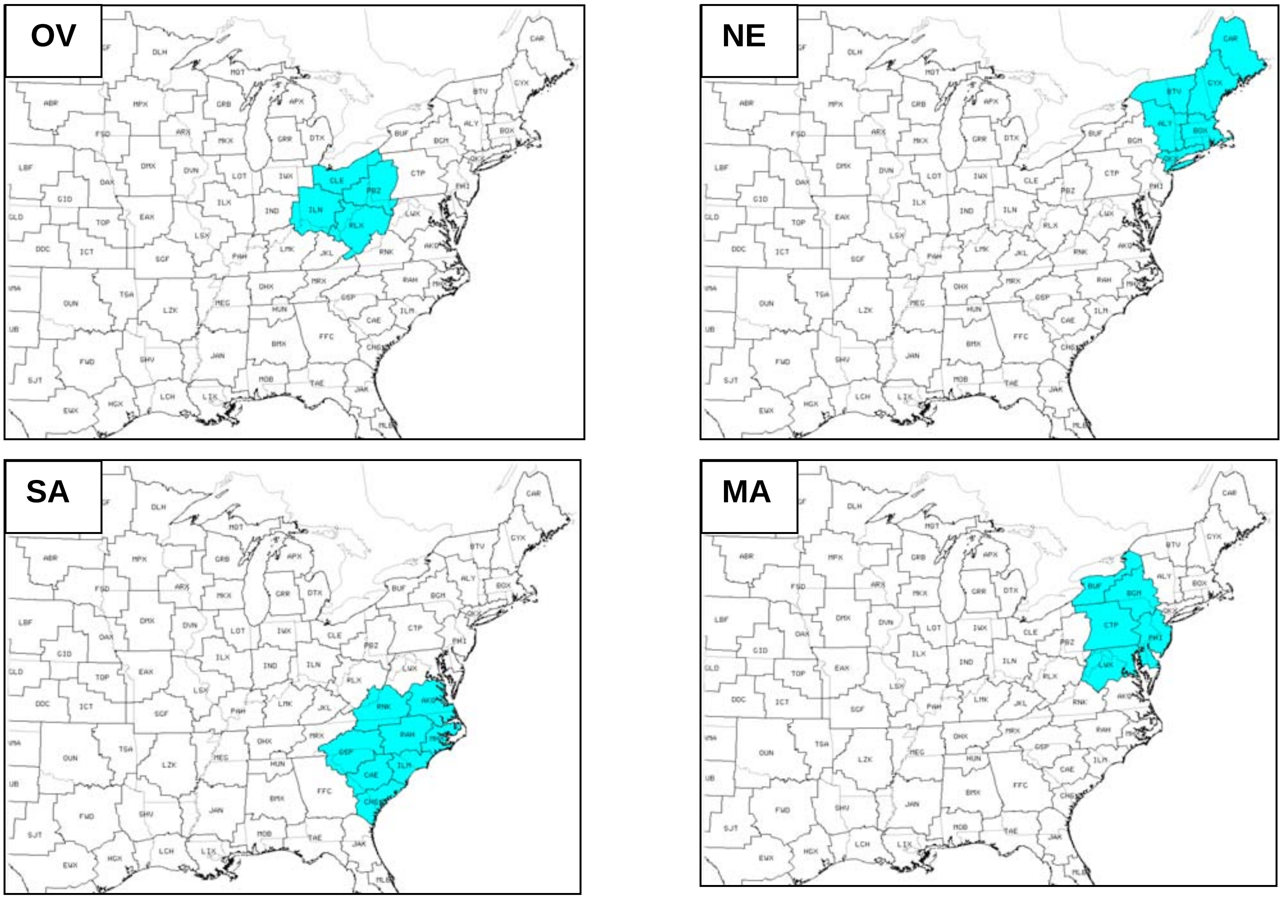

Fig 1. Four sub-regions within NWS Eastern Region, as defined for this study. The upper-left panel is "Ohio Valley" (OV), upper-right is "New England" (NE), lower-left is "South-Atlantic" (SA), and lower-right is "Mid-Atlantic" (MA). The panels in all the following images correspond to this arrangement.

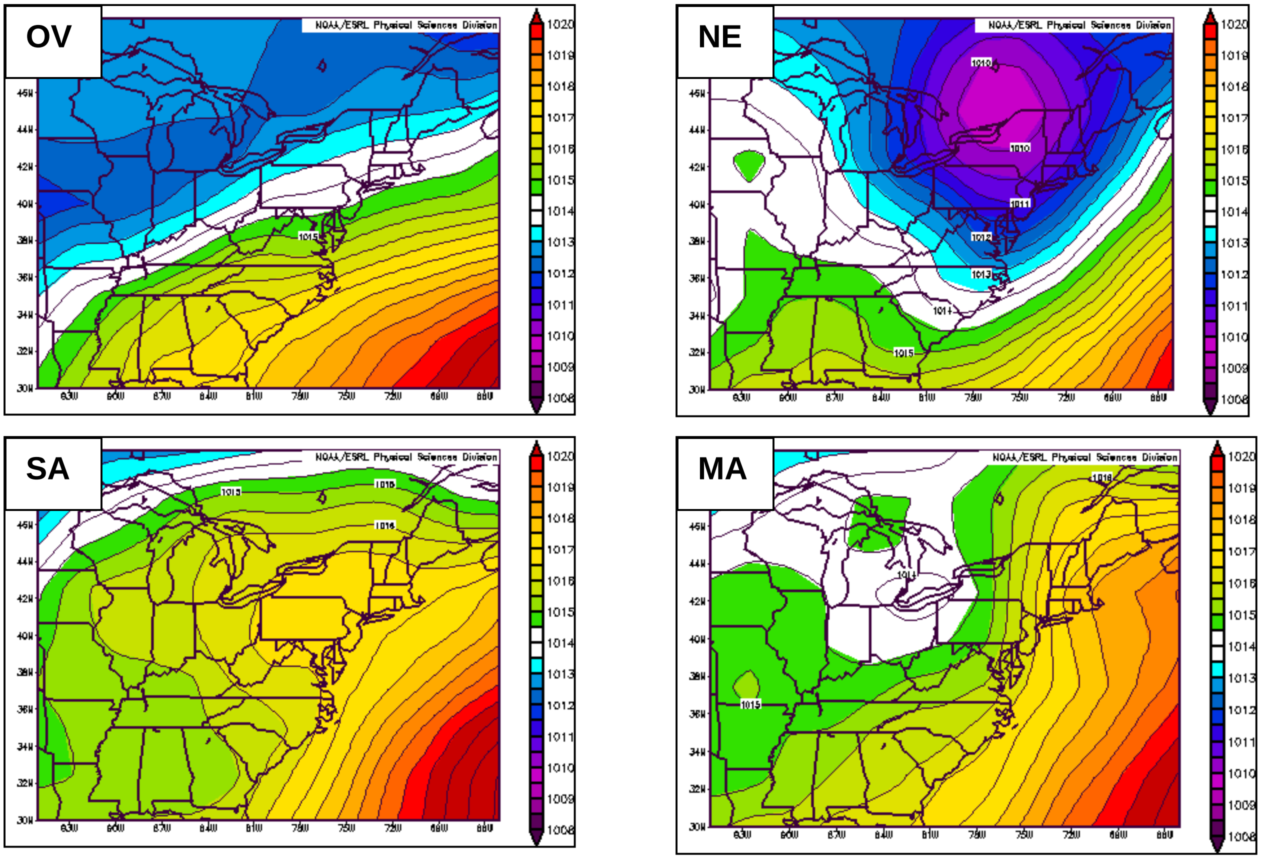

Fig 2a. Mean sea-level pressure, daily composite means, from the NCEP/NCAR global re-analysis. The four panels correspond to the four sub-regions in fig 1.

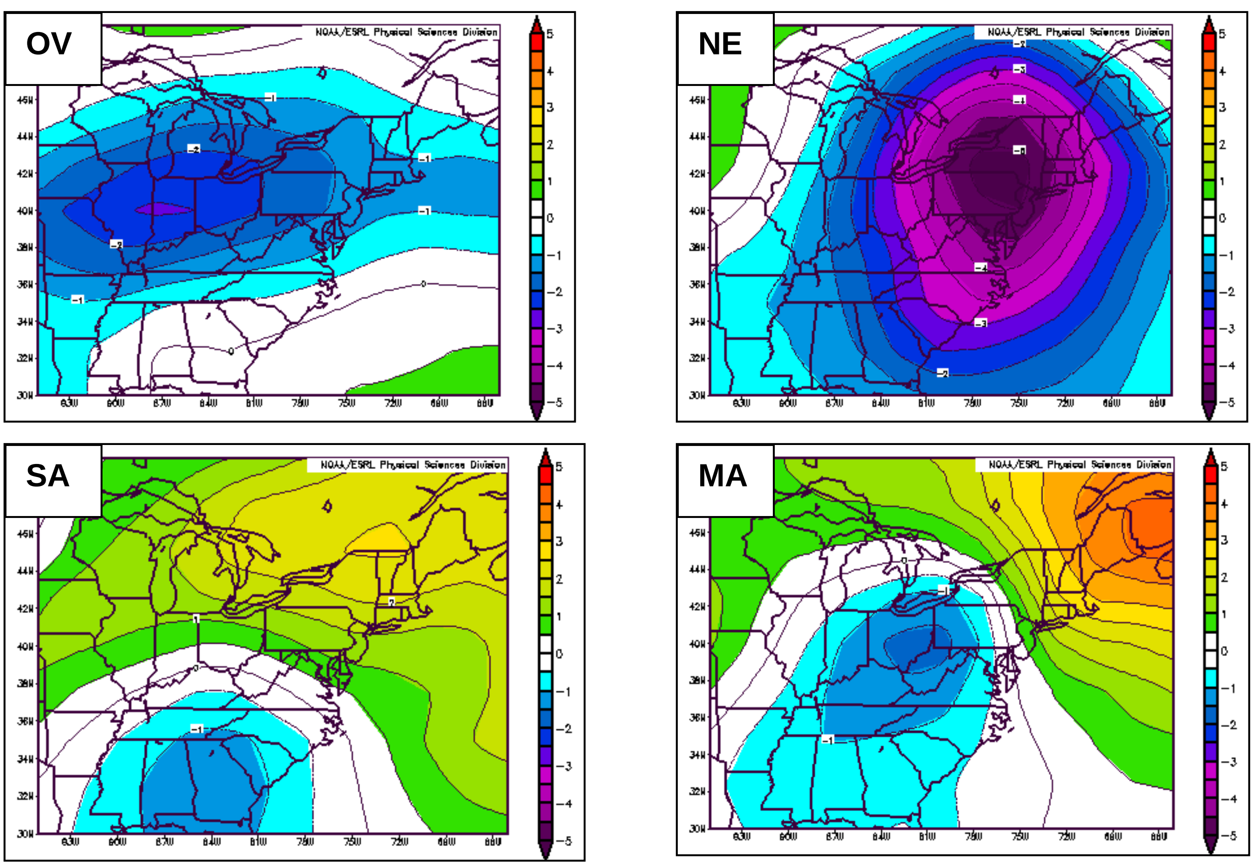

Fig 2b. As in fig 2a above, except daily composite anomalies.

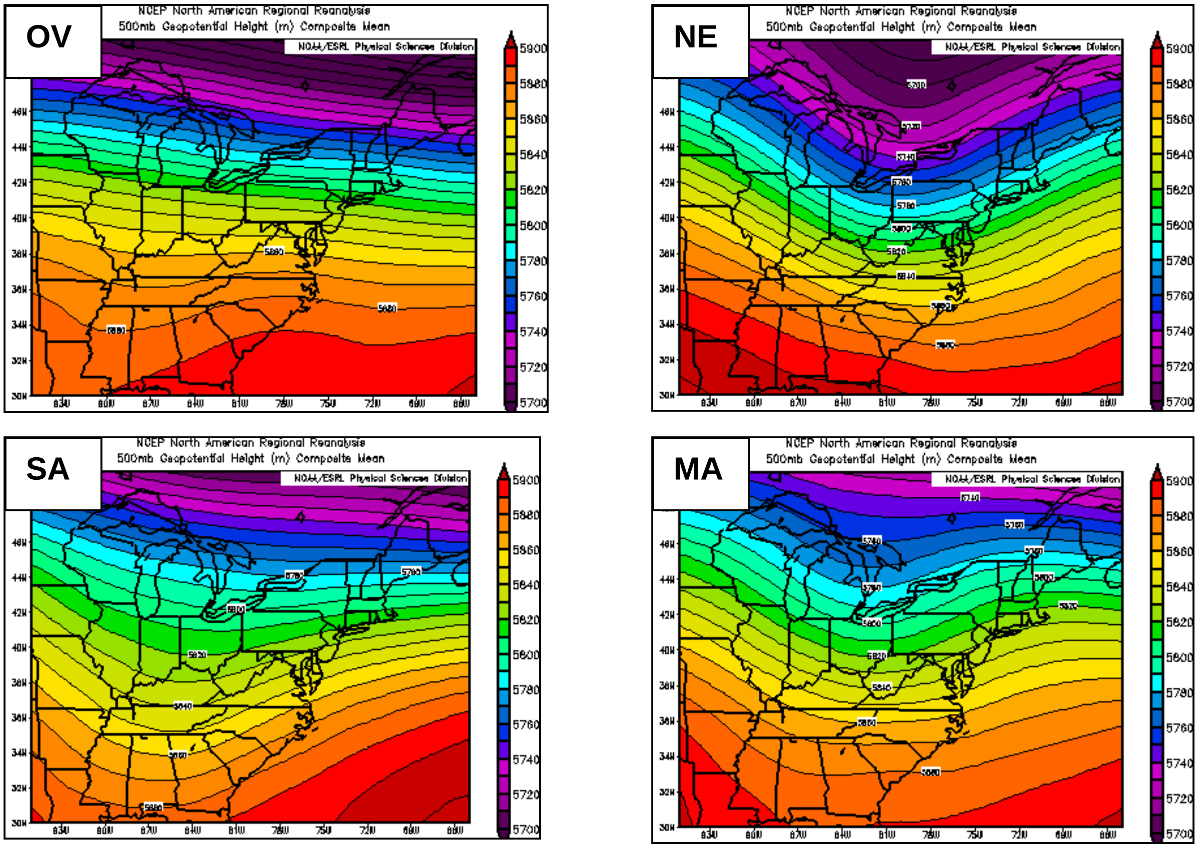

Fig 3a. 500 mb height (m), daily composite means, from the NARR.

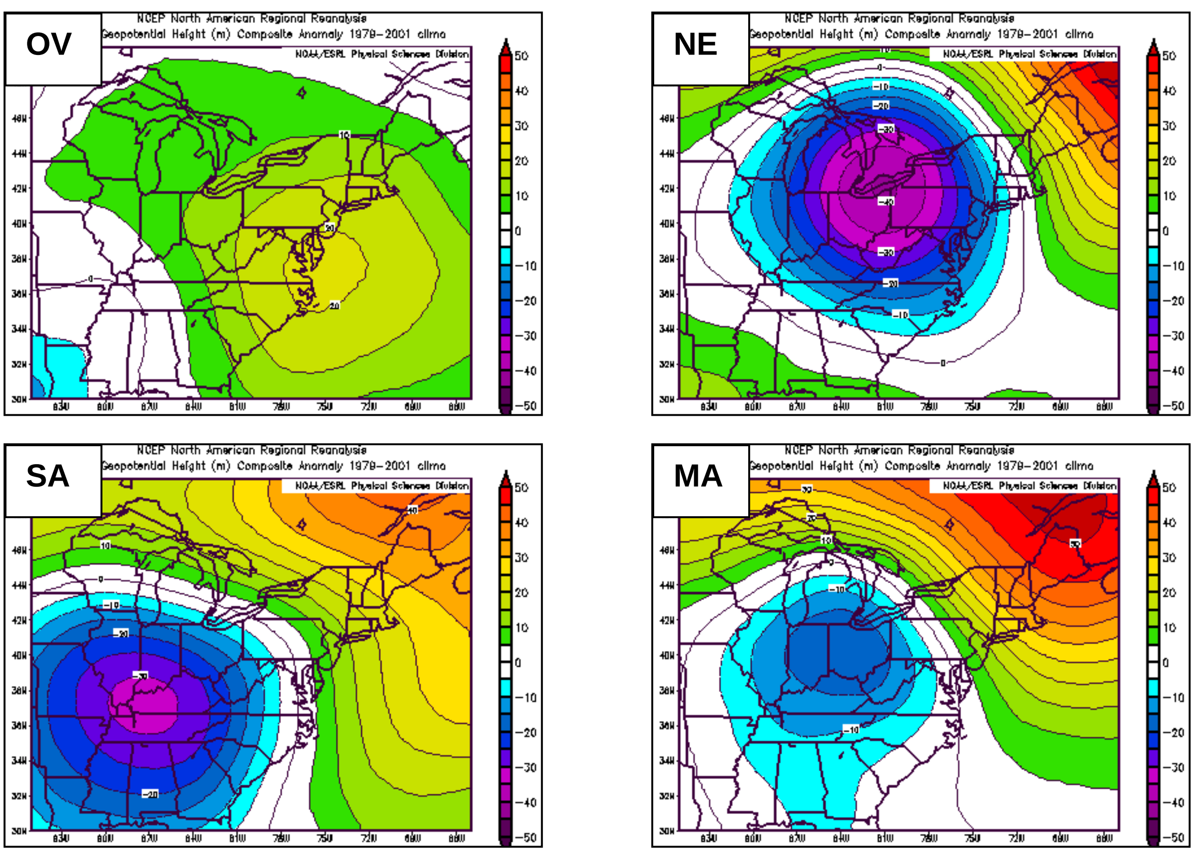

Fig 3b. As is fig 3a, except composite anomalies.

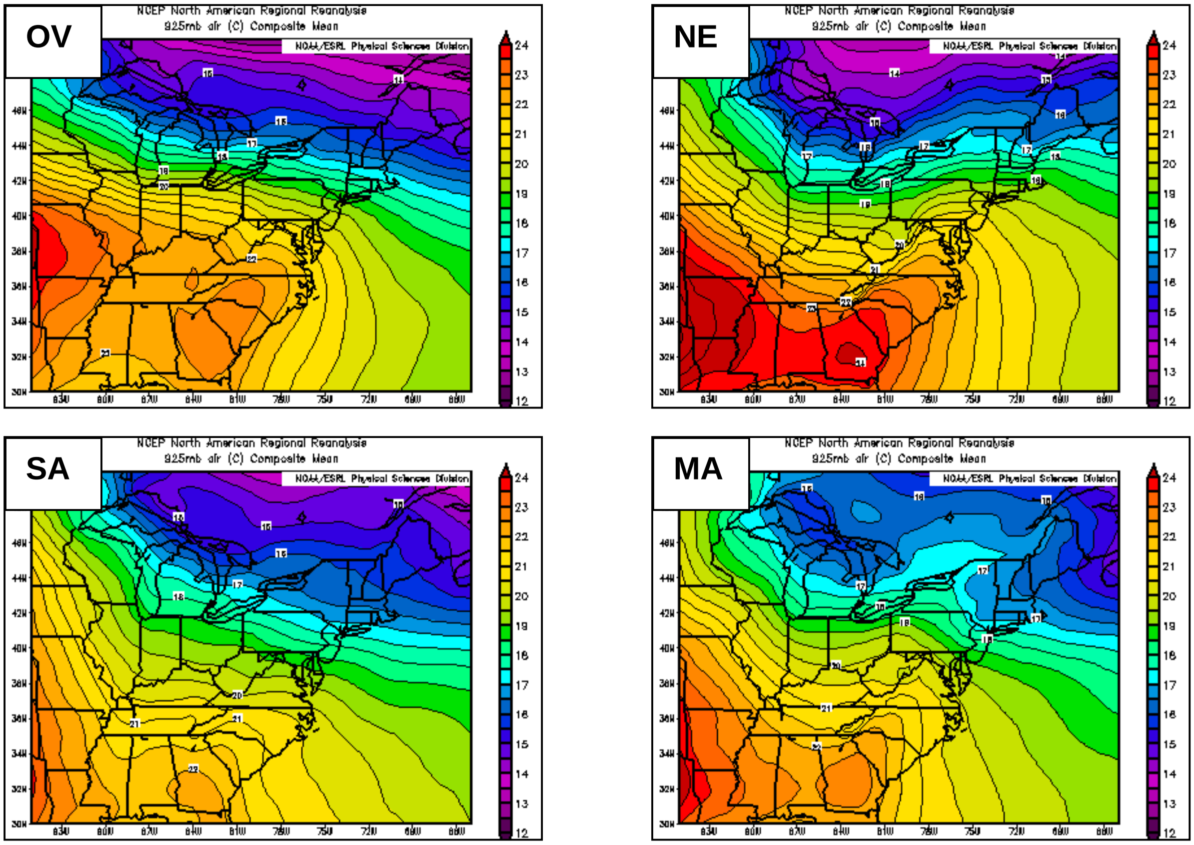

Fig 4a. 925mb temperature (deg C), daily composite means, from the NARR

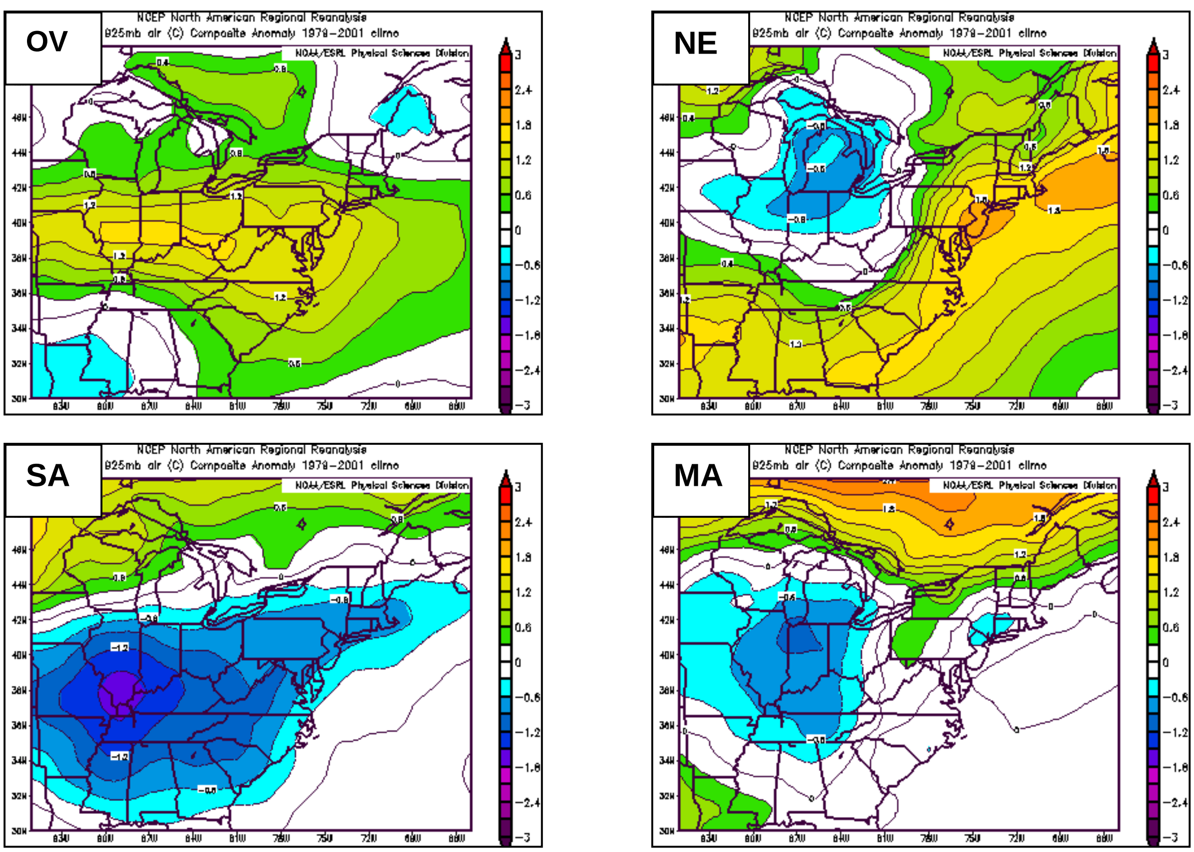

Fig 4b. As in fig 4a, except temperature anomalies.

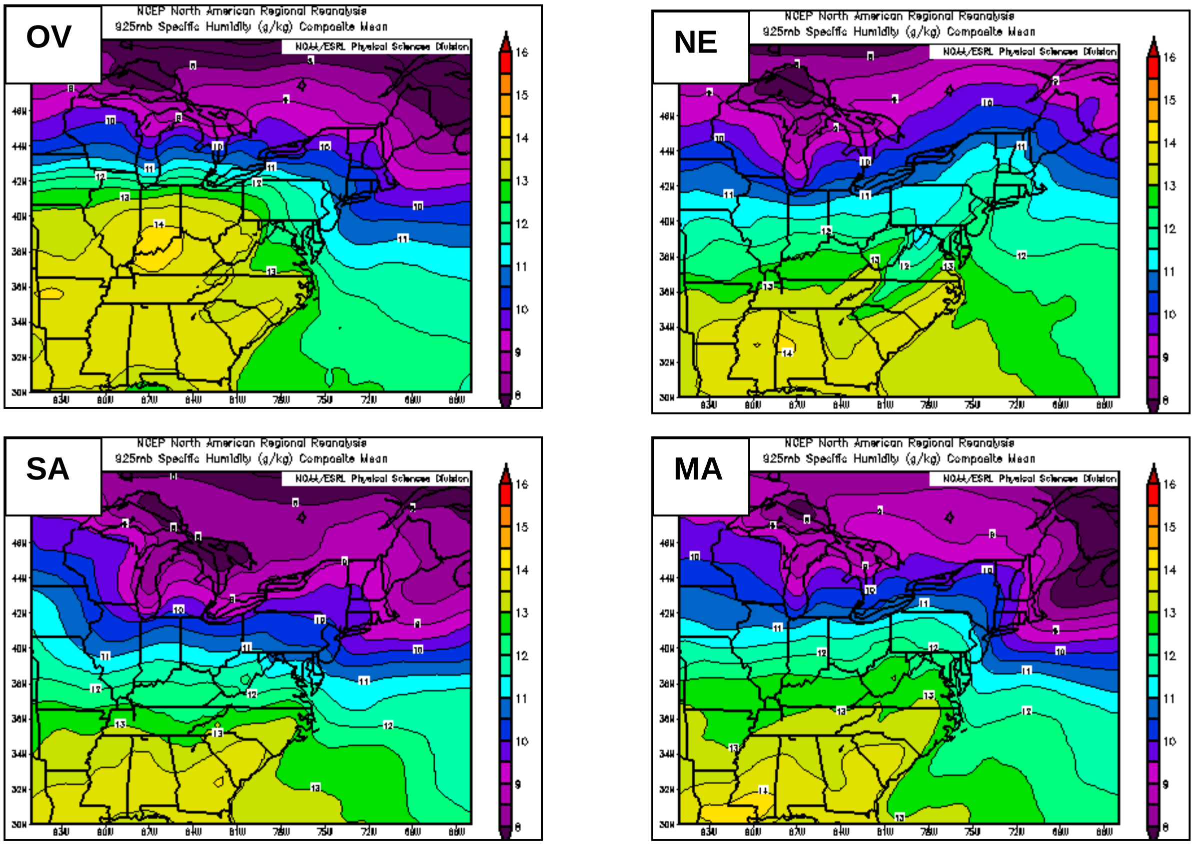

Fig 5a. 925mb specific humidity (g/kg), daily composite means, from the NARR.

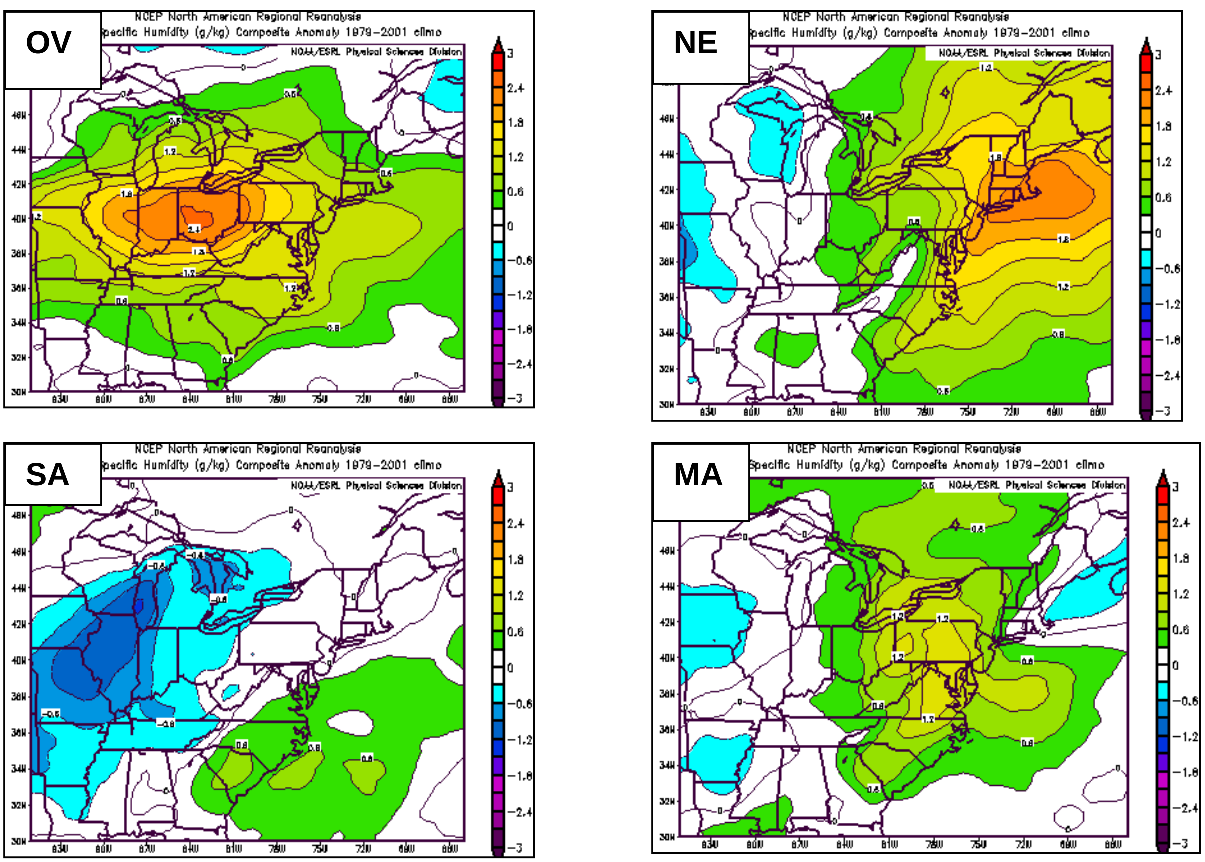

Fig 5b. As in fig 5a, except specific humidity anomalies.

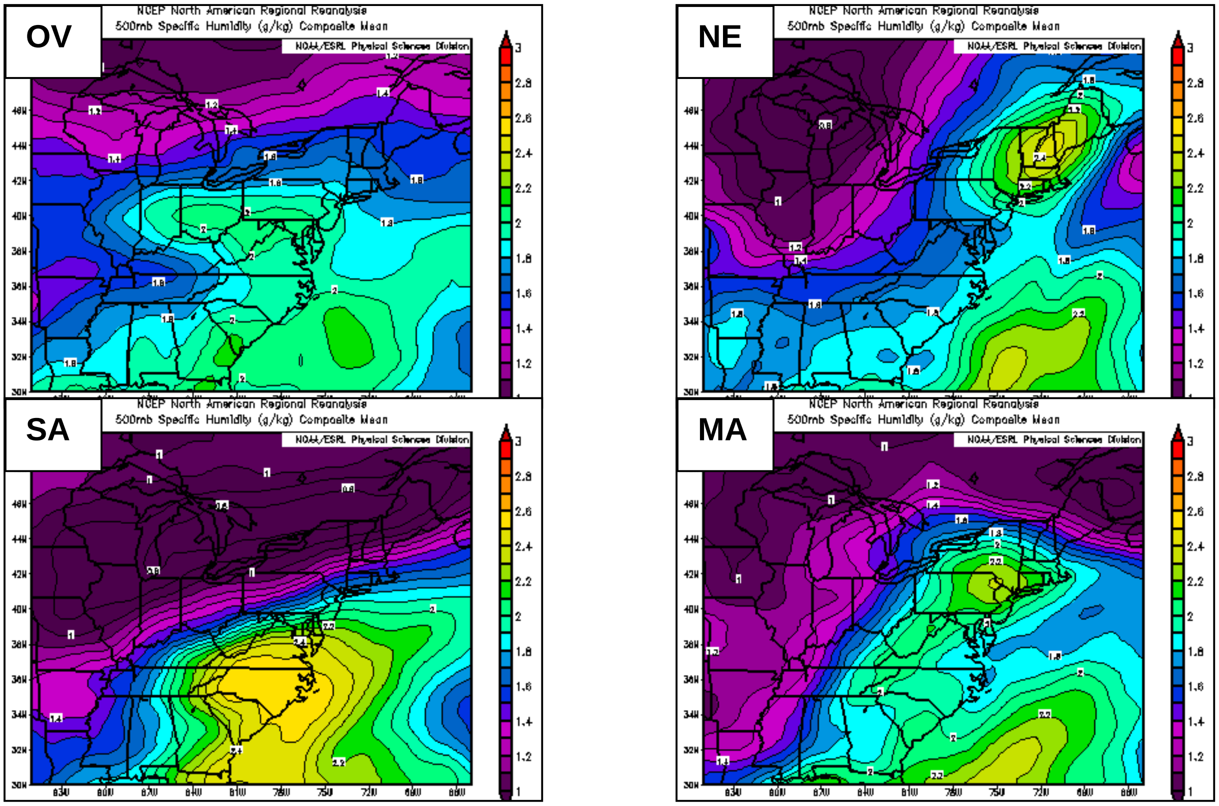

Fig 6a. 500 mb specific humidity (g/kg), daily composite means, from the NARR.

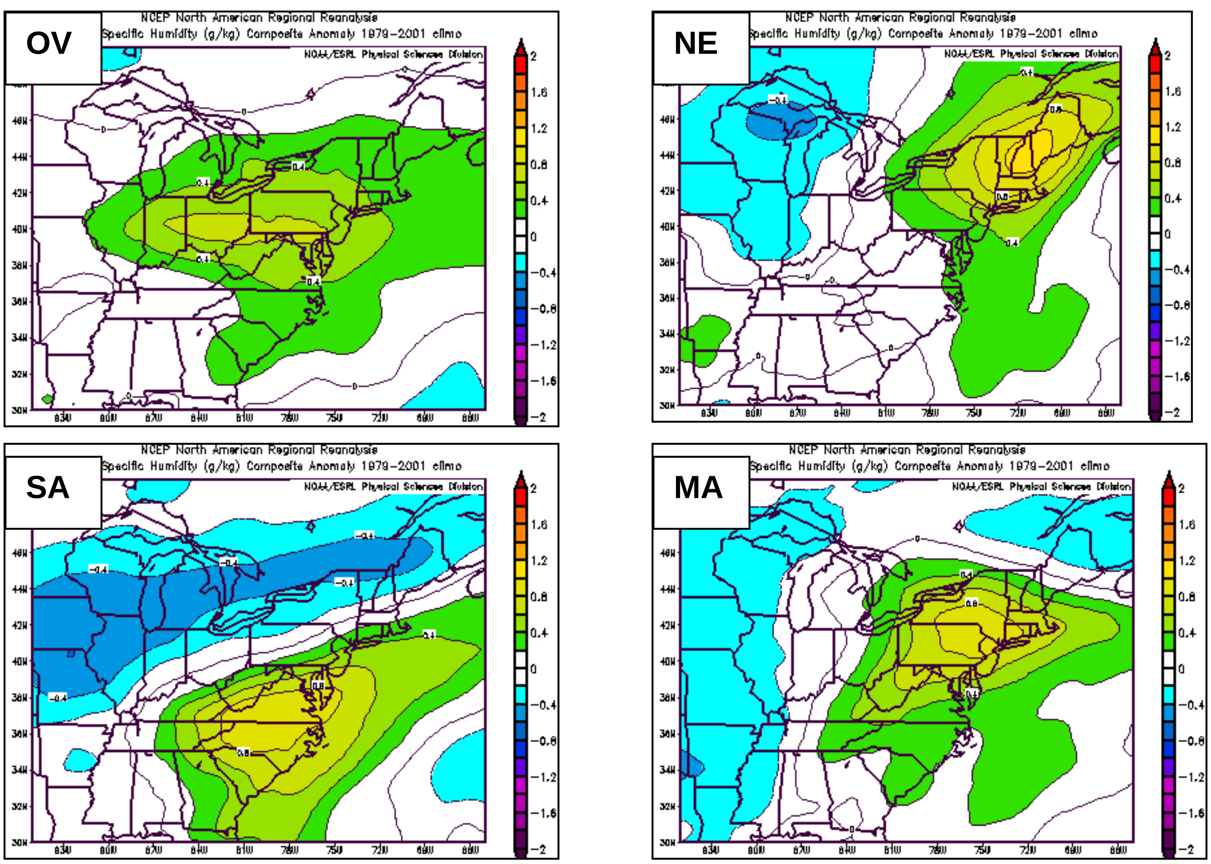

Fig 6b. Same as fig 6a, except composite anomalies.

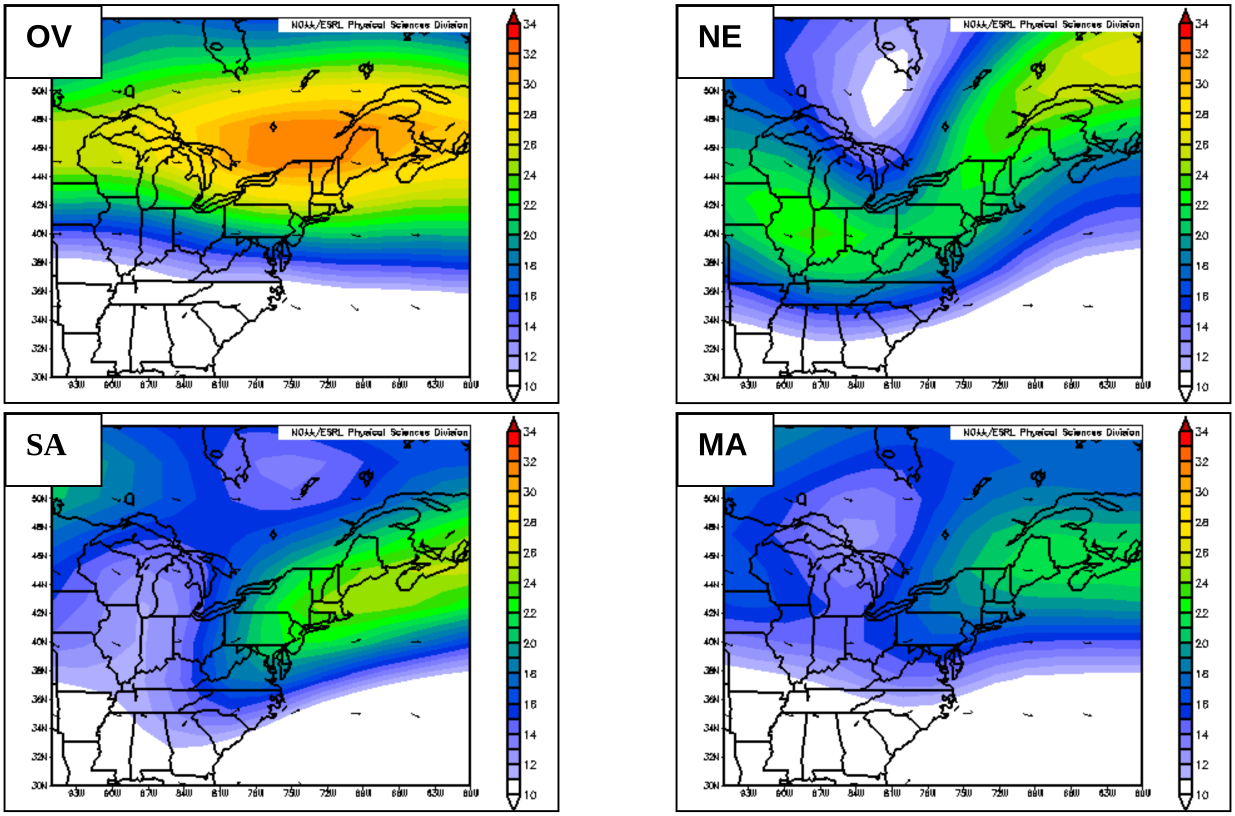

Fig 7. 250mb total vector wind (m/s), daily composite means, from the NCEP/NCAR GR. Map area extends farther north and east than in previous figs.

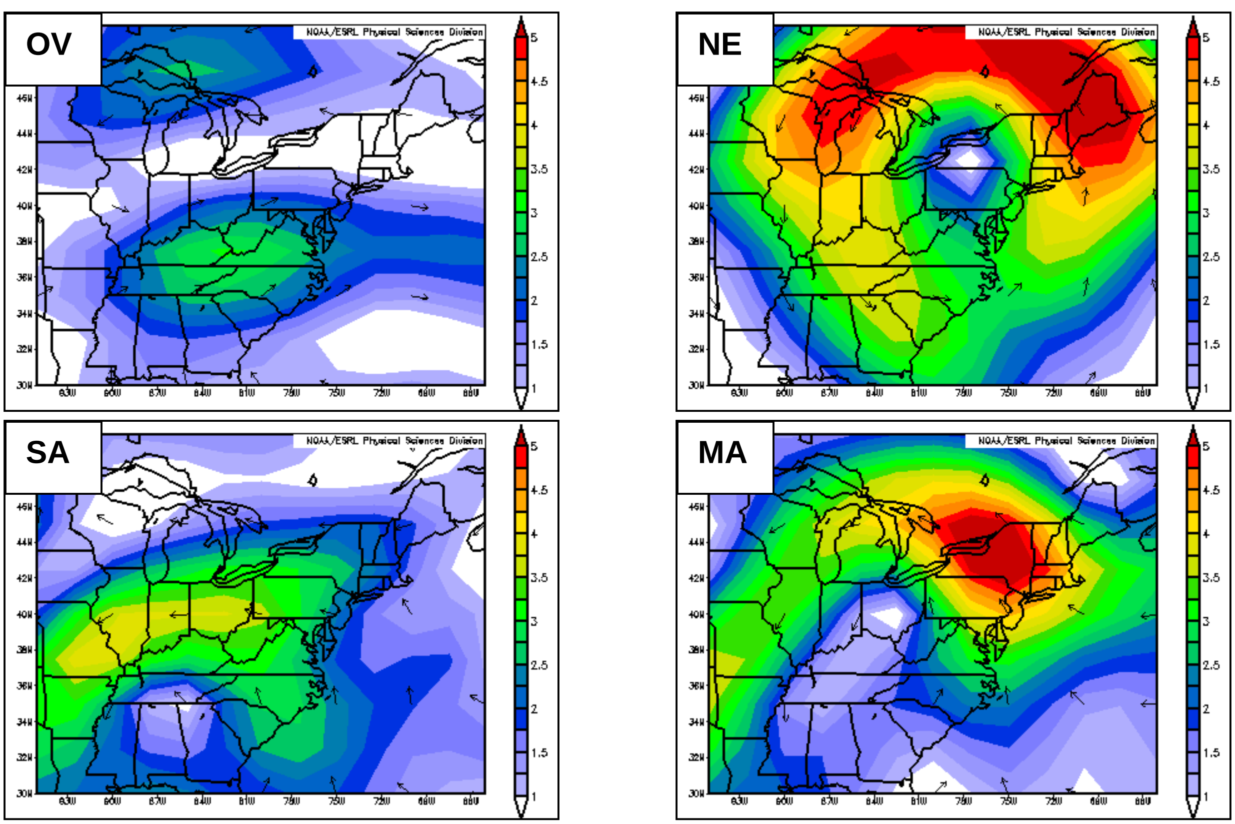

Fig 8. 850mb total vector wind (m/s), daily composite anomalies, derived from the NCEP/NCAR global reanalysis. Color shading shows the anomaly magnitude, arrows show the direction.

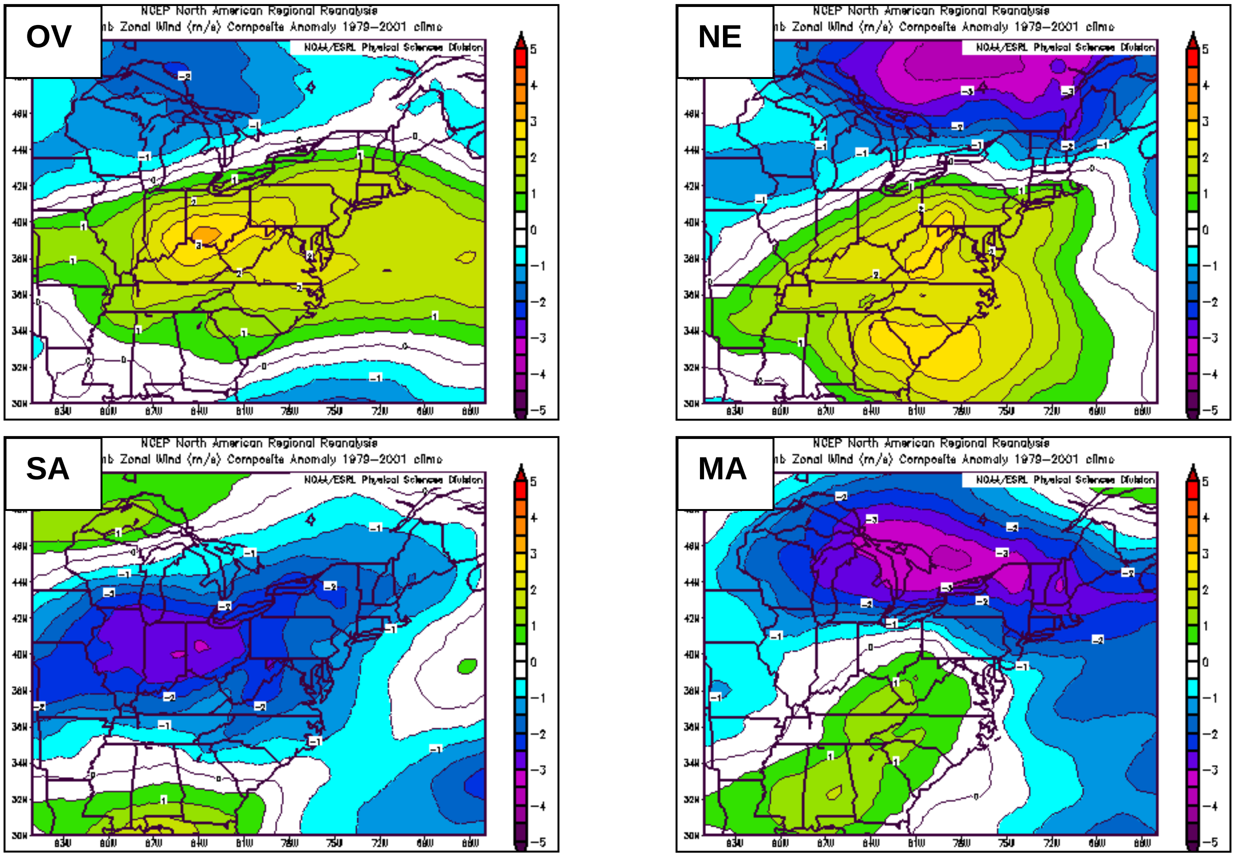

Fig 9a. 850mb zonal wind component, daily composite anomalies, from the NARR.

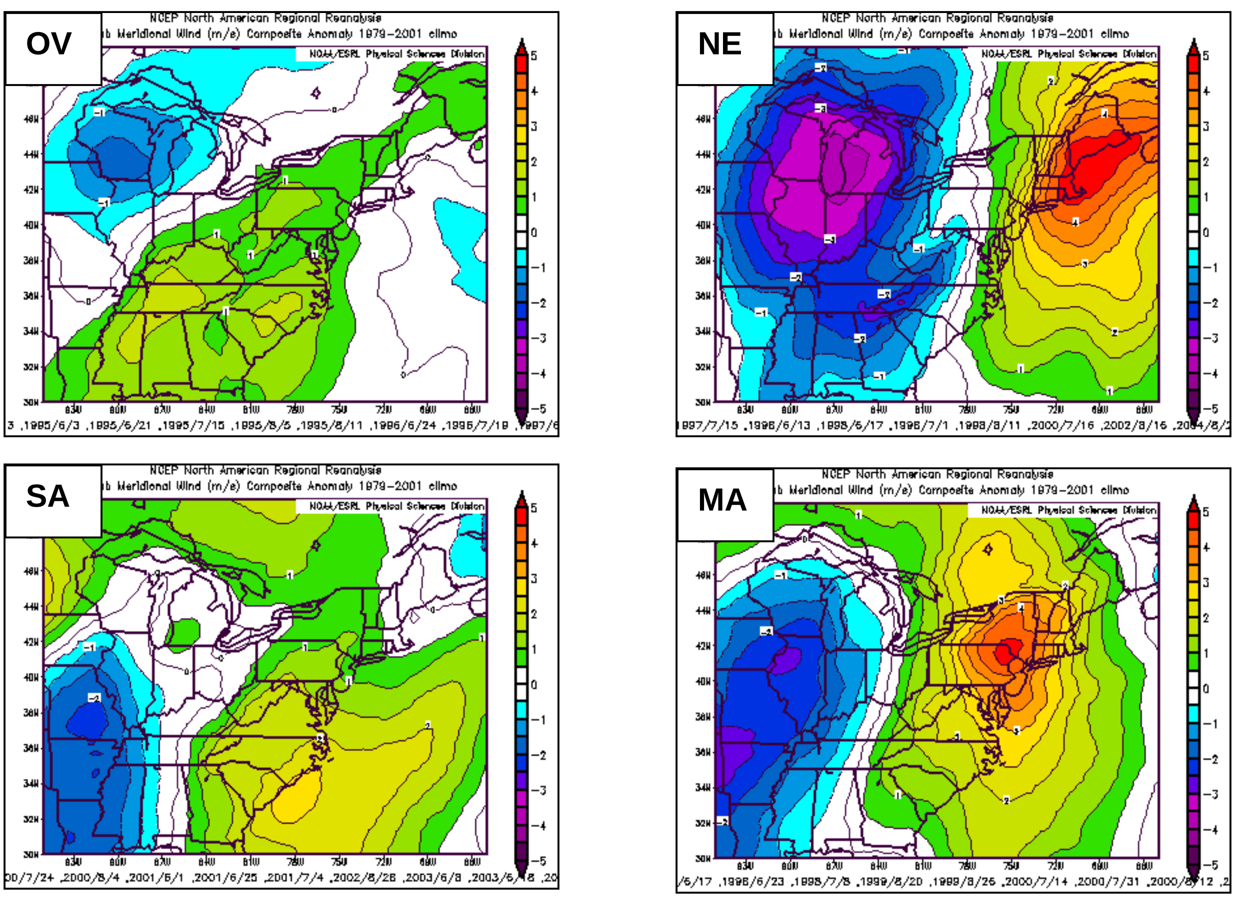

Fig 9b. As in fig 9a, except meridional wind component.

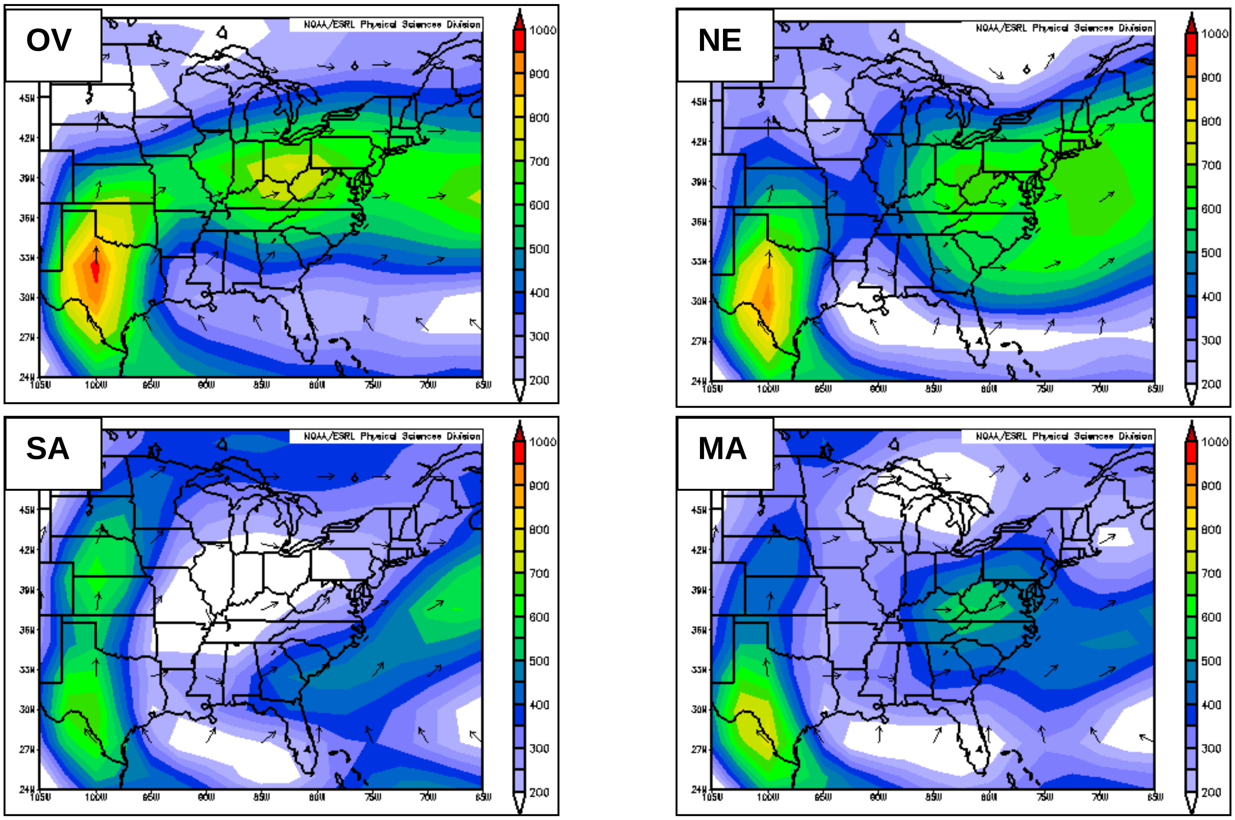

Fig 10a. 850mb moisture transport ((g/kg)*(m/s)), daily composite means, from the NCEP/NCAR GR. Note map area expanded south and west.

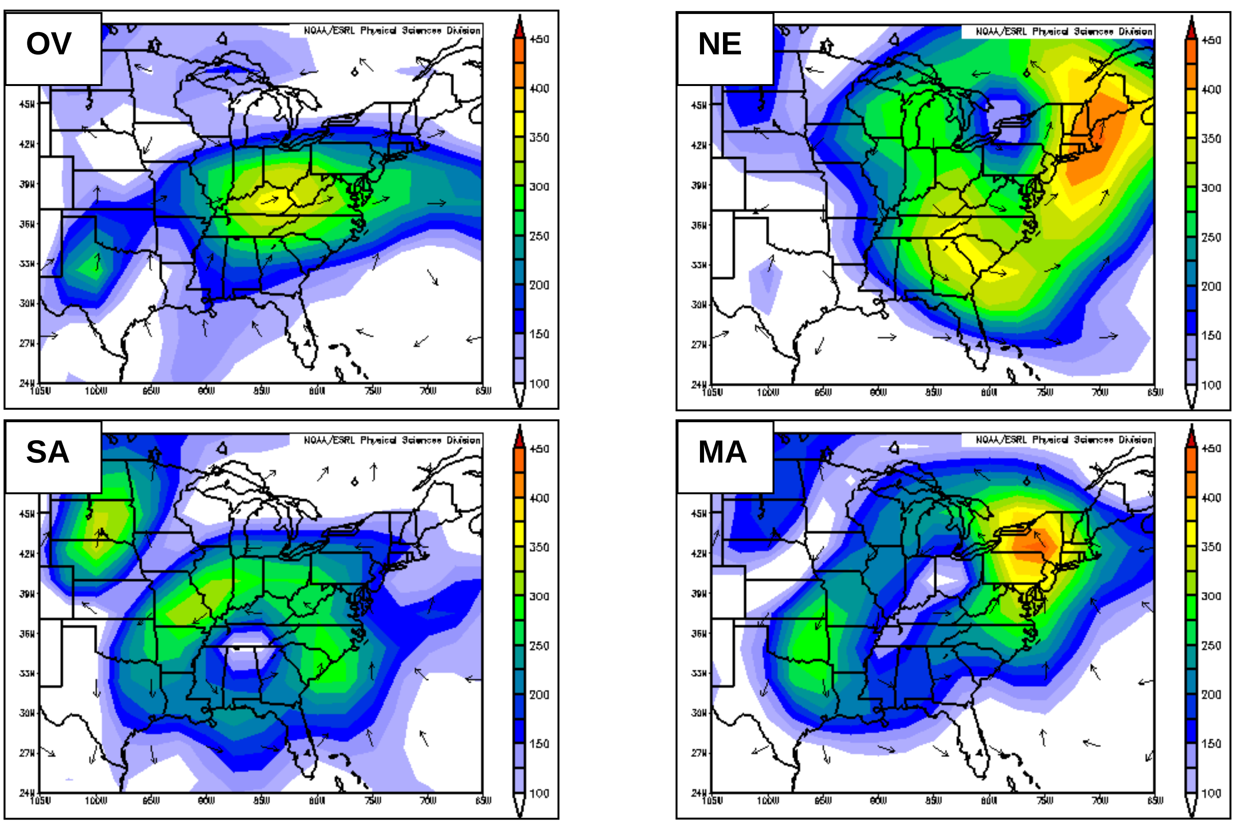

Fig 10b. As in fig 10a, except composite anomalies.

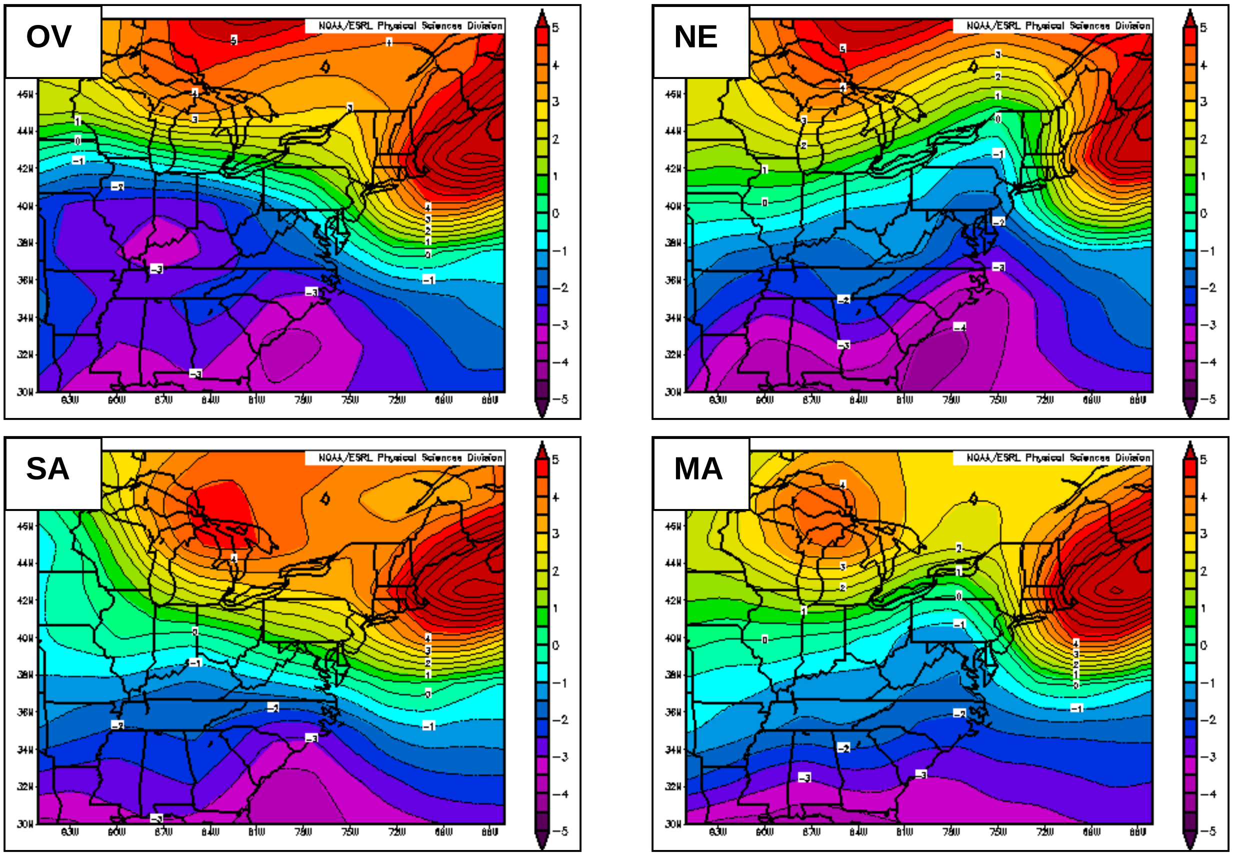

Fig 11a. Surface-based lifted index (deg C), daily composite means, from the NCEP/NCAR global reanalysis.

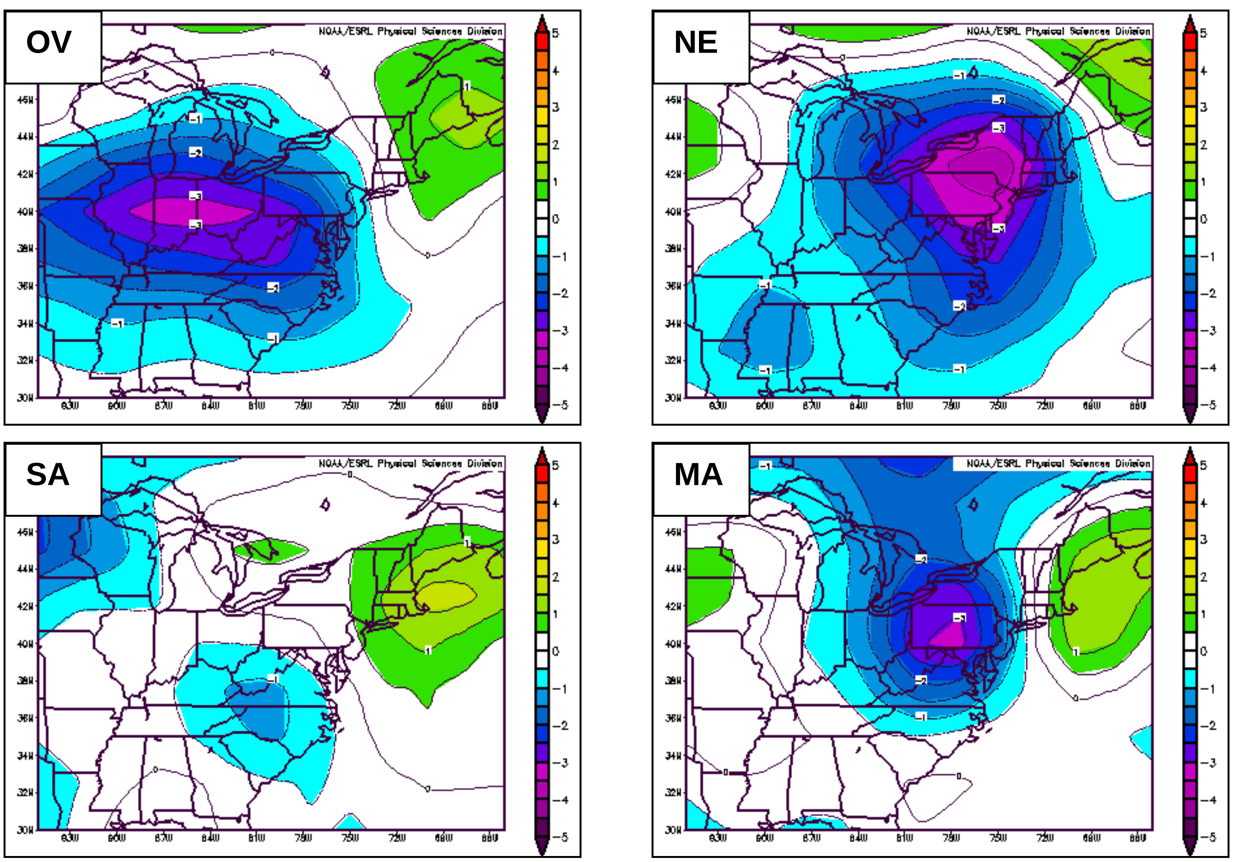

Fig 11b. As in fig 11a, except daily composite anomalies.