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Analysis of the Western U.S. Winter Storm 3-7 January 2008: Part II - a Forecasting Perspective using Ensemble Datasets

CHRIS SMALLCOMB
National Weather Service, Weather Forecast Office, Reno, Nevada

RANDALL GRAHAM
National Weather Service, Weather Forecast Office, Salt Lake City, Utah

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ABSTRACT

The major winter storm that affected much of the western United States from 3-7 January 2008 will be assessed using ensemble prediction system (EPS) datasets in the forecasts leading up to the event. It will be shown that the consistent trend of lowering spreads, increasing anomaly magnitudes, and rising probabilities in successive ensemble forecasts led toward significant lead times in issuing outlook statements and winter storm warnings for this event. Examples of specific datasets readily available on the Internet are shown throughout the article.

1. Introduction

Within the past decade research has shown how standardized anomalies are an effective tool in the forecast process. Of recent note, Stuart and Grumm (2006) demonstrated the use of standardized anomalies in predicting significant East Coast Winter storms. Junker et al. (2008) analyzed 500 hPa height, precipitable water, and 850 hPa moisture flux anomalies in relation to prolonged heavy precipitation episodes in northern California. In addition, Junker et al. (2009) showed the utility of using standardized anomalies derived from ensemble guidance to anticipate rare precipitation events along the west coast. Toth et al. (2001) demonstrated the value of using climatic data and ensemble spread to distinguish between forecasts of small and large uncertainty. It was found that forecasts that converged toward a similar solution typically were more likely to verify and were therefore associated with lower uncertainty. As forecasts converge toward a common solution, the spread decreases thereby leading to larger climatic anomalies in the ensemble prediction system (EPS). A skillful EPS will also provide forecasters

Corresponding author address: Chris Smallcomb, National Weather Service, 2350 Raggio Parkway, Reno, NV 89512
E-mail: chris.smallcomb@noaa.gov

with information as to the most likely outcome associated with a particular forecast period as well as offering insight into alternative outcomes of the event and possible extreme solutions (Buizza et al. 1999, Sivillo et al. 1997, Fritsch et al. 2000). Utilizing ensemble mean and spread, as well as spaghetti plots, forecasters can gain insight into the level of uncertainty associated with a particular forecast.

The objective of this article is to analyze NCEP GFS Ensemble (GEFS, Buizza et al. 2005) spread and anomaly forecasts leading up to the major winter storm of 3-7 January 2008 in the western United States. A d(Prog)/d(t) approach, comparing successive forecasts for the same valid time period, will be used to demonstrate where ensemble spread and anomaly information could be leveraged to improve the forecast. Graham et al. (2009a) summarized the impacts of this storm across the western United States and correlated them to analyzed anomalies. Although the event impacted much of the western U.S., this review will focus on the NWS Reno area of responsibility (Fig. 1) due to the first author's more intimate knowledge of local forecaster intentions. The precipitation magnitudes of the January 2008 event combined with high winds created blizzard conditions across the Sierra Nevada region. In the Reno, Nevada and Lake Tahoe areas, many people purchased food and other supplies in anticipation of being unable to do so during and immediately after the storm, in part due to the forecasts of a potentially historic winter storm event. This event demonstrates that anomalies derived from ensemble forecasts can be utilized to provide critical information well in advance of a high impact event. *Forecasters made proper use of spread and probabilistic data to* ***increase confidence****, and anomaly data to heighten* ***awareness of a high-impact event*** *of historical proportions occurring.*

After a brief data and methodology description in section two, sections three and four will describe the ensemble forecasts for this event, with section five discussing how this data can be used to assess confidence in a high-impact event occurring in the extended portions of the forecast.

2. Data and Methodology

GEFS forecasts from 27 December 2007 to 1 January 2008 will be examined, valid for the period 4-5 January 2008. This defines the "long term" portion of the forecast for most National Weather Service (NWS) offices. GEFS graphics shown in this discussion are from the Pennsylvania State University Meteorology Department website (http://eyewall.met.psu.edu/ensembles/) and are readily available to forecasters for operational use. While western U.S. centered images would be useful for this particular paper, the images presented are the ones available to forecasters on the web so the authors figure there's value in using those over customized plots.

For additional information on the creation of these graphics, readers are encouraged to review Grumm and Hart (2001). Any assertions as to the thoughts or actions of local forecasters were gleaned through personal communication during or after the event. Date/time references will use DD/HHMM format; all times are assumed to be UTC.

3. Large Scale Pattern

Early indications of a large-scale pattern favorable for a significant event became evident with the 27/0000 GEFS run. At this time, most individual members depicted a deep upper trough off the Pacific Northwest coastline valid at 04/0600 (Fig. 2), a 198 hour forecast. This is a favorable upper trough position for heavy snow in the Sierra Nevada Mountains (O'Hara 2007). While the GEFS indicated moderate to high spreads, exceeding 80 meters, in and west of the mean trough axis, there was still a consensus between most of the members in developing an amplified wave at 500 hPa off the Pacific Northwest coast. A 500 hPa height anomaly of -2 standard deviations (SD) was forecast in the center of the trough from the GEFS mean (Fig. 2).

A d(Prog)/d(t) analysis valid at 04/0600 showed increasingly negative forecast anomaly values toward the valid time within the aforementioned upper trough (Fig. 3). Early on in the forecast (27/0000 GEFS), spread fields indicated that uncertainty lie in both the phase and amplitude of the main trough, with a relative maximum in spread (1 SD of 60-80 m) located from the base of the mean trough westward. Two sets of clustered solutions were apparent, with one showing a deep tough immediately off the Pacific coastline and the other showing a less amplified and further west position. As the forecast evolved, the primary uncertainty became the amplitude of the upper trough, as indicated by the relative maximum in spreads located within the mean trough axis. However, the maximum spread decreased substantially in subsequent forecasts, with areas of 1 SD greater than 60 meters disappearing starting with the 31/0000 GEFS. As the 500 hPa height spreads decreased, the anomalies increased to greater than -3 SD in the 30/0000 GEFS forecast (126 hours) at the center of the upper trough. When examining the EPS mean, spread is an important component in the output of significant anomalies. If the EPS were to have significant spread or exhibit a bimodal distribution (grouping of members into two distinct solutions), it is much less likely to produce significant anomalies. Therefore, consensus of a majority of EPS members plays a role in the forecast of significant anomalies. Given the underdispersive nature of EPSs (Eckel and Mass 2005), there is always the possibility that significant anomalies forecast by the EPS could be the result of underdispersion rather than the result of a true high confidence forecast.

Consistent with the spread/anomaly plots, a d(Prog)/d(t) analysis of the NCEP Relative Measure of Predictability (RMOP, Toth et al. 2001) at 500 hPa indicated increasing confidence of a substantial trough developing off the Pacific Northwest coastline. More information on the RMOP can be found in the reference, but the general idea is that when many ensemble members fall into the same group/cluster as the ensemble mean the atmosphere is inherently more predictable than when they are spread out. In the RMOP, heavier weight is given to more recent ensemble forecasts. After two unsettled cycles of the GEFS, the ensemble mean settled on a solution starting with the 28/0000 forecast (Fig. 4). According to the RMOP charts, a widespread area of greater than 90% predictability and greater than 50% probability was depicted associated with the large scale trough encompassing much of the western U.S. and northeast Pacific Ocean basin. Given the rarity of this event, the fact that the predictability was this high this far out in the forecast is significant.

Similar to the 500 hPa height spreads and anomalies, the GEFS MSLP fields indicated the potential for a major event. MSLP spreads associated with the surface low of between 4-8 hPa were forecast by the 28/0000 GEFS. These values are relatively modest considering the length of the forecast. They dropped to below 2 hPa in the 01/0000 GEFS valid at 05/0000. Directly linked to the spread trends, the spaghetti plots of the 992 and 1008 hPa contours were highly variable in the 27-29/0000 GEFS forecasts; however they started tightening up with the 30-31/0000 model cycles. The lower spread and the general trend increased confidence in the ensemble mean verifying since most of the contours were clustered around the mean solution.

As spreads decreased in successive GEFS forecasts, the magnitude of the MSLP anomalies increased appreciably within the surface low off the Pacific Northwest (Fig. 5). The anomalies were already considerable at the beginning of the forecast analysis period; the 28/0000

GEFS showed maximum anomalies of at least -3 SD associated with the mean surface low valid at 05/0000, eight days in advance. Starting with the 31/0000 GEFS cycle, widespread -4 SD anomalies were forecast stretching from near the mean surface low center into Oregon and Washington at the same valid time. The return period for a MSLP anomaly of -4 SD across the western U.S. is about once every five months (Graham and Grumm 2009b), however these anomalies persisted for additional valid times (not shown), making the cumulative occurrence even more rare.

4. Wind and Precipitation Fields

With a significant MSLP anomaly forecast over the Pacific Northwest, the GEFS mean indicated a corresponding tight MSLP gradient over California and Nevada. This implied significant upslope flow impinging on the Sierra Nevada at 05/0000, a pattern favorable to producing heavy precipitation and strong winds. A recurring challenge to local forecasters is whether or not precipitation will make it past the barrier of the Sierra Nevada Mountains into western Nevada. Substantial flood events have occurred in Reno, NV due to this "spillover" precipitation (Wallmann and Milne 2007). Ingredients for efficient spillover include, 1) frontogenetical and/or ascending branch jet circulations aloft traversing the Sierra Nevada, 2) decreased static stability, 3) strong crest level winds, and 4) substantial precipitable water (PW) plume interacting with the mountains. Indeed heavy rains did fall in the Reno area on 4 January resulting in localized flooding and almost 25% of the normal annual rainfall (Graham et al. 2009).

Starting with the 29/0000 GEFS, a +1 to 2 SD anomaly developed in the 250 hPa zonal-component wind forecasts valid at 05/0000 (Fig. 6). Far western Nevada, including the Reno area, was forecast to be in the left-exit ascent region of the jet streak, enhancing spillover potential in conjunction with decreased static stability (not shown). An increasing anomaly trend is also noted in the 700 hPa wind fields through the 01/0000 run for the valid time of 05/0000 (Fig. 7). A widespread area of +3 SD meridional-wind anomalies is forecast across the Great Basin, with smaller areas of +3 SD in the zonal-wind fields impinging on the Sierra Nevada. An axis of greater than +4 SD in the meridional-wind field develops over Idaho and Utah beginning with the 31/0000 GEFS, then retrogrades with future runs into Oregon and northwestern Nevada. This data gave forecasters confidence in exceptionally strong winds at 700 hPa, a common pressure level for forecasting ridge-top winds in many western states, which increased confidence in blizzard conditions in the mountains and spillover precipitation in the valleys.

Significant winter storms in the Sierra Nevada region are often accompanied by a zonally oriented moisture plume spanning much of the Pacific Ocean (Adaniya 2007). In this case, while the large scale dynamical fields in the GEFS indicated a major weather event; the initial PW anomaly forecasts from the GEFS were less bullish, though still indicated above average PW values. Starting with the 28/0000 GEFS, PW anomalies greater than +1 SD were forecast valid at 05/0000 across portions on the western U.S., though those were spotty in nature (Fig. 8). Rather abruptly on the 31 December forecast, increased PW anomalies were noted across California and much of the Great Basin. PW anomalies of nearly +3 SD impinging on the upslope side of the Sierra Nevada, combined with the intense 700 hPa flow, were a clear signature of potential for heavy precipitation. The PW and wind fields can be combined into moisture flux anomalies (not shown) which have been shown to be a useful tool in anticipating heavy precipitation in the western U.S. (Junker et al. 2008).

Confidence levels in anomalously high moisture spreading over the Sierra and western Nevada were increased with each successive model run, as spreads in the PW fields fell below 1 mm as early as the 30/0000 GEFS. One of the core products forecasters use to assess confidence levels with ensemble data are probabilistic fields, most notably the probability of precipitation exceedance graphics. Starting with the 28/0000 GEFS, 80% of the members produced at least 1 inch (25.4 mm) of precipitation valid during the 04/1800 to 05/1800 period (Fig. 9), covering the northern two-thirds of California. This is a relatively high probability given the lead time associated with this forecast. Starting with the 29/0000 run, at least 90% of the members met or exceeded the one inch threshold. A rather impressive aspect in the GEFS forecasts at this time was that the areal coverage of the 2.5 inch (63.5 mm) mean contour was large. Considering the coarse resolution of the GEFS (~105 km), this is remarkable.

5. Discussion

The consistent convergence of lowering spreads, increasing anomaly magnitudes, and rising probabilities in successive GEFS forecasts helped increase forecaster confidence in a major weather event occurring. While the trends in the ensemble solutions were certainly favoring a major winter storm, it appears that a tipping point occurred with the 31/0000 GEFS. At this time, a sufficient number of ensemble spread and anomaly products came together to indicate a high confidence in a widespread major winter storm for the Sierra Nevada Mountains and western Nevada valid 4-5 January. Negative anomalies greater than -3 SD were depicted in the 500 hPa height fields associated with the large scale trough off the western U.S. coastline, coupled with small spreads and individual ensemble member solutions clustered around the mean. The RMOP had a large area of close to 80% probability of occurrence associated with this upper trough, further enhancing forecaster confidence. The MSLP spreads based on the 992 and 1008 hPa contours had dropped dramatically as well, in conjunction with strong positive zonal-component wind anomalies at 700 hPa impinging on the Sierra Nevada Mountains.

Adding to this, by the 31/0000 GEFS forecast spreads dropped and PW anomalies had increased substantially upstream of the Sierra Nevada to between 2 and 3 SD above normal. The intense 700 hPa wind anomalies combined with the high PW anomalies is the classic Sierra Nevada heavy precipitation pattern discussed in Junker et al. (2008). Directly related to these anomalies nearly all the GEFS members produced impressive rainfall totals, helping indicate high confidence in a major precipitation event in the probabilistic QPF graphics.

It should be noted that EPSs have traditionally had a significant problem with underdispersion (Eckel and Mass 2005; Jones and Colle 2007). This historical issue with underdispersion limits the ability of forecasters to objectively assess forecast uncertainty as indicated by EPS output (Novak 2008). It is possible that rather than a skillful forecast, the GEFS was simply very underdispersive in this case, though the lack of dispersion still suggested a high probability of a high end event. The high probabilities and low spreads may not be calibrated but are still meaningful.

On a related note, one of the challenges in this research is defining what constitutes a "high spread" versus "low spread" in un-calibrated ensemble output for a given field and forecast hour. It is our assertion based on operational experience that forecast data leading up to this event showed relatively low spread, especially considering the rarity of the event. Durante et al. (2006) developed a forecast confidence product that addresses this concern for near surface atmospheric fields, however relatively little is discussed in the literature about "*typical spreads*" in synoptic scale upper atmospheric variables (e.g. 500 hPa heights).

One of the primary features of the ensemble model forecasts ahead of this event was that the ensemble means in a number of fields were showing anomalous levels. This information was utilized to provide a forecast of a potentially significant weather event, with use of lowering spreads and increasing probabilities to **increase confidence**, and significant anomalies to heighten **awareness of a high-impact event** of historical proportions occurring, as show in the Reno NWS area forecast discussion from 29/1015 (Fig. 10a). It should also be mentioned that the NOAA/NWS Hydrometeorological Prediction Center used the anomaly information to produce long-range forecasts of significant precipitation in this event, as documented in Junker et al. (2009).

While many forecasters primarily use the 500 hPa ensemble data to assess uncertainty and anomalies in the large scale environment, that alone is insufficient to identify an extreme event. As shown in the area forecast discussion issued at 30/1000 (Fig. 10b), the forecaster noted the developing positive anomalies in the 700 mb wind fields. Then, while not having yet reached the tipping point in the GEFS forecasts described earlier, with their increased confidence forecasters at the Reno NWS began issuing strongly worded Special Weather Statements on 30 December, five days in advance of the event (Fig. 10c). Finally, in response to two additional consecutive days of strong anomalies and low spreads in the GEFS forecasts after the tipping point, Winter Storm Watches were posted at 01/2301 for the Sierra Nevada Mountain portions of the NWS Reno forecast area, valid from 04/1800 to 05/1800. These were eventually upgraded to Winter Storm and Blizzard Warnings for the same valid periods.

This paper demonstrated the utility of EPS data in forecasting a rare winter storm with long lead times. It was shown that an optimal combination of spread, anomaly, and probabilistic data from an EPS can help considerably in this endeavor. Future work may include examining EPS data in additional notable weather events of high-impact, along with (perhaps more importantly) looking at lower-predictability events that were not particularly well forecast to see how EPS data may (or may not) have contributed to a better forecast.

Acknowledgements. The author would like to thank the forecasters at NWS Reno for giving him motivation to examine this case in-detail and, more importantly, for actively using EPS products in operations. He would also like to specifically thank Jane Hollingsworth, Meteorologist-in-Charge at NWS Reno, for providing the time and resources allowing him to complete this research. Rich Grumm, NWS State College, PA, provided beneficial initial reviews of this manuscript.

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TABLES AND FIGURES

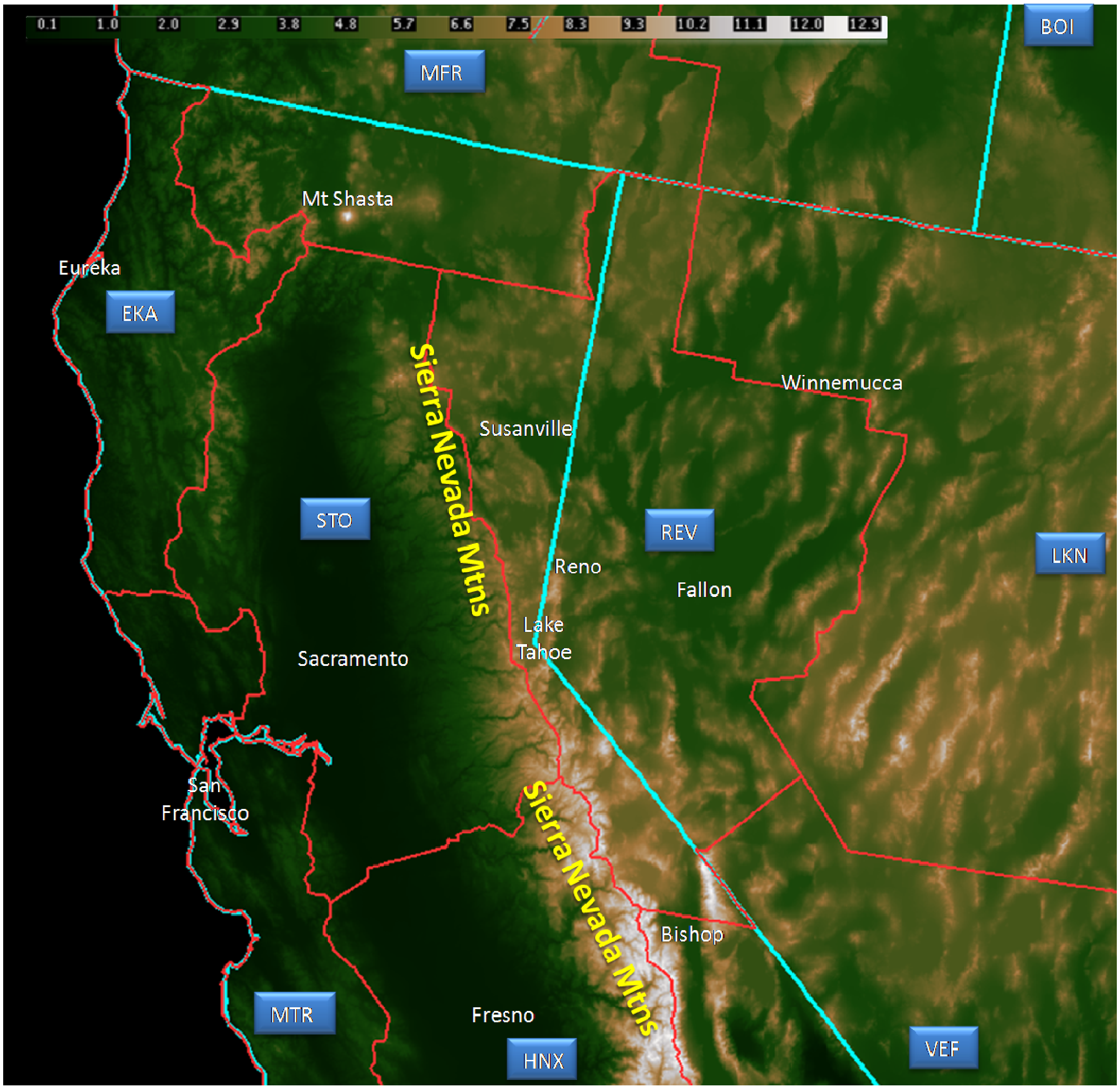

Figure 1. Topographic map showing key locations around the NWS Reno forecast area. The Reno forecast area stretches west to east from the Sierra Nevada crest (elevations approximately 12,000 feet or 3.7 km MSL) to the western Great Basin (lowest elevation ~3,000 feet or 0.9 km MSL). Shading indicates elevations in kft. State outlines in light blue, NWS forecast areas outlined in red with three-letter office identifier in the blue rectangles (REV is Reno's), mountains in yellow, and key locations in white.

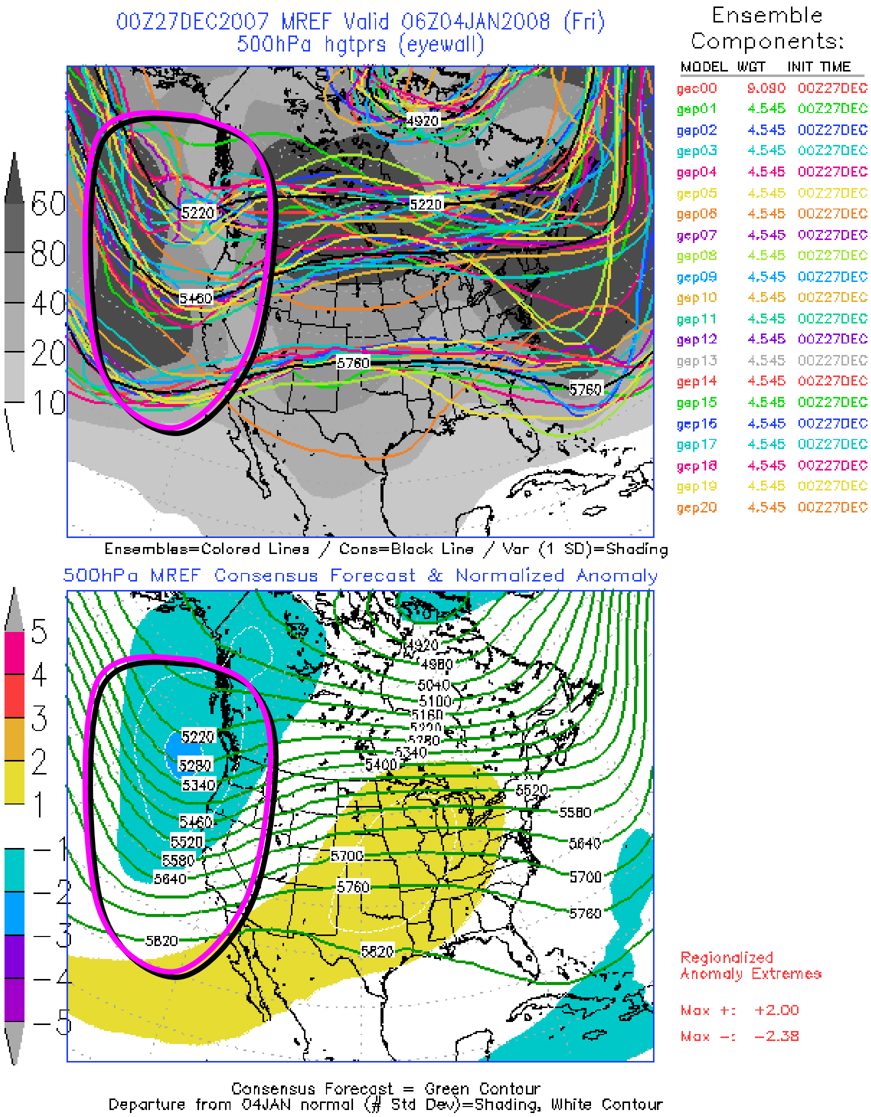

Figure 2. Static image of 500 hPa spread and anomaly data from the 27/0000 GEFS forecast valid 04/0600. The top panel displays a spaghetti plot of the 576, 546, 522, and 492 decameter heights, with individual ensemble members noted by colored lines, and the mean in black. Spreads (defined as the 1 standard deviation level) are shaded in gray, with a scale in meters to the left of the image. Note for this image and any successive 500 hPa charts, the top number in the spread scale is 600 meters (last zero covered up). The bottom panel shows the ensemble mean (green lines) and the anomaly values (shaded). Anomalies shown are in standard deviations. Pink lines indicate features described in the text.

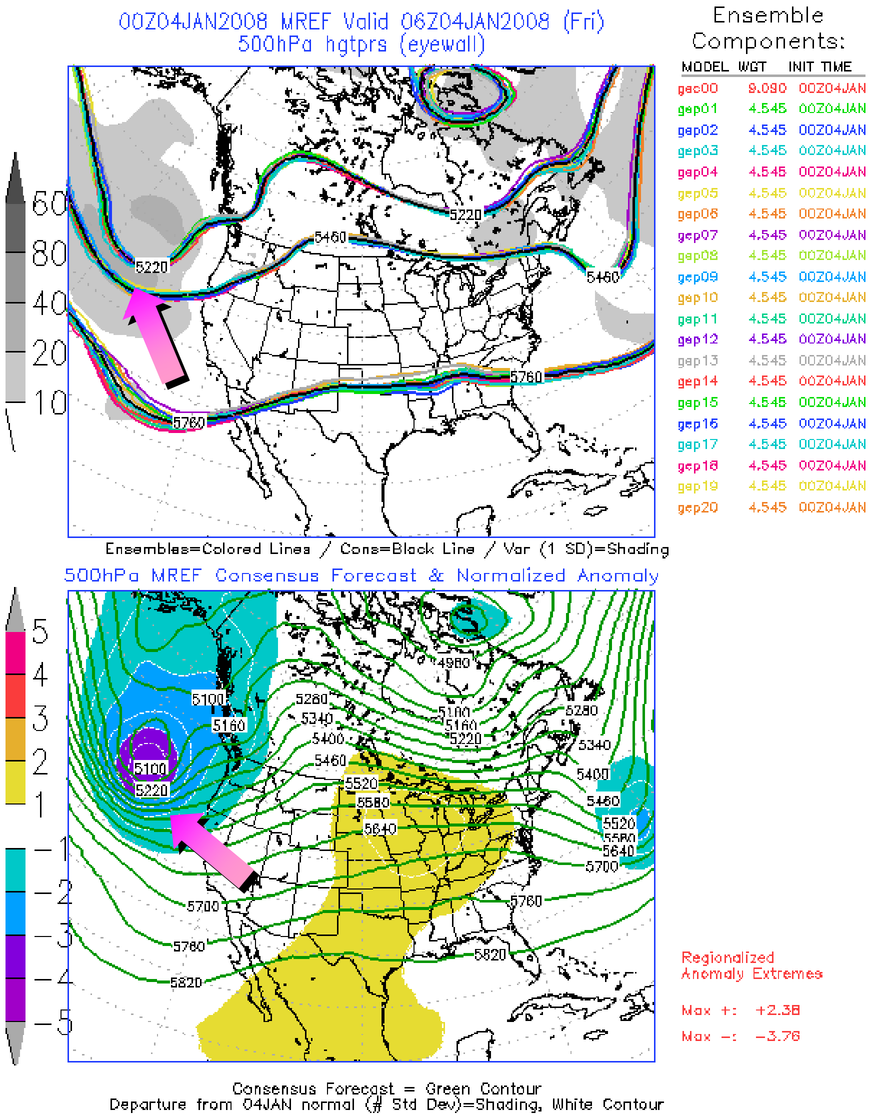

Figure 3. Loop of the 500 hPa spread and anomaly forecasts from the GEFS, all valid at 04/0600. Plots are laid out the same as in Figure 2. The GEFS forecast initialization time is noted at the upper-left of the figure. All runs are initialized at 00 UTC. Pink arrows indicate features described in the text.

NOTE: This figure is an animation. A representative image is shown above. Link to animation.

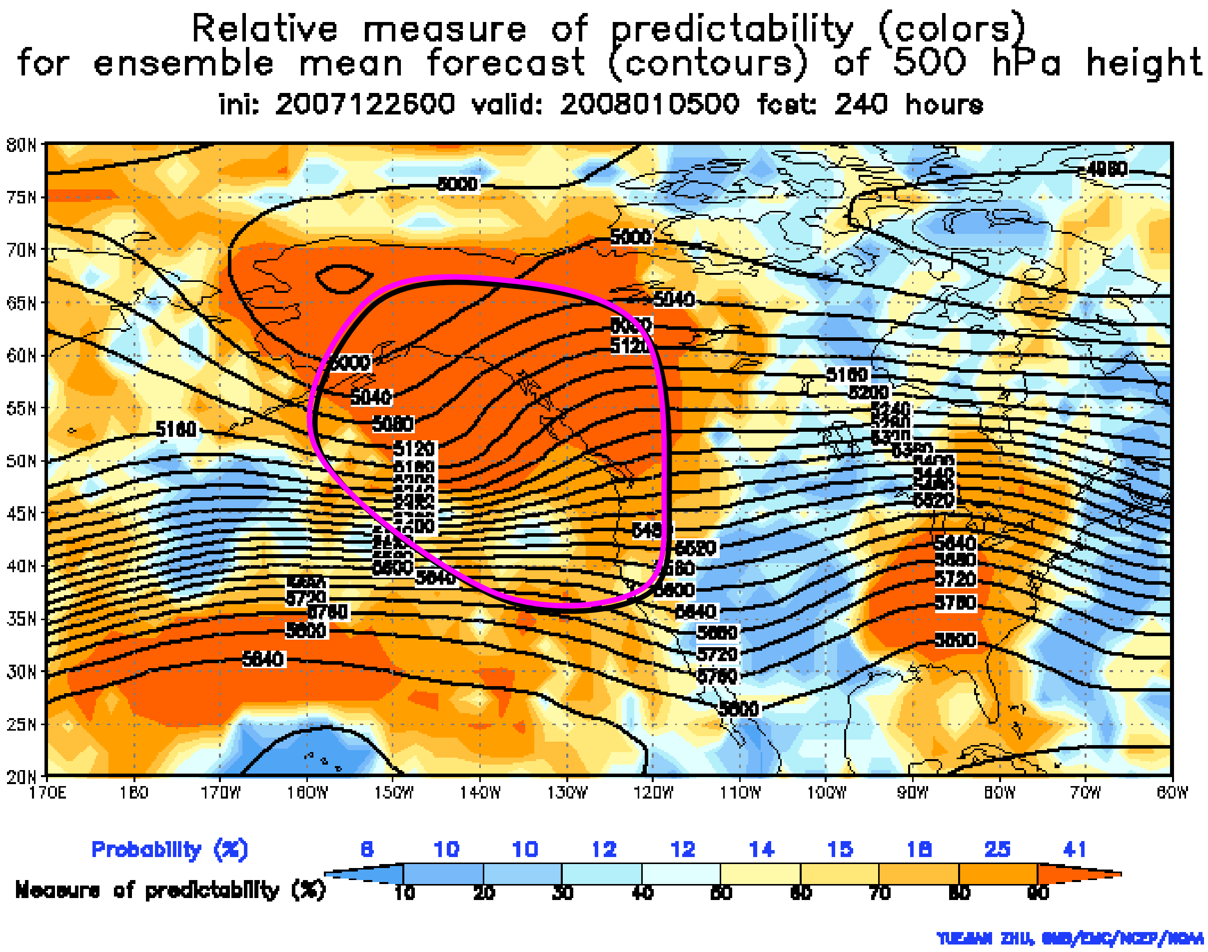

Figure 4. Loop of the NCEP Relative Measure of Predictability (RMOP), all valid at 05/0000. The black lines indicate the GEFS mean 500 hPa heights, with the shading corresponding to the predictability and probability values noted in the color bar at the bottom. The GEFS forecast initialization time is noted following the word "ini:" near the top, in YYYYMMDDHH format. All runs are initialized at 00 UTC. Pink line indicates geographical area described in the text.

NOTE: This figure is an animation. A representative image is shown above. [Link to animation.]

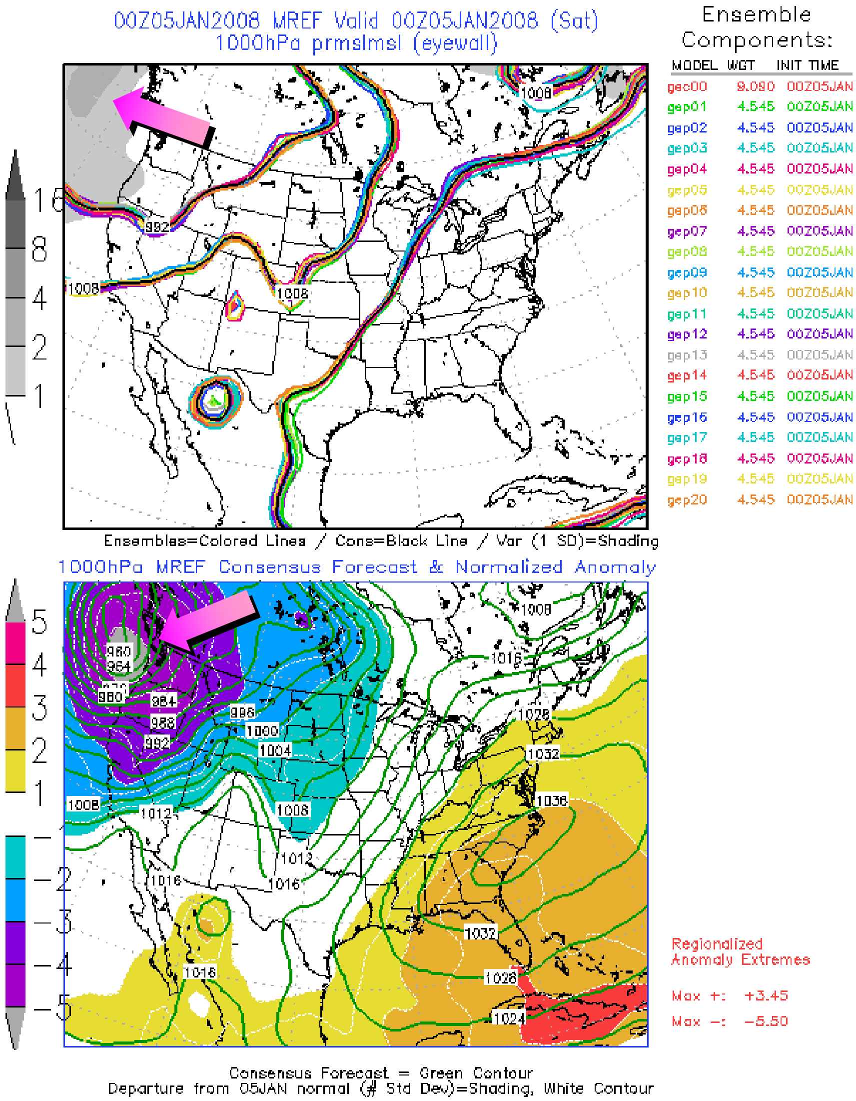

Figure 5. Loop of the mean sea level pressure (MSLP) spread and anomaly forecasts from the GEFS, all valid at 05/0000. Plots are laid out the same as in Figure 2. The GEFS forecast initialization time is noted at the upper-left of the figure. All runs are initialized at 00 UTC. Pink arrow indicates features described in the text.

NOTE: This figure is an animation. A representative image is shown above. Link to animation.

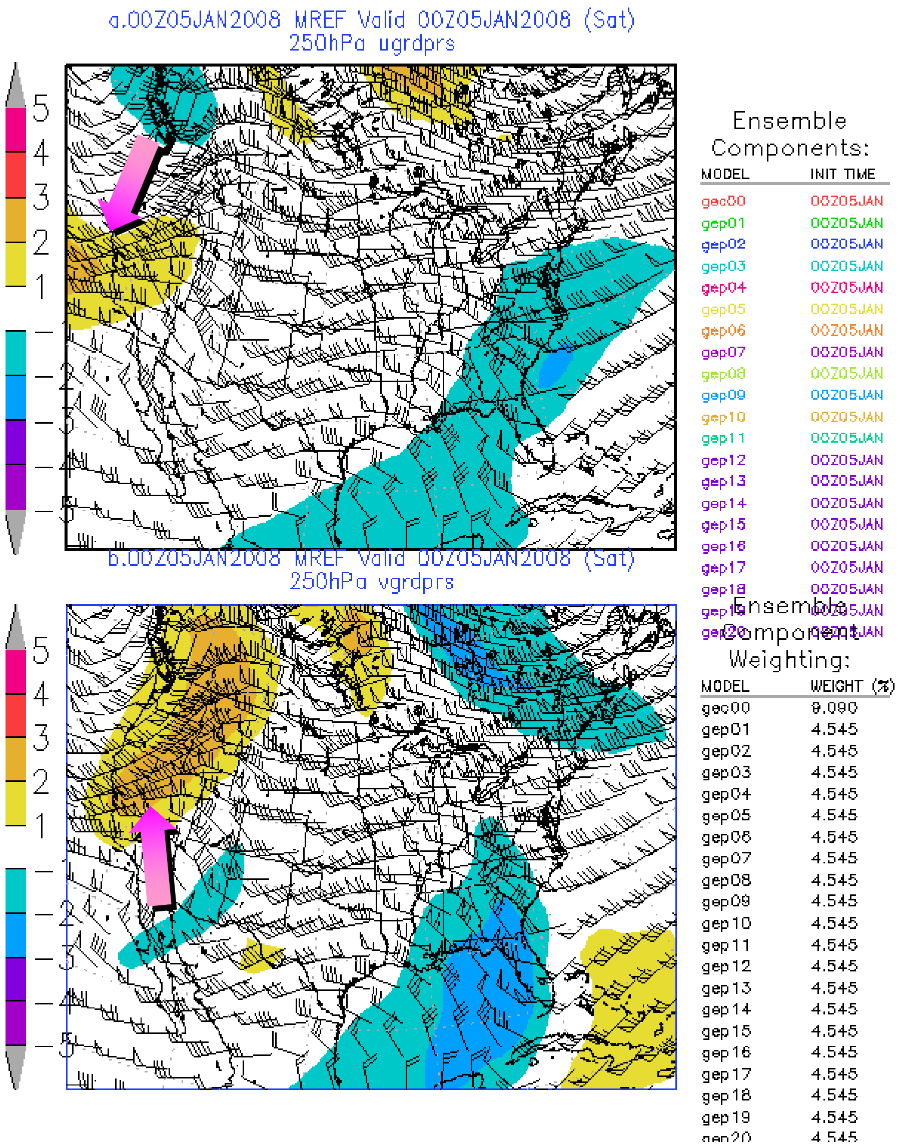

Figure 6. Loop of the 250 hPa mean wind barbs and associated anomalies (shaded). Anomalies are shown for the zonal (top) and meridional (bottom) components to the full wind field. All forecasts are valid at 05/0000. The GEFS forecast initialization time is noted at the upper-left of the figure. All runs are initialized at 00 UTC. Pink arrows indicate features described in the text.

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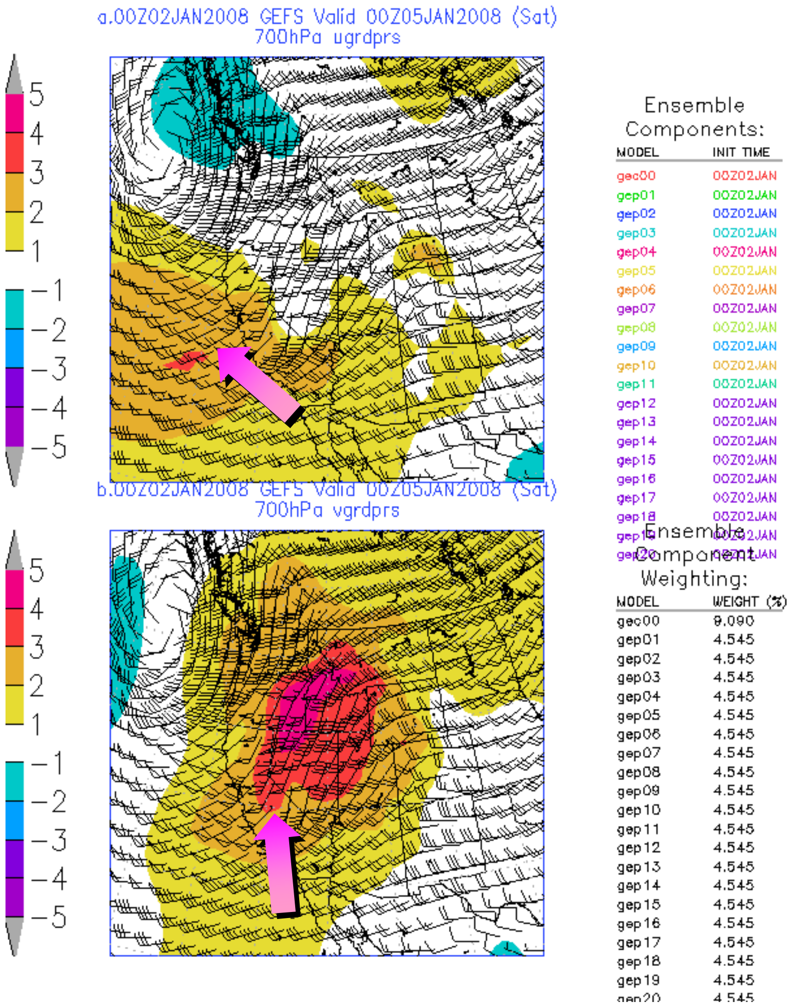

Figure 7. Loop of the 700 hPa mean wind barbs and associated anomalies (shaded). Anomalies are shown for the zonal (top) and meridional (bottom) components to the full wind field. All forecasts are valid at 05/0000. The GEFS forecast initialization time is noted at the upper-left of the figure. All runs are initialized at 00 UTC. Pink arrows indicate features described in the text.

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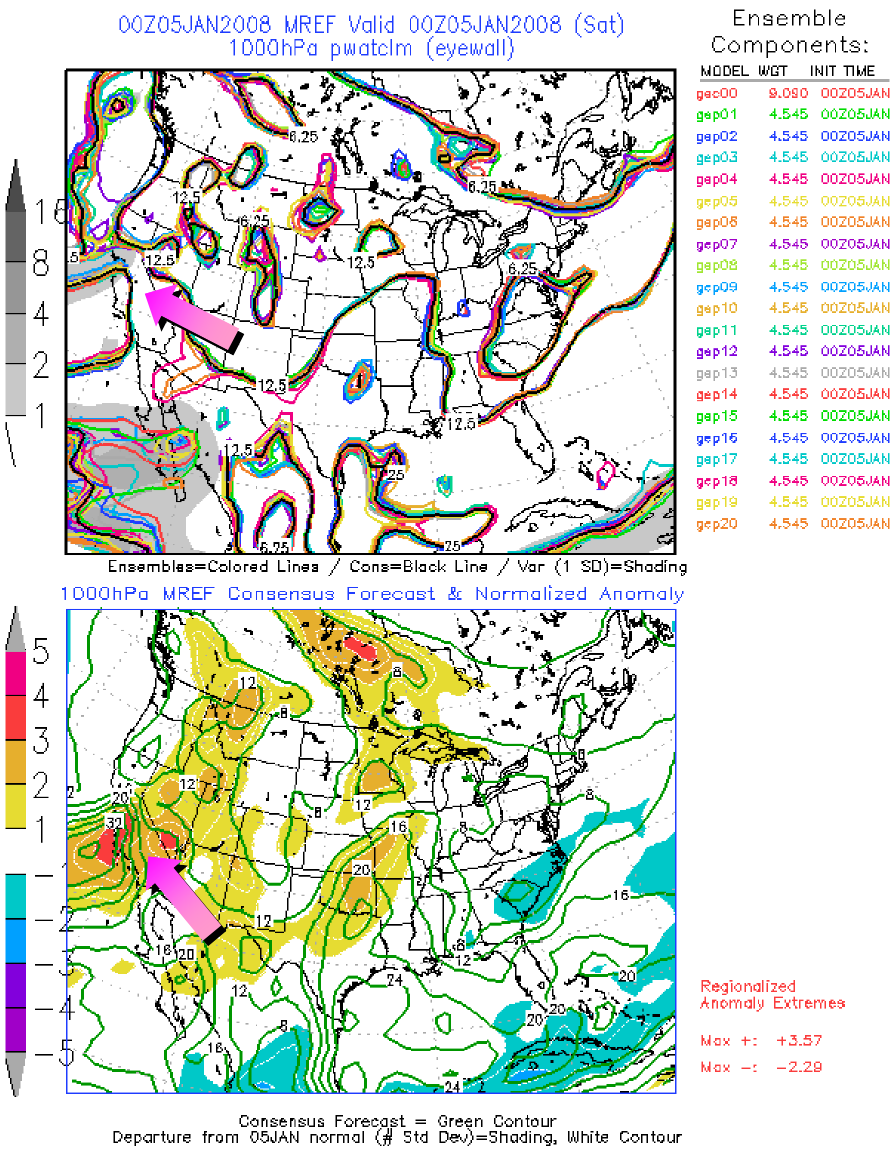

Figure 8. Loop of the precipitable water (PW) spread and anomaly forecasts from the GEFS, all valid at 05/0000. Plots are laid out the same as in Figure 2, except using PW data. The GEFS forecast initialization time is noted at the upper-left of the figure. All runs are initialized at 00 UTC. Pink arrow indicates features described in the text.

NOTE: This figure is an animation. A representative image is shown above. Link to animation.

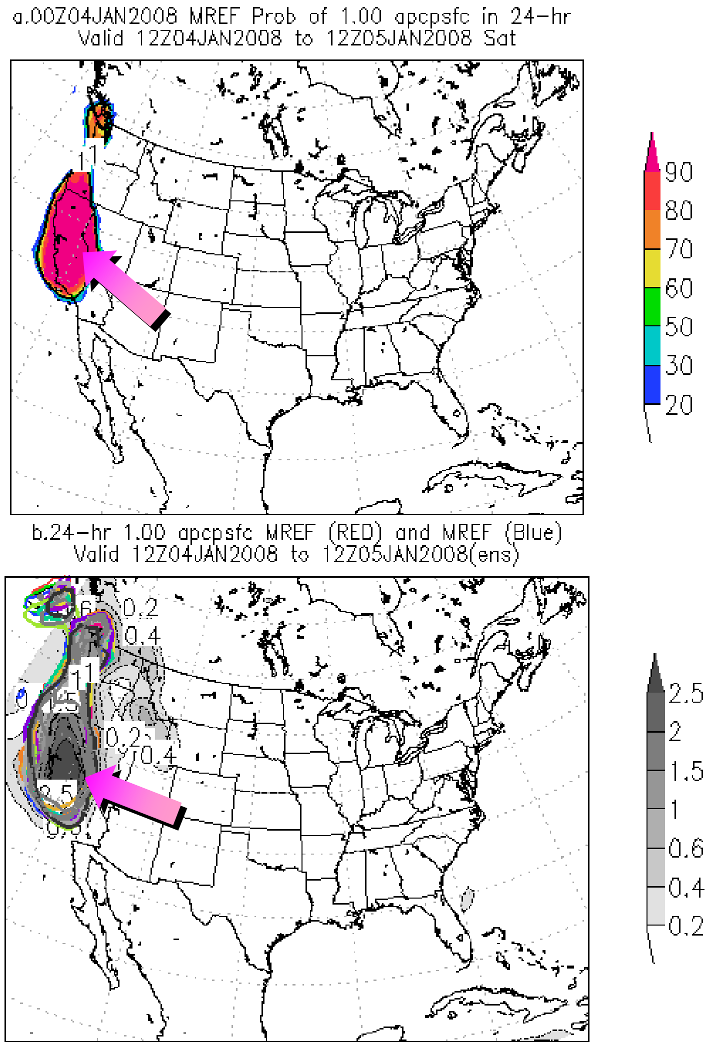

Figure 9. Loop of the probability of exceedance graphics for 1 inch (25.4 mm) from the GEFS, all valid from 04/1200 to 05/1200. The top panel shows the percentage of GEFS members producing at least 1 inch of precipitation during the valid time interval. The bottom panel displays contours of the 1 inch isohyet from each GEFS member (colored lines), with the mean precipitation forecast shaded in gray. The GEFS forecast initialization time is noted at the upper-left of the figure. All runs are initialized at 00 UTC. Pink arrows indicate features described in the text.

NOTE: This figure is an animation. A representative image is shown above. Link to animation.

a)

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THERE CONTINUES TO BE GOOD SUPPORT AMONG BOTH ENSEMBLE AND
DETERMINISTIC RUNS FOR THIS CHANGE AND CONFIDENCE IS GROWING FOR A
TURN TOWARD MUCH WETTER CONDITIONS THURSDAY INTO NEXT WEEKEND.
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b)

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IT IS INTERESTING TO NOTE THE H7 FLOW IN THE GFS PEAKS AROUND 90KT
FRIDAY AND 75KT AGAIN LATE SATURDAY! THESE WINDS ARE JUST ONE
PARAMETER THAT ARE SHOWING STRONG ANOMALIES SUGGESTING THIS WILL BE
AN UNUSUALLY STRONG STORM SYSTEM. PERSONS PLANNING TRAVEL THROUGH THE
SIERRA LATE WEEK SHOULD CLOSELY MONITOR THE LATEST STATEMENTS ON THIS
DEVELOPING STORM SYSTEM.
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c)

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SPECIAL WEATHER STATEMENT
NATIONAL WEATHER SERVICE RENO NV
353 AM PST SUN DEC 30 2007

...PROLONGED PERIOD OF WET AND WINDY WEATHER LIKELY LATE WEEK INTO
NEXT WEEKEND...

CONFIDENCE IS INCREASING WITH RESPECT TO SIGNIFICANT SNOWFALL IN THE
SIERRA. LATEST PROJECTIONS SUGGEST STORM TOTALS BETWEEN 5 AND 10 FEET
OF SNOW ARE POSSIBLE ALONG THE CREST WITH MULTIPLE FEET DOWN TO LAKE
LEVEL AND HIGHER ELEVATIONS ALONG THE EASTERN SIERRA. IN
ADDITION...WINDS ARE FORECAST TO BE UNUSUALLY STRONG WITH A POTENTIAL
FOR WIDESPREAD BLIZZARD CONDITIONS.
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Figure 10. Sections of statements from NWS Reno that are referenced in the text.