Introduction to Ensemble Sensitivity:

The ensemble sensitivity technique does automatically what many forecasters often do manually: it matches patterns and attempts to find a correlation between a forecast pattern and upstream features. Empirical orthogonal functions (EOFs) are used to derive dominant patterns from the ensemble spread. The goal of the technique is to facilitate quick analysis of correlations between forecast patterns and the particular upstream features that determine the final solution. On the webpage developed at Stony Brook University, ensemble sensitivity tools are available for a variety of ensemble systems, including the SREF and GEFS.

How to Use and Interpret Ensemble Sensitivity (Example discussion in red)

1. **Identify a forecast event (Eastern US only) and forecast time of interest (Day 1, Day 2, etc.):**
2. **Go to the ensemble sensitivity webpage**
3. **Choose ensemble forecast system (red buttons: GEFS is the default)**
4. **Identify the geographic region that best captures the potential event (three regions available)**
5. **Click on the "EOFs and MSLP/Spread" link for the forecast day of interest**
    a. **Analyze the mean/spread in the top-left corner (see Fig. 1, top-left).**

Mean/Spread: Note that the mean MSLP forecast shows an intense cyclone centered over western NY. The forecast spread is maximized both west and east of the mean center, suggesting that uncertainty exists in the west-east position of the cyclone center at Day 3.

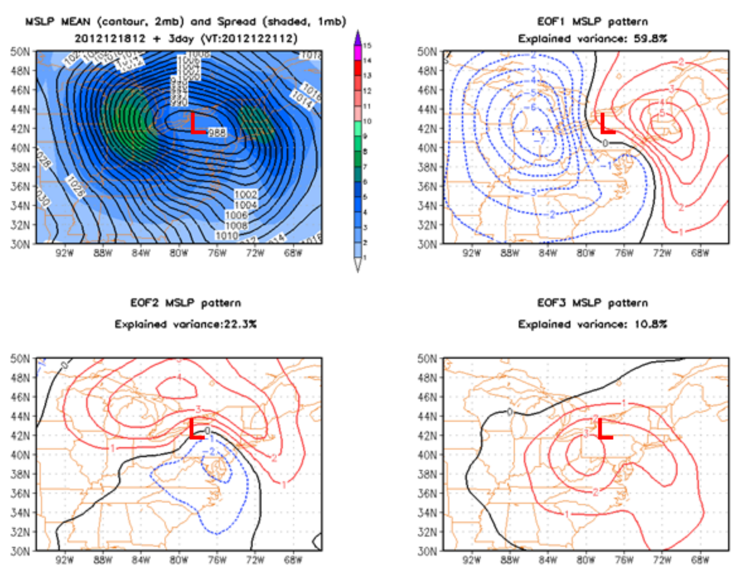


Figure 1: 3-day GEFS forecast of (top-left) ensemble mean MSLP (contoured) and ensemble spread (shaded). The leading EOF (top-right), second EOF (bottom-left), and third EOF (bottom-right) are also shown.

    b. **Analyze the first EOF and determine whether it is a position or amplitude pattern (see Fig. 1, top-right).**

EOF1: The first EOF always explains the highest percentage of the spread. Note the dipole pattern, with the cyclone center near the zero line. This EOF confirms that positional uncertainty is the dominant factor that accounts for most (60% in this case) of the forecast spread. *Dipole = positional uncertainty.*

EOF2 & EOF3: Because these always explain less variance than EOF1, we won't go into detail here. However, note that EOF2 is also a dipole pattern, suggesting north-south positional uncertainty. EOF3 exhibits a monopole pattern, suggesting that intensity uncertainty explains some of the spread. *Monopole = intensity uncertainty.*

6. **Click on the link corresponding to EOF1 sensitivity for the period containing the day of interest (if we're interested in Day 3, click on the "Days 3-0.5" link).**
    a. **Look first at the top-left panel – this is the sensitivity at the valid forecast time (see Fig. 2, top-left).**

Sensitivity: Now that we know the dominant pattern of uncertainty (EOF1: west-east position) for our forecast storm at Day 3, we want to determine what upstream features will influence the west-east position of the storm.

The sensitivity plot is simply a correlation between the EOF pattern and the 500mb heights. EOF1 shows lower pressures to the west of the mean position, i.e. a more westward track. We can imagine that for EOF1 to occur, 500mb heights would need to fall west of the mean storm and rise to the east. In fact, this is shown in Fig. 2 at the valid time (top-left). Translation:

Cool colors: "If 500mb heights are lowered in this region, EOF1 occurs."

Warm colors: "If 500mb heights are raised in this region, EOF1 occurs."

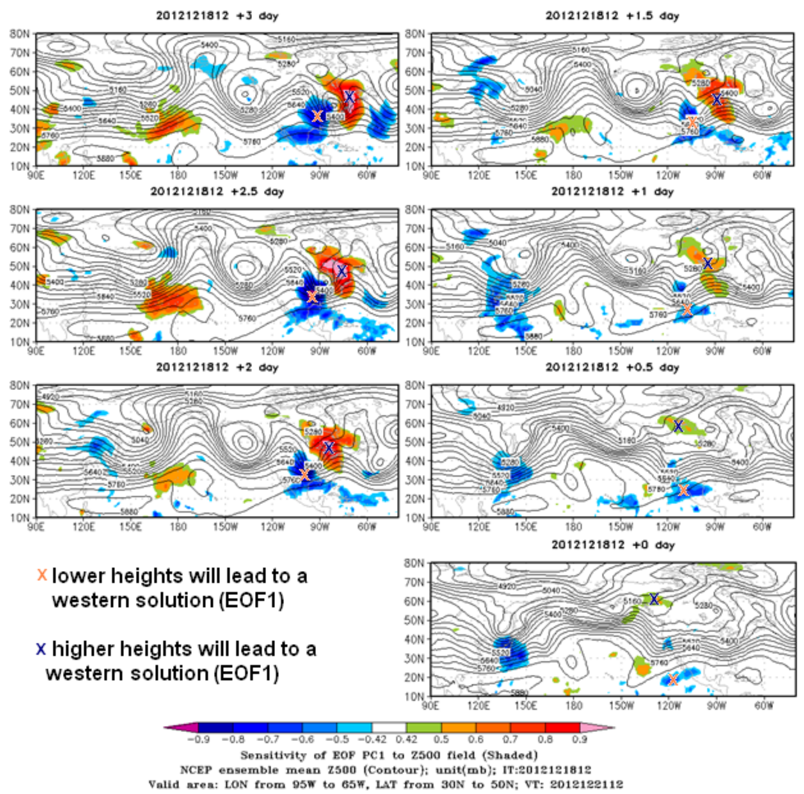


Figure 2: Sensitivity of EOF1 to 500mb heights between the Day 3 forecast (top-left), moving backwards in time to the ensemble initialization at Day 0 (bottom-right).

    b. **Progress backwards in time (i.e., from the valid time (+3 Day) all the way back to the initialization time (+0 day). If a coherent pattern exists at +0 Day, it means that the Day 3**

forecast is sensitive to the model initialization. Is there a particular synoptic feature that is coherent as you progress backwards toward the initialization time?

In this case, a coherent pattern is traceable back to +0.5 days (12hrs after the initialization). This may be about the time we are looking at these products. If we notice lower 500mb heights compared to the mean forecast over the blue region at this time, we may get a hint that EOF1 will come true (western solution at Day 3). Similarly, if we notice higher heights over northern Canada, EOF1 may be more likely. In summary, the west-east position of the cyclone is sensitive to the leading edge of a trough over Mexico, as well as a weak trough in northern Canada.

7. **What does this tell us? Sensitivity analysis:**
    a. **Identifies features in the current pattern that will determine the final solution.**
    b. **Provides a hint about where to watch for deviations from the model forecast.**
    c. **Enables situational awareness about upstream features most critical to the forecast challenge of the day.**

Understanding and Interpreting Ensemble Sensitivity Figures

I. Background:

The ensemble sensitivity is calculated for forecast days 0-6 for three regions on this web page: region1 over the eastern U.S. and western Atlantic, region 2 over the northeast U.S. and coastal waters, and a floater region 3.

A user can select from several model combinations: NCEP (20 members), CMC (20 members), NCEP + CMC, and ECMWF (50 members). Regions 1 and 2 are available for all models, while region 3 works for NCEP only.

To calculate the ensemble sensitivity at each grid point across the full ensemble domain, it requires correlating some forecast metric J_i for each ensemble member in the forecast region of interest (regions 1, 2, or 3) with some state variable X_i (SLP anomaly, 500Z anomaly, etc…, in which the anomaly for each member i is the member minus the ensemble mean) at each grid point across the full domain at the same or different forecast time. The ensemble sensitivity at a point is simply the correlation of J_i with X_i at that grid point within the domain. In other words, if there is a 20-member ensemble, there will be 20 values of J_i and 20 of X_i at each point in the domain to do the correlation at each point. When you view the shaded ensemble sensitivity values, it is simply that correlation number (0 = no correlation; 1.0 = perfect correlation).

Basically, the computer is doing automatically what many forecasters often do manually. Forecasters can take the time to note a subset of members has a similar forecast in a region of interest (e.g, cyclone closer to the coast); then, the forecaster may look upstream and see if those members share a particular feature upstream (e.g. deeper trough, or negative height anomaly at an upstream location). Therefore, the human brain is trying to do pattern matching between members, which is basically the same correlation the ensemble sensitivity is doing, but forecasters would have to view tens or hundreds of maps (and have a very good memory!!) to see these patterns, which is why this ensemble sensitivity was developed. It does all the work for you!!

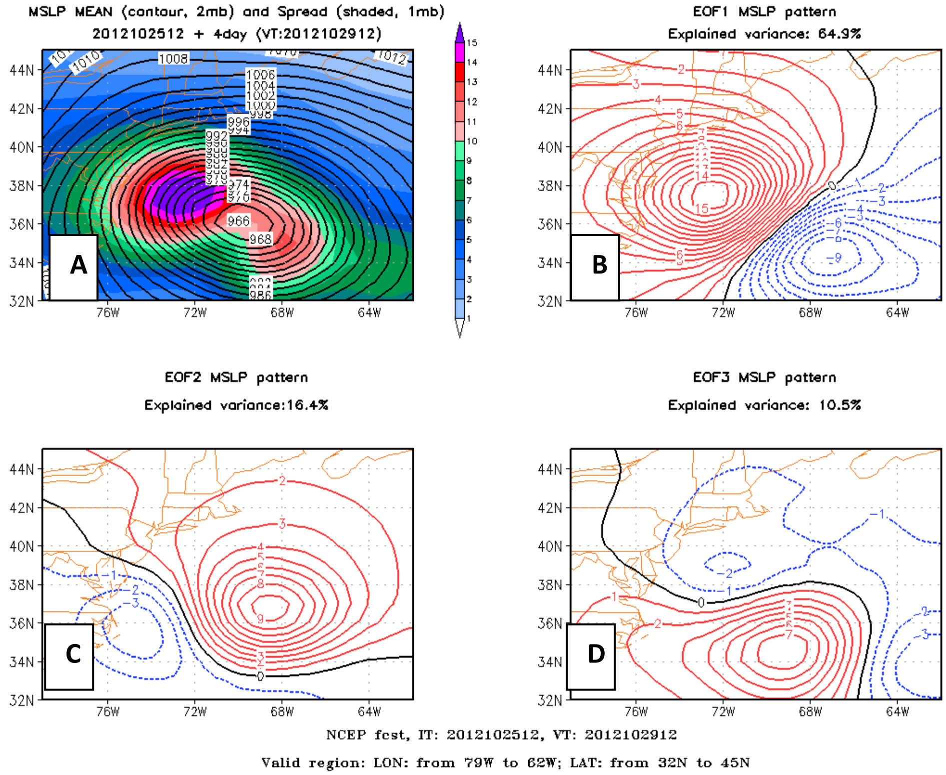
II. Forecast Metric (J) Definition

The ensemble sensitivity is only as good as the forecast metric J that is defined, since it has to be relevant to the forecaster. As noted above, forecasters are often trying to determine why certain members have a particular cyclone position/track or have a deeper or weaker system. They are also often interested in why the most recent ensemble cycle is different with the storm track/strength from the previous run cycle. Therefore, we have defined the forecast metric J using two different approaches.

a. EOF Approach for J

By using Empirical Orthogonal Functions (EOF) applied to the ensemble variance (spread), one can determine those spatial patterns in the spread that explain most of the variability. The EOF summary figures on the web page display the three most prevalent patterns that explain the highest amount of variance between the ensemble members at a specified forecast time. Below, figure 3 shows a sample EOF Summary, with interpretations of what these figures mean and how to read them as applied to a 4-day forecast of hurricane Sandy from the GEFS ensemble initialized at 1200 UTC 25 October.

Figure 3



Plot A displays a summary of the ensemble MSLP, with shading representing the spread in the MSLP between the ensemble members for the Day 4 GEFS forecast for hurricane Sandy. It is evident that there are many members that are pointing towards a more westward track of the system, as seen by the larger spread values to the left of the MSLP minimum.

Plot B displays the EOF pattern that explains the most variance between the ensemble members. In this example, this leading pattern explains more than half of the variance (65%) between the ensemble members for the Day 4 forecast. This pattern that explains the most variance is known as EOF1. For this EOF1, there is a dipole pattern centered around the ensemble mean storm. This pattern presents the uncertainty in the position of the cyclone, either closer to the coast or farther away from the coast.

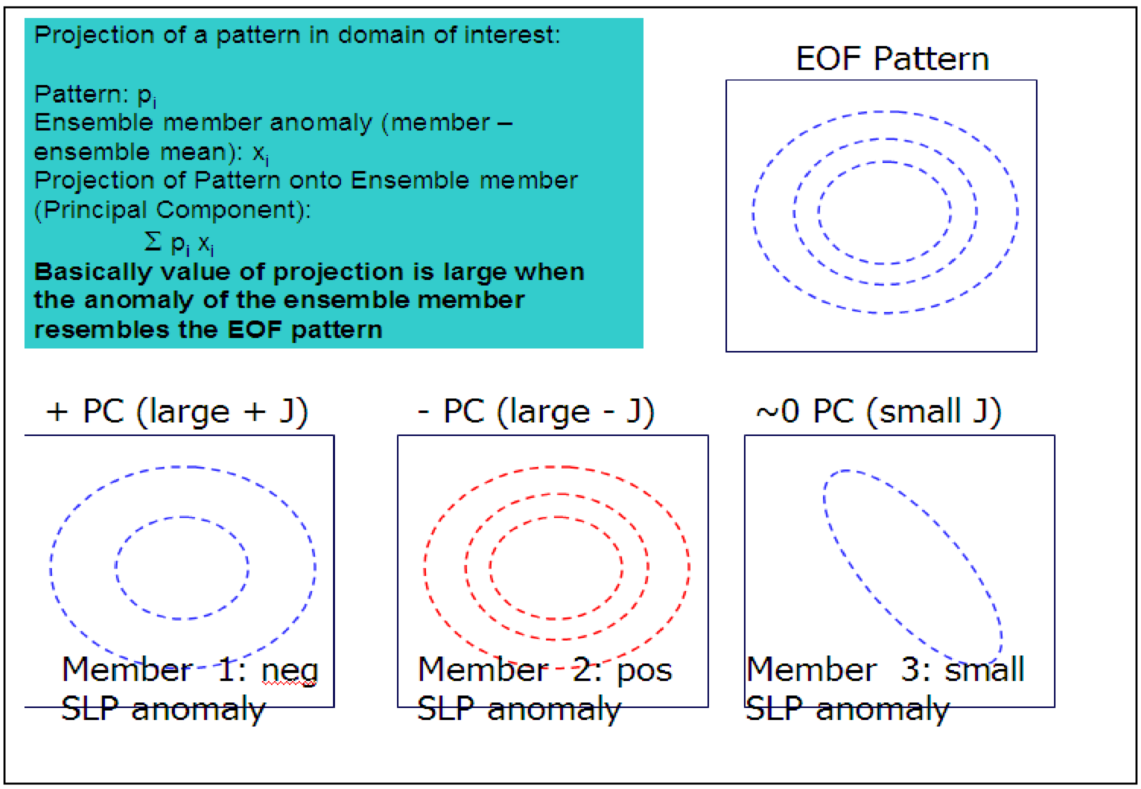
Plot C displays the EOF pattern that explains the second most variance associated with the Day 4 Forecast ensemble members. In this case, 16% of the variance can be explained due to this pattern. This is pattern is known as EOF2. This pattern represents the amplitude of the cyclone, with red lines indicating a weaker storm (seen by the positive SLP anomaly) over the same location as the MSLP low in Plot A.

*** NOTE 1: The ensemble sensitivity is not going to work well if the EOF explains less than 25% of the variance. Therefore, most of the uncertainty with Sandy was for the track/position of the storm. Plot D is not worth considering as well.

*** NOTE 2: The EOF patterns will change for each case, so EOF1 will not always be the position uncertainty. If a particular storm has most of the uncertainty associated with the amplitude, then EOF1 will be the amplitude. Even if a storm has most of the uncertainty associated with position, the dipole can take on different orientation. In other cases, the leading EOF may signify a combination of position and amplitude uncertainties, and the dipole will not be centered around the ensemble mean cyclone position.

To define J, we need to project this EOF pattern onto each of the ensemble member's SLP anomaly (recall, the anomaly = member forecast – ensemble mean). The following figure 4 illustrates what is meant by projection, which statistically is referred to as the Principle Components (PCs) of each of the ensemble members. As seen in figure 2 below, let's assume the EOF pattern represented a deeper system, seen by the blue dashed lines, which represent negative MSLP anomalies. Those members that project strongly also have negative SLP anomalies that match the EOF pattern. These members with strong projections have a positive PC (i.e. member 1), while a member that forecasts a weaker cyclone with positive SLP anomaly though a similar pattern has a negative PC (i.e. member 2) If there is little match in the pattern, the PC is near zero (i.e member 3). Back to the example in Fig. 3 for the dipole pattern shown in Fig. 3B – negative towards the east-southeast and positive towards the west-northwest – a positive projection on this pattern signifies that the ensemble member has the forecast storm displaced towards the east-southeast of the ensemble mean, while a negative projection signifies that the member has a forecast storm more towards the west-northwest closer to the coast.

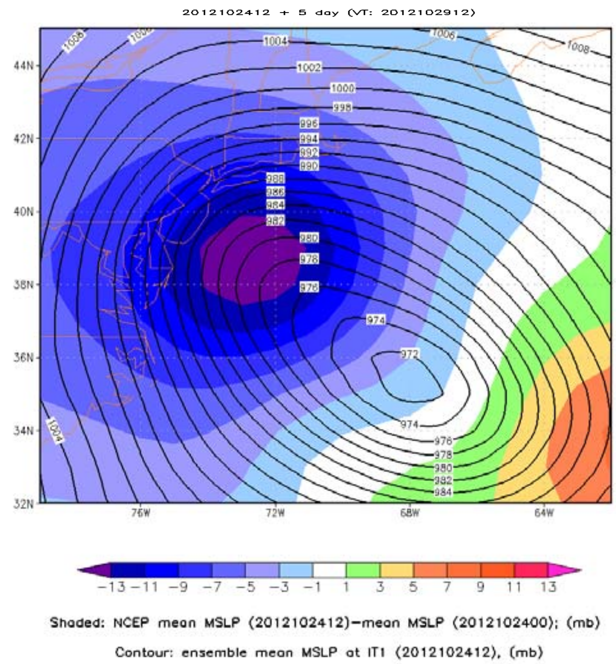
Figure 4



b. Other Approach for J (Using the dModel / dT)

There are many other ways to define J. For example, if one subtracts the ensemble mean SLP forecast between two adjacent run cycles of the GEFS for a cyclone (valid at the same time), you will likely see a patterns similar to the EOFs above. For example, a dipole pattern may result, which would indicate a shifted cyclone track between runs; alternatively, an amplitude pattern may results, which may indicate a weaker or stronger forecasted cyclone from the previous model run. Figure 5 shows the former example, where a current GEFS run has Hurricane Sandy closer to the coast then the previous run, demonstrating a shifted cyclone track. Once again we can use this pattern and project it onto each of the ensemble members to define J. However, because there are two ensemble runs involved, you have to pick which run cycle to project this pattern onto (the most recent or the previous cycle). The ensemble sensitivity option for NCEP dmodel/dt on the web page uses this approach, and there are separate sensitivities calculated depending what cycle you project the difference pattern onto.

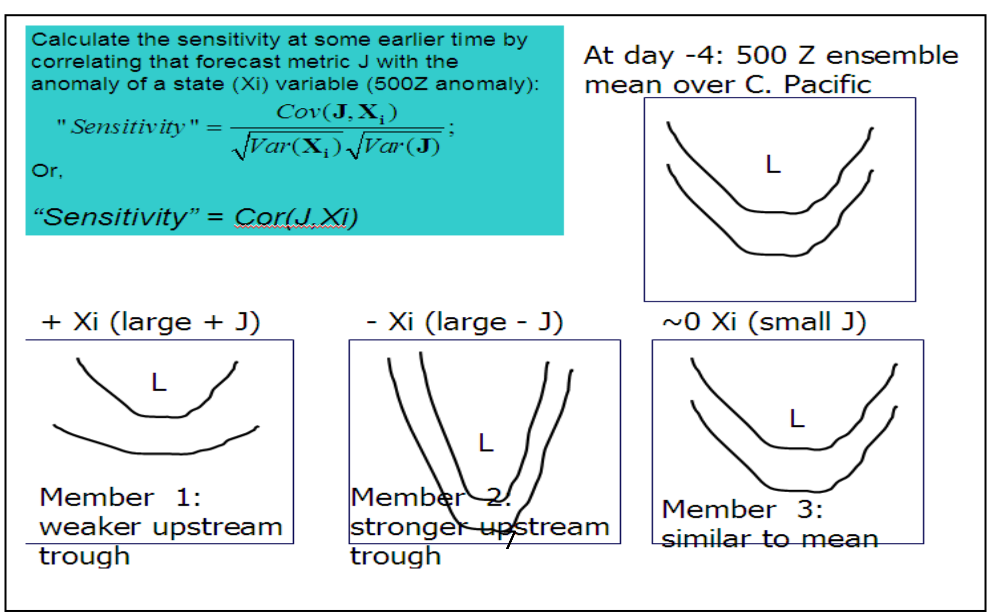
Figure 5



III. The Correlation Step for Ensemble Sensitivity

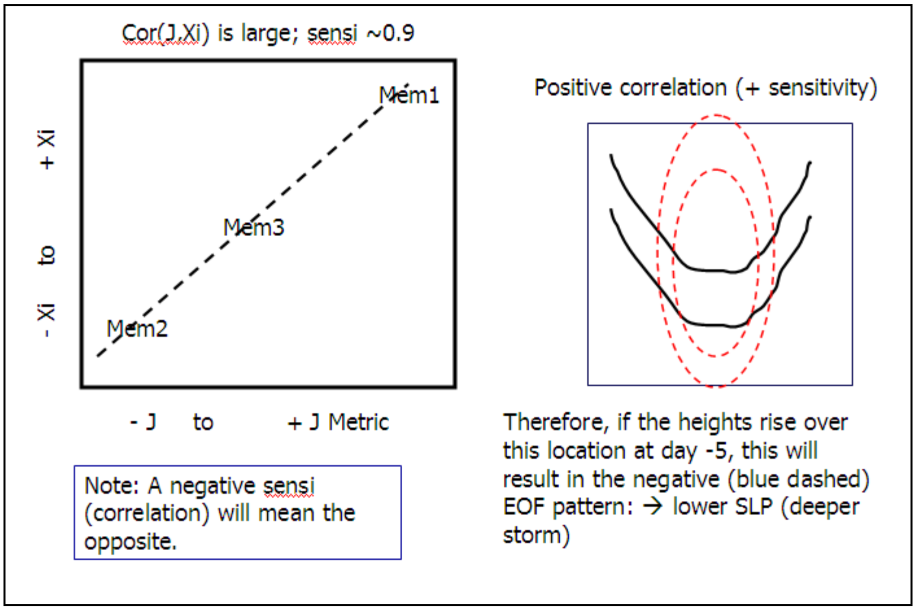
The ensemble sensitivity value at some upstream point is the correlation between the forecast metric J for each member using the forecast region (1, 2, or 3) with some state variable at that upstream point. The below figure 6 illustrates how this correlation works. Let's say we defined our metric J as we did in the previous section – that is as a projection of deeper amplitude pattern onto the individual members of the ensemble; but now we are interested in the upstream sensitivity over the central Pacific 4 days before our valid time. Figure 4 will help illustrate this. There is a trough in the ensemble mean forecast over the central Pacific in the upper right plot, but some members are weaker with this trough (member 1) or deeper (member 2), while

Figure 6



member 3 looks like the ensemble mean. The members with a weak, strong, moderate trough have a 500Z height anomaly (Xi) that is positive, negative, and zero, respectively. Now we can do the correlation between J_i and X_i for the i ensemble members. As illustrated in Fig. 7, there is high correlation in this 3-member example. When the J_i is positive, so is X_i, and visa versa; thus, the sensitivity (correlation) is positive. Therefore, this means if you raise the heights for this trough over the central Pacific, it will reveal the EOF pattern shown above in the previous section (dashed blue = deeper cyclone) 4 days later. For the NCEP GEFS the correlation will involve all 20 members, while the ECMWF involves 50. The more members you have the more robust

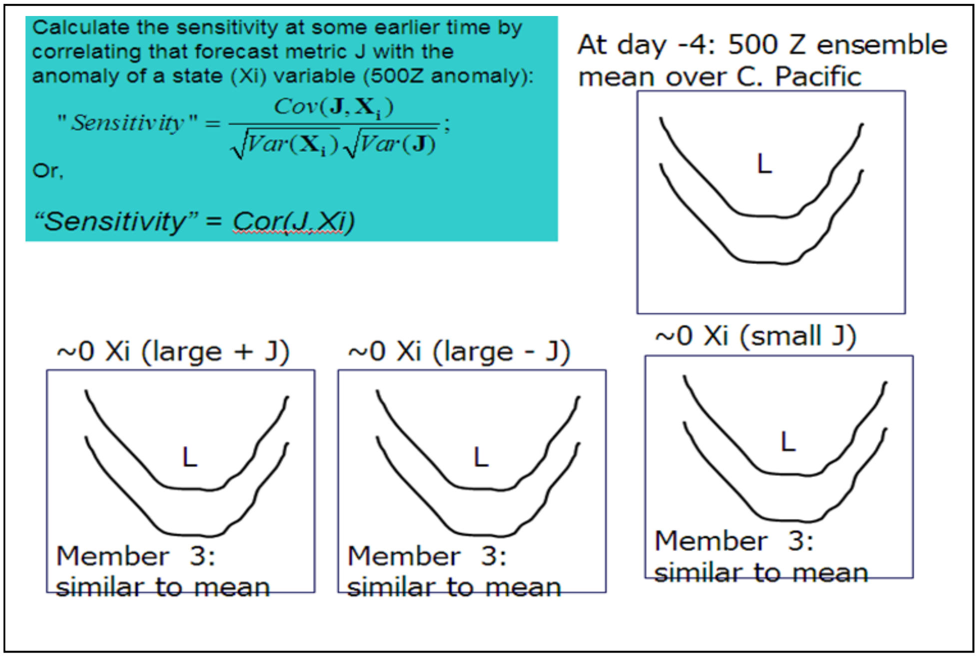
Figure 7



the statistical correlation will be; therefore, we also have a combined NCEP+CMC option, so the number of members is doubled. The sensitivity is only shaded on the web page plots when the correlation is significant at the 0.95 level, which is a correlation of at least 0.42 for the 20-member GEFS ensemble, and 0.28 for the 50-member EC ensemble.

Figure 8 shows another example over this same central Pacific, with the same EOF pattern and J_i (Fig. 4) as the previous example, but in this case all the members are the same at day -4 over the central Pacific. While the X_i anomalies are the same between members, each member has different J_i values as the previous example. As a result, the correlation between X_i and J_i would be very small, and there would be no sensitivity. This makes physical sense, since all the ensemble members have the same solution upstream for the central Pacific trough, yet produce different forecasts within our downstream boxed domain (members have different J_i values) There is clearly no relationship between this Pacific trough and cyclone uncertainty within the downstream box. Forecasters could figure this out by flipping through many maps to realize that this central Pacific trough was the same between members etc..., but the ensemble sensitivity did the work for them.

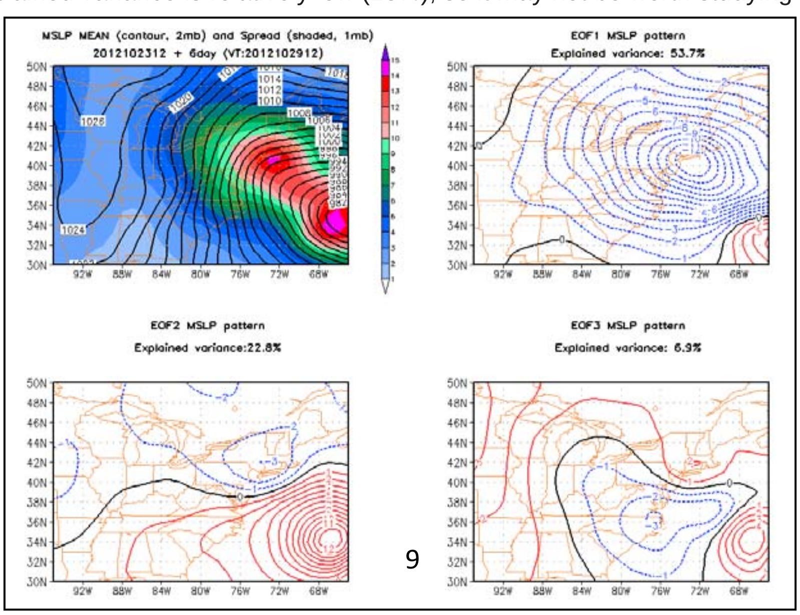
Figure 6



IV. Real Example

Once you understand the basic/idealized example above, you are ready to tackle an actual case using the ensemble sensitivity web page (Figs. 9,10). Let's look at the **day 6 forecast** initialized at **1200 UTC 23 October** for hurricane Sandy (valid 29 October) from the GEFS using **region 1**. Clearly, most of the variance (54%) is associated with EOF1, namely a cyclone closer to the coast (negative/blue dashed lines in EOF1 centered near the coast mean that many members have the cyclone there). EOF2 is associated with the amplitude of the system (a weaker system shown by the positive SLP anomalies located near the MSLP center), but the explained variance is relatively low (23%), so it may not be worth studying in depth.

Figure 9



Now that we know we want to target EOF1, we can select the 500Z (the state variable X_i) under the EOF1 for this 6 day forecast. There are two selections that can be made: a ‘Days 3.5-6’ and a ‘Days 0-3’ plots, which display the ensemble sensitivity evolution from the current time (Day 0) through the forecast day (Day 6). Both plots are shown below. For interpretation, it is best to start with the end of the forecast (day 6) to look at the sensitivity and then work backwards slowly towards the initialization.

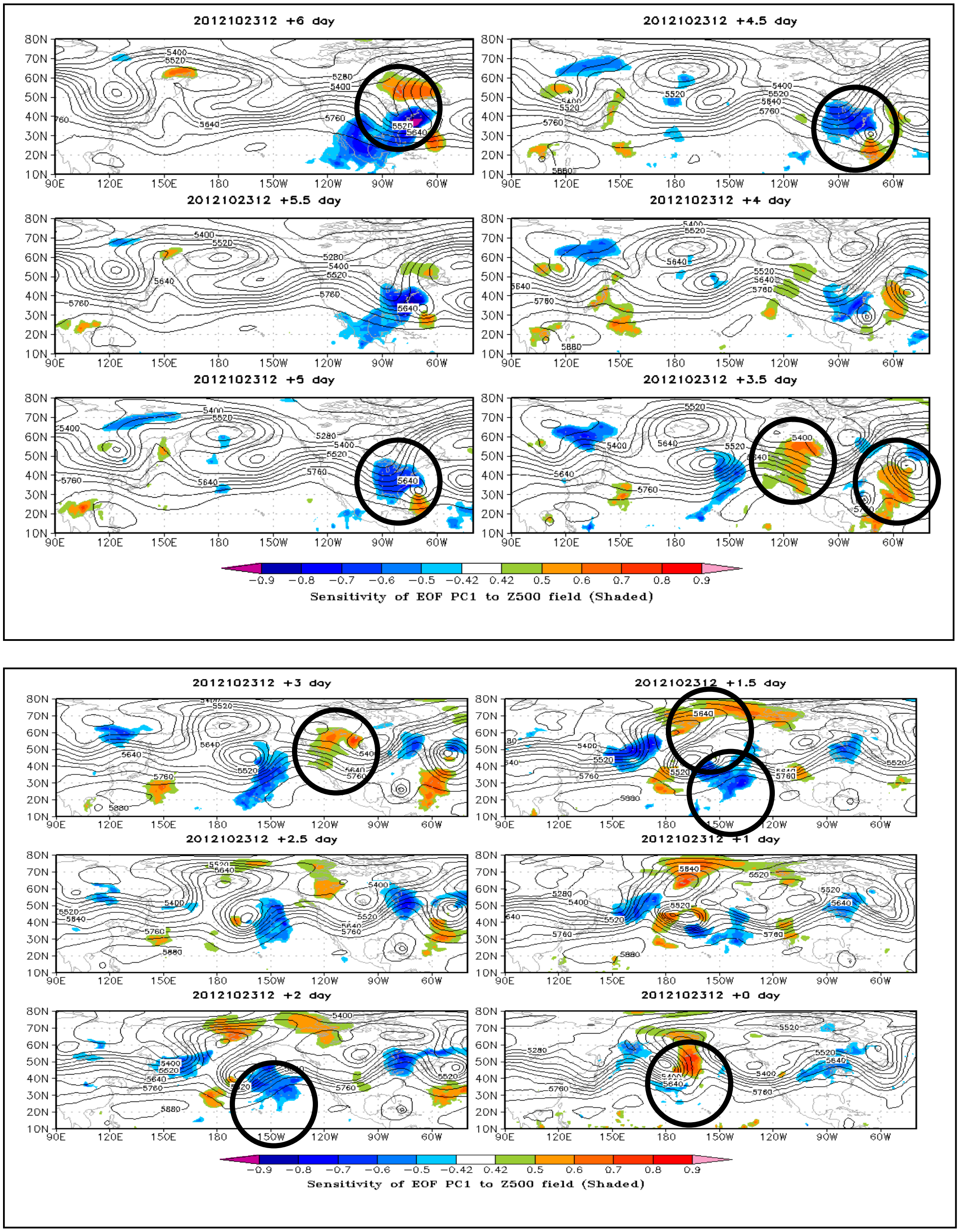
At day 6, we are looking at the same time period as the EOF calculations in the EOF Summary Plots for region 1 at day 6, so there is no surprise that the maximum correlation (sensitivity) is in the region 1 domain. The negative (blue) sensitivity is associated with the trough, and the positive (orange) sensitivity with the downstream ridge. Therefore, a negative sensitivity with the trough means if the heights are lowered it will yield the EOF1 pattern of a cyclone closer to the coast. Meanwhile, if the heights are raised for the downstream ridge, it will also favor the EOF1 pattern of a cyclone closer to the coast.

After looking at day 6, now we can follow this sensitivity pattern backwards towards shorter-lead times for this same 1200 23 October 2012 GEFS forecast in the same figure below. The maximum sensitivity shifts upstream with this trough to the Midwest region at day 4.5, while by days 3.5 to 3, there was a “hand-off” of the sensitivity to an upstream ridge over the western U.S. and British Columbia (positive sensitivity) and eastern side of the trough over the east-central Pacific. Therefore, if you lower the heights just east of this east-central Pacific trough or raise the heights over the western U.S, it is associated with the EOF1 pattern of a cyclone closer to the coast at day 6. There is also some correlation to the east of Sandy at days 3-3.5. Namely, if you raise the heights here, that will also favor a more westward track.

Looking at the days 0-3, the sensitivity can be traced all the way back to the initialization day 0 for the major trough and downstream ridge system over the central Pacific. Note that for many cases this day 0 correlation may not show up, since it takes time for the differences between members to be realized through correlation. A strong day 0 correlation definitely suggests some initial condition uncertainties. There is sensitivity with the ridge that erupts northward into the Arctic during days 0-2, and the amplitude of the base of the central Pacific trough at day 1. If this trough is deeper or higher heights into the Arctic, it is associated with the EOF1 pattern (cyclone closer to the coast).

Note that there are regions where there is relatively large sensitivity far from the U.S. east coast (Siberia at day 3.5). Although there is a correlation here, it is likely a “false” correlation, and not physically linked to our region 1 domain. Some common (meteorological) sense is needed here. Physically, there is no way a disturbance over Siberia at day 3.5 can impact the U.S. east coast at day 6. This is the risk of doing simple correlation, since there can be correlations between members and fields that are meaningless. Therefore, a forecaster has to think physically when interpreting these plots—Does it make physical sense? Usually the most meaningful sensitivity patterns move with important synoptic features (with troughs and ridges and wave packets). This is why it is important to look at a series of times for this ensemble sensitivity, not just jump from the final time (day 6) to the beginning time (day 0). In this case, we can follow the development of this particular negative sensitivity region from day 3.5 to day 6, and in the figure we can see no indications that this negative sensitivity propagates towards the U.S. east coast (either bodily or in form of a wave packet) over these 2.5 days, hence we conclude that this particular negative region is most likely not causally related to the shift in Sandy’s position.

Figure 10:


2012102312 +6 day
2012102312 +4.5 day
2012102312 +5.5 day
2012102312 +4 day
2012102312 +5 day
2012102312 +3.5 day
−0.9 −0.8 −0.7 −0.6 −0.5 −0.42 0.42 0.5 0.6 0.7 0.8 0.9
Sensitivity of EOF PC1 to Z500 field (Shaded)
2012102312 +3 day
2012102312 +1.5 day
2012102312 +2.5 day
2012102312 +1 day
2012102312 +2 day
2012102312 +0 day
−0.9 −0.8 −0.7 −0.6 −0.5 −0.42 0.42 0.5 0.6 0.7 0.8 0.9
Sensitivity of EOF PC1 to Z500 field (Shaded)

After one looks at 500Z, one can look at the SLP evolution for the sensitivity, which is a little noisier typically, but will make more sense after one understands the 500Z evolution.

For the 1200 UTC 23 October GEFS run, the sensitivity moved rapidly downstream with a Rossby wave packet, which created that “hand-off” of sensitivity from the eastern Pacific trough at day0 to the west coast ridge by day 3, and then the mid-west trough by day4.5. There is increasing evidence that the sensitivity (ensemble uncertainty) moves downstream at the speed of a Rossby wave packet, which is much faster (typically speed of upper jet) than the phase speed of the individual troughs and ridges.