15B.2 THE EFFECTS OF MODEL INITIALIZATION ON MODEL FORECASTS OF TROPICAL CYCLONES

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1. INTRODUCTION

Research and experience shows that tropical cyclones are steered by the mean flow in the tropospher, between the surface and 100 hPa, although weaker storms with smaller vertical extents may be steered by the flow at lower levels (Franklin, et. al, 1996, George and Gray, 1976).

The accuracy of track forecasts of tropical cyclones has improved significantly over the last 39 years. The National Hurricane Center (NHC) official 72-hour average forecast track errors have decreased from about 450 nautical miles (nm) to less than 150 nm since 1970. Beginning in 2003, the NHC began to issue official 96 hour and 120-hour forecasts. Although the record for these extended range forecasts is short, they also appear to be improving with time. The importance of being able to forecast the track of a tropical cyclone cannot be overstated. Ships at sea need time to maneuver away from a tropical cyclone, and when storms near land, evacuation plans depend critically on the ability to forecast the track accurately.

Within this general trend in the forecast track errors, there are particular storms that are more difficult than average to forecast accurately. These storms are noted in the reports available on the NHC website in the season archives. Each report contains a section comparing the track errors for the particular storm with the average errors over the previous 5 years. In 2008, for instance, 12 of the 17 storms that occurred had enough forecasts to be statistically significant, and of these 12 storms, only two of them, Hanna and Omar, had track errors larger than the previous 5 year average. In 2009, only 8 storms had enough forecasts to be statistically significant, and of these, 3, Danny, Erika, and Grace had larger track errors than the 5 year average. For 2010, the complete analysis of the season is incomplete, but of the 11 storms with analyzed with enough forecasts to be significant, there were 3 storms (Colin, Danielle, and Lisa) that had larger track errors than average.

Hurricane Lisa of 2010 is an example of such a storm. According the NHC report for Lisa, official forecast track errors were "much larger" than the mean errors for the previous five years, and at lead times of three to five days, were twice as large. For forecasts of lead times of 72 hours, the official forecast track error was 330 nm, compared with the average between 2005 and 2009 of 144 nm. All of the guidance models had average track errors much larger than 144 nm, ranging from 194 nm to nearly 400 nm. Lisa developed from a strong wave that moved off the African coast on 9/16/2010, and slowly gained strength, becoming an official tropical cyclone by 1800 UTC, 9/20/2010. Lisa moved slowly for much of its early life, as the steering currents were weak. The best track plot from the NHC report is shown in Fig. 1.

As can be seen in Fig. 1, Lisa moved slowly to the north, then turned sharply to the east after 1200 UTC on September 21, and weakened for about 18 hours. Lisa began to strengthen again after this, and turned towards the northeast and then the north after 1800 UTC on September 23. It was these two sharp turns, and the eastward motion in between them, that proved difficult to forecast. Most of the model guidance and the official forecast showed Lisa moving northward or northwestward. Figures 2a and 2b show the tracks from a wide selection of the available models, together with the best track, for forecasts made on September 20, 22 23, and 24 all beginning at 0000 UTC.

Notice how virtually none of the model forecast tracks show the storm turning towards the east, and none of them can simulate the two right angle turns in the best track.

In the next sections of this paper we will examine the uncertainty in the initial conditions for the model simulations of Lisa, and will make some comparisons with other storms to gain perspective. In particular, Section 2 examines variations in the initial analyses of the GFS and UKMET global models in the vicinity of Lisa. Section 3 discusses regression calculations based on work by Goerss (2007), and compares this with the spread in the NWS ensemble model member tracks. Section 4 discusses results from model runs using the Advanced Research (ARW) version of the Weather Research and Forecasting model (WRF model). Conclusions are in Section 5.

2. Operational Forecast Models

The initial model grids for the GFS and UKMET global models, as depicted using Gempak software, are shown in Figs. 3, 4, and 5 for 9/20/2010 and 9/22/2010 and 9/24/2010, all at 0000 UTC.

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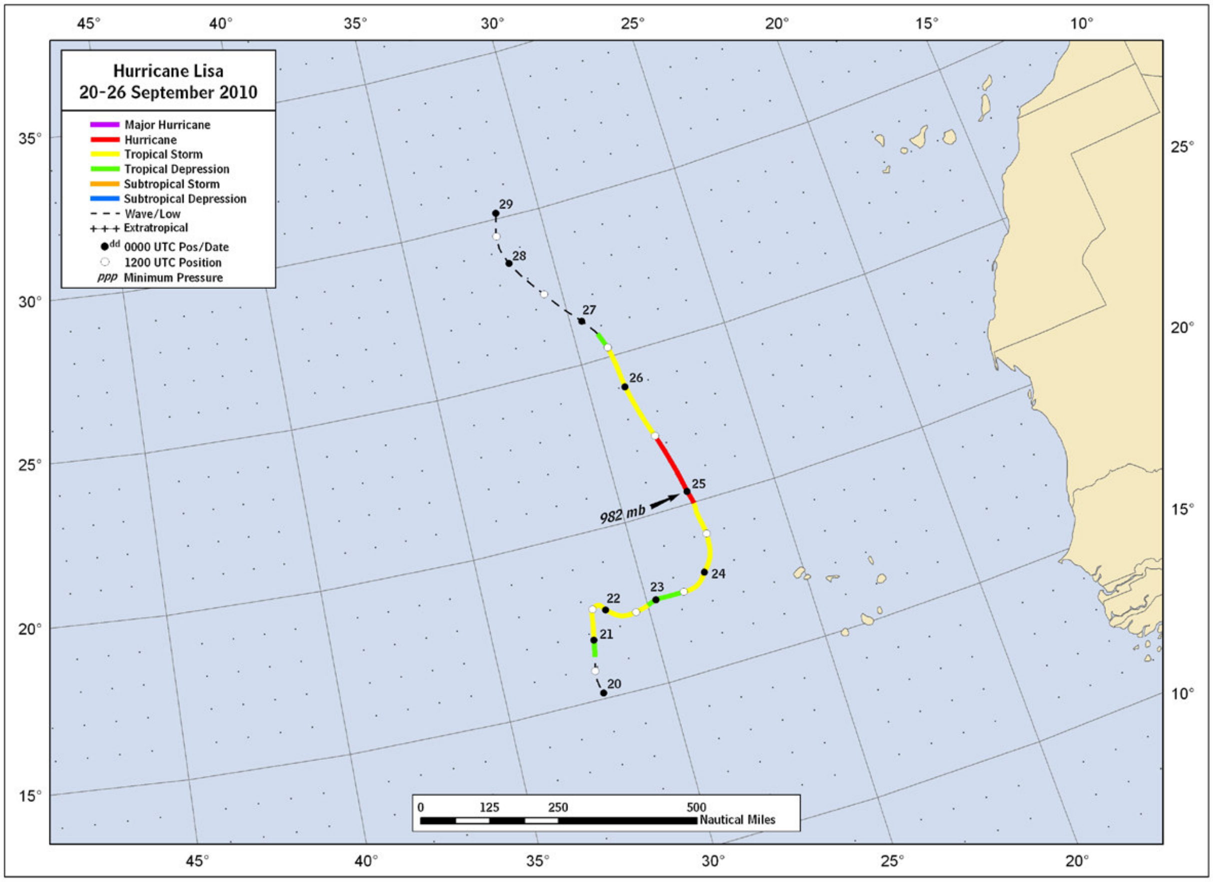
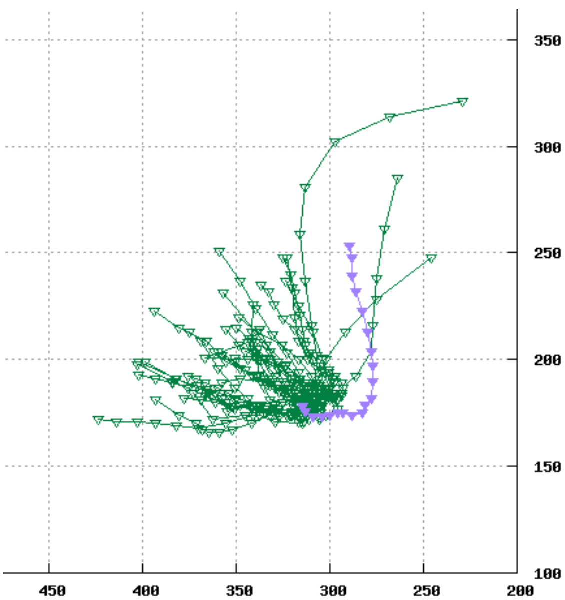


Figure 1. Official National Hurricane Center best track for Hurricane Lisa.



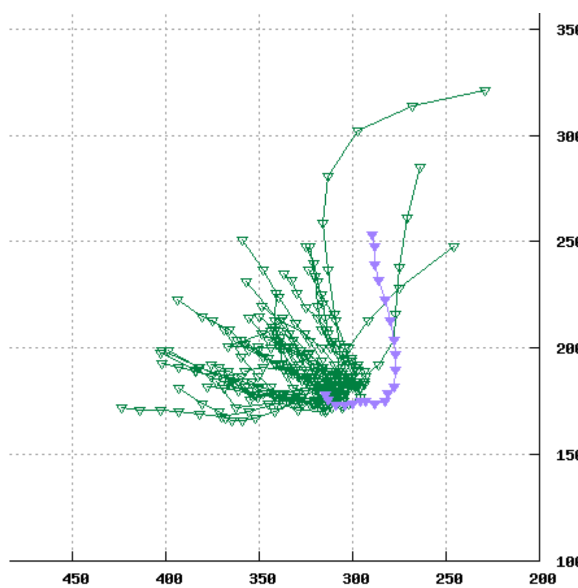


Figure 2a. Model tracks for forecasts for Hurricane Lisa, shown with green triangles. Best track from NHC shown in purple triangles. Left side for forecasts beginning 0000 UTC, September 20, 2010, right side for forecasts beginning 0000 UTC, September 22, 2010.

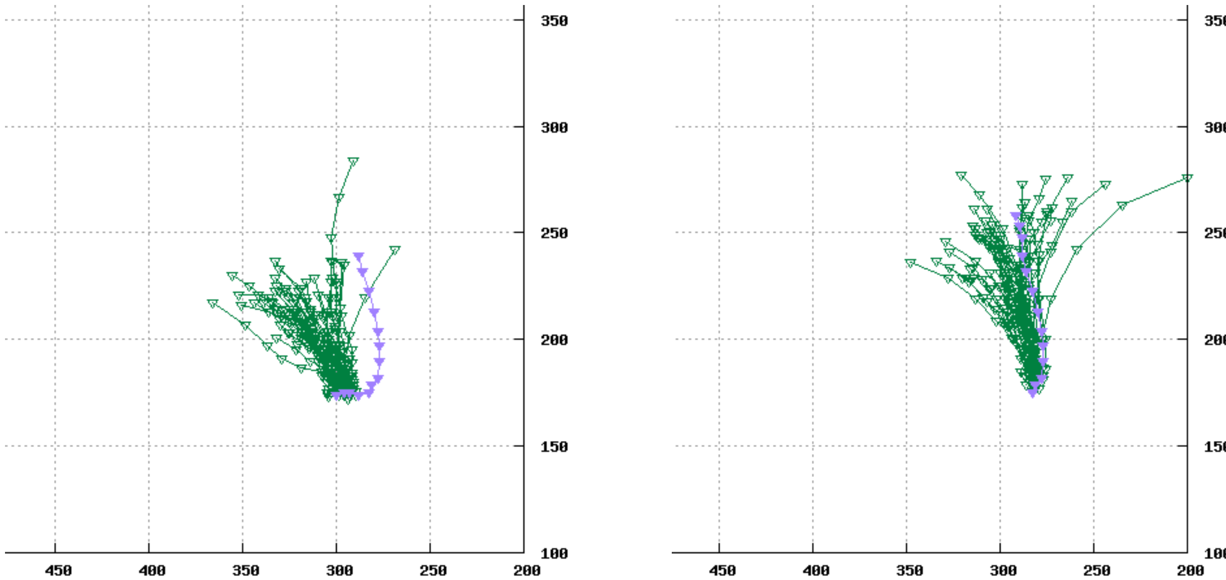


Figure 2b. As in Fig. 2a, but for forecasts beginning 0000 UTC, September 23, 2010 (left side) and for forecasts beginning 0000 UTC, September 24, 2010 (right side).

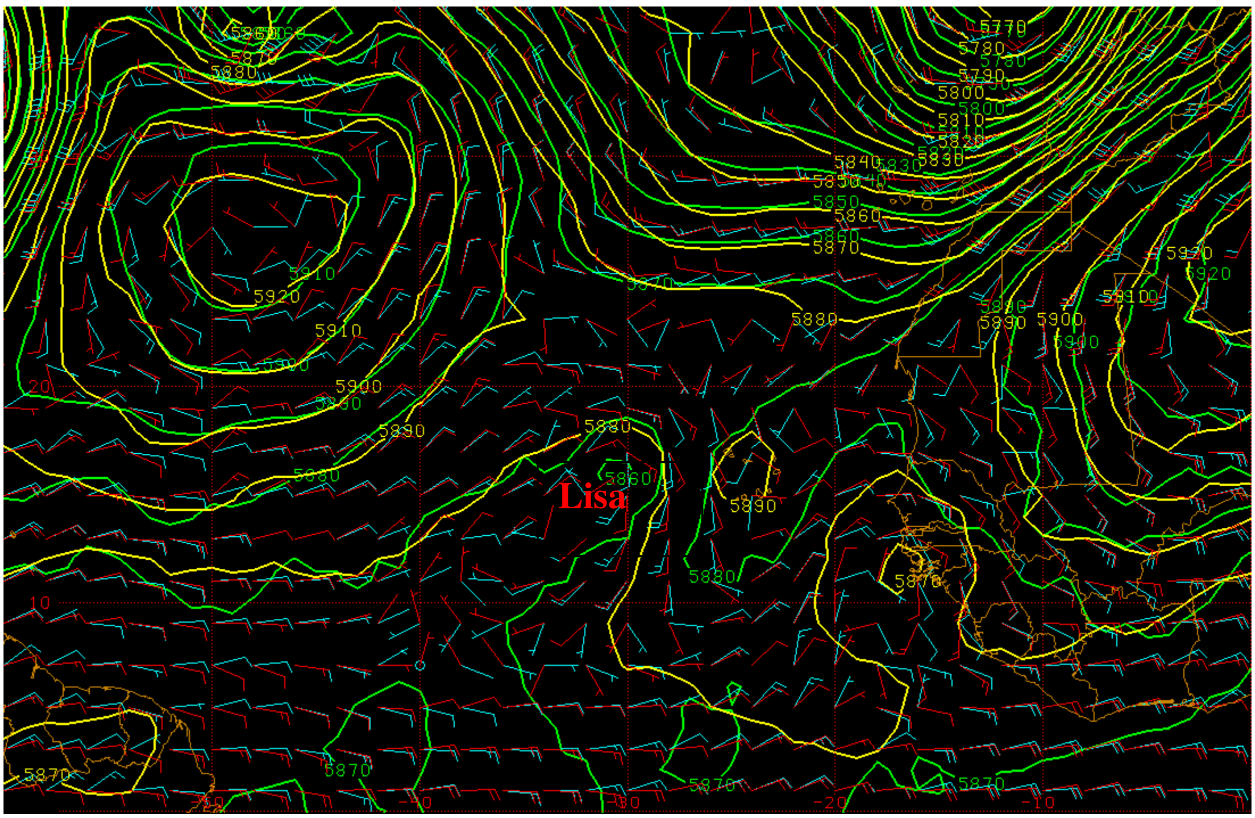


Figure 3. 500 hPa heights at 1 dm intervals for model initializations valid at 0000 UTC, 9/20/2010. GFS heights are in green, with cyan wind barbs (knots) and the UKMET heights are in yellow with red wind barbs (knots). The approximate location of Lisa at this time is labeled with her name.

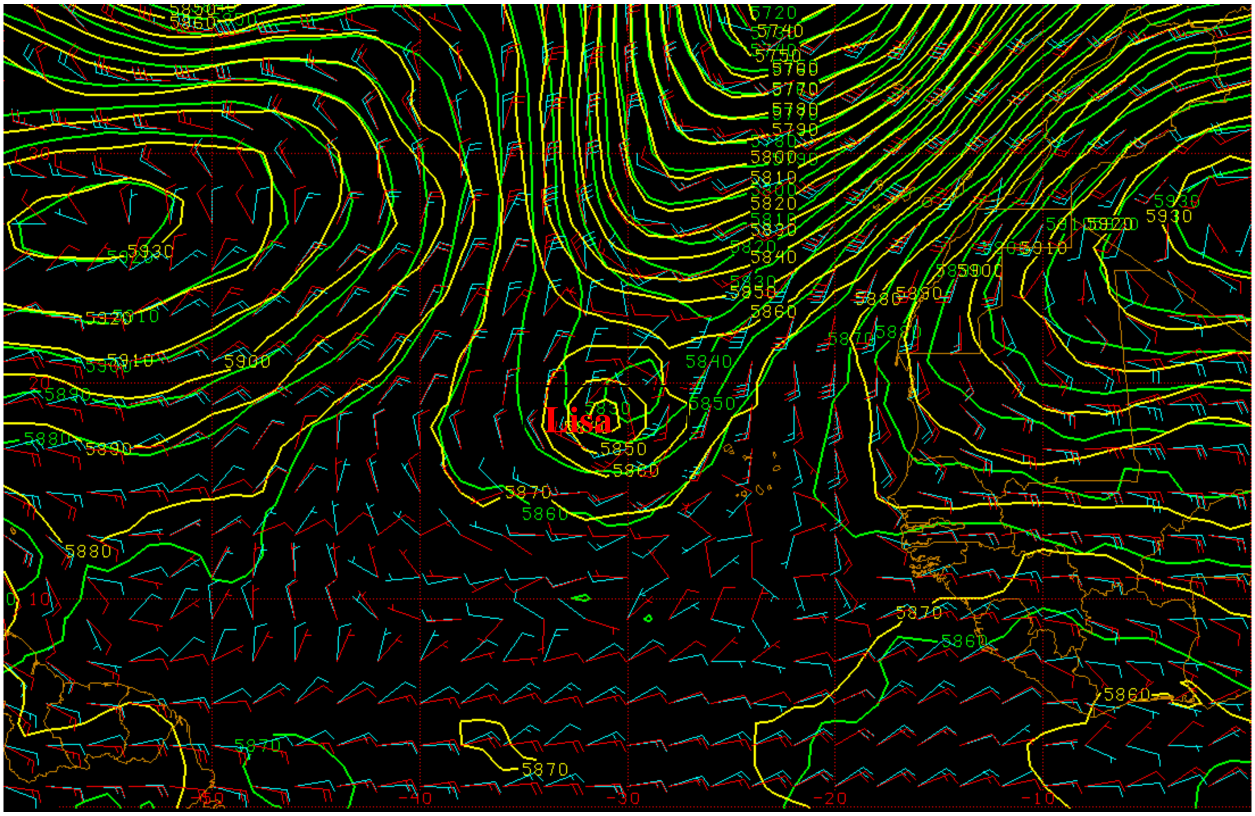


Figure 4. As in Fig. 3, except valid at 0000 UTC, 9/22/2010.

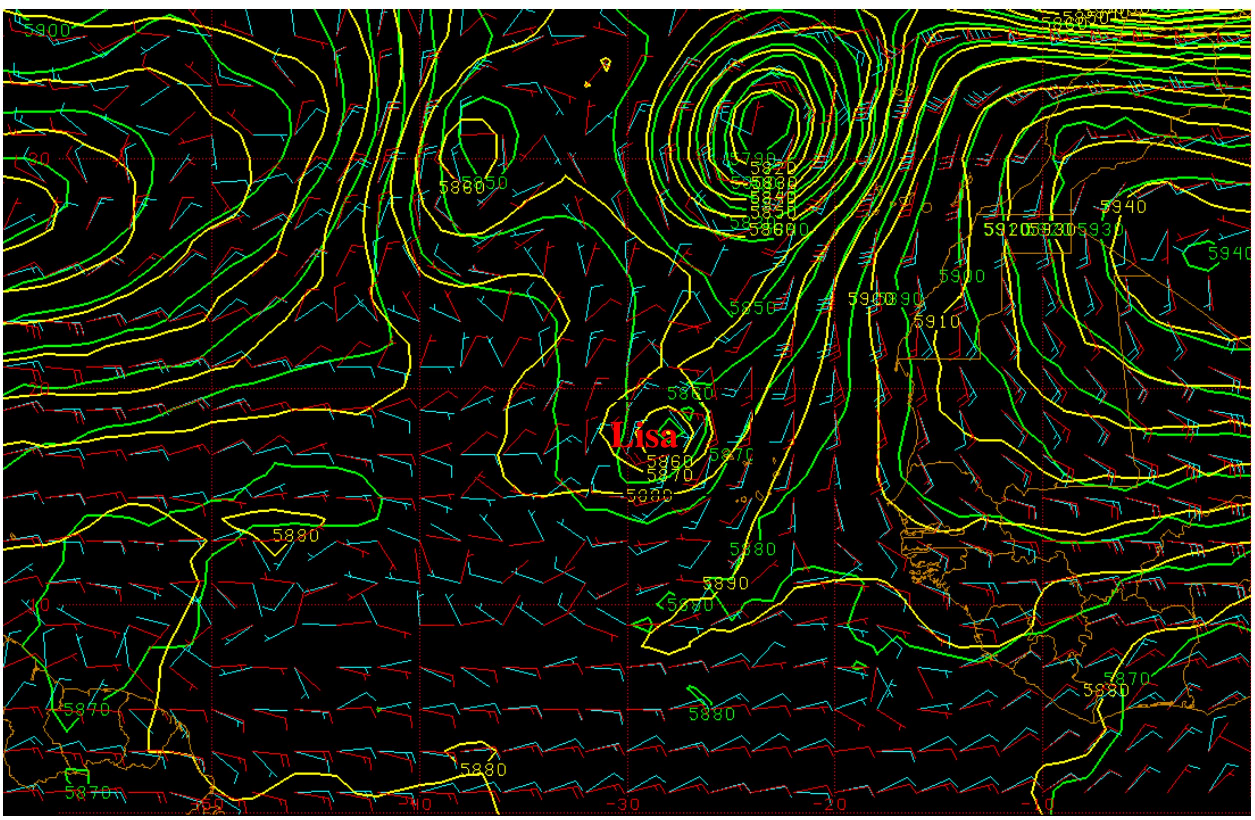


Figure 5. As in Fig. 3, except for 0000 UTC, 9/24/2010.

The height fields in the two models agree with each other almost perfectly. Height differences are on the order of 1 – 2 dm at most. The winds are not in agreement in the vicinity of Lisa. Wind directions vary by as much as 60 degrees, while wind speeds vary by 30 – 50 %.

3. Radii of Probability by Goerss (2007)

Goerss (2007) used multiple regression to measure the uncertainty in model forecasts. In particular, Goerss used regression to explain the forecast track errors in a consensus model used by the NHC for operational forecasting. Discussions with the personnel at the NHC indicate that they rely on consensus models to help them forecast the track. Goerss used a consensus model called CONU as a major predictor in his regression analysis. CONU is a consensus of the tracks from at least two of five models: 1) the Geophysical Fluid Dynamics Laboratory Hurricane Prediction System, 2) the National Weather Service's Global Forecast System, 3) the Navy Operational Global Atmospheric Prediction System, 4) the GFDL model run at Fleet Numerical Meteorology and Oceanography Center, and the United Kingdom Met Office global model. From the regression, which explained only 15% of the variance in the error at 48 hours, but nearly 50% of the variance at 120 hours, Goerss computed the radii of circular areas around the forecasts that included 73% - 76% of the verifications (referred to as Goerss Predicted Consensus Error (GPCE) circles. These radii are routinely computed and made available to the NHC forecasters, and are based largely on the spread in the model forecast tracks. We will use it here as a proxy for this model spread.

Figure 6 shows the plots of all the radii for the forecasts of Lisa, for all lead times out to 120 hours, which is the longest lead time for which the radii are computed. The presence of a peak for all lead times shows up clearly beginning on the September 20, and continues through September 24, with a single exception for the forecast made at 1800 UTC on September 22. This period of time includes both the turn to the east on September 22 and the turn to the north on September 24.

4. NCEP Ensemble Tropical Model Output

The NWS runs a 20 member ensemble model for tropical cyclone forecasting, and Fig. 7 shows the spread in the ensemble members in the same format as the radii in Fig. 6. The spread is computed by finding the ensemble mean position at a given lead time, and then computing the great circle distance from that mean for each member. The standard deviation of these distances is plotted in the figure for the same lead times as in Fig. 6. Gaps in the plots occur at forecast times when forecast locations from fewer than 6 of the members were available.

This plot shows a marked increase in the ensemble spread 48 hours before the first turn, with a peak in spread just after the turn. The spread then drops quickly to a level at or below the initial values on September 18, and only rises to a small peak at 1200 UTC on September 24. While the presence of the first peak is similar to the plot of GPCE radii, the rapid drop for forecasts beginning on September 22 -24 is quite different.

We would like to be able to infer the presence of uncertainty in the forecasts from the sizes of the GPCE radii, or from the ensemble spread. Preliminary analysis of Hurricane Earl (not shown here), a storm that had much lower average track errors than average, shows that the GPCE radii are only slightly smaller in size, and the ensemble spread is also only slightly smaller as well. The trend in the GPCE radii do reflect the locations in the track where the uncertainty was the largest, at the two right angle turns. But only by analyzing many more storms will we be able to be sure if the magnitudes of the radii or the ensemble spread are sufficient to predict the uncertainty in the forecast tracks.

5. WRF Model Simulations

The initial conditions for a model run are certainly going to be important in determining how well the model will simulate the storm's forecast. The unanswered question is to what extent are the initial conditions conducive to large model variability? When the tropical atmosphere has weak steering currents, we have seen in Section 2 that the model initializations from different national forecast offices, using different methods of initialization, produce widely variable wind flow from very similar height fields. This reflects in part, the lessening of the influence of the earth's rotation, measured with the Coriolis force, on the winds. In mid-latitudes, with a strong Coriolis force, gradient wind balance dominates the wind flow. The further into the tropics we look, the less important that balance becomes, which may explain why the differences between the initializations become much larger.

We further investigated the importance of the initial conditions by making multiple model runs using the Advanced Research (ARW) version of the Weather Research and Forecasting model (WRF model), varying the initial conditions but keeping the boundary conditions the same. Two nests were used: an outer nest with 30 km grid spacing, and an inner, moving nest with 10 km grid spacing. The domains are shown in Fig. 8.

The simulations were run beginning at 0000 UTC on 9/20/2010, and on each subsequent day through 9/24/2010. All the runs ended at 0000 UTC, 9/27/2010, when Lisa officially became a remnant low, rather than a tropical cyclone. The key model parameterizations were: WSM simple ice for cloud physics, RRTM long wave radiation, Dudhia shortwave radiation, Monin-Obukhov surface physics,

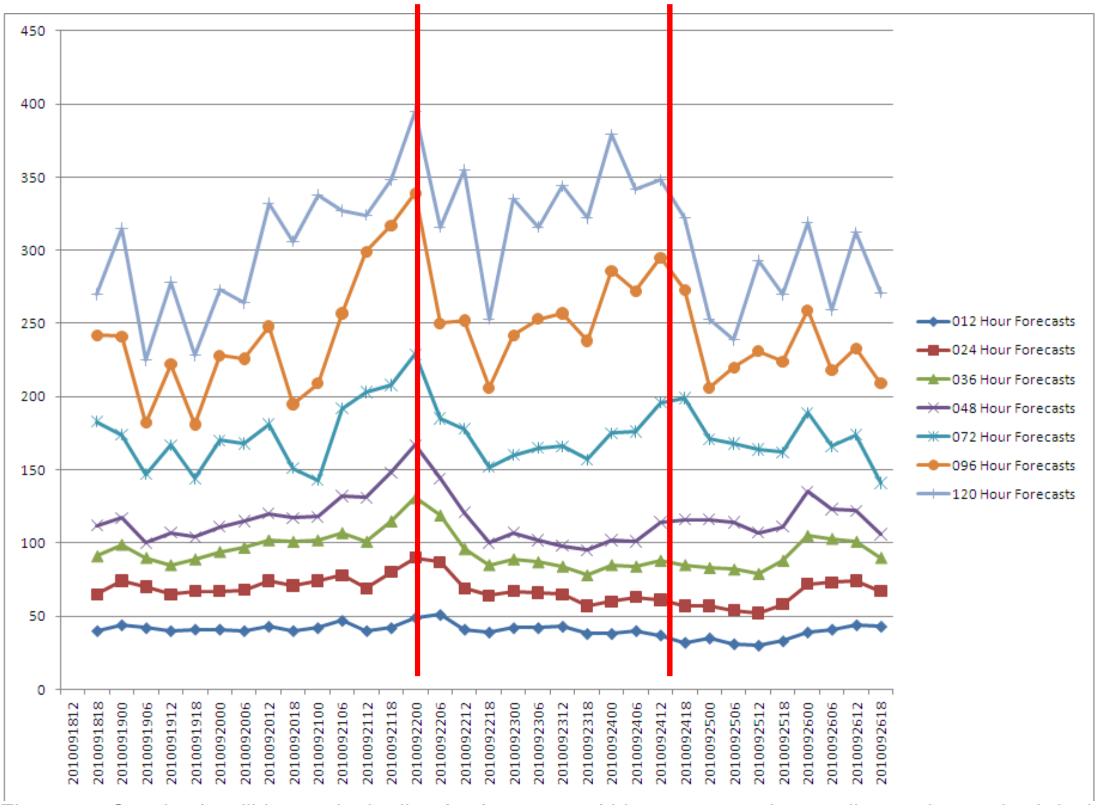


Figure 6. Graph of radii in nautical miles for forecasts of Lisa, computed according to the method devised by Goerss (2007). Dates are the dates when the forecasts were initialized. Turns in Lisa's track are shown with red lines.

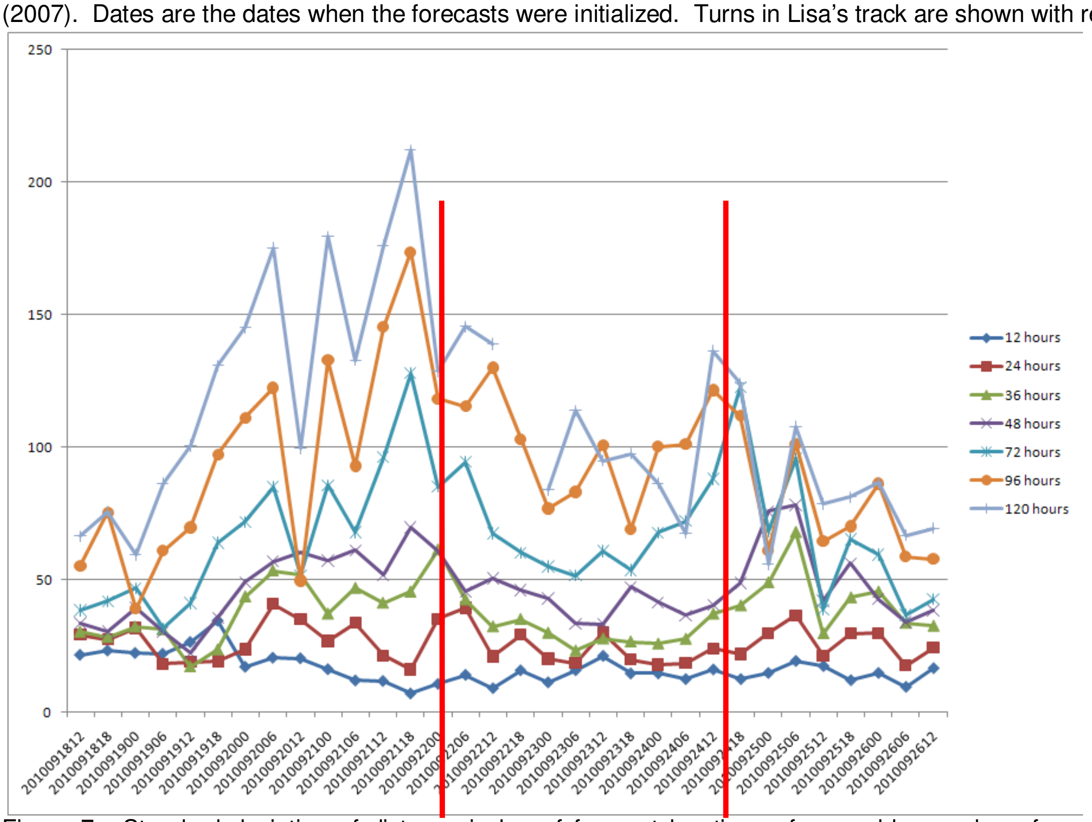


Figure 7. Standard deviation of distance in km of forecast locations of ensemble members from the consensus location, for forecasts for Hurricane Lisa. Dates are the dates when the forecasts were initialized. Turns in Lisa's track are labeled with red lines.

YSU boundary layer, and the Kain-Fritsch cumulus scheme in both nests. The inner nest moved by tracking the circulation at 700 hPa. The GFS 1^{o} latitude x 1^{o} longitude analysis grids available every six hours, were used for boundary conditions for all runs.

Being unable to afford to purchase initialization data for the ECMWF or the UKMET, GFS forecast initial conditions were used as a proxy for "different" initializations. Three runs were made for each start time. One used the GFS analysis grids for initial conditions (denoted GFS run), the second used the 6-hour forecast grids from the 1800 UTC model run the day before (denoted f06 run), and the third used the 12-hour forecast grids from the 1200 UTC model run the day before (denoted f12 run).

Figure 9 shows the 9/22/2010, 0000UTC initialization of the 500 hPa heights from the GFS run and the f06 run. The two look very similar, with all the features in the same places, and the heights within 1 dm of each other. These model runs were initialized just as Lisa was turning abruptly to the east. Figure 10 shows the initializations from the GFS run and the f12 runs superimposed, and it's clear again that the two fields are very similar, with the largest difference less than 2 dm, just to the north of Lisa. The winds are not as similar in these initializations. Figure 11 shows the vector wind differences between the f06 initialization and the GFS initialization at 500 hPa. The f06 run winds show a relative flow towards the west in the vicinity of Lisa. The same pattern is present in Fig. 12, which has the vector difference between the f12 run and the GFS run. Given this flow pattern, one would expect Lisa to move more towards the west in the f06 and f12 runs, than in the GFS run. This pattern of relative flow persisted throughout these simulations. Figure 13 shows the tracks from all three simulations, along with the best track from the NHC archives. The relative westward motions of the forecast initial condition runs show up very well here.

The model simulations begun at 0000 UTC, September 24, 2010, don't show the same disparity in tracks. Figure 14 shows the vector differences in the 500 hPa winds for the f06 and GFS initializations, and Fig. 15 the shows the same fields for the f12 and GFS runs. While there are differences, the differences are smaller and much less coherent. The resulting tracks, shown in Fig. 16, are all very similar.

6. Conclusions

Hurricane Lisa was a tropical cyclone whose track was difficult to forecast. Track errors were much larger than the average over the past five years. The model forecasts, shown in Fig. 2, show wide discrepancies, especially early in Lisa's life, prior to the two sharp turns in her track. By September 24, the spread shown in Fig. 2 appears to be smaller. Plots of the Goerss radii of probability and the spread in the GFS ensemble runs show some of this uncertainty, but are in disagreement about the level of uncertainty near the second turn, and how long that uncertainty continues. The ARW model simulations discussed here do capture the uncertainty in the tracks, with the uncertainty remaining high prior to the turns, and decreasing after the second turn.

More storms need to be analyzed to determine if measuring the levels of uncertainty in any of these three ways can be used to provide true guidance to the reliability of the forecast tracks. Preliminary work with another storm from 2010, Earl, suggests that neither the size of the GPCE radii nor the level of the ensemble spread provides the kind of guidance needed.

7. References

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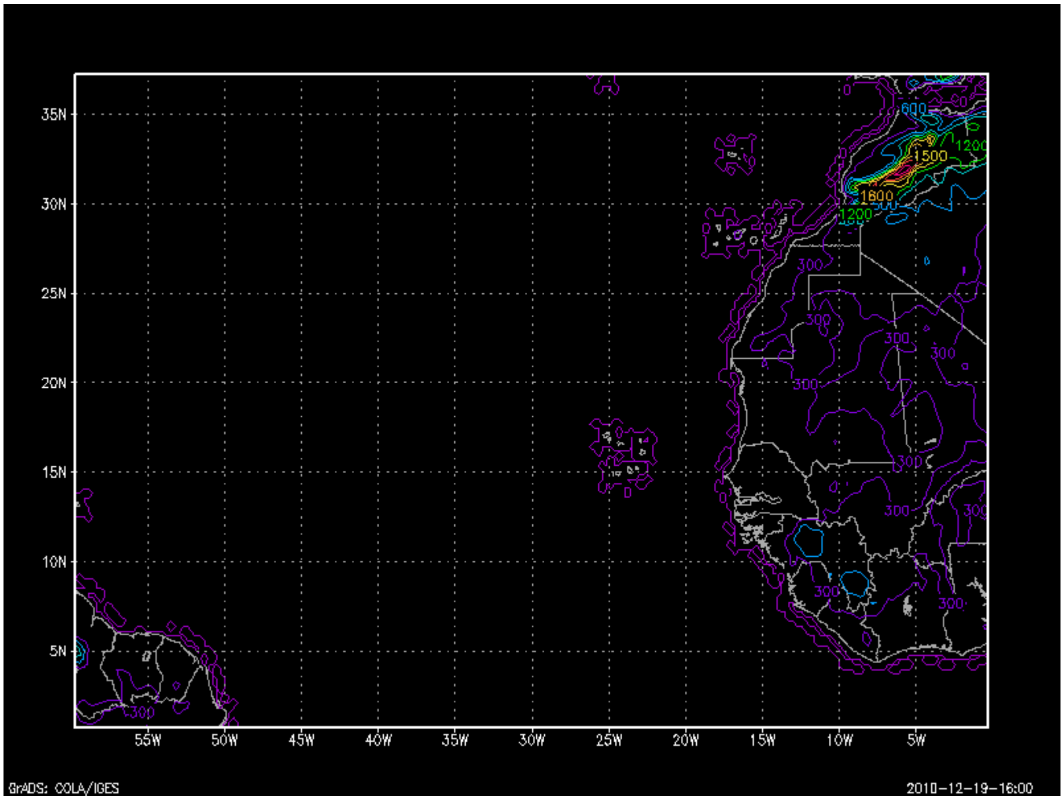

Figure 8. Plot of domains used for ARW model simulations. Outer domain with 30 km grid spacing is shown by whole map, while the initial location of the moving 10 km grid spacing inner grid is outlined with the red rectangle.

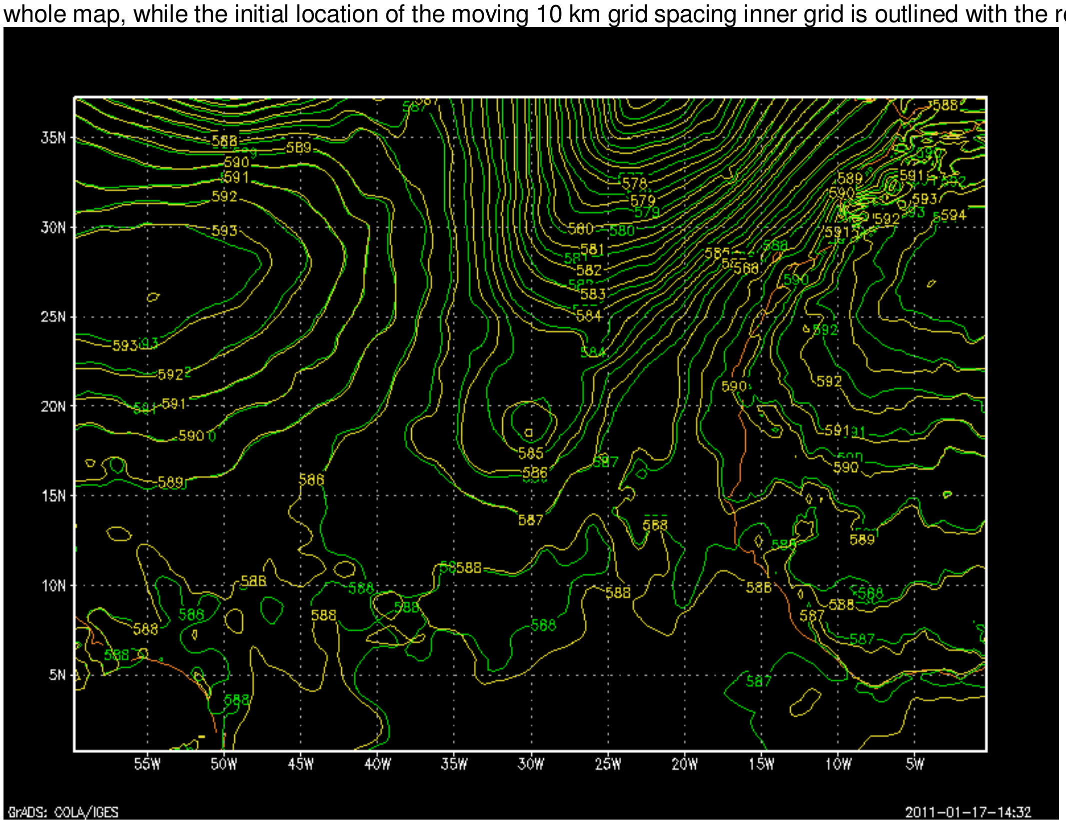

Figure 9. 500 hPa heights (at 1 dm spacing) from model initialization at 0000 UTC, 9/22/2010.   Green contours for GFS analysis initialization, yellow contours for initialization from 6 hour forecast from previous model run.

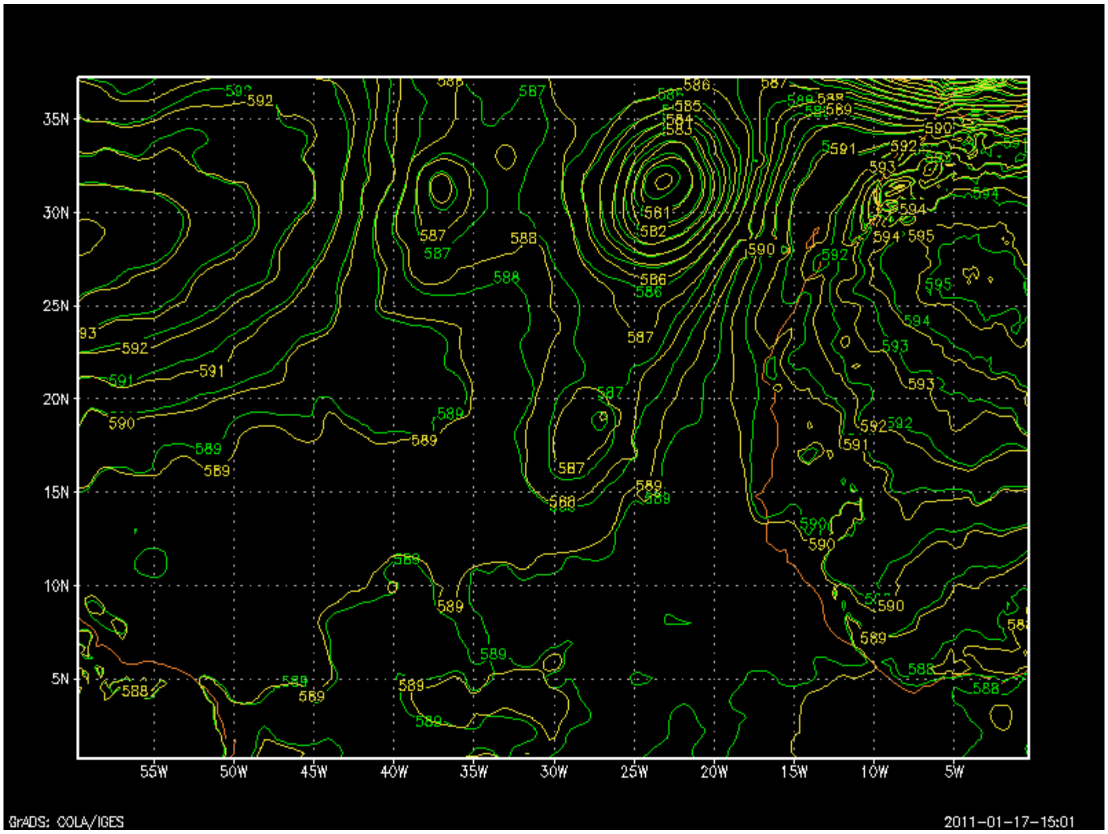

Figure 10. As in Fig. 9, except for model initialization at 0000 UTC, 9/24/2010.

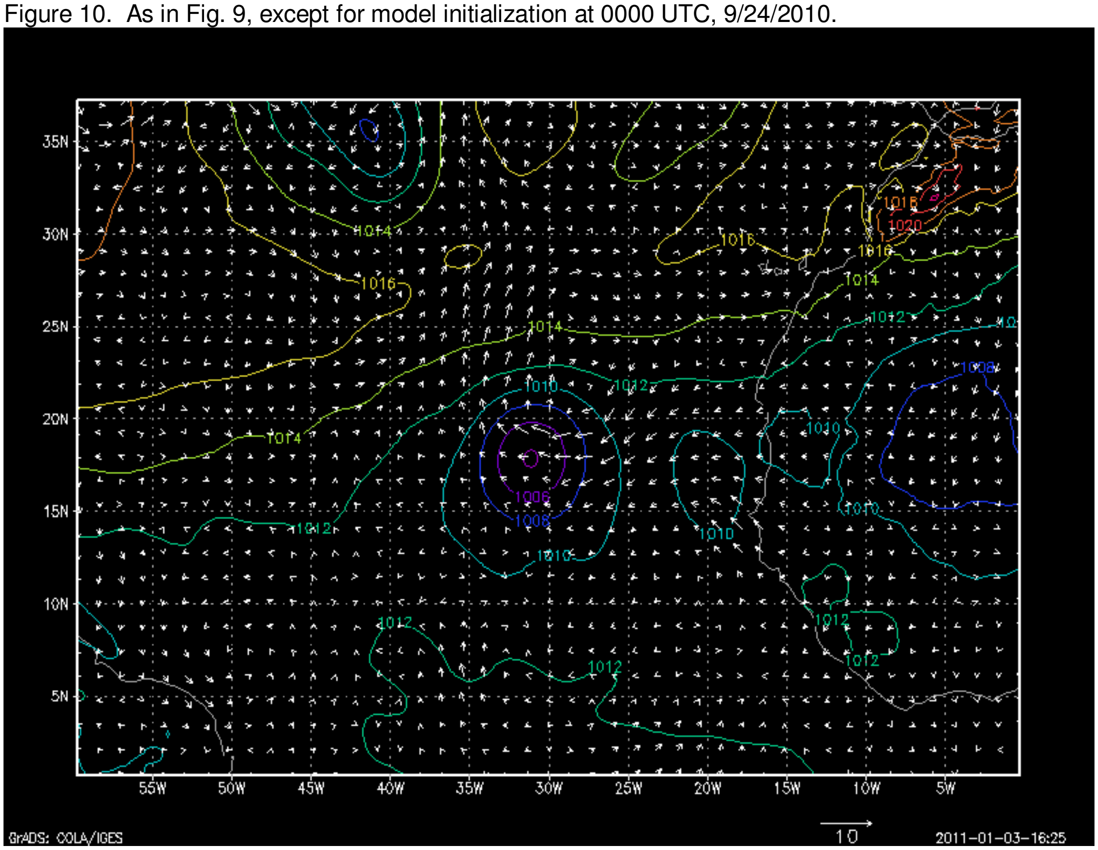

Figure 11. Mean sea-level pressure from GFS initial conditions – color contours at 2 hPa intervals. Vector wind difference between GFS initial conditions and 6 hour forecast initial conditions in white arrows at 500 hPa, valid at 0000 UTC, 9/22/2010.