Geostationary Hyper-Spectral Sounder (Geo-HSS) Constellation: A Global OSSE Assessment

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Project Description

This study aims to show the potential impacts of a constellation of geostationary hyper-spectral sounders (Geo-HSS Constellation) on global medium-range forecasts. The global Observing System Simulation Experiment (OSSE) system utilized here has multiple components:

- The Goddard Earth Observing System Model, Version 5 (GEOS-5) Nature Run (G5NR) is a two-year free-running model initialized from real-world conditions on May 16th, 2005 (Gelaro et al. 2014). In the OSSE framework used here, this is treated as the "true state of the atmosphere." As such, all observations are simulated from the G5NR from a period 15 months into the G5NR (August-September 2006).
- All simulated observations are then assimilated into the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) medium-range forecast model (NOAA/NWS/NCEP/EMC 2015). The "research resolution" of the Q1FY15 3DEnVar model is used due to computational constraints. In this research version, the Gridpoint Statistical Interpolation (GSI) produces analyses at a spectral truncation of T254 (~50 km), the same resolution used for the 80 member forecast ensembles that is part of this hybrid data assimilation system. Following a 2-week spinup period for each experiment, 7-day forecasts are generated every day at 00Z at spectral truncation of T670 (~20 km).

Two experiments are run using the setup described above:

- The CONTROL experiment that assimilates simulated versions of every observation type that was assimilated operationally in August-September 2014.
- The TEST experiment that differs from CONTROL in the following ways:
    - Five Geo-HSS instruments are added, assuming that the future Geo-HSS satellites will have the same channel set as the Infrared Atmospheric Sounding Interferometer (IASI), an instrument currently flown in sun-synchronous orbit on MetOp-A and MetOp-B from the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT). Though IASI has 8078 channels, only 160 of these are assimilated operationally in the NCEP/GFS system; only these 160 channels are therefore assimilated in TEST. These Geo-HSS satellites are spaced around the Equator in order to provide global coverage of the tropics and midlatitudes up to ~50° latitude.
    - With the introduction of Geo-HSS, the current geostationary radiance observations assimilated into GSI should be considered obsolete. As such, radiances from Geostationary Operational Environmental Satellite 15 (GOES-15) and Spinning Enhanced Visible and Infrared Imager (SEVIRI) onboard MeteoSat 10 (M10) are not assimilated in zcegh.

Simulated Infrared Radiances and Cloud Amount Tuning

Any assessment of the added value of an InfraRed (IR) instrument (such as IASI) must take clouds into account, as thick to moderately-thick clouds are opaque at IR wavelengths. Channels that typically measure surface conditions instead report cloud-top conditions, yielding much colder radiances. Assimilating these cloudy radiances as if they are clear radiances degrades the analysis, as the model attempts to fit much colder radiances to the lower levels of the atmosphere. To prevent this, in the case of real observations, a cloud-check algorithm in GSI attempts to identify cloud-top heights, then rejects any channel with greater than 2% transmittance below cloud-top height. This method is effective, though many false positives and negatives are noted in comparisons to cloud-profiling radar and lidar (McCarty 2014).

In the OSSE framework described here, there are two additional considerations for infrared radiances:

- The G5NR does not provide every variable needed for accurate cloud simulation in the Community Radiative Transfer Model (CRTM), used to simulate and assimilate radiances. A cloudy-radiance simulation from G5NR (E. Maddy, personal communication) required many assumptions with respect to cloud fraction and effective radius. Initial testing of these cloudy radiances yielded negative analysis impacts for both control IR and microwave radiances, making them unsuitable for OSSE use.
- The G5NR has more clouds than the real world. As such, IR-focused OSSEs that use the cloud amounts from the G5NR could underestimate the impact of IR instruments. On the other hand, ignoring clouds altogether would overestimate potential IR-instrument impacts.

To address the second point above, a cloud-amount tuning method was developed. In this, an iterative process is set up for every IR instrument in both CONTROL and TEST experiments. First, every channel (i) is assigned a critical pressure level $(PLEV_i)$ of 500 hPa. If the cloud-top pressure at a given location is less than $PLEV$, that point is identified as cloud-effected for channel i. The percentage of cloudy observations world wide determined by $PLEV$ for one day in the OSSE (2006081500) is compared to the amount of cloudy scenes identified as cloudy by GSI on a per-channel basis from real-world observations (2014081500). If the OSSE channel is cloudier than its real-world counterpart, $PLEV_i$ is decreased by 1 hPa; if the channel is less cloudy, $PLEV_i$ is increased by 1 hPa. This process continues iteratively until the optimal tuned value of $PLEV$ is reached for each channel. Figure 1 below shows the tuned cloud-top heights for IASI_MetOp-B; these tuned heights are used for each Geo-HSS instrument. For example, if G5NR cloud-top is 500 hPa, channels with a wavenumber less than 700 /cm are considered clear, while most channels above 700 /cm are considered cloudy.

Given the cloud-tuned $PLEV$ values, if a radiance is identified as cloud-impacted, that radiance is set to zero in the input file. Then, GSI is modified to bypass the cloud-check algorithm altogether. Additional changes to GSI were necessary to ensure profiles with zero-value radiances were not entirely thrown out, as radiances above cloud top should still be assimilated to be consistent with operations.

Analysis Impacts

Figure 2 shows the mean Geo-HSS Constellation impacts on global analyzed temperature at 0000 UTC for each day during the experimental period, in terms of (red) Root Mean Square Error (RMSE), (black dotted) bias, and (black dashed) standard deviation (SD). Negative values denote reduction in these values, and circles/squares denote statistical significance. There is a statistically-significant reduction in RMSE, bias, or SD at most levels, with a few exceptions. RMSE differences between 400-500 hPa are not statistically-significant. A statistically-significant increase in temperature bias is noted at 100 and 400-500 hPa, and bias differences at 700-825 and 1000 hPa are not statistically-significant. Finally, the increase in standard deviation at 400 hPa is slight, but statistically significant nonetheless, due to the low variability of this metric during the experimental period. Though slight, the consistency of these improvements through the troposphere and stratosphere is promising, and shows a positive impact on the assimilation system's representation of the atmosphere.

Figure 3 shows the analysis-time impacts on geopotential height. While statistically-significant reductions in RMSE are noted above 100 hPa and between 500-700 hPa, significant increases in RMSE are noted between 150-300 hPa, with impacts at 400 and below 850 hPa are not statistically-significant. The magnitude of biases compared to G5NR largely increase at a statistically-significant level, with the exception of above 70 hPa and at 700 hPa, where significant reductions are noted. Finally, SD largely is reduced, except for significant increases 150-250 hPa and not statistically-significant impacts at 300 and below 850 hPa.

Global Forecast Impacts

Figure 4 highlights any differences between mean geopotential height anomaly correlation at 500 hPa in the Northern Hemisphere extratropics (NHX). Positive values in the lower half of this figure show that Geo-HSS is, on average, bringing the forecast closer to the G5NR. The largest impacts are noted in days 5-7, though it should be noted that these are within the 95% confidence interval bars plotted, and thus should not be considered statistically significant. Figure 5 shows 120-hour (5-day) forecast skill through the experimental period for both control and Geo-HSS cases. While the average AC score (denoted in legend) is higher for Geo-HSS, the time series reveals that much of this improvement comes from one forecast verified on August 22nd.

The Continental United States (CONUS) shows similar results in Figure 6 to the NHX results. The magnitude of these differences is larger, however, and at day 7 forecast improvement with Geo-HSS appears to be statistically significant at the 95% confidence level. The time series in Figure 7 for 5-day forecasts again shows that for most days, forecast skill with GeoHSS is comparable to a control case. It's a few cycles in particular (notably those associated with drop-out cases around September 1st and 20th verification) that show the greatest improvement in forecast skill.

While NHX and CONUS show largely positive impacts from the Geo-HSS Constellation, the Southern Hemisphere extratropics (SHX) dieoff curve in Figure 8 shows largely negative (though nonsignificant) impacts. The time series in Figure 9 suggests the September 10th verification shows the greatest negative impact. This is an important case to look into for two reasons. First, while the control forecast skill went up from the previous days' forecast, the Geo-HSS forecast skill decreases. Second, while negative results are troubling, they can be important windows into technical issues with assimilating a new or existing instrument, and identifying and correcting these issues can lead to greater improvements overall.

While NHX, SHX, and CONUS improvements are demonstrated using 500 hPa geopotential height anomaly correlation, tropical forecast improvements are demonstrated in Figures 10 and 11 using 200 hPa vector wind RMSE, as upper-level winds are the primary metric used to assess large-scale tropical forecasts. In Figure 10, negative differences represent reductions in RMSE, and therefore positive impacts from the Geo-HSS Constellation. While there are no additional wind observations assimilated in association with the Constellation, we still see improved forecasts through day 4, with forecast differences around 66 hours (2.75 days) being statistically significant. Impacts days 5-7 turn negative though not statistically-significant. The time series of RMSE in Figure 11 shows more differences in day-to-day forecast skill compared to figures 5, 7, and 9.

Tropical Cyclone Impacts

There are 17 tropical cyclones (TCs) wholly located temporally within the experimental period, spread out over the Atlantic, East Pacific, and West Pacific basins. As the Geo-HSS Constellation is geostationary and provides full tropical coverage, an assessment of potential TC track and maximum wind speed error impacts is warranted.

Figure 12 shows one such TC, here labeled "AL03". This TC reaches Category 3 strength on 2006091100, shortly before making landfall near the Alabama-Mississippi border. Given the importance of this storm for regional modeling partners and American interests, GFS 7-day forecasts are run every 6 hours for the lifetime of this storm, instead of only every 24 hours as was done through the rest of the experimental period. The black curve shows the track of the storm within the G5NR, blue the track for the CONTROL GFS forecast initialized at 2006090718, and green the track for the corresponding TEST forecast. Note that for this forecast initialization time, both experiments put landfall near the Alabama-Florida border, almost 100 km east of the best track.

Figure 13 compares the mean track error for CONTROL (black) and TEST (blue) as a function of forecast lead time. Black stars near the bottom of the figure denote differences greater than a 95% confidence interval. Track error is reduced in the TEST case between 12 and 60 hours, with 18-30 hour differences statistically significant. Conversely, TEST track errors are greater past 60 hours, with 72-hour forecast differences statistically significant. It should be noted, however, that only five forecasts produce storm tracks that reach 72 hours in length.

Figure 14 presents wind intensity errors for AL03 in both experiments. Only slight differences between the two experiments are noted, with no differences statistically significant. Given the lack of new wind observations in the Geo-HSS experiment, this result isn't surprising. Note that large wind errors at analysis time in Figure 14 are due to the reduced resolution of the research version of NCEP/GFS; these errors would be reduced if the model were run at full resolution.

More robust statistics are available when taking all 17 TCs into account. Figures 15 and 16 shows track and wind errors, respectively, similar to Figures 13 and 14. Here, however, standard error intervals are noted with black and blue shading for control and Geo-HSS, respectively. (Only 00Z-generated forecasts are included, in order to be consistent throughout the experimental period.) When taken together, no differences between the two experiments can be considered statistically significant. There does appear to be slight improvement with Geo-HSS in track forecasts in the 60-72-hour period, and again in the 6-7 day period.

Summary of Current Work and Next Steps

In most cases, the impact of large-scale assimilation of geostationary hyper-spectral radiances on medium-range forecasts appears to be slight. Individual forecasts show clear improvement with Geo-HSS in NH, particularly over CONUS; however, there are cases with clear degradation in SH. The impact on tropical cyclones varies storm-to-storm, with no differences greater than 1 SD when all 17 TCs are taken into account.

Work continues on identifying the causes of significant forecast differences, including the deep CONUS drop-out in experiment CONTROL, and how Geo-HSS helped to mitigate this drop-out in experiment TEST. More importantly, however, work is ongoing in understanding the cause of analysis degradation and SH forecast drop-outs when assimilating Geo-HSS. Identifying causes here can help improve overall model analysis/forecast for Geo-HSS, in a process similar to how adjustments are made to operationally assimilate observations by NCEP.

References

Gelaro, R., and Coauthors, 2014: Evaluation of the 7-km GEOS-5 Nature Run. *Technical Report Series on Global Modeling and Data Assimilation,* **36**, R. D. Koster, Ed. NASA/TM–2014-104606/Vol. 36

McCarty, W, 2014: Progress Towards the Assimilation of Cloud Affected Infrared Radiances at the GMAO. *12th JCSDA Technical Review & Science Workshop*, May 22nd, 2014.

NOAA/NWS/NCEP/EMC Global Climate and Weather Modeling Branch, 2015: Running Global Model Parallel Experiments. 6.0, February 18th, 2015.

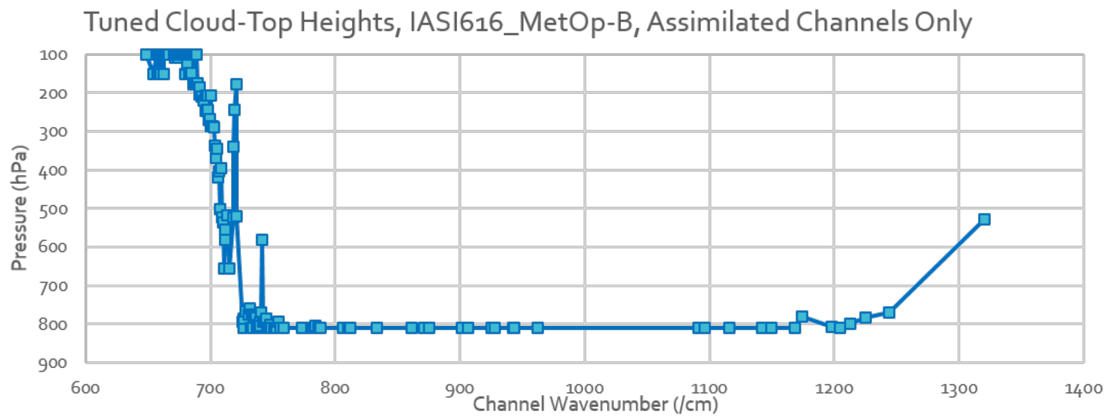

Figure 1. Critical pressure level $(PLEV)$ for G5NR as a function of IASI channel wavenumber. The cloud-amount tuning method described in the test was applied to assimilated IASI_Metop-B channels.

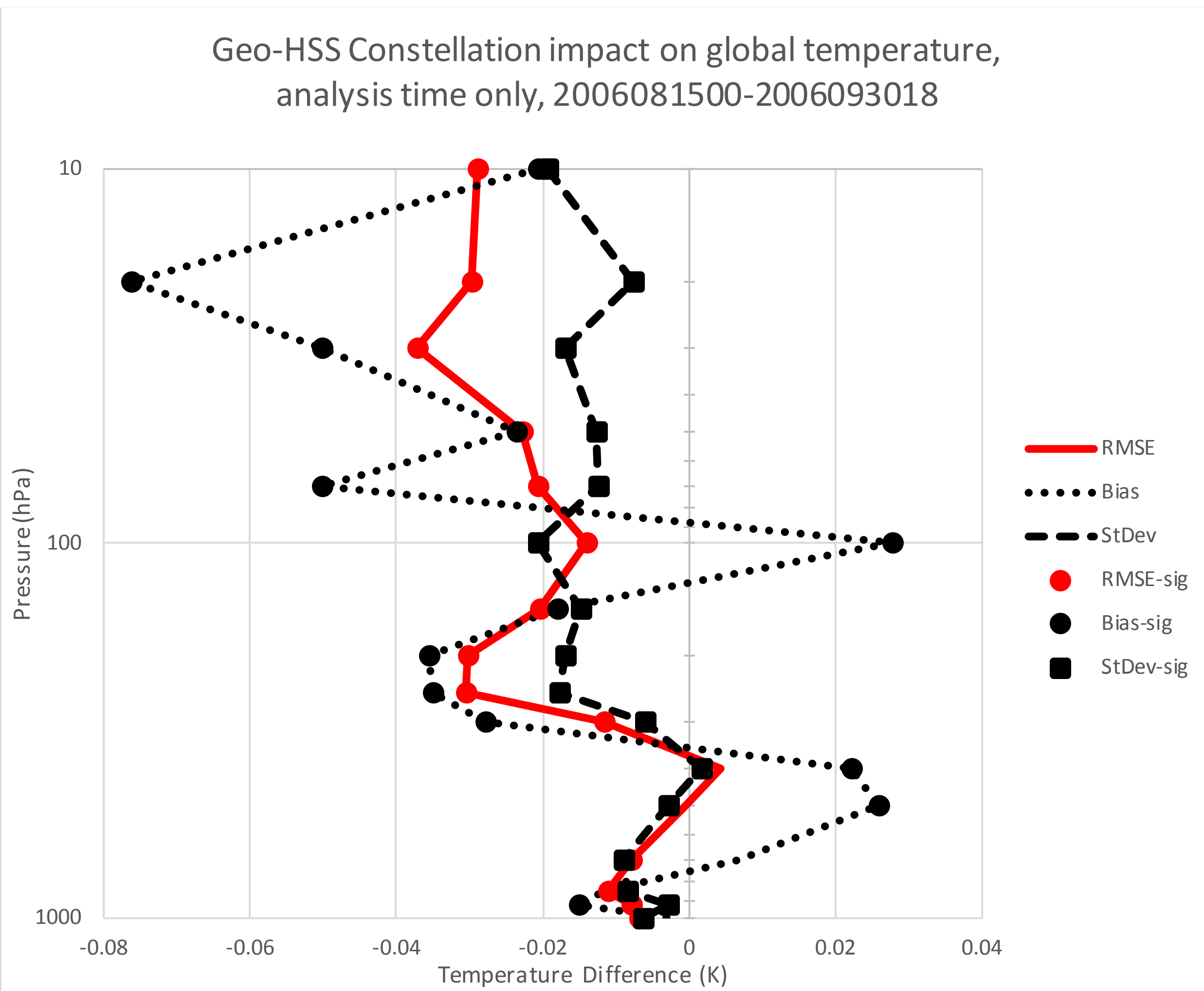

Figure 2. Geo-HSS Constellation impact on analysis temperature, in terms of (red) RMSE, (black dotted) bias, and (black dashed) standard deviation. Negative values denote reduction in these values due to Geo-HSS assimilation, and circles/squares denote differences statistically-significant at 95% confidence.

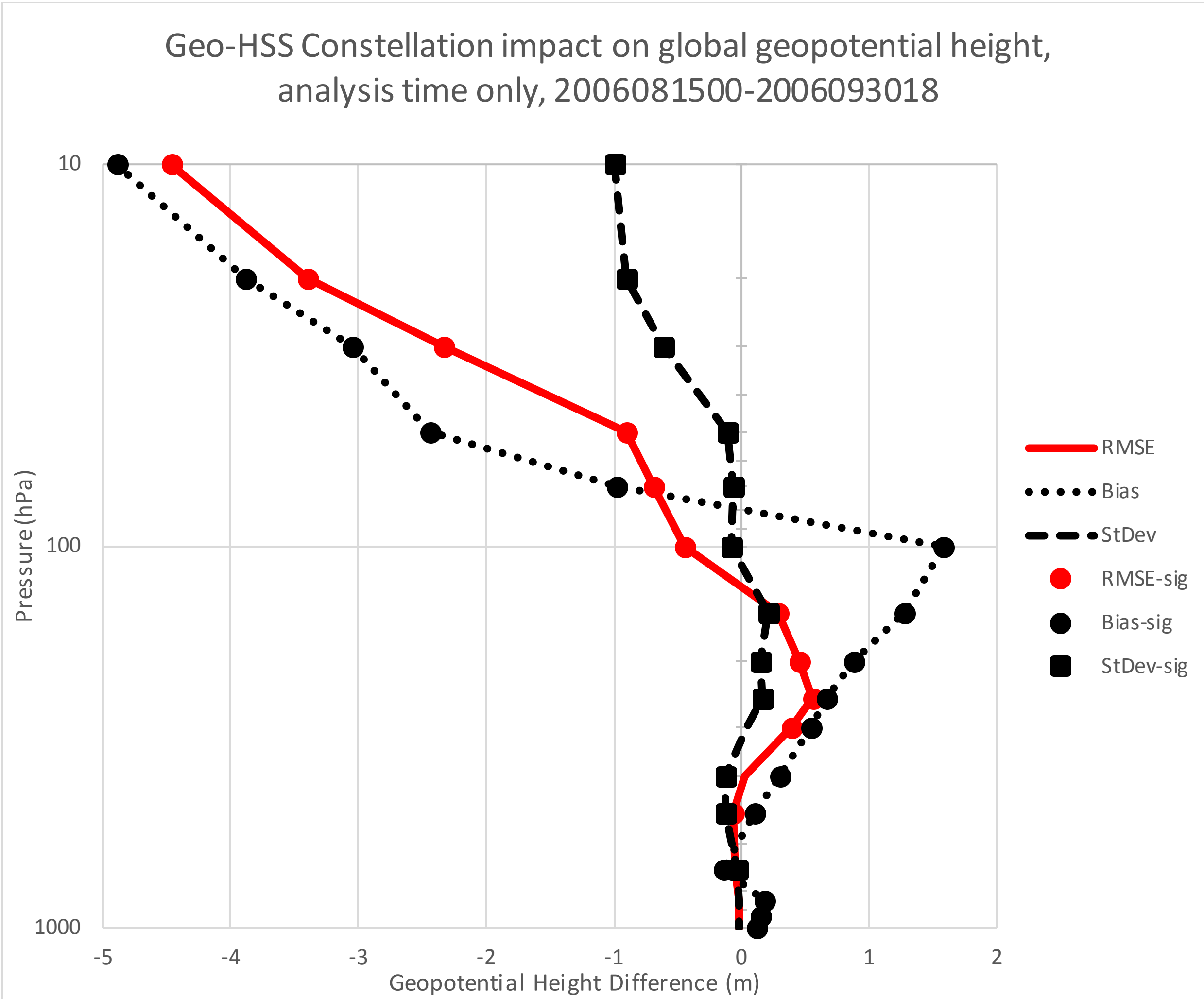

Figure 3. As in Figure 2, but for geopotential height.

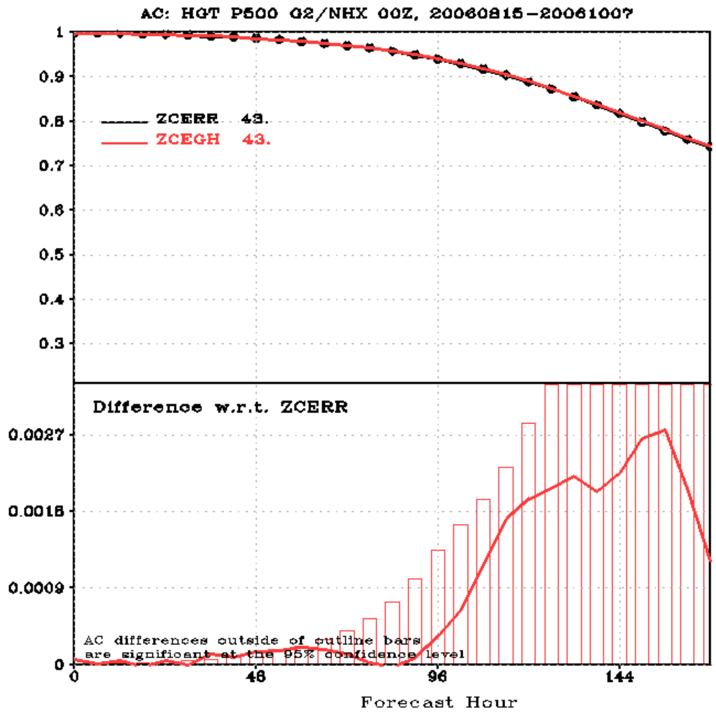

Figure 4. (top) 500 hPa Geopotential Height Anomaly Correlation for the Northern Hemisphere extratropics, verified over 20060815-20060930 for CONTROL (zcerr, black) and TEST (zcegh, red) cases. (bottom) Difference between the TESTcase and the control, with positive values indicating improvement. Red boxes are 2-σ (95%) confidence intervals for the null hypothesis that there is no difference between CONTROL and TEST.

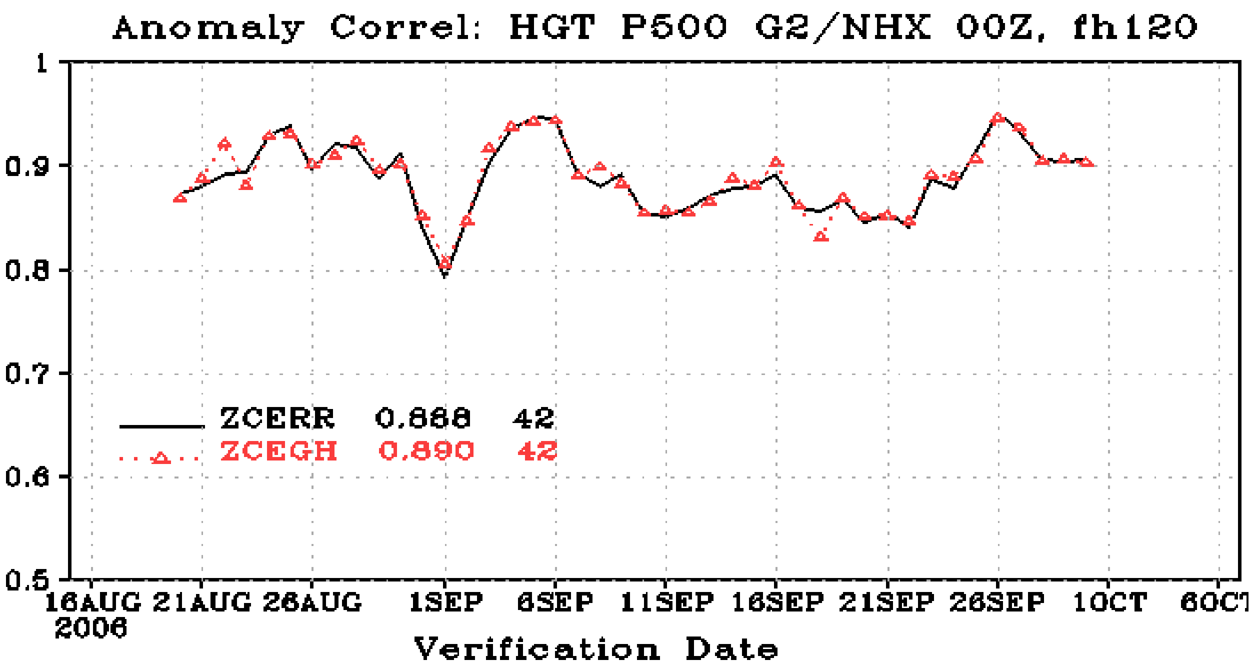

Figure 5. 120-hour (5-day) 500 hPa Geopotential Height Anomaly Correlation for the Northern Hemisphere extratropics, verified over 20060820-20060930 for CONTROL (zcerr, black) and TEST (zcegh, red) cases.

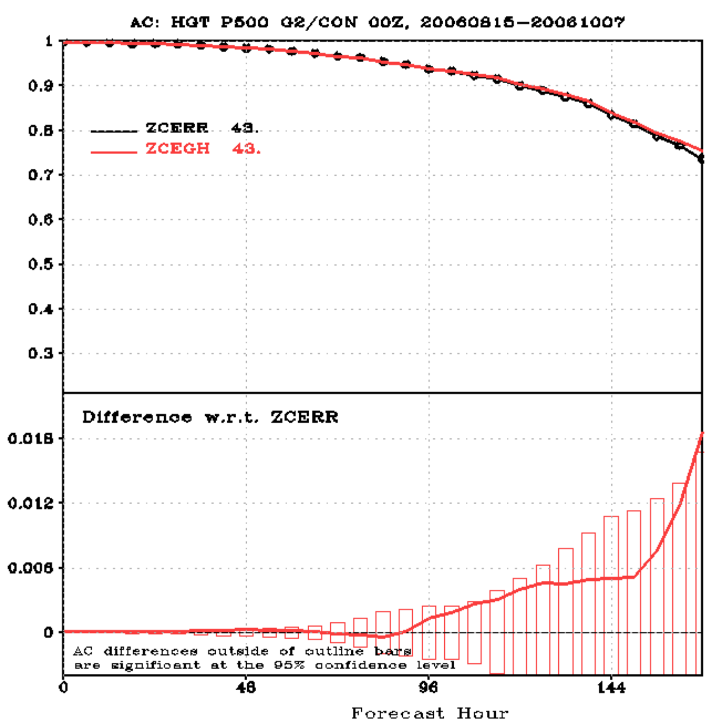

Figure 6. As in Figure 4, but for the Continental United States.

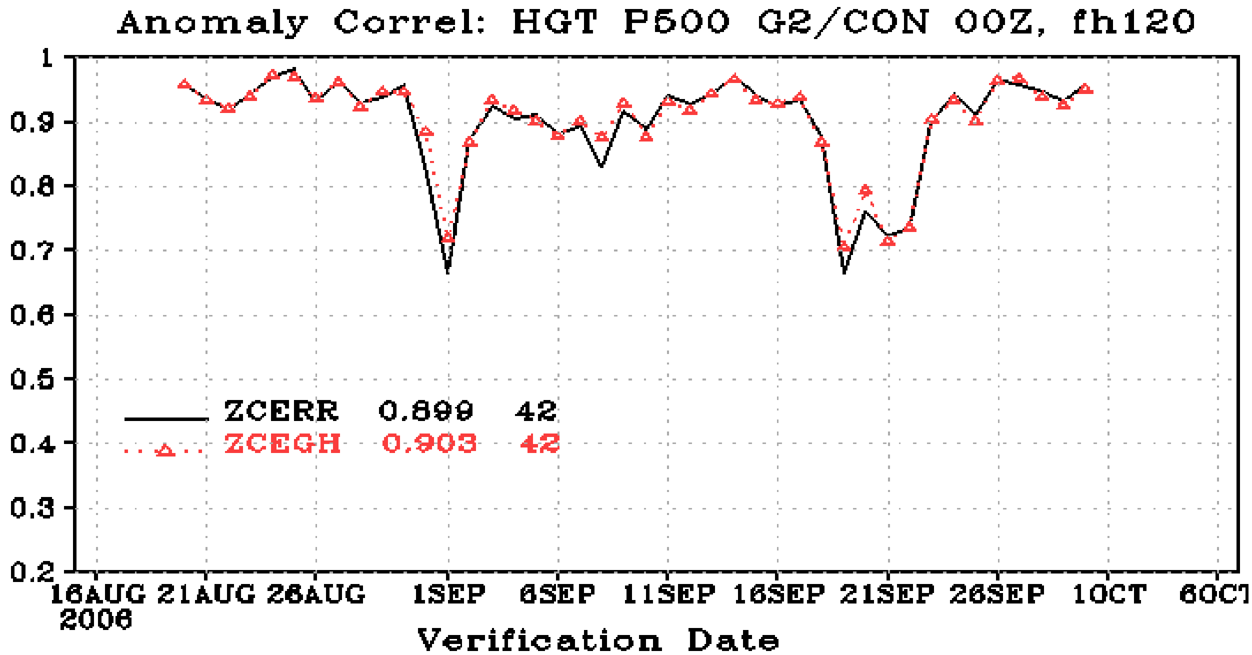

Figure 7. As in Figure 5, but for the Continental United States.

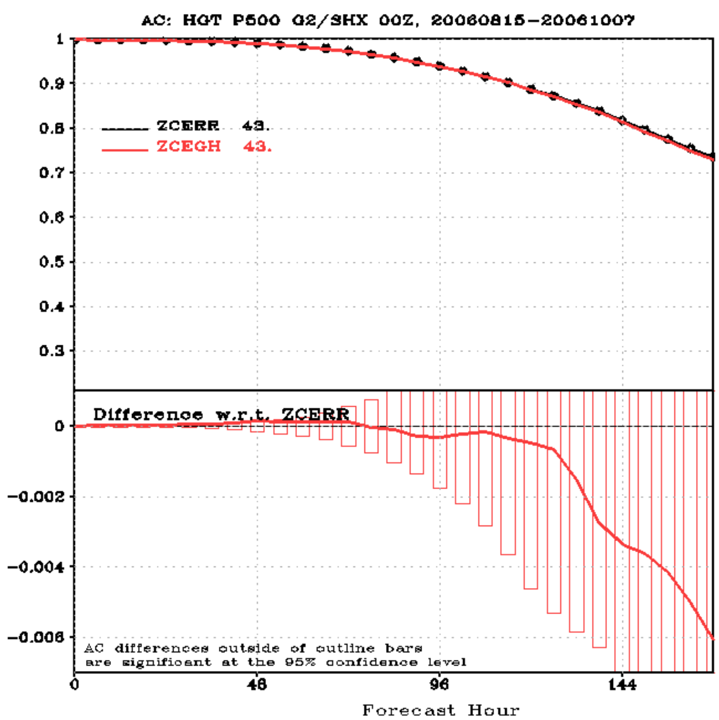

Figure 8. As in Figure 4, but for the Southern Hemisphere.

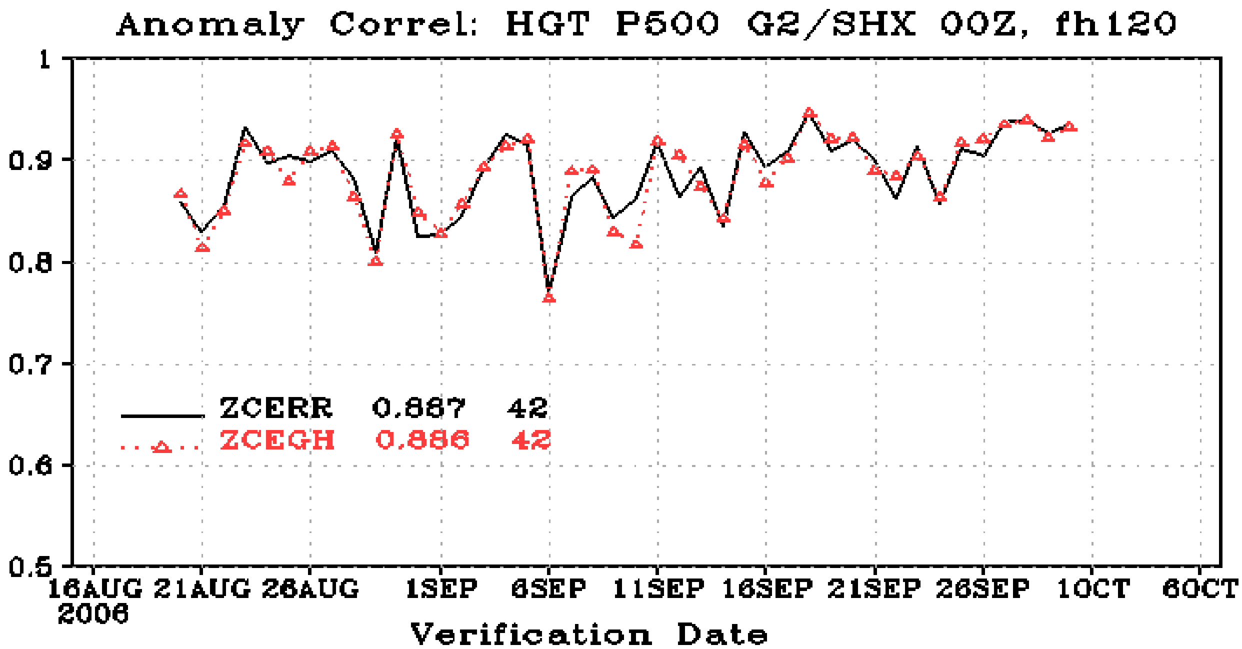

Figure 9. As in Figure 5, but for the Southern Hemisphere.

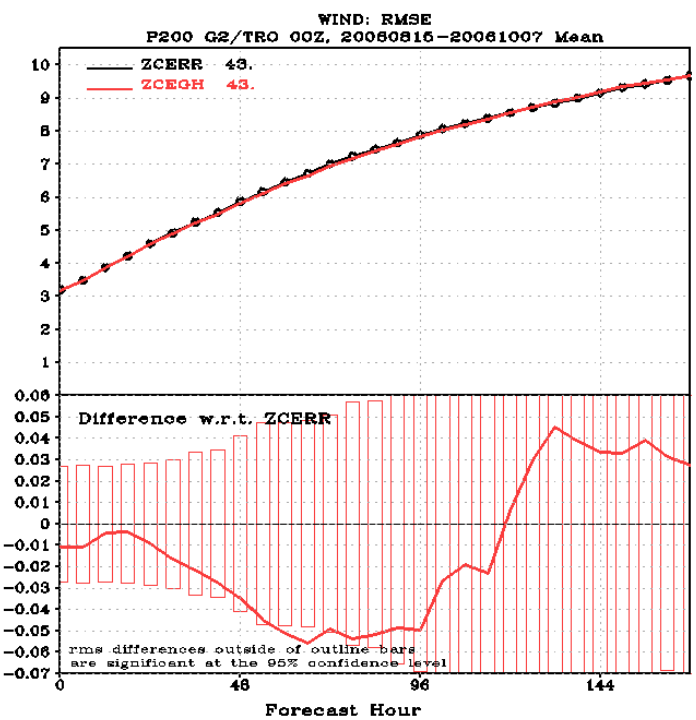

Figure 10. As in Figure 4, but for the 200 hPa Vector Wind Root-Mean-Square Error for the Tropics.

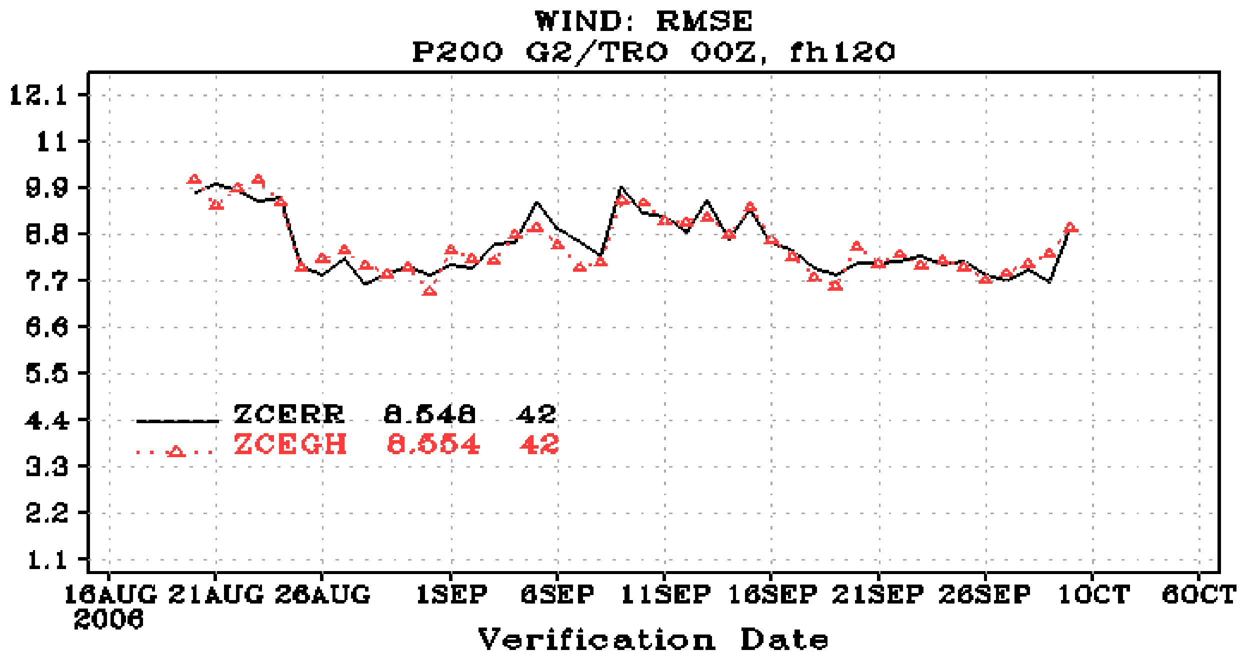

Figure 11. As in Figure 5, but for the 120-hour (5-day) 200 hPa Vector Wind Root-Mean-Square Error for the Tropics.

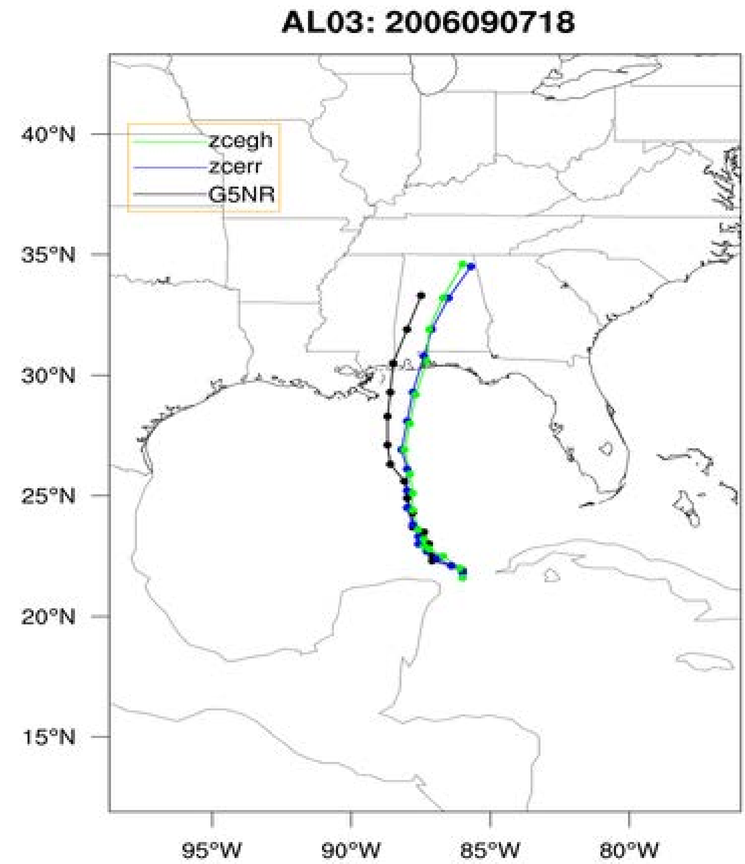

Figure 12. Forecast and verification tracks for Tropical Cyclone AL03. Black denotes best-track center locations, while the blue (CONTROL) and green (TEST) denote center locations from forecast initialized on 2006090718.

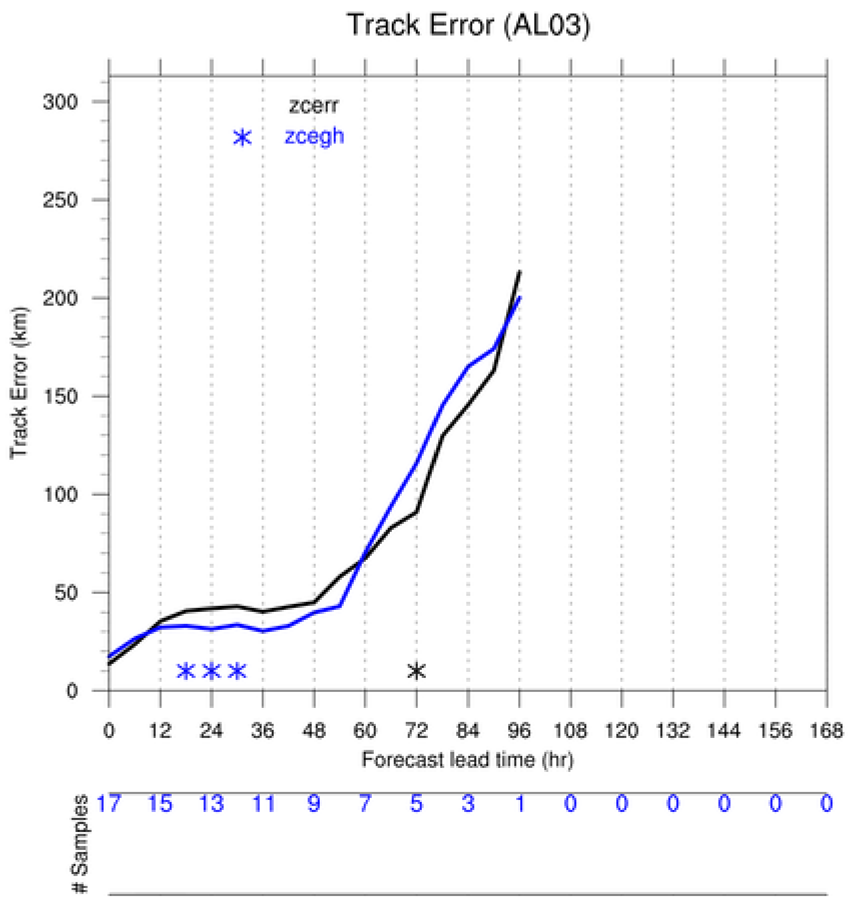

Figure 13. Mean track error as a function of forecast lead time for Tropical Cyclone AL03 for CONTROL (black) and TEST (blue) cases. Black stars denote difference statistically-significant at 95% confidence.

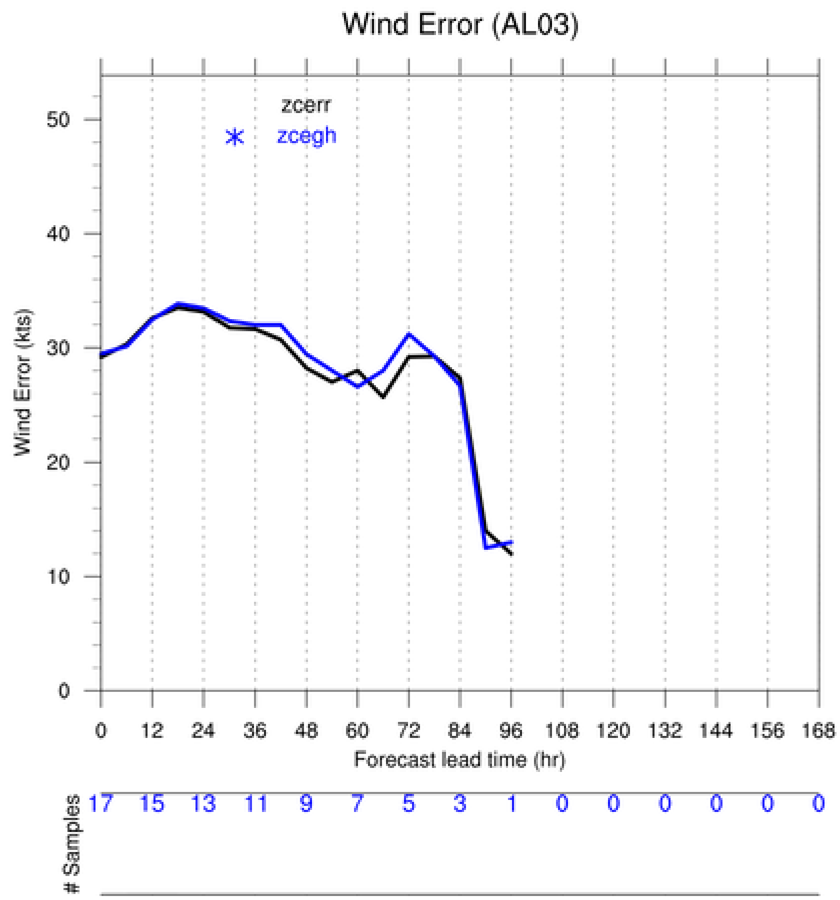

Figure 14. Mean maximum wind error as a function of forecast lead time for Tropical Cyclone AL03 for CONTROL (black) and TEST (blue) cases.

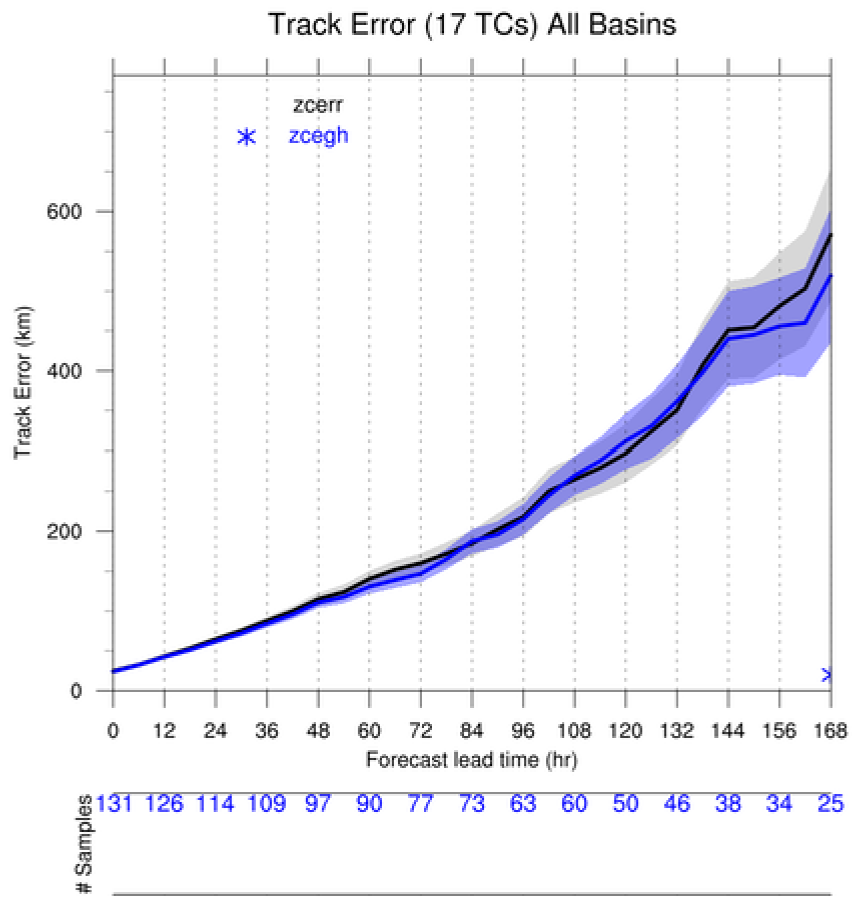

Figure 15. As in Figure 13, but for all storms over all basins, and with standard error intervals added.

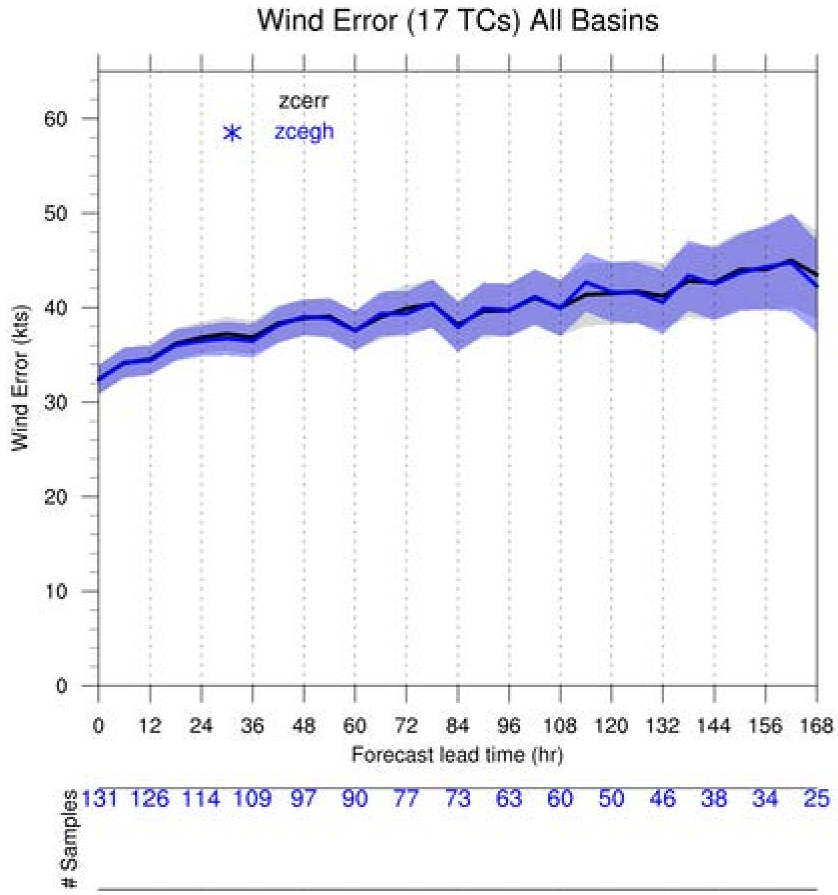

Figure 16. As in Figure 14, but for all storms over all basins, and with standard error intervals added.