Observing System Simulation Experiments for an Early-Morning-Orbit Meteorological Satellite in the Joint Center for Satellite Data Assimilation

Lars Peter Riishojgaard[1,2], Sean P.F. Casey[1,2,3,4], Michiko Masutani[2,5], Jack Woollen[2,5], Tong Zhu[2,4] and Robert Atlas[6]

[1]*Earth System Science Interdisciplinary Center (ESSIC)*
[2]*Joint Center for Satellite Data Assimilation (JCSDA)*
[3]*Cooperative Institute for Climate and Satellites (CICS)*
[4]*NOAA/NESDIS/STAR*
[5]*NOAA/NWS/NCEP/EMC*
[6]*NOAA/AOML*

1. Introduction

Following the reconfiguration of the nation's most important future meteorological satellite program into two separate programs, JPSS (NASA/NOAA) and DWSS (DoD), the agencies implementing these new systems are now in the process of reassessing the expected impacts of their respective systems. In the case of polar orbiters, one of the primary applications is data assimilation and numerical weather prediction (NWP), and the impact on forecast skill of numerical models is therefore one of the most important assessment metrics.

Over the last several decades, Observing System Simulation Experiments (OSSEs; see e.g. Arnold and Day 1986, Atlas et al. 1985, Atlas 1997, Masutani et al.,2010a) have been conducted assessing the impact of new candidate observing systems on numerical weather prediction applications and for preparing to immediately benefit from observing systems that have already been approved for future deployment by Stoffelen et al (2006), Masutani et al. (2010b), Riishojgaard et al, (2012).

Since 2006, the Joint Center for Satellite Data Assimilation has coordinated Joint OSSE collaboration across a number of groups within NASA and NOAA. The backbone of the collaboration is the shared use of a simulated realization of a long sequence of atmospheric states—the "Nature Run" in OSSE terminology—provided by the European Centre for Medium-Range Weather Forecasts, and coordinated validation, simulation of observations and calibration of the OSSE systems (Andersson and Masutani, 2010).

The Joint Center in collaboration with the USWRP OSSE testbed has made this Joint OSSE capability available to the Cost Analysis and Program Evaluation group of the Office of the Secretary of Defense (CAPE/OSD) for assessment of the expected consequences of a variety of possible programmatic decisions regarding e.g. an instrument payload located in the so-called "early morning orbit" (0530 Local Equatorial Crossing Time). This orbit has traditionally been covered by the Defense Meteorological Satellite Program (DMSP), and was one of the two orbits intended to be covered by the NPOESS program, which was canceled in February 2010.

2. Data/Methodology

The basic question addressed through the impact experiments described here is the following: What is the expected impact on the medium-range forecast skill of the Nation's primary global operational numerical weather prediction system, namely the NCEP Global Forecast System. In order to assess this, the following five baseline experiments have been performed:

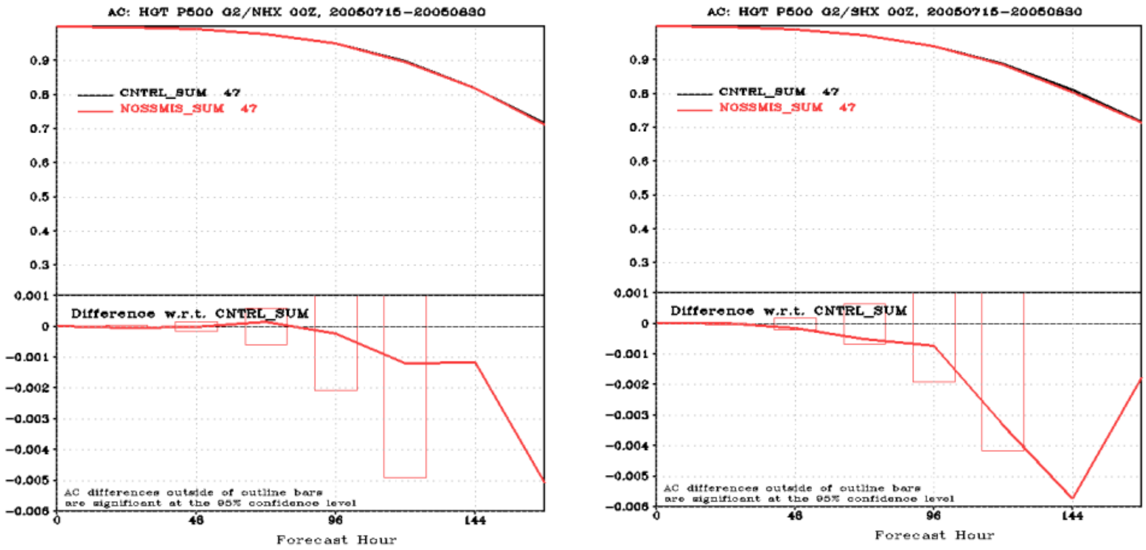

Figure 1. Experiment impacts on 500 hPa anomaly correlation. (left) Northern Hemisphere. (right) Southern Hemisphere.

1. A control run in which all relevant observations from observing systems (conventional and space-based) other than DWSS are assimilated (*cntrl*)
2. Same as 1., but without any early morning orbit coverage (no NOAA-16/DMSP-F17) (*nossmis*)
3. Same as 2., but with JPSS (i.e. CrIS and ATMS) added in the early morning orbit (*atmscris*)
4. Same as 2., but with VIIRS in the early morning orbit (i.e., polar winds) (*viirs*)
5. Same as 2., but with VIIRS and ATMS in the early morning orbit (*atmsvirs*)

Most of the instruments for which data were simulated for these experiments had real-world equivalents with available data in May and June 2012. Observation times and latitude/longitude information from actual satellite orbits from these two months were used to simulate the instruments that were used for all five experiments, as well as SSMI/S-F16 for the *cntrl* case. Observation locations from ATMS & CrIS onboard Suomi/NPP were shifted 60° eastward in longitude to simulate these observations in the new early-morning-orbit for *atmscris* (and *atmsvirs* for ATMS). MODIS observations from Aqua were also shifted 60° eastward in longitude and used to simulate VIIRS measurements for cases *viirs* and *atmsvirs*.

Simulation of satellite radiances was conducted using the Community Radiative Transfer Model (CRTM) developed at JCSDA (Han et al, 2006, Weng et al. 2006). Some evaluations of simulated radiance for early OSSE are described in Zhu et al. (2012).

We use the NCEP GDAS system based on the May 2011 version of GFS, coupled with a May 2012 version of the GSI trunk. While the GDAS is currently run operationally at a horizontal resolution of T-574 (roughly corresponding to 25 km), we use here a horizontal resolution of T-382 (or 40 km, the resolution previously used for operations), as we are limited by the T-511 resolution of the current Nature Run. Two experimental periods were chosen; one encompassing the months of July and August 2005 (indicated by the suffix "_*sum*)" of the nature run, and one encompassing the months of January and February 2006 (indicated by the suffix "_*win*"). For each period, the first two weeks are discarded as a spin-up period; the experiment itself then encompasses the remaining 45 days for forecast impact analysis. Seven-day forecasts were launched every 6 hours (00Z, 06Z, 12Z, 18Z). Sections 3 and 4

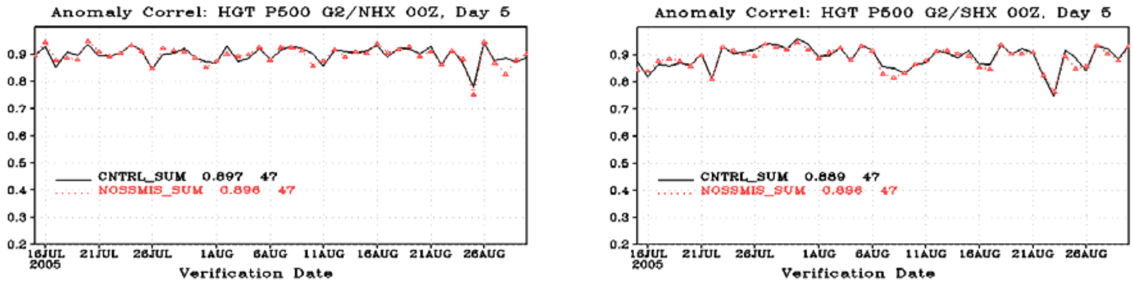

Figure 2. Time progression of day 5 (120 hour) anomaly correlation. (left) Northern Hemisphere. (right) Southern Hemisphere.

describe results from the summer season experiment for forecasts initialized at 00Z. Section 5 discusses how these results change when looking at forecasts initialized at different times. Section 6 compares all analysis time forecasts to the nature run, to see which experiment brings the model analysis closer to the "true state" of the atmosphere. Section 7 describes differences between results from the summer and winter seasons.

3. Impact of Removing SSMI/S

The first question to answer is whether the lack of early morning sounding coverage affects medium-range weather forecast skill. To do this, we first compare experiment *nossmis* to the *cntrl* case. Figure 1 shows the impact of the test experiments on 500 hPa Anomaly Correlation (AC) for the Northern (left) and Southern (right) hemispheres. AC is correlation between forecast and the best estimate of truth (here, the nature run) and varies between 0 and 1. Therefore higher values of AC indicate better forecast. Rectangles in the lower portion of the figures denote the 95% confidence interval; curves above or below these rectangles are said to be statistically significant, while curves within the rectangles are considered non-significant to two standard deviations. Degradations are noted beginning 4 days out (96 hours) in the Northern Hemisphere and 3 days out (72 hours) in the

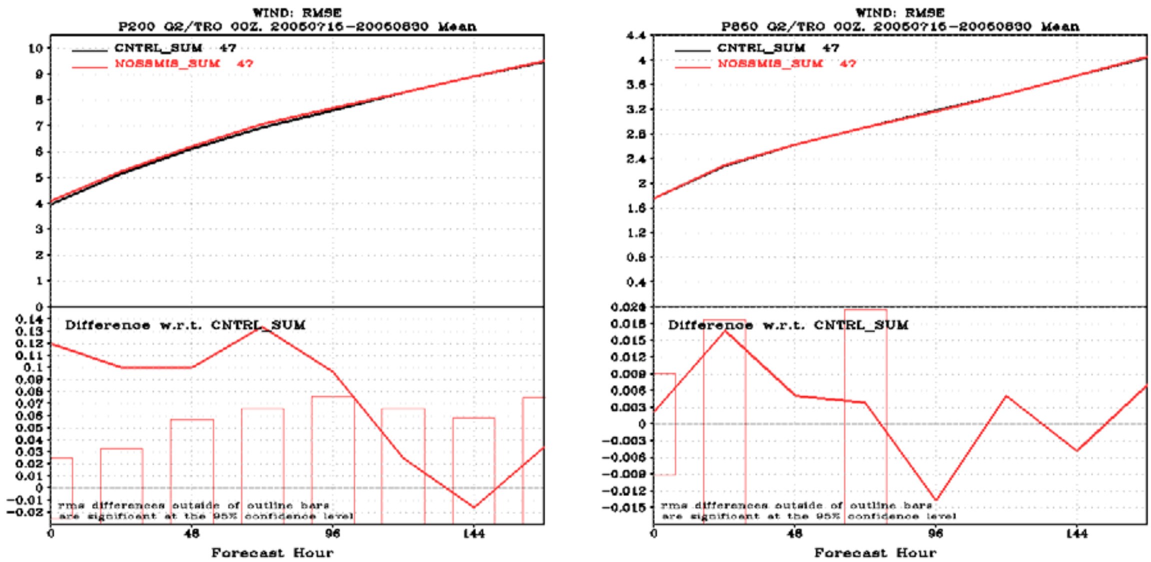

Figure 3. Impact of losing SSMI/S on wind speed RMSE. (left) 200 mb. (right) 850 mb.

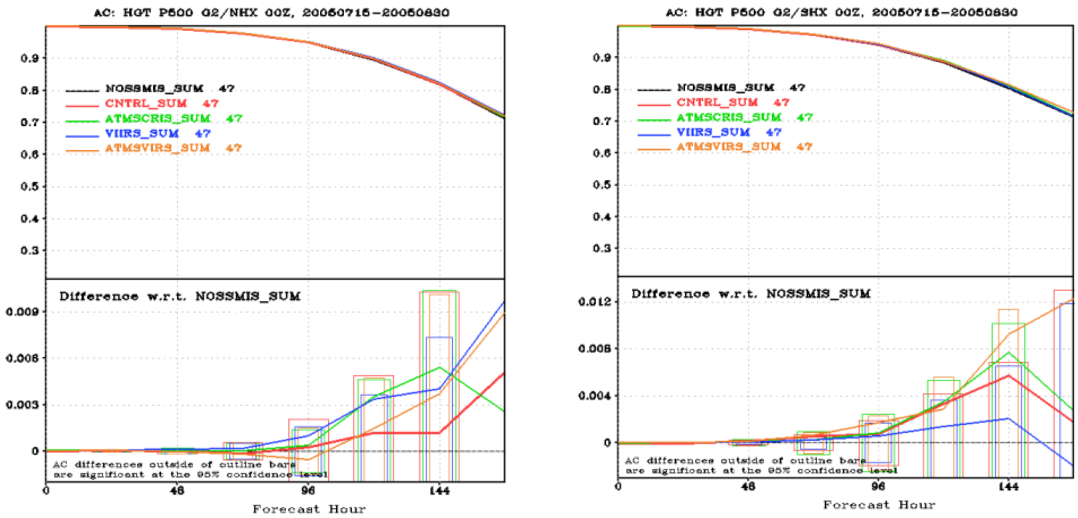

Figure 4. Experiment impacts on 500 hPa anomaly correlation. (left) Northern Hemisphere. (right) Southern Hemisphere.

Southern Hemisphere; however, none of these differences are significant at the 95% confidence interval.

Figure 2 shows time series of day 5 (120 hour) AC. For the northern hemisphere (left), the curves remain mostly similar, though there are many days (e.g, 31 July, 10 August and 25 August) where *cntrl* significantly outperforms *nossmis*. In the southern hemisphere plot (right), we also see many days where *cntrl* outperforms *nossmis*, such as 26 July, and 7-9 August.

Figure 3 shows the impact of losing SSMI/S on tropical wind speed Root Mean Square Errors (RMSE) at 200 hPa (left) and 850 hPa (right). Since RMSE indicate the magnitude of difference between forecast and estimated truth, smaller RMSE indicate a better forecast. At 200 hPa the effects of losing SSMI/S are significant immediately at analysis time, and continuing to be significant for four days following forecast initialization. This suggests that losing the early-morning-orbit coverage with no instrument replacement would significantly hamper model analysis of upper-level tropical winds, which is vital for the development and propagation of tropical cyclones. Effects are also noted in the lower troposphere (850 hPa), but these effects are much smaller.

4. Comparison of Different Early-Morning-Orbit Alternatives

After seeing the effects of losing SSMI/S, we now want to see which of the three suggested payload configurations for the early morning orbit would have the greatest forecast impact. We now

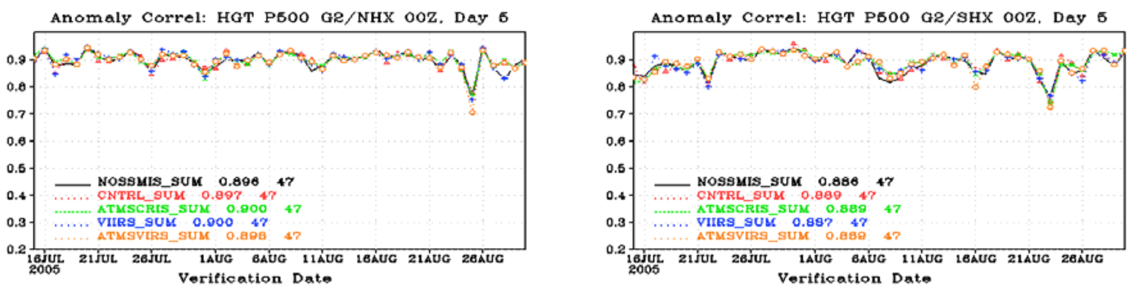

Figure 5. Experiment impacts on 500 hPa anomaly correlation. (left) Northern Hemisphere. (right) Southern Hemisphere.

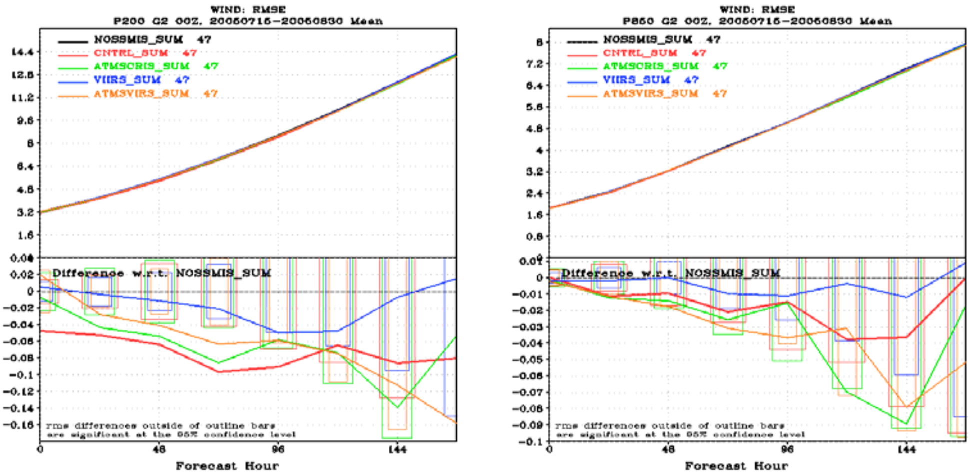

Figure 6. Experiment impacts on wind speed RMSE. (left) 200 mb. (right) 850 mb.

use case *nossmis* as the base case, and compare the remaining four experiments (*cntrl*, *atmscris*, *viirs*, *atmsvirs*) to *nossmis*. Figure 4 shows the 500 hPa AC for the Northern (left) and Southern (right) hemispheres. In the Northern Hemisphere, all four instrument configurations show improvement compared to *nossmis*, though none of the results appear significant. The same is noted for the Southern Hemisphere, though greater spread is noted between the experiments, with *atmsvirs* performing the best and *viirs* performing the worst.

Figure 5 shows time series of day 5 (120 hour) AC. All experiments perform better on some days and worse on others compared to *nossmis*. However, the mean values suggest that the *nossmis* case performs worst with *atmscris* performing best when comparing impacts for both hemispheres. 28 August in the Northern Hemisphere is particularly striking. Without early-morning-orbit coverage, anomaly correlation approaches 80%, and adding *viirs* alone shows no impact. With either SSMI/S or one of the ATMS cases, however, anomaly correlation is closer to 90% this day.

Figure 6 shows the impact of the test experiments on the tropical wind speed RMSE at 200 hPa (left) and 850 hPa (right). Cases *cntrl*, *atmscris*, and *atmsvirs* all show significant reductions in upper-level tropical wind RMSE from 24 to 72 hours out. The contribution of *viirs* is non-significant throughout, both at 200 and 850 hPa (right). While the impacts are not as striking in the lower troposphere, the two ATMS cases as well as the *cntrl* case show reductions in RMSE.

5. Impacts as a function of forecast initialization time

Sections 3 and 4 all showed impacts for forecasts initialized at 00Z. While describing instrument impacts for forecasts initialized at 06Z, 12Z, and 18Z would be repetitive, a general inference can be made using a side-by-side comparison such as that in Figure 7. Here the impacts on global 500 hPa anomaly correlation are plotted. For 00Z (upper left) and 12Z (lower left), no significant impacts are noted with the exception of the day 6 forecast for *atmsvirs* at 00Z. More significant impacts, however, are noted for 06Z (upper right) and 18Z (lower right), particularly for case *atmscris* though all cases show significant impacts for at least one forecast time. While satellite data availability does not change through a 24-hour cycle, ground-released radiosondes are usually only available at 00Z and 12Z. The absence of radiosondes at 06Z and 18Z can lead to reductions in assimilated observations of in situ temperature, wind and moisture on the order of 100,000. This means information provided by satellites

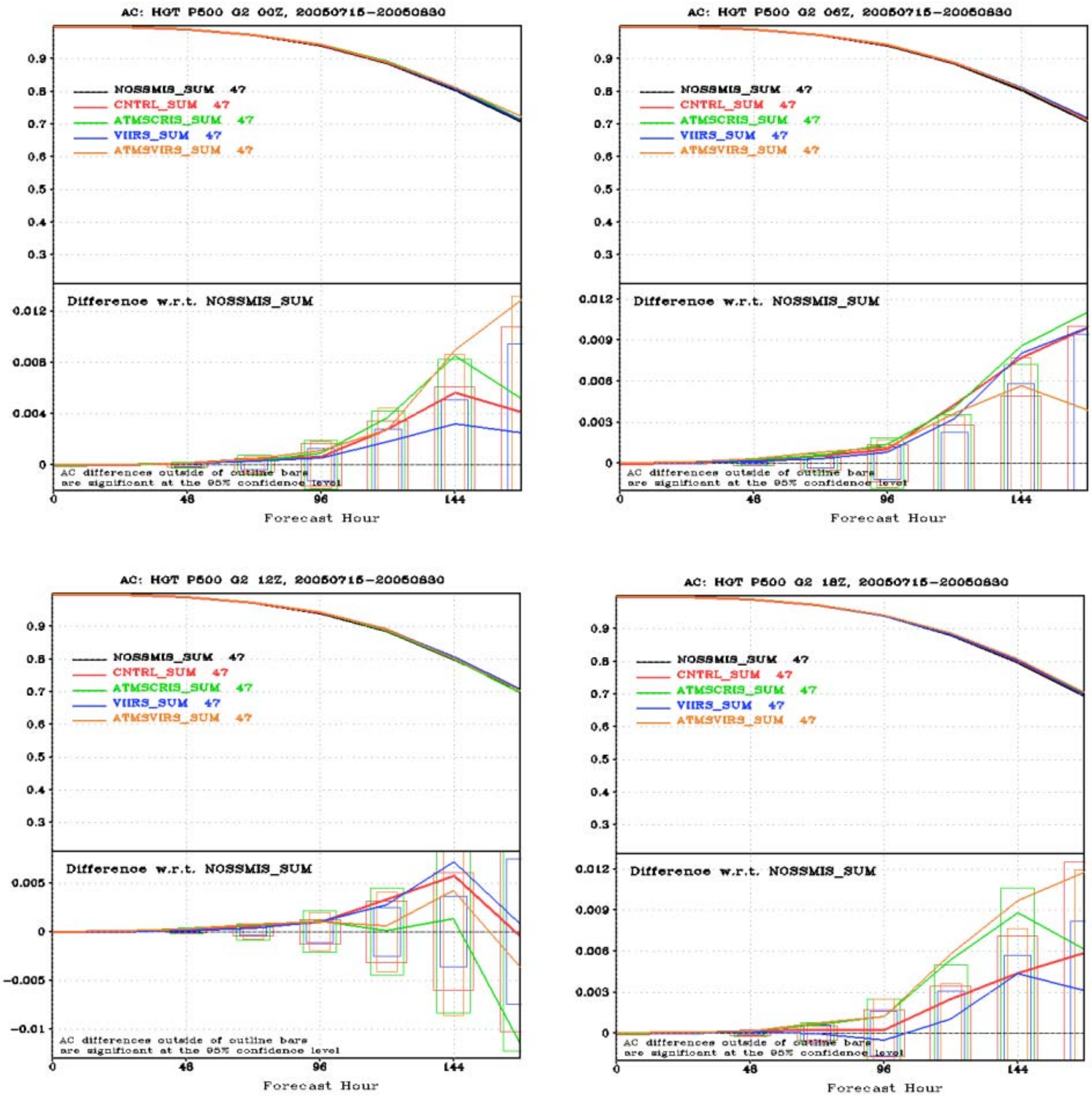

Figure 7. Experiment impacts on global 500 hPa anomaly correlation, for forecasts initialized at (upper left) 00Z, (upper right) 06Z, (lower left) 12Z, and (lower right) 18Z.

becomes even more important at these forecast times, especially when no other instrument is present in this particular orbit (such as in this study).

6. Total Departure from Nature Run

Contrary to data assimilation and NWP using actual data, the "true" state of the atmosphere is perfectly known in the context of an OSSE (since it is given by the nature run), and we can therefore compare both experiments to the nature run, over all forecast initialization times, to see which experiment is closer to "truth" over time. Again, we first look at the impact of losing SSMI/S. In Figure 8, pink/red colors on right indicate areas where *nossmis* is closer to the nature run; blue is where *cntrl* is

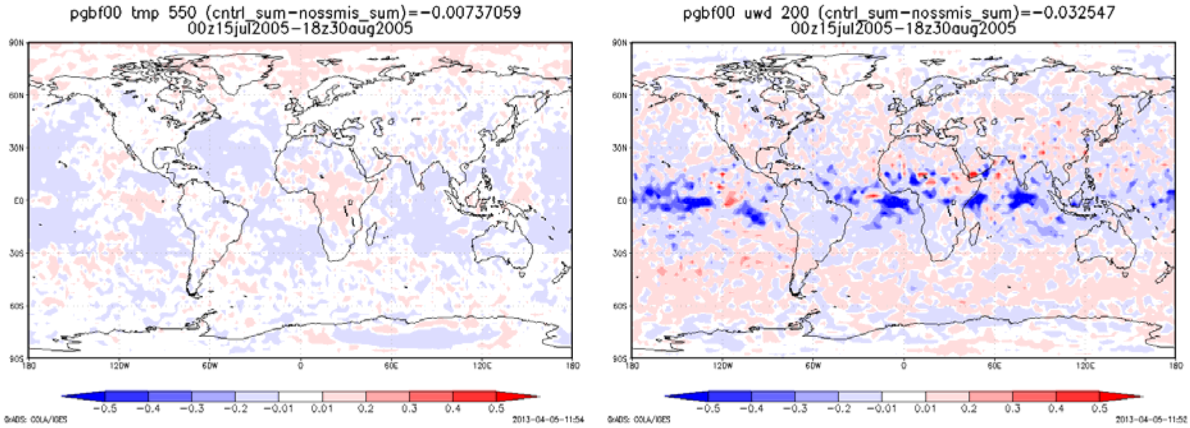

Figure 8. Difference of time mean RMSE (analysis-NR) between *cntrl* and *nossmis*. (left) 550 mb temperature. (right) 200 mb zonal wind. Blue areas indicate degraded analysis in *nossmis*.

closer to nature run. Mid-tropospheric temperature comparisons (550 hPa, left) show degradation in the subtropics. As expected from Figures 3 and 6, upper-level zonal wind impacts are greatest in the tropics, with significant departures from the true state noted in the Inter-Tropical Convergence Zone (ITCZ).

Different experiments will have varying impacts depending on the pressure level chosen. It is useful, therefore, to look at the total improvement/degradation throughout an atmospheric column (here chosen to be 200 to 1000 hPa). We derive a comparative metric (TD_{tot}) reflecting cumulative distance from nature run truth between two OSSE experiments, by computing RMSE(*nossmis*-NR)-RMSE(exp2-NR) formed at each level and gridpoint sampled over some period of time, then horizontally and vertically averaging the gridpoint differences to produce a single composite value.

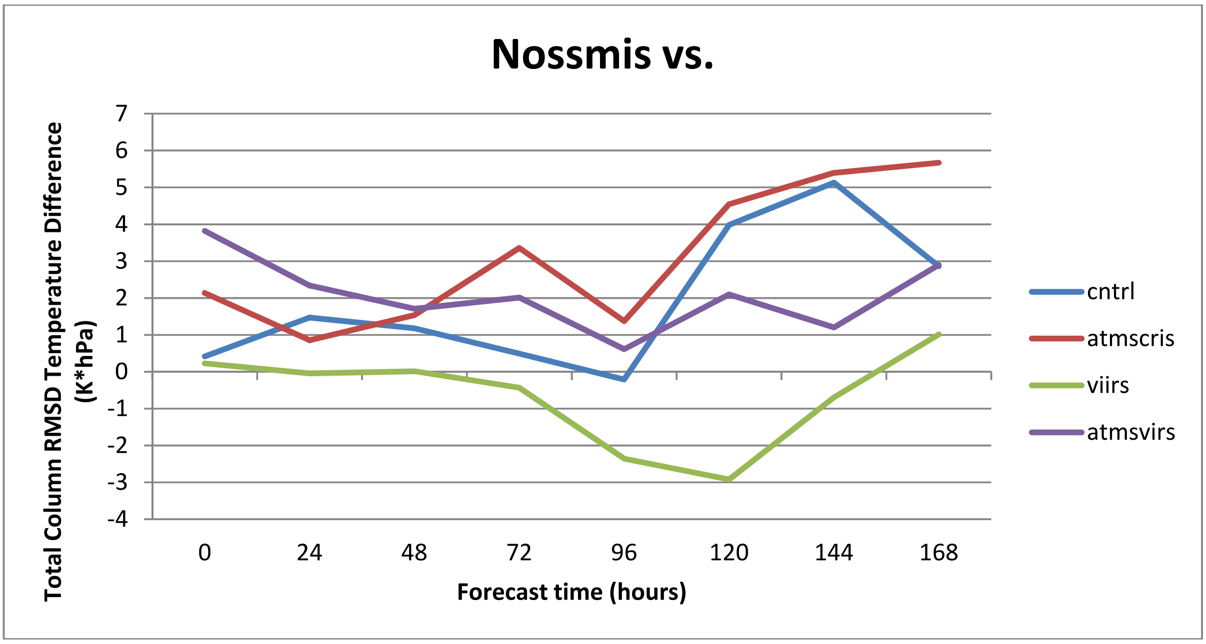

Figure 9. Total Temperature Departure (TD_{tot}) of all four early-morning-orbit experiments vs. *nossmis*, calculated every 24 hours from forecast initiation.

Figure 9 compares TD_{tot} values for all experiments, calculated every 24 hours from forecast initiation. It appears that case *atmsvirs* performs best at analysis time and up to 2 days from forecast initiation, while case *atmscris* performs best for medium-range (3 to 7 day) forecasts. Case *cntrl* also shows improvement for much of the forecast cycle. Case *viirs* shows neutral impact to degradation on medium-range forecasts.

7. Comparison of Seasonal Impacts

Similar to Section 5, a full description of the January/February seasonal impacts of an early-morning-orbit would prove repetitive. However, general notes concerning differences compared to July/August impacts can be highlighted. Figure 10, as an example, shows the experimental impacts on

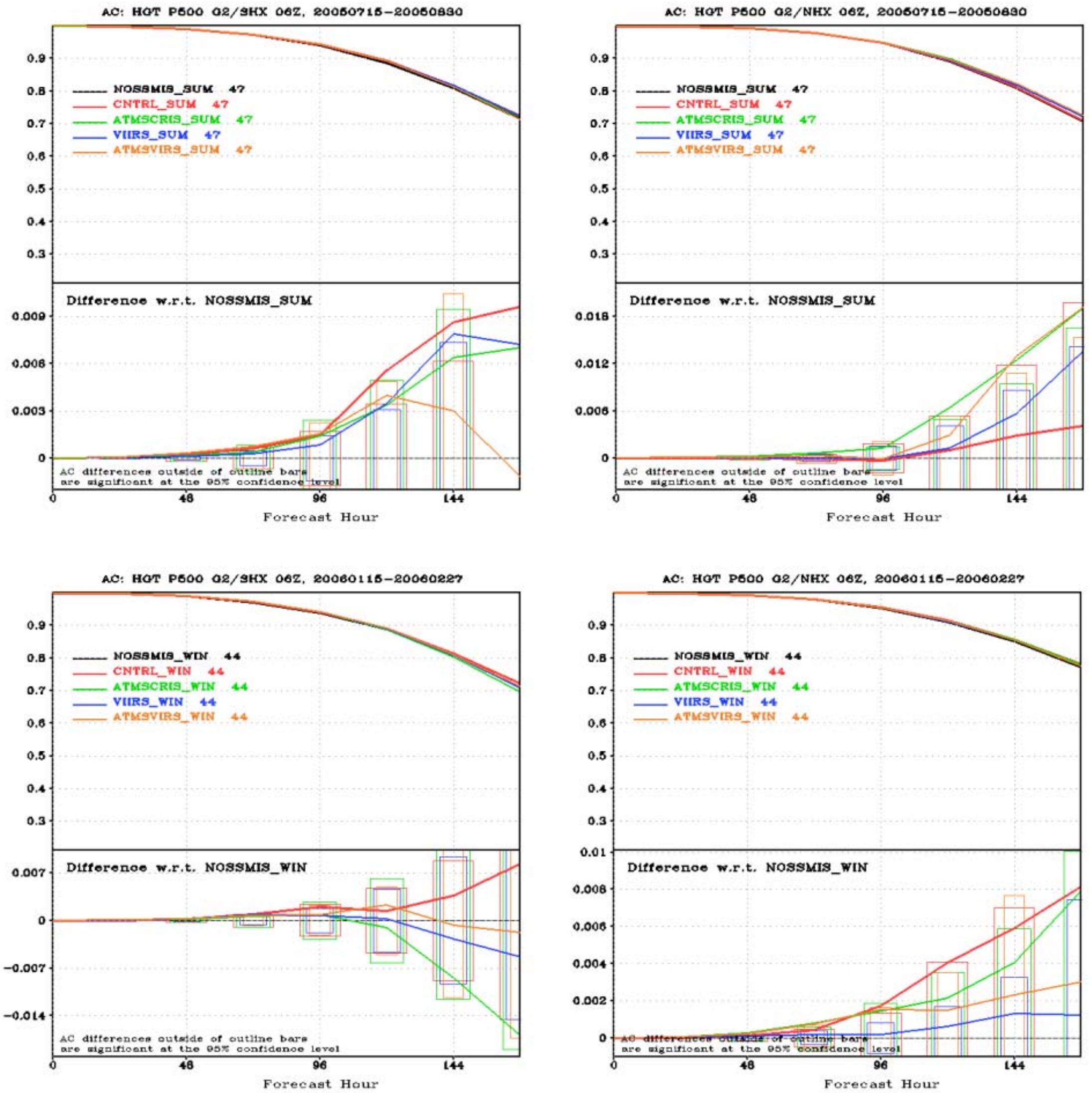

Figure 10. Experiment impacts on 500 hPa anomaly correlation for forecasts initialized at 06Z. (Upper left) July/August Southern Hemisphere, (upper right) July/August Northern Hemisphere, (lower left) January/February Southern Hemisphere, and (lower right) January/February Northern Hemisphere.

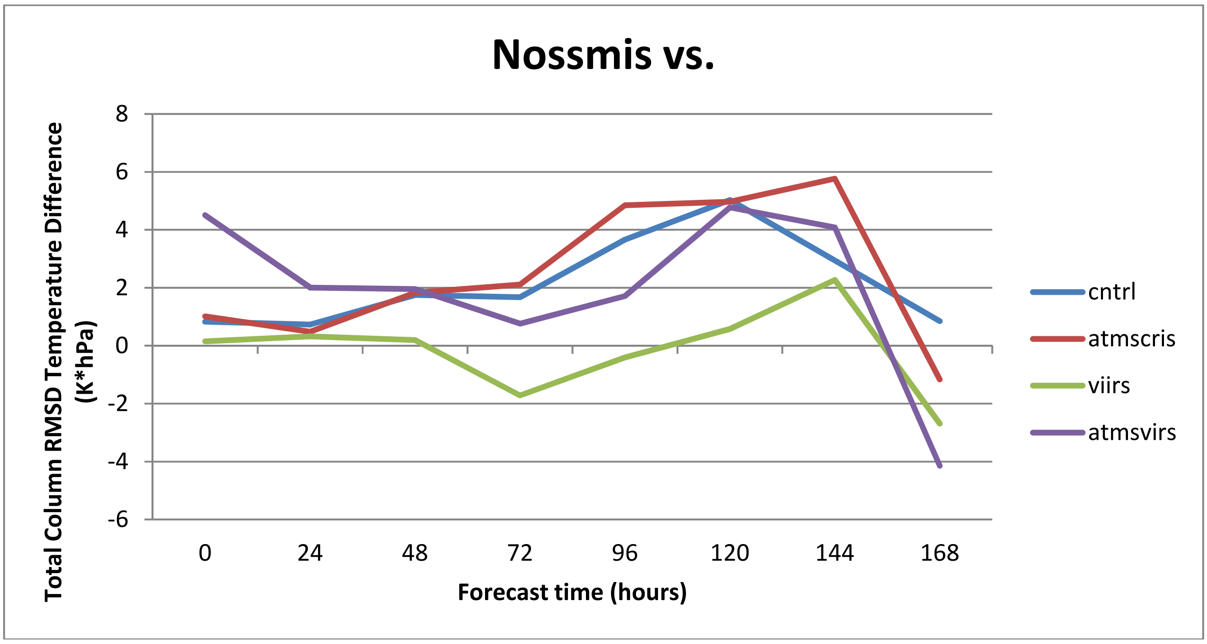

Figure 11. As in Figure 9, but for January/February.

500 hPa anomaly correlation for forecasts initialized at 06Z. Significant impacts are noted in the winter hemispheres [July/August Southern Hemisphere (upper left) and January/February Northern Hemisphere (lower left)] for the *cntrl* case, with mostly improvements from the other experiments compared to *nossmis*. The summer hemisphere experiments, however, show more neutral results. For July/August Northern Hemisphere (upper right), only *atmscris* shows significant improvement (day 5), though all experiments show some magnitude of improvement. For January/February Southern Hemisphere (lower left), however, the ATMS cases and the *viirs* case show degradation, though again these are nonsignificant.

Figure 11 recreates Figure 9 for the January/February season. As before, the ATMS cases show the greatest improvement overall, while SSMI/S also shows improvement and *viirs* neutral impact to degradation. All experiments show a dropoff in impact at day 7; investigation of this issue is ongoing, but given that these differences are noted at the end of the forecast cycle the reader should not read too much into this.

8. Conclusions

The results of the early-morning-orbit OSSE demonstrate the importance of a meteorological satellite in this orbit. Losing SSMI/S leads to decreases in model analysis and forecast skill, especially in the Southern Hemisphere and tropical wind fields. Improvement is noted for a combination of ATMS/CrIS or a combination of ATMS/VIIRS; VIIRS alone causes little improvement. Greater impacts are noted for forecasts initialized at 06Z and 18Z due to the absence of radiosonde data at these times. Similar impacts are also noted between July/August and January/February on a global scale, with the respective winter and summer hemispheres demonstrating similar results, though some non-significant differences are noted.

It should also be noted that only planetary-scale diagnostics have been performed for the experiments run and summarized in this report. Tropical cyclone diagnostics as well as other regional measures are likely to shed additional light on the impact of data from an early morning orbit satellite mission. Additional diagnostics should also include near-surface and flight level wind fields.

The verification statistical program used to compare experiments produced more comparison metrics than can reasonably be summarized in this report. Interested readers are invited to peruse the global results located at:

http://www.jcsda.noaa.gov/vsdb/users/scasey/ossesum/vsdb.php (July/August)
http://www.jcsda.noaa.gov/vsdb/users/scasey/ossewin/vsdb.php (January/February)

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