

**PROJECT TITLE:** Advancing forecast verification and model development efforts through the development of a flexible satellite-based verification system for the Global Forecasting System

**INVESTIGATORS:**

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**PROJECT DURATION:** 2 years (2016-2018)

**TIME PERIOD ADDRESSED BY REPORT:** March 2017 – August 2017

**1. PROJECT OVERVIEW**

This project will use simulated satellite brightness temperatures to evaluate the ability of advanced parameterization schemes in the GFS model to produce accurate cloud and water vapor forecasts. Model output from both full-resolution and coarse-resolution GFS model simulations employing different parameterization schemes will be converted into simulated infrared and microwave brightness temperatures for both clear- and cloudy-sky conditions using the Community Radiative Transfer Model (CRTM) included in the Gridpoint Statistical Interpolation (GSI) system or in the Unified Post Processor (UPP). The satellite simulator capabilities of the CRTM will be enhanced by increasing the consistency between the cloud property assumptions made by a given microphysics parameterization scheme and those used by the CRTM when computing cloud-affected brightness temperatures. These enhancements will be part of a flexible satellite-based forecast verification system that incorporates a variety of statistical methods.

We will rigorously evaluate the accuracy of the simulated cloud and water vapor fields generated by each suite of parameterization schemes through comparison of observed and simulated infrared and microwave brightness temperatures from multiple geostationary and polar-orbiting satellite sensors. The forecast accuracy will be assessed for different regions using traditional grid point statistics and neighborhood-based methods such as the Fractions Skill Score (FSS) and probability distributions. Satellite-based verification metrics developed during this project will be used in combination with traditional operational verification methods to provide a comprehensive assessment of the impact of the advanced parameterization schemes on the GFS forecast accuracy over a range of spatial and temporal scales. Though the project initially focuses on the GFS model, the verification system will be developed to be extensible and beneficial to other model development efforts in the NGGPS framework. Our research efforts will be closely coordinated with collaborators at the Environmental Modeling Center (EMC) and the Global Model Test Bed (GMTB) at the Developmental Testbed Center (DTC) to ensure operational relevance.

## 2. RECENT ACCOMPLISHMENTS

During the past six months, our efforts have primarily focused on assessing the accuracy of GFS model forecasts generated by our collaborators at EMC and the DTC, examining the impact of different ice cloud property lookup tables in the CRTM that are used when computing simulated infrared brightness temperatures, and transferring several changes that we have made to the GSI to the NOAA Virtual Laboratory (VLAB) for potential inclusion in future versions of the operational GSI. Each of these tasks is discussed in more detail below.

### *2.1. Enhancements to the CRTM and GSI satellite simulator capabilities*

As discussed in the previous report, we made several changes to the satellite simulator capabilities of the CRTM and GSI during the first six months of the project that together enhanced the accuracy of simulated cloud-affected brightness temperatures and promoted a more effective evaluation of the GFS model output. During this reporting period, all of these changes were made available to Andrew Collard (NOAA/NCEP/EMC) through a new branch in the NOAA VLAB Community GSI code repository (comgsi-git) named “NEBUDA\_SIMTB”. Documentation for the GSI changes checked into this branch is provided in VLAB/Redmine Feature #34694. We will continue to work with the GSI developers as they determine which features they would like to include in future versions of the operational GSI. A review of the changes is provided below.

- Enhanced the satellite simulator capabilities of the CRTM through inclusion of a new function that computes the effective particle diameters for each cloud species explicitly predicted by a given microphysics parameterization scheme. This is an important modification when using more advanced cloud microphysics schemes. Sections were added for the WSM6 and Thompson schemes. Support for other microphysics schemes can be added as needed.
- Expanded the GSI so that it can read GFS sigma level files that include all of the cloud microphysical fields generated by the WSM6 and Thompson microphysics schemes.
- Added a new namelist option and code modifications that allow the GSI to choose the nearest neighbor in space and time to a given observation rather than using the standard interpolation approaches. This approach is useful for cloud verification because it prevents interpolation issues in regions where cloud properties change rapidly in space and time.
- Added new cloud related diagnostic output for the forecast fields that is collocated with the observation locations.
- Added new routines to process all-sky infrared radiances from the Meteosat-10 SEVIRI and GOES-13/15 Imager sensors.

In summary, the goal of this task was to create an analysis system where the GSI can be run in “single cycle mode” so that it can be used to evaluate the forecast accuracy and in the process leverage the extensive quality control and data processing procedures that have already been developed for data assimilation applications. Use of the GSI in single cycle mode allows us to easily create simulated brightness temperature datasets that are collocated with the observations.

## *2.2. Analysis system development and data preparation*

During the past six months, we continued to assess the accuracy of two GFS model forecast datasets generated by collaborators at EMC and the DTC. For the EMC datasets, the GFS was run at its native spectral resolution (T1534) whereas for the DTC datasets, the model was run at a much coarser T574 spectral resolution. The full model sigma level files are included in the EMC datasets, which allows us to run the GSI in “single-cycle mode” to compute simulated brightness temperatures; however, the DTC datasets only include pressure level files and therefore simulated brightness temperatures are computed using the UPP. It should also be noted that the EMC and DTC datasets cover different time periods. The different model resolutions and data availability (sigma versus pressure level files) introduces complexity in the verification system; however, it also allows us to develop a more flexible system that is relevant both to operational model developers and data assimilation researchers. This is true because detailed analysis of the full-resolution model forecasts will be useful for researchers developing new parameterization schemes whereas analysis of the coarse-resolution GFS model forecasts will provide insight into the accuracy of the cloud and water vapor fields used during the data assimilation step.

We have retrieved various satellite and model datasets and have written numerous scripts to process the data, visualize the modeled and observed satellite brightness temperatures, and analyze the accuracy of the forecast cloud and water vapor fields. To make the model verification system as portable as possible, it is being written using only Python, Fortran, and Bash scripting. Given differences in data format, the EMC and DTC datasets require different processing steps and code development. For the EMC datasets, we used our modified version of the GSI (see Section 2.1) to generate input files containing all-sky infrared brightness temperature for the Meteosat-10 SEVIRI and GOES-13/15 Imager sensors with full spatial resolution. Access to the full-resolution satellite datasets allows us to more thoroughly assess the accuracy of the high-resolution GFS forecasts. Scripts were written to convert the standard GSI binary diagnostic output into netCDF4 format files for analysis and visualization purposes. Python scripts were written to visualize the simulated and observed brightness temperatures for both sensors. In contrast, the DTC datasets already contain simulated satellite brightness temperatures; however, these were computed using pressure-level data rather than the full-resolution model sigma level data. For this dataset, we again use SEVIRI and GOES-13/15 Imager brightness temperatures for the analysis, with the observed satellite datasets obtained from a data archive at the Space Science and Engineering Center (SSEC) at the University of Wisconsin-Madison. We are using a variety of statistical methods to assess the forecast accuracy, including standard grid point statistics such as root mean square error, bias, and mean absolute error, along with neighborhood methods such as the fractions skill score and probability distributions that are less sensitive to small displacements in the cloud field.

## *2.3. Model forecast assessments – Sensitivity to CRTM ice cloud property lookup tables*

As mentioned previously, we were given access to a large set of GFS model simulations that were run at T1534 spectral resolution using experimental configurations employing different microphysics schemes. These model simulations were performed by Ruiyu Sun at EMC to assess the performance of the WSM6 and Thompson microphysics schemes, both of which are candidates for future inclusion in the GFS and FV3 models. We are supporting their model development efforts through a detailed evaluation of the forecast

accuracy via comparisons of simulated and observed infrared brightness temperatures. An extensive set of 10-day long forecasts covering parts of July and December 2014 was generated using each microphysics scheme. Our analysis focuses primarily on the WSM6 scheme because there was a major bug in the implementation of the Thompson scheme in this version of the GFS that led to unrealistically warm brightness temperatures due to insufficient upper-level clouds. The bug severely limited the occurrence of homogeneous nucleation of ice particles, which meant that ice clouds could mostly only form through the upward transport of other cloud hydrometeor types (e.g., cloud water), thereby greatly limiting the spatial extent of upper level clouds. In addition, though the implementation of the WSM6 scheme has no known bugs, inspection of the data archive revealed that some forecast datasets were corrupted during their archival. This means that only select time periods during July and December (rather than the entire months) are available for our analysis. Nonetheless, we were still able to access extensive GFS model forecast data sets that will promote a useful analysis of the model forecast accuracy. In total, we have useful data from 28 forecast cycles, 10 from July and 18 from December. In this report, we will assess the accuracy of four forecast cycles from July (03, 04, 05, and 27). Results compiled using more forecast cycles will be presented in the next project report.

Simulated infrared brightness temperatures for select bands sensitive to clouds and water vapor were generated for the SEVIRI and GOES Imager sensors using the CRTM in the GSI while running it in “single-cycle mode”. Given the importance of assumptions made by the CRTM for forecast verification, extensive effort was spent assessing the impact of using different ice cloud scattering property lookup tables in the CRTM when computing the simulated brightness temperatures. As described in the previous project report, these include two versions of the lookup tables already included in the latest distribution of the CRTM (version 2.2.3), hereafter referred to as the “Original” and “TAMU” lookup tables, and a new lookup table that was generated based on Baum et al. (2014). A brief overview of their most important differences is provided here. Comparison of the phase function expansion coefficients (used to reconstruct the scattering phase function from a sum of Legendre polynomials) revealed major differences for the hail/ice hydrometeor category between the Original and TAMU lookup tables. The newer TAMU lookup table had reasonable values for the expansion coefficients, whereas the Original lookup table had values that were near zero or even negative in some places. These coefficients should never be negative, which indicates that they were computed in error. The only way to correct this error would be to recompute the coefficients using the  $\delta$ -fit code with the single particle scattering properties integrated over the assumed size distribution, both of which are unknown due to lack of documentation in the CRTM. The “Baum” lookup tables were computed based on the single particle scattering properties for roughened ice particles from Yang et al. (2013) that were integrated over a gamma size distribution assuming a mixture of 9 habits: solid/hollow bullet rosettes, solid/hollow columns, plates, droxtals, small/large aggregate of plates, and an aggregate of solid columns. This lookup table differs from the Original and TAMU lookup tables in that the particle effective radii extend from 5  $\mu\text{m}$  to 60  $\mu\text{m}$ , whereas, the other lookup tables extend from 2  $\mu\text{m}$  to 100  $\mu\text{m}$ . Because the  $\delta$ -fit code was not available to us, we used our own code to decompose the scattering phase functions into their Legendre expansion coefficients, which was done using the more traditional delta-M method (Wiscombe 1977). These coefficients were then interpolated to the CRTM lookup table effective radii and wavelength points.

Our analysis of the July 2014 WSM6 experiments has uncovered systematic errors in the cloud and water vapor forecasts along with a large sensitivity in the simulated brightness temperatures for ice clouds to the CRTM cloud property lookup tables. Figure 1 shows a representative comparison of the observed and simulated GOES-15 6.5  $\mu\text{m}$  brightness temperatures (sensitive to clouds and water vapor in the upper troposphere) from a 24-h forecast valid at 00 UTC on 28 July 2014 using the Original, TAMU, and Baum lookup tables. The first thing to note is that the simulated brightness temperatures are generally too cold within the clear-sky areas in the middle of the images (yellow colors), which indicates that there is a moist bias in the upper troposphere during the model forecasts. Because this bias was already present during earlier forecast lead times and also occurred when the Thompson scheme was used (not shown), this indicates that the forecast bias is likely due to a moist bias in the initialization datasets. In areas with active convection, such as along the Inter-tropical Convergence Zone and North America, it is evident that the simulated brightness temperatures are slightly warmer than observed when the Original lookup table was used (Fig. 1b). The brightness temperatures computed using the TAMU and Baum lookup tables (Figs. 1c, d) were even warmer, and did not represent the observed imagery as well as the Original lookup table.

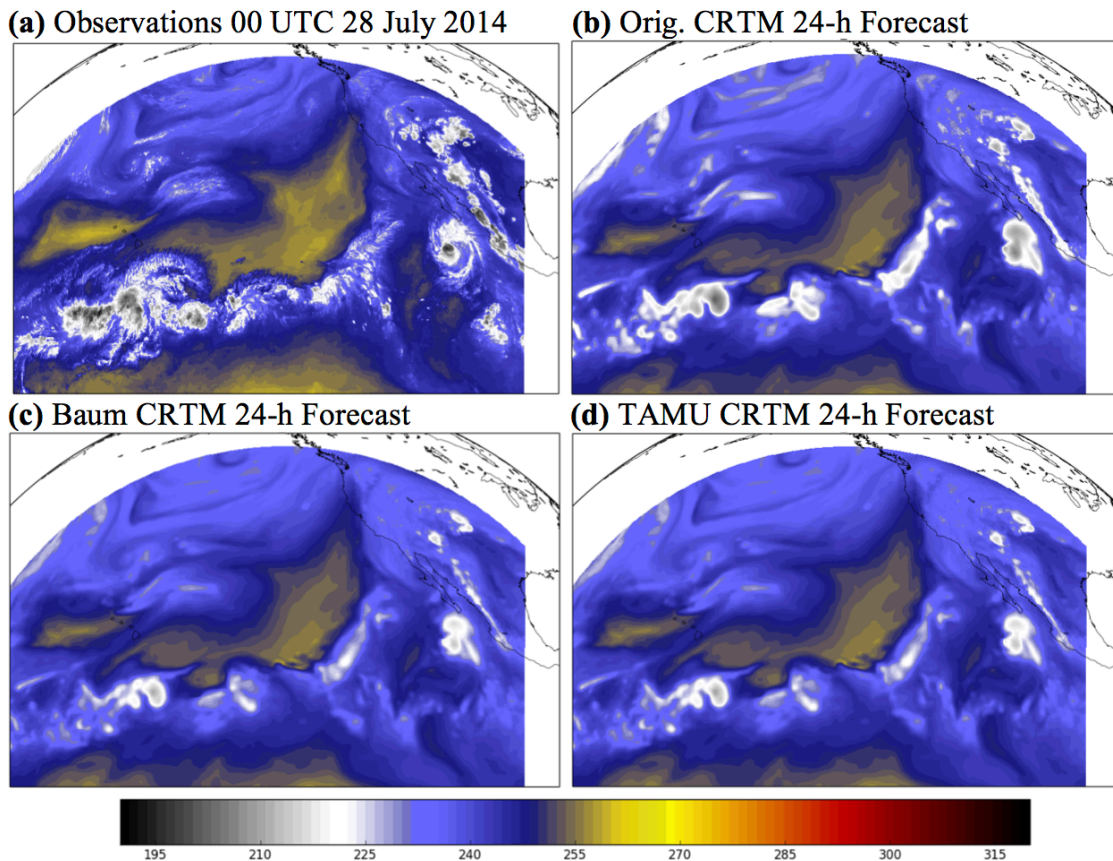
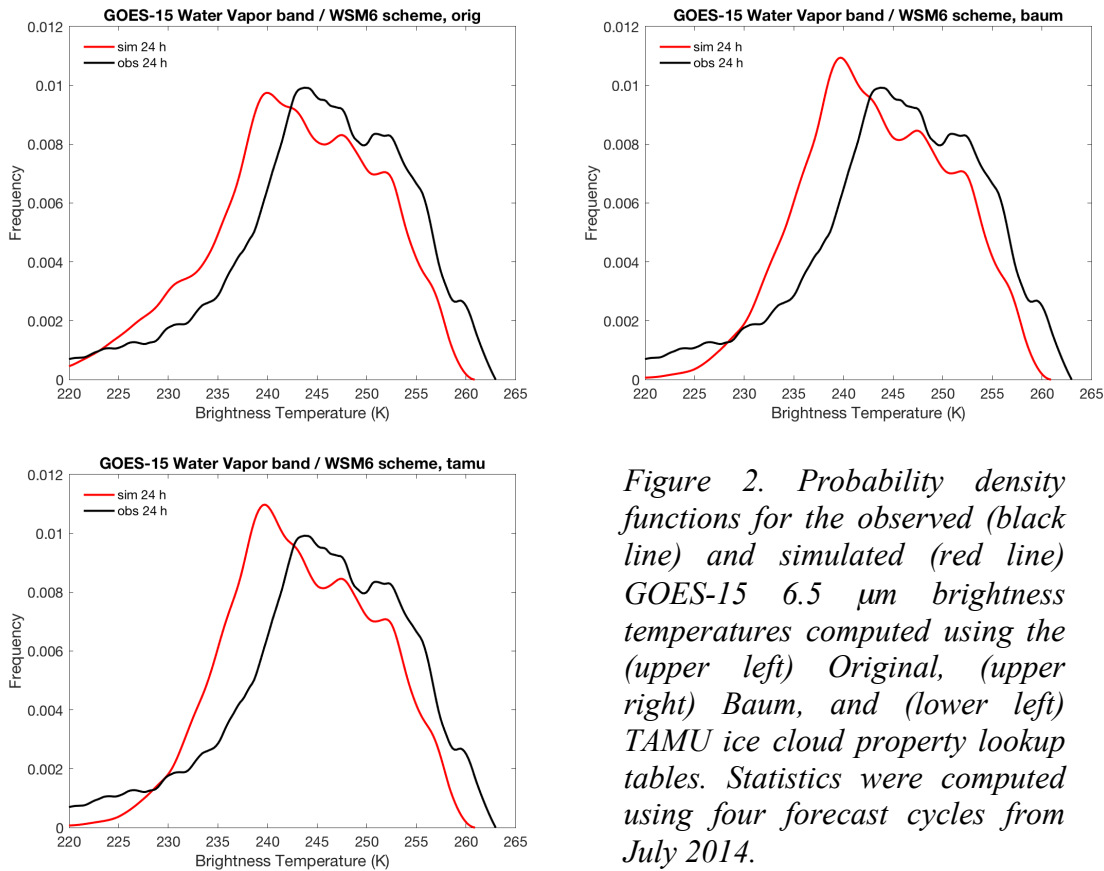


Figure 1. Observed and simulated GOES-15 6.5  $\mu\text{m}$  brightness temperatures (K) for a 24-h forecast using the WSM6 scheme valid at 00 UTC on 28 July 2014. The observed brightness temperatures are shown in panel (a) while the simulated brightness temperatures computed using the Original, Baum, and TAMU cloud property lookup tables are shown in panels (b), (c), and (d).

To examine both of these biases more closely, Fig. 2 shows probability density functions (PDFs) for the observed and simulated brightness temperatures for the same region shown in Fig. 1, but computed using four forecast cycles. Overall, the PDFs display the same characteristics shown in Fig. 1, including the large moist bias (as indicated by the leftward shift of the red lines) and the sensitivity to the cloud property lookup table, with the TAMU and Baum PDFs deficient in brightness temperatures colder than 230 K. The presence of these biases in the long-term statistics indicates that these are persistent biases rather than transient biases.



*Figure 2. Probability density functions for the observed (black line) and simulated (red line) GOES-15 6.5  $\mu\text{m}$  brightness temperatures computed using the (upper left) Original, (upper right) Baum, and (lower left) TAMU ice cloud property lookup tables. Statistics were computed using four forecast cycles from July 2014.*

Additional insight into the systematic errors in the simulated brightness temperatures can be found by calculating the bias at various forecast lead times. In Fig. 3, the bias is shown out to 9 days for northern hemisphere sectors covered by GOES-15 and GOES-13 6.5  $\mu\text{m}$  water vapor imagery and the full disk region covered by the SEVIRI 6.2  $\mu\text{m}$  water vapor imagery. In all cases, the bias is negative during the entire forecast period, with the bias exceeding -3 K at some lead times in the GOES-13 and 15 sectors. Overall, the Original CRTM lookup table produces the coldest biases while the Baum and TAMU lookup tables produce nearly identical but less negative biases at all lead times. The simulated GOES brightness temperatures exhibit relatively small changes in bias during the forecast period, whereas the simulated SEVIRI brightness temperatures exhibit an increasingly negative bias as the lead time increases. The smaller biases obtained using the TAMU and Baum lookup tables, however, are misleading because of the impact of compensating biases between the warmer-than-observed brightness temperatures in cloudy regions and the colder-than-observed brightness temperatures in clear-sky regions, as was seen in Fig.

2. This result shows the importance of evaluating more than just the average forecast skill over large areas when assessing forecast accuracy. We will more systematically assess the forecast accuracy for clear and cloudy sky regions during the next reporting period by partitioning the results using a cloud mask.

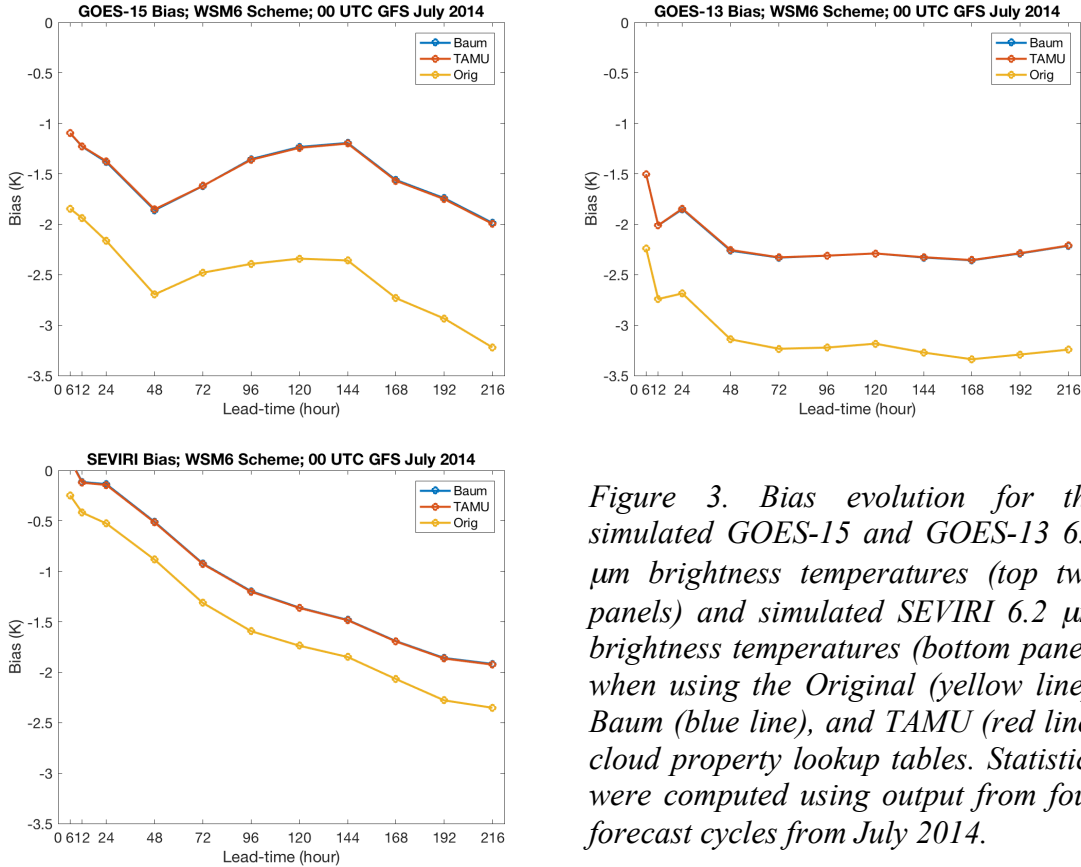


Figure 3. Bias evolution for the simulated GOES-15 and GOES-13  $6.5 \mu\text{m}$  brightness temperatures (top two panels) and simulated SEVIRI  $6.2 \mu\text{m}$  brightness temperatures (bottom panel) when using the Original (yellow line), Baum (blue line), and TAMU (red line) cloud property lookup tables. Statistics were computed using output from four forecast cycles from July 2014.

The error characteristics for the infrared window band differ slightly from those found in the water vapor band. Figure 4 shows a representative example comparing the observed and simulated GOES-15  $10.7 \mu\text{m}$  brightness temperatures for a 24-hour forecast when the WSM6 microphysics scheme is used. As was shown in Fig. 1, the simulated brightness temperatures were too warm in regions containing upper-level clouds when the Original lookup table was used, but were even warmer when the TAMU and Baum lookup tables were used. Comparison of the observed and simulated imagery shows that the forecasts were not able to realistically capture the small-scale details of the cloud field, both for low-level stratocumulus clouds and for upper-level cloud features. The lack of very cold brightness temperatures in convective regions in the tropics is likely due to the coarse resolution of the model that prevents it from properly resolving the most intense convective features. It is encouraging though to see that the 24-hour forecast did a reasonable job depicting the locations of the upper-level cloudy regions; however, it is also evident that the representation of the low- and mid-level clouds in terms of their structure and coverage is deficient across most parts of the domain. This can be seen more clearly in the PDFs shown in Fig. 5, where the forecasts are deficient in brightness temperatures between 275 and 290 K. This suggests that there could be problems with the cumulus or planetary boundary layer schemes or fluxes from the ocean surface.

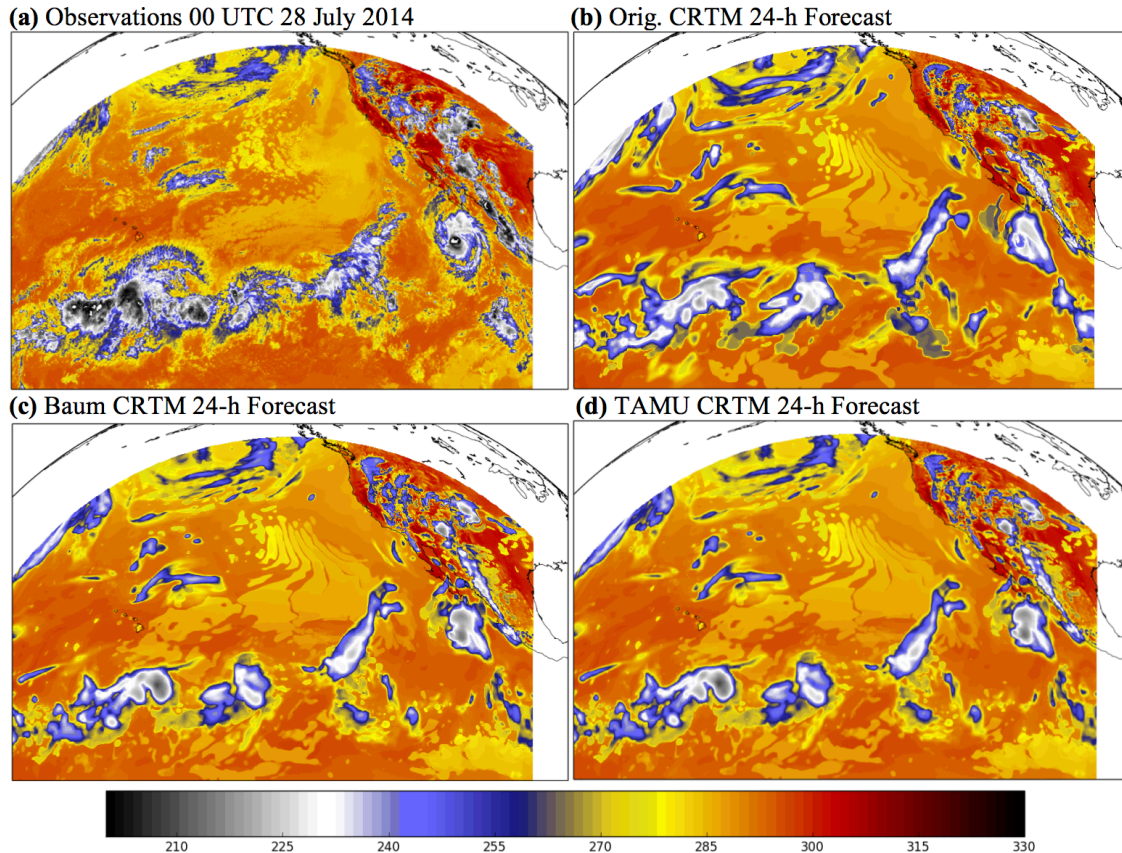


Figure 4. Observed and simulated GOES-15  $10.7 \mu\text{m}$  brightness temperatures (K) for a 24-h forecast using the WSM6 scheme valid at 00 UTC on 28 July 2014. The observed brightness temperatures are shown in panel (a) while the simulated brightness temperatures computed using the Original, Baum, and TAMU cloud property lookup tables are shown in panels (b), (c), and (d).

Figure 6 shows the simulated GOES-15  $10.7 \mu\text{m}$  brightness temperature bias plotted as a function of forecast lead time computed using the July 2014 WSM6 forecasts. As was seen previously, the Baum and TAMU lookup tables produce similar results and have a smaller bias than the original CRTM lookup table, even turning from a negative bias into a positive bias for the GOES-13 and GOES-15 sectors. The overall biases are smaller for the SEVIRI sector regardless of which lookup tables were used and after the first 24 h of the forecasts, the simulated bias is negative for all lookup tables. In summary, the results indicate that the TAMU and Baum lookup tables generally produce warmer brightness temperatures for ice clouds than did the Original CRTM lookup table.

During the next 6 months, we will finish the analysis of all of the July and December 2014 GFS forecasts to obtain a more comprehensive view of the model performance and the impact of the CRTM ice cloud property lookup tables on the simulated brightness temperatures. We will also more closely study the behavior of various cloud regimes, such as stratocumulus clouds, extratropical cyclones, and tropical convection. We will also employ cloud masks to better understand reasons for brightness temperature biases in both the water vapor and infrared channels for all sensors.



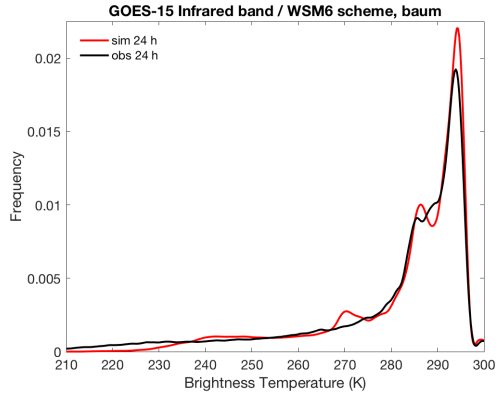
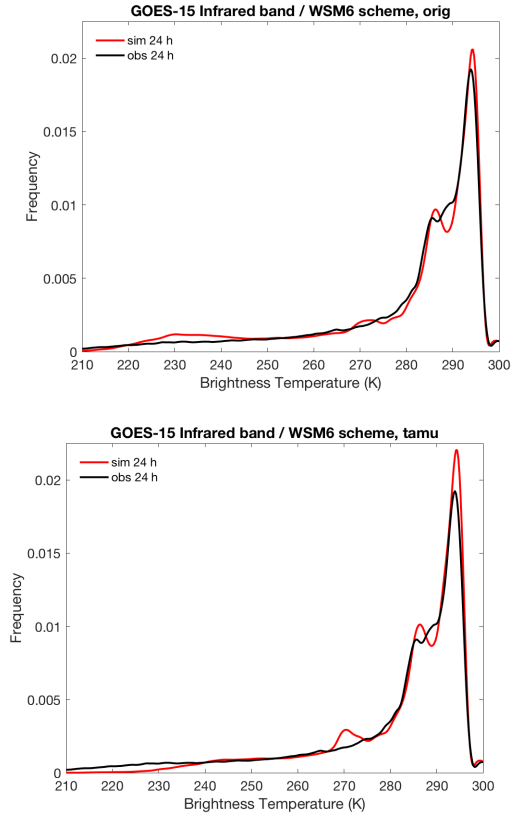


Figure 5. Probability density functions for the observed (black line) and simulated (red line) GOES-15 10.7  $\mu\text{m}$  brightness temperatures computed using the (upper left) Original, (upper right) Baum, and (lower left) TAMU ice cloud property lookup tables. Statistics were computed using four forecast cycles from July 2014.

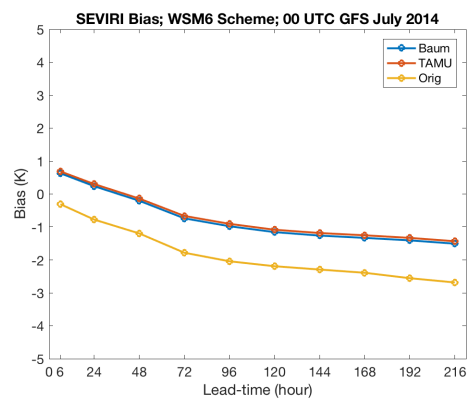
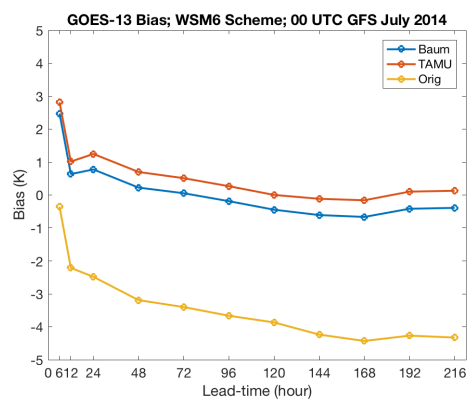
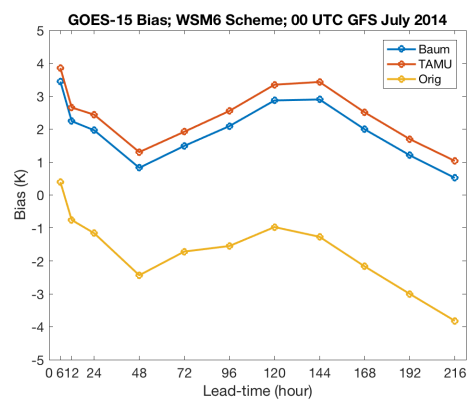


Figure 6. Bias evolution for the simulated GOES-15 and GOES-13 10.7  $\mu\text{m}$  brightness temperatures (top two panels) and simulated SEVIRI 10.8  $\mu\text{m}$  brightness temperatures (bottom panel) when using the Original (yellow line), Baum (blue line), and TAMU (red line) cloud property lookup tables. Statistics were computed using output from four forecast cycles from July 2014.

#### *2.4. Coarse-resolution GFS model forecasts*

In addition to the GFS forecasts provided by EMC, we are also assessing the accuracy of coarser-resolution GFS model forecasts provided by our collaborators at the DTC. This set of GFS forecasts was run at T574 spectral resolution (~27 km) and will be used by the DTC to assess the performance of two new cumulus parameterization schemes, including the Simplified Arakawa-Schubert (SAS; Pan and Wu 1995) and Grell-Freitas (2014) schemes. Both sets of simulations employ the Zhao-Carr microphysics scheme. The DTC datasets include simulated infrared brightness temperatures from the GOES-13/15 Imager and Meteosat-10 SEVIRI sensors that were computed using the UPP. We will assist their assessment efforts through comparisons of observed and simulated infrared brightness temperatures. Unlike the EMC datasets that will be used to assess the accuracy of the deterministic, high-resolution forecasts, we will use these coarser-resolution simulations as a proxy to evaluate the accuracy of the cloud and water vapor fields in the global ensemble used during the data assimilation step. Results from this analysis will be presented in the next project report.

### **3. ISSUES DELAYING CURRENT OR FUTURE PROGRESS**

Progress was delayed at the beginning of the reporting period because a key member of the project team (C. Rozoff) moved from UW-CIMSS to a new position at NCAR. He will continue to work on the project; however, progress was delayed by approximately 2 months as the necessary sub-contract was set-up to support his work. It is anticipated that his effort will increase during the next several months to compensate for these delays, with no additional impact on the future progress of the project.

### **4. INTERACTIONS WITH EMC AND OTHER NOAA-FUNDED SCIENTISTS**

During the past 6 months, we have had several conversations with researchers at EMC and the DTC to discuss the model simulations that we are using during this project and to coordinate the cloud property settings used by the GSI. We are also participating in the NGGPS telecons in order to stay abreast of recent research performed by other groups. Lastly, we have had several conversations and email exchanges with researchers at EMC and GFDL concerning the availability of FV3 model output and the JCSDA concerning the status of the Unified Forward Operator (UFO). Based on these conversations, it is anticipated that we will be able to start assessing the accuracy of FV3 model forecasts by the end of the next reporting period.

### **5. CHANGES IN PROPOSED PROJECT**

None.

### **6. OUTCOMES TRANSITIONED TO OPERATIONS**

Given the early stages of this project, no outcomes have been transitioned to operations; however, the software changes described in Section 2.1 have been made available to EMC through a new branch in the NOAA VLAB Community GSI code repository.

## 7. BUDGET ISSUES

None.

## 8. PRESENTATIONS

Otkin, J. A., S. Nebuda, C. Rozoff, R. Sun, A. Collard, E. Liu, V. Tallapragada, M. Harrold, and L. Bernardet, 2017: Advancing Forecast Verification and Model Development Efforts through Development of a Flexible Satellite-Based Verification System for the Global Forecasting System. *NGGPS Annual Review Meeting*, College Park, MD.

## 9. JOURNAL ARTICLES

None.

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