Assessment of Ensemble Forecast Sensitivity to Observation (EFSO) Quantities for Satellite Radiances Assimilated in the 4DEnVar GFS

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Introduction

The Ensemble Forecast Sensitivity to Observation (EFSO) formulation (Kalnay et al. 2012) has been implemented at NCEP. For the GFS, this approach requires Ensemble Kalman Filter (EnKF) products as input, and has been implemented within the current source code that provides EnKF functionality at NCEP (Ota et al. 2013, Groff et al. 2016). As with the adjoint Forecast Sensitivity to Observation Impact (FSOI) approach (Langland and Baker 2004, Zhu and Gelaro 2008), EFSO capabilities effectively enable a simultaneous forecast impact estimate for any and all observations assimilated in an NWP system. The EFSO formulation incorporates the relationship between kalman gain and analysis-error covariance to construct observational increments that can be projected forward in time with a forecast model, enabling an estimate of the forecast impact due to assimilating individual observations. The ensemble of analyses resulting from the applicable EnKF update can be used in the representation of analysis-error covariance, and accordingly the kalman gain. This study pertains to 24 hour moist total EFSO calculations that are based on the application of EnKF output from the 4DEnVar GFS for December 2014.

Objective

Most previous FSOI/EFSO studies have emphasized observing system summary statistics. These studies have been helpful in addressing some of the overarching questions that relate to observing systems, such as quantifying the share of forecast influence by observation type. In this study, we highlight variability in 4DEnVar GFS EFSO quantities for CrIS and AMSU-A radiances .wrt. innovation, bias correction, Field of View (FOV) location and Cloud Liquid Water (CLW) amount. The intent is that this conditional EFSO information can provide direct insights for further enhancement of variational radiance bias correction approaches, improved quality control procedures and guidance for prioritizing forward operator development.

Methodology

- $\overline{\mathbf{x}}_t^f$ → Ensemble Mean Forecast from Analysis
- $\overline{\mathbf{x}}_t^g$ → Ensemble Mean Forecast from Background
- $\mathbf{x}_t^{truth}$ → Verification at Forecast Time (self analyses)
- $\mathbf{e}_t^f \equiv \overline{\mathbf{x}}_t^f - \mathbf{x}_t^{truth}$ → Error in forecast from analysis
- $\mathbf{e}_t^g \equiv \overline{\mathbf{x}}_t^g - \mathbf{x}_t^{truth}$ → Error in forecast from background
- C → Norm operator defining the forecast error metric (moist total)
- $\mathbf{R}$ → Covariance matrix of observation errors
- $\mathbf{X}_t^f$ → Perturbations in forecast from analysis at forecast time
- $\mathbf{HX}_0^a$ → Analysis perturbations in observation space
- $\delta\mathbf{y}_o$ → observation minus background in obs space (i.e. innovation)
- $\left(\Delta e_t^{f-g}\right)_{j,l}$ → Forecast error reduction per observation (i.e. EFSO)
- ρ_j → Evolving localization of observation response in forecast
- K → Number of ensemble members

Cross Covariance applied in EFSO, enables estimate for the projection of analysis perturbations to forecast time

$$\left(\Delta e_t^{f-g}\right)_{j,l} = \frac{1}{2(K-1)}\left(\delta\mathbf{y}_o\right)_l\left[\rho_j\mathbf{R}^{-1}\left(\mathbf{HX}_0^a\right)\left(\mathbf{X}_t^{f\mathrm{T}}\right)_j C_{jj}\left(\mathbf{e}_t^f+\mathbf{e}_t^g\right)_j\right]_l$$

Note that negative EFSO quantities indicate forecast benefit, whereas positive EFSO quantities indicate forecast detriment.

EFSO Asymmetries .wrt. Innovation Sign for Cross-track Infrared Sounder (CrIS) Radiances

In the operational 4DEnVar GFS, CrIS channels within both the long-wave IR CO_2 band and long-wave window portion of the IR spectrum are assimilated. These assimilated channels primarily provide temperature sounding information by taking advantage of the well mixed nature of CO_2 in the atmosphere.

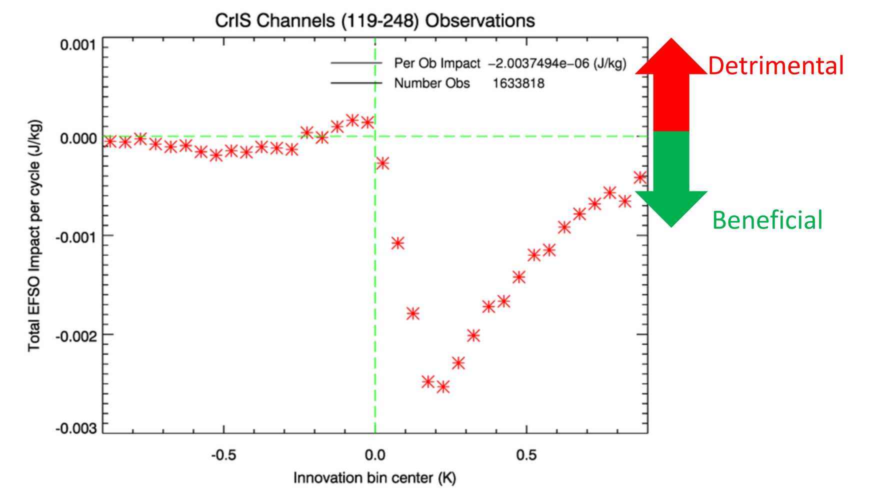


Figure 1: Total EFSO impact versus binned bias corrected innovation for a subset of CrIS temperature sounding and "dirty" window channels.

Partitioning EFSO quantities for a subset of CrIS temperature sounding channels into bias corrected innovation bins reveals large asymmetries in EFSO suggested impact .wrt. innovation sign. In particular, EFSO suggest the assimilation of negative innovations was far more problematic in comparison to assimilation of positive innovations. In the absence of model biases, such asymmetries may be indicative of cloud contamination, situation dependent limitations in the application of variational bias correction or forward operator errors.

Partitioning of EFSO Impacts Based on Enhanced Radiance Bias Correction

EFSO quantities for the same subset of CrIS temperature sounding channels are strongly dependent on the result of variational bias correction. The per observation impacts for positive bias corrected innovations that had corresponding positive non-bias corrected innovations were beneficial across all positive bias corrected innovation bins. However, for positive bias corrected innovation bins with corresponding non-bias corrected innovations, per observation impacts were relatively neutral. Similarly, for negative bias corrected innovation bins there was a notable contrast in impact when partitioning observations based on the direction and magnitude of bias correction. This information may provide insights for the implementation of new predictors that can further enhance variational radiance bias correction.

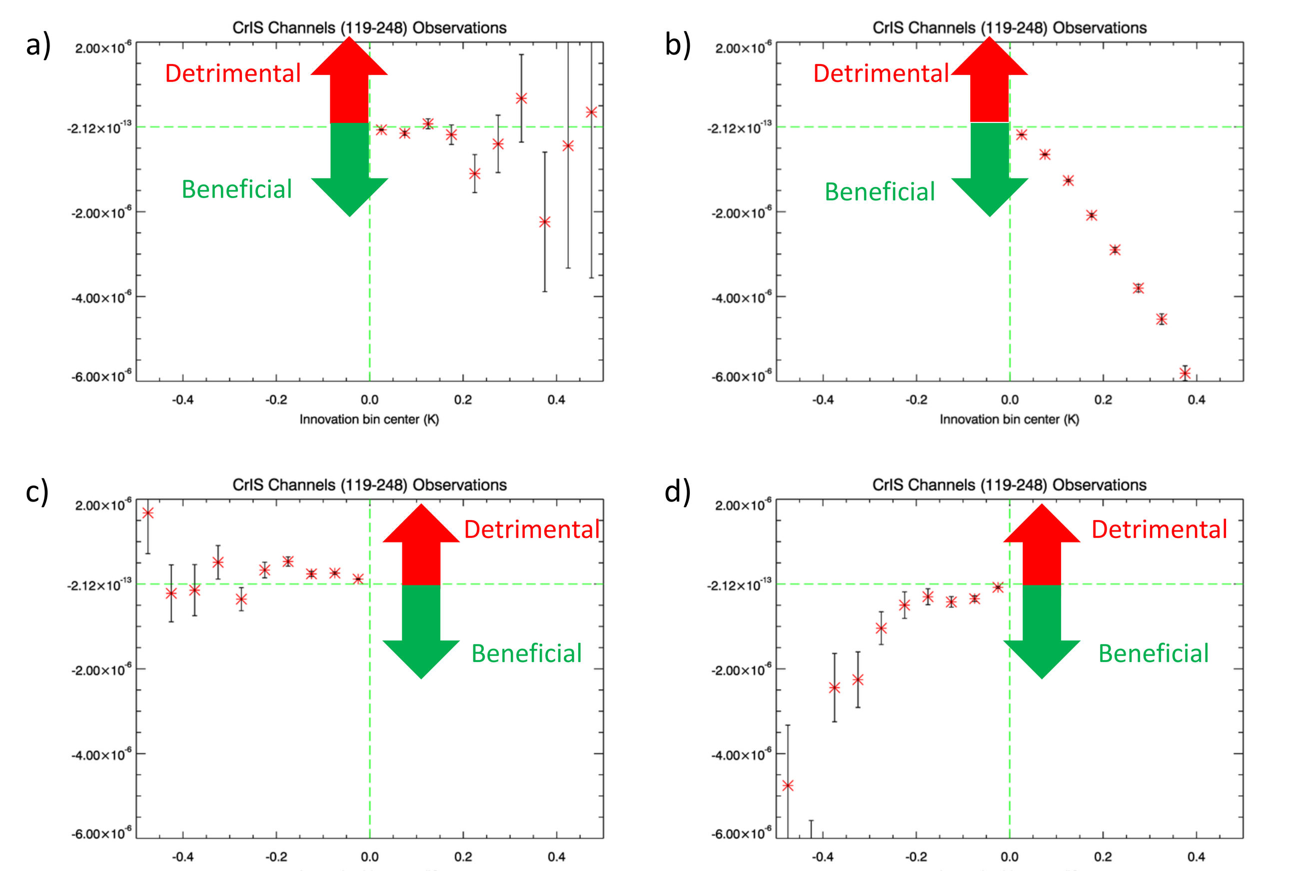


Figure 2: Binned bias corrected innovation versus mean per observation EFSO. a) For observations with negative non-bias corrected innovations. b) For observations with positive non-bias corrected innovations. c) Observations where bias corrected innovation minus non-bias corrected innovation is less than -.1K. d) Same as c, but where bias corrected innovation minus non-bias corrected innovation is greater than .1K.

Composite Mean EFSO Impact Maps for Advanced Microwave Sounding Unit-A (AMSU-A) Surface Channels

Composite mean EFSO maps can be helpful in highlighting coherency between EFSO suggested impact and climatological features. Among the AMSU-A channels, channel 2 is the most sensitive to variability in surface conditions. 7.5° by 7.5° composite mean EFSO maps for AMSU-A channel 2 suggest that assimilation of these channels is relatively problematic poleward of 40N and 40S. Furthermore, composite mean detriment is coincident with the circumpolar Southern Hemisphere storm track and the region of the southeastern Pacific that is coincident with persistent subtropical stratocumulus clouds..

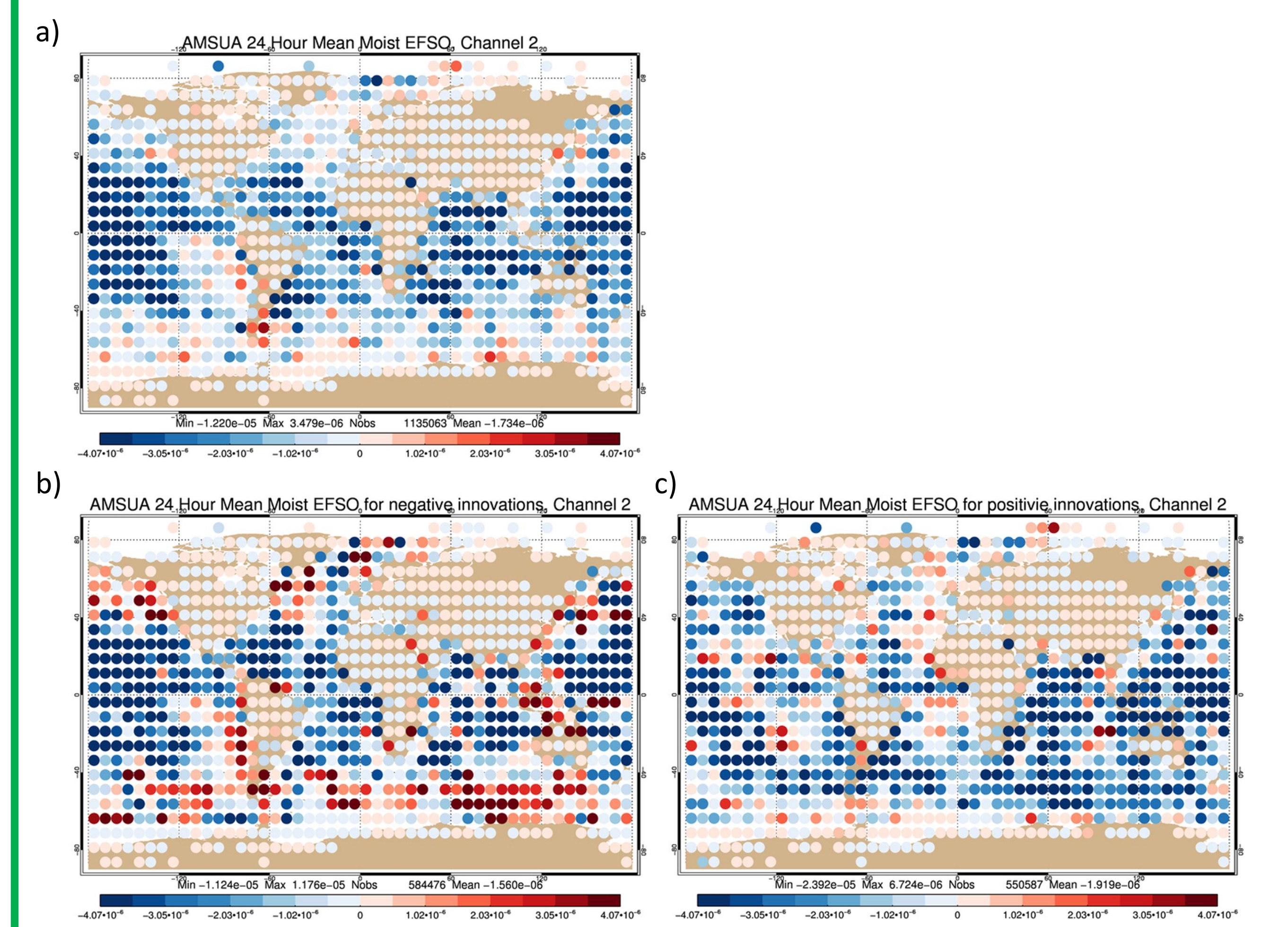


Figure 3: 7.5° by 7.5° Composite mean EFSO maps for AMSU-A Channel 2.
a) All observations, b) negative innovations, c) positive innovations

As shown in figures 3b and 3c, the aforementioned spatial coherency with composite mean EFSO detriment is most apparent among negative innovations as opposed to positive innovations. 1° by 1° composite mean EFSO maps for AMSU-A surface channels 1 through 3 indicate that for Southern Hemisphere sea ice Field of Views (FOVs), positive innovations tend to be more problematic than negative innovations. As indicated in figure 5, it is worth noting here that GFS analyses tend to be warmer than ECMWF analyses at 850 hPa over Southern Hemisphere sea ice.

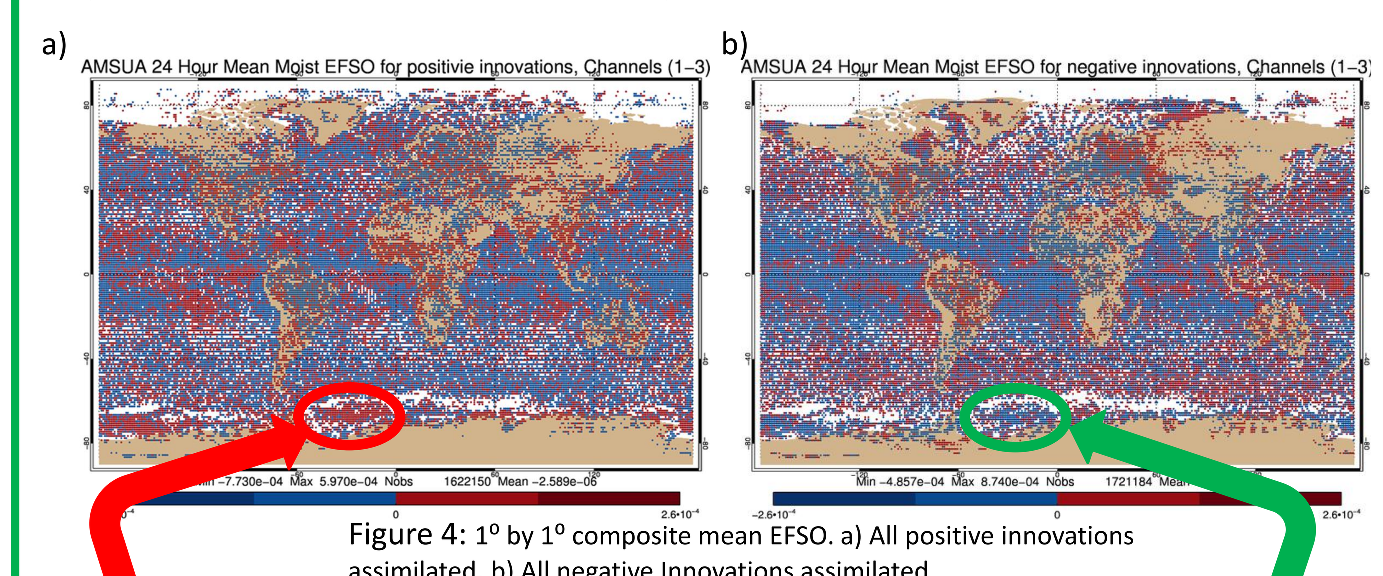
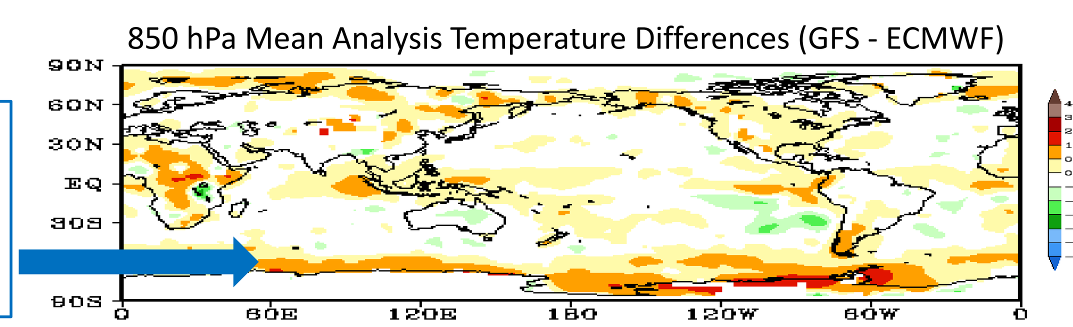


Figure 4: 1° by 1° composite mean EFSO. a) All positive innovations assimilated, b) All negative Innovations assimilated

Vast majority of highlighted boxes are detrimental

Vast majority of highlighted boxes are beneficial



GFS analyses consistently warmer than ECMWF analyses over SH sea ice

Figure 5: Mean analysis temperature differences (GFS – ECMWF)

Composite Mean EFSO Impact Maps for AMSU-A Temperature Sounding Channels Partitioned According to Cloud Liquid Water (CLW) Amount

For AMSU-A it is relevant to partition EFSO impact by CLW. The overall per observation benefit from assimilating AMSU-A temperature sounding channels generally increases with CLW amount. However, as composite mean EFSO maps for AMSU-A channels 6 through 8 indicate, negative innovations were on average detrimental for most regions when the corresponding retrieved and guess CLW amounts exceeded .27 kg/m^2. This result indicates that addition of cloud water over ocean from assimilation of these channels is generally coincident with EFSO detriment.

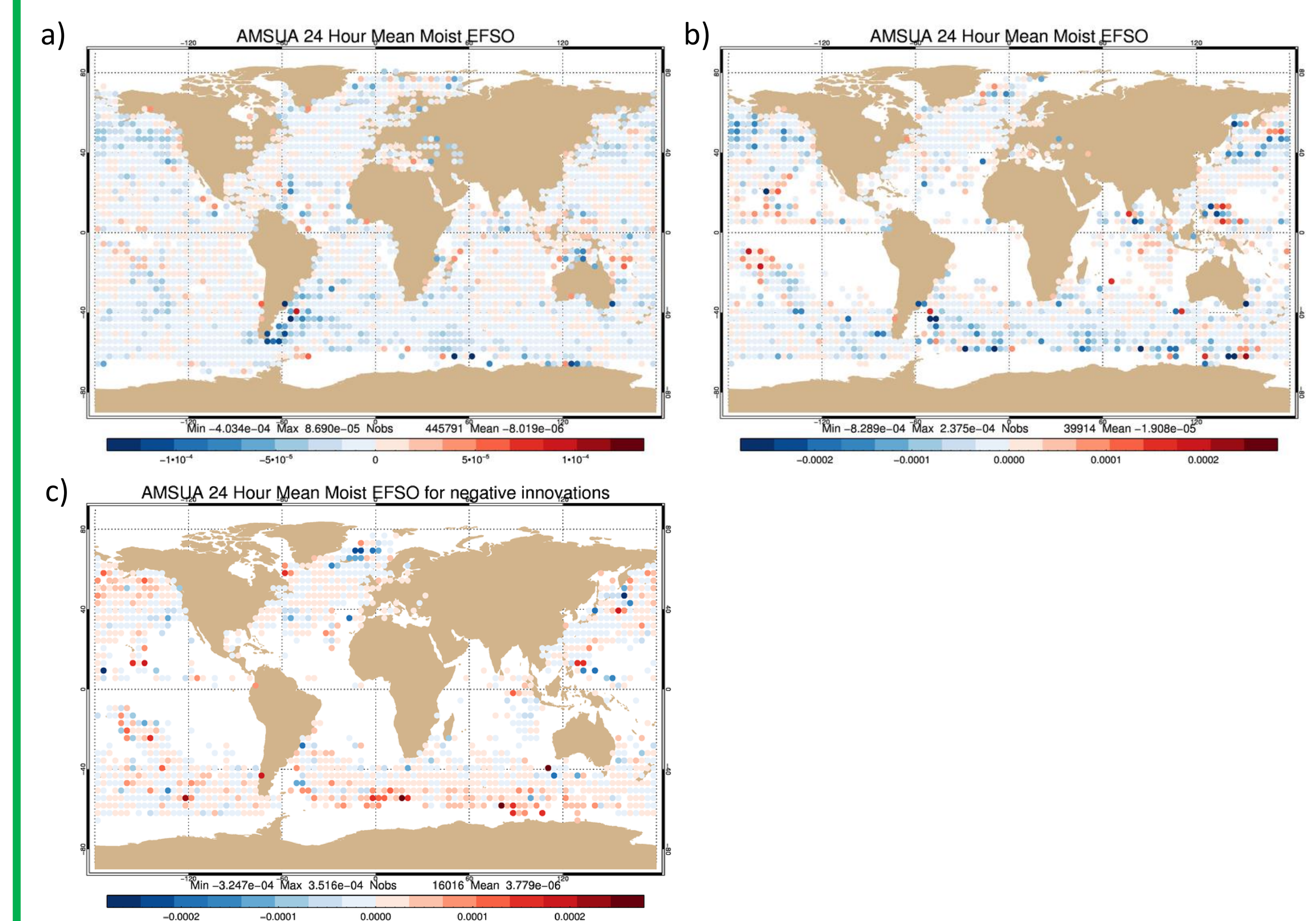


Figure 6: 3.75° by 3.75° composite mean EFSO maps for AMSU-A channels 6 through 8. a) All observations with corresponding retrieved and guess CLW amounts in excess of .1 kg/m^2. b) All observations with corresponding retrieved and guess CLW amounts in excess of .27 kg/m^2. c) Negative innovations with retrieved and guess CLW amounts in excess of .27 kg/m^2

Summary

EFSO quantities for CrIS and AMSU-A radiances were partitioned by innovation, bias correction, location and CLW amount. For CrIS temperature sounding channels, total EFSO versus binned bias corrected innovation revealed large asymmetries .wrt. innovation sign. For AMSU-A surface channels, composite mean EFSO maps indicate that there are spatially varying EFSO asymmetries .wrt. innovation sign. Coincident with Southern Hemisphere sea ice, the vast majority of composite mean forecast impact boxes for AMSU-A surface sensitive channel observations associated with negative (positive) innovations were beneficial (detrimental). In the absence of model biases these asymmetries are likely indicative of cloud contamination (for CrIS), representative errors in surface conditions, forward operator errors or situation dependent limitations in the application of variational bias correction .

EFSO quantities for CrIS temperature sounding channels are strongly dependent on the result of variational radiance bias correction. Future efforts are planned to test the utility of this information in further improving variational radiance bias correction.

For coincident retrieved and guess CLW in excess of .27 kg/m^2, negative innovations for AMSUA channels 6 through 8 were detrimental overall. This result suggest that the addition of cloud water from assimilating these channels is coincident with EFSO detriment.

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