Satellite Data Assimilation in the GEOS Atmospheric Data Assimilation System

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Acknowledgements to: Yanqiu Zhu, Amal El Akkraoui, Ming-Jeong Kim, Wei Gu (NASA GMAO) and Will McCarty (NASA HQ).

Outline

- Brief overview of Goddard Earth Observing System – Atmospheric Data Assimilation System (GEOS-ADAS)
- Microwave radiance assimilation in the GEOS
  - Assimilate AMSR2 data in all-sky conditions
  - Assimilate new ATMS-NOAA21 data
- Explore better assimilation of geostationary infrared observations
- Summary and on-going work

GEOS hybrid 4D-EnVar atmospheric data assimilation system

- Cost function:

$$J(\delta x) = \tfrac{1}{2}\,\delta x^{T}\,\mathbf{B}\,\delta x + \tfrac{1}{2}\,(y - y^{o})^{T}\,\mathbf{R}^{-1}\,(y - y^{o}) + J_c$$

where,

δx, four dimensional correction (increment) to a background state x^{b};

B and **R** represent the four dimensional extensions of the background and observation error covariance matrices, respectively,

y^{o}, observations,

$y = \mathbf{H}\,(x^{b} + \delta x)$ is the observation-space equivalent of the model state interpolated using the nonlinear observation operator **H**,

J_c encompasses additional constraints such as the dry air conservation imposed on the analysis.

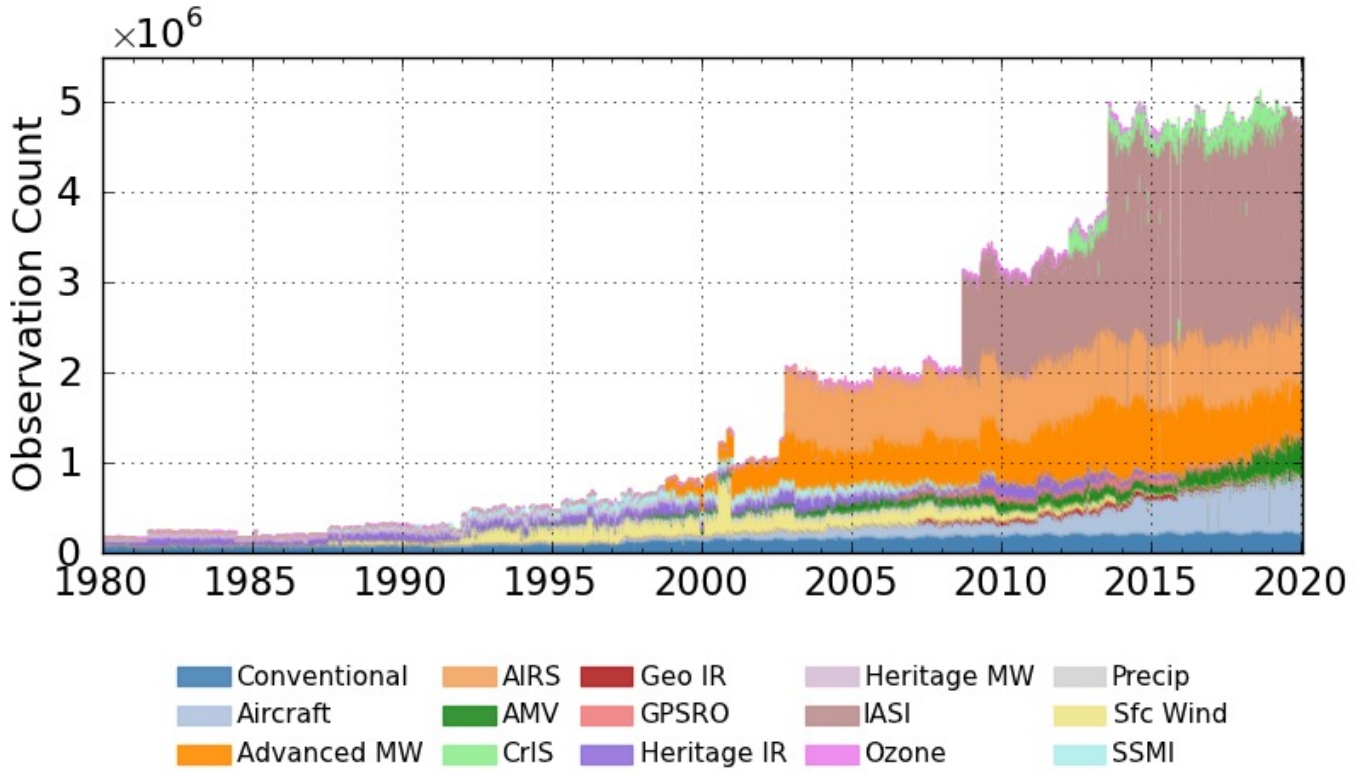
In the hybrid 4D-EnVar, the background error covariance **B** is the sum of climatological covariance estimates $\mathbf{B_c}$ and localized ensemble-based covariances $\mathbf{B_e}$:

$$\mathbf{B} = \beta_c^2\,\mathbf{B_c} + \beta_e^2\,\mathbf{B_e}$$

- The near-real-time GEOS analysis is conducted with 32 ensemble members and 1 central analysis which rely on about 50-km horizontal atmospheric states. All atmospheric states are made by the nonhydrostatic cubed-sphere general circulation model.

(*Todling and El Akkraoui, 2018; Akkraoui A. E., et al., 2023*)

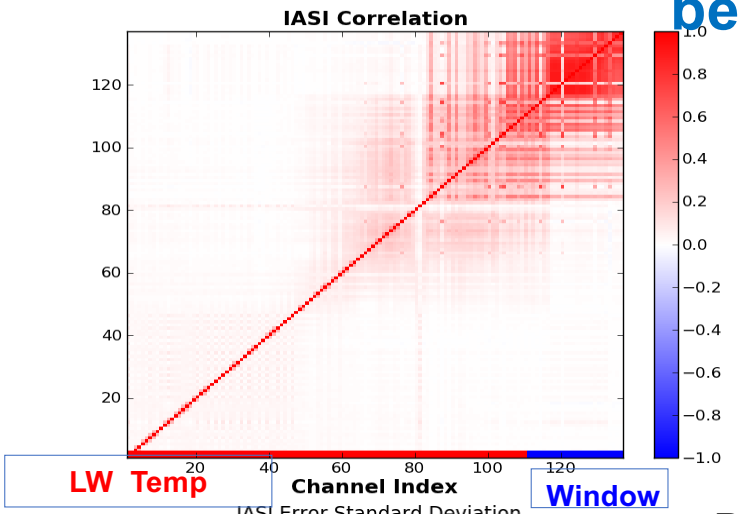
Satellite and conventional observations in MERRA2

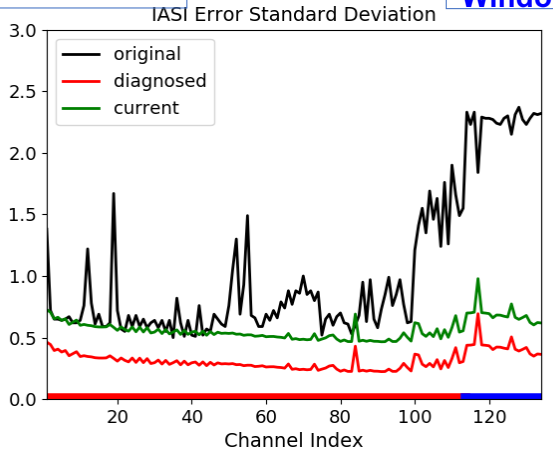


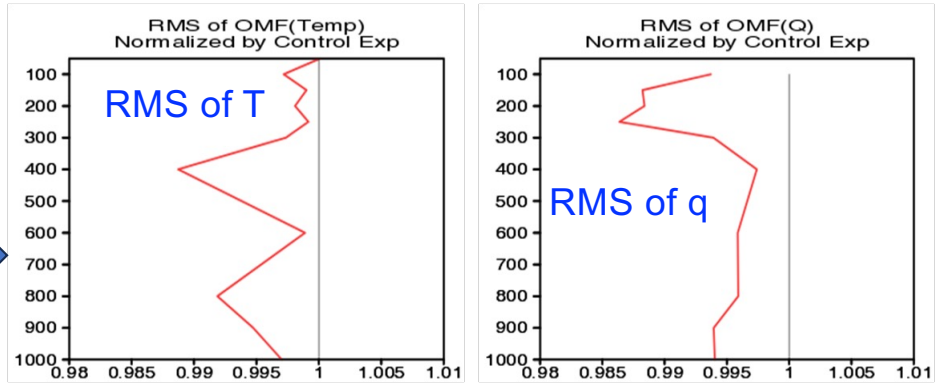
- New data types in GEOS ADAS
  - – IASI Metop–C;
  - – CRIS–FSR on Suomi-NPP and NOAA 20;
  - – GPM/GMI, AMSR2/GCOM-W1;
  - – Commercial GNSS-RO data.

(*Courtesy of Amal El* Akkraoui)

Impact of considering correlated observational errors between infrared channels

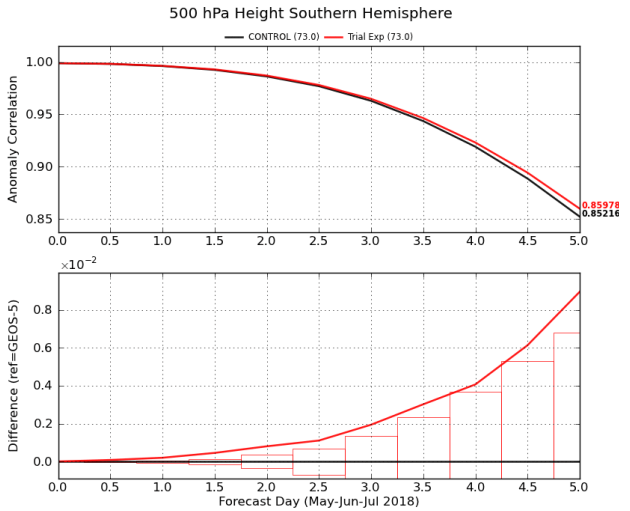






Reduced the RMS of OmFs for rawinsonde T and Q

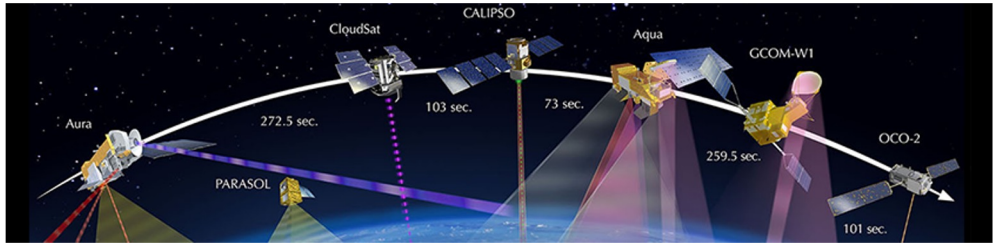
Improved the overall forecast skills of GEOS

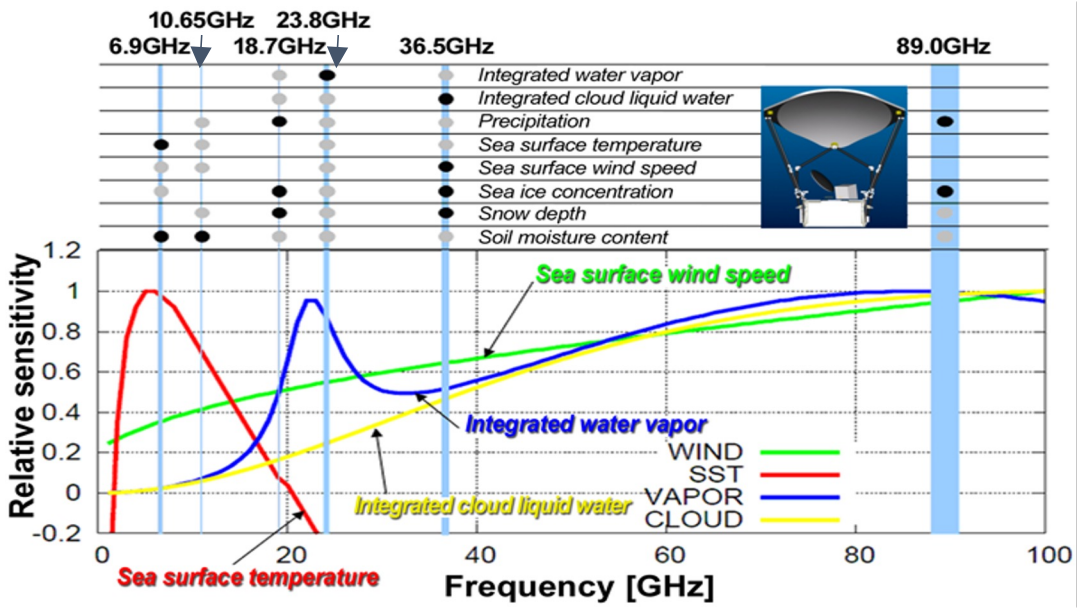


(*Courtesy of Wei Gu*)

All-sky microwave radiance data assimilation in GEOS

- Advanced Microwave Scanning Radiometer 2 / Global Change Observation Mission 1st – Water
  - Launched in 2012
  - Part of A-Train satellite constellation
  - Lower frequency channels (ch1 - 6, 6.9 - 10.7 GHz) good for sea surface temperature (SST).
  - Ch 7 - 14 (18.7 - 89 GHz) are good for moisture, cloud and rain detection.
- GMAO assimilates its brightness temperature data over ocean.
- **Cloud hydrometeors state and control variables** (liquid, ice, rain and snow clouds).
- Cloud analysis increments are updated the 2nd outer loop but are not added in model simulations in the next cycle.



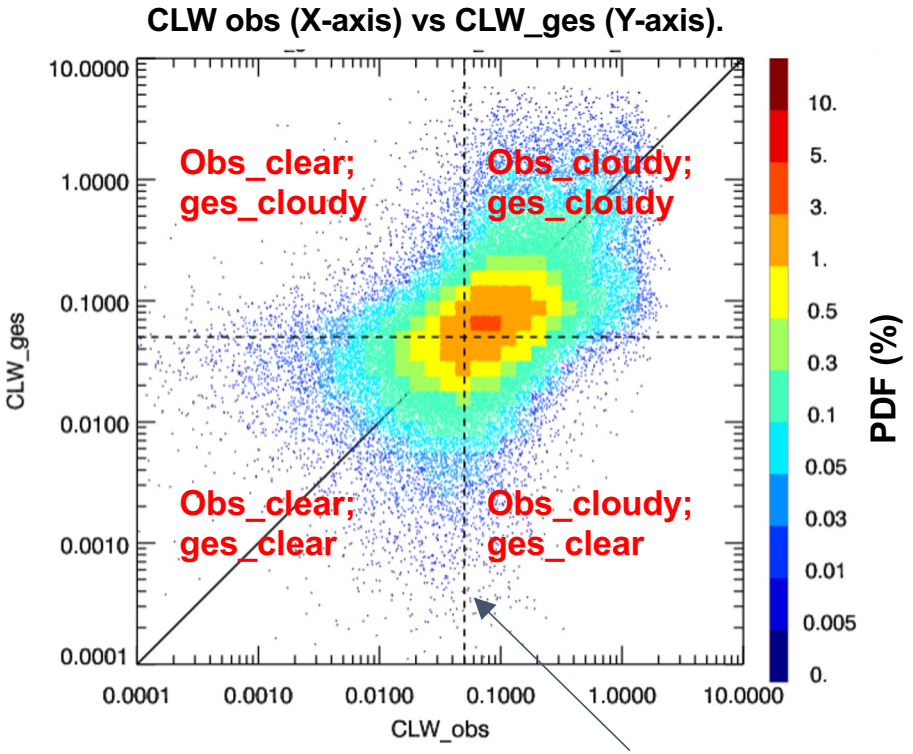


Identify observed and forecasted / guess clouds

Observed clouds (CLW_obs) are retrieved from **observed** brightness temperature (Tb) data, using the retrieval algorithm developed by K. Garrett for AMSR2.

Forecasted /Guess clouds (CLW_ges) are retrieved from **Tb forecasted** by a radiative transfer model (CRTM) with inputs from GEOS-5 profiles including clouds. They are not prognostic clouds in GEOS GCM.

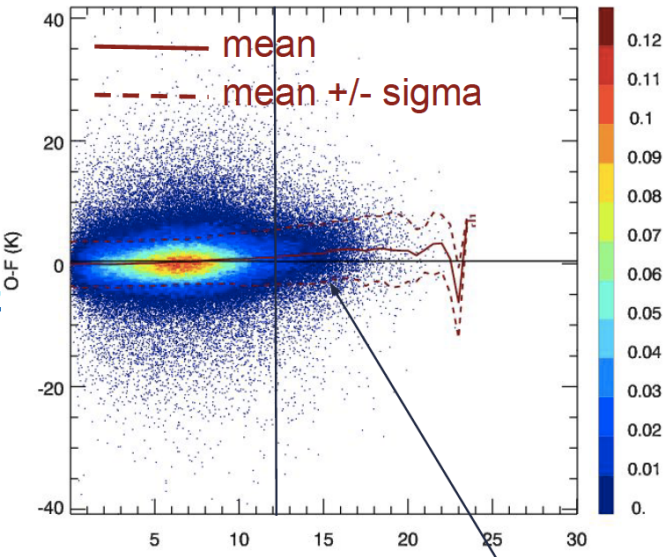
➔ "See clouds through the same lens."



Dashed lines are 0.05 kg/m^2, cloud threshold values for cloudy conditions.

Quality control

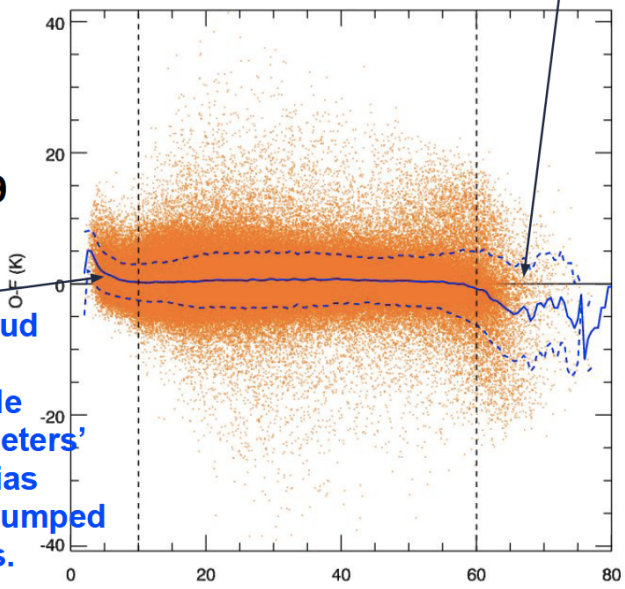
Tb O-F, Ch9 23V GHz



Surface wind speed (m/s)

Bias is due to uncertainties in surface emissivity simulation. Data are tossed out.

Tb O-F, Ch9 23H GHz

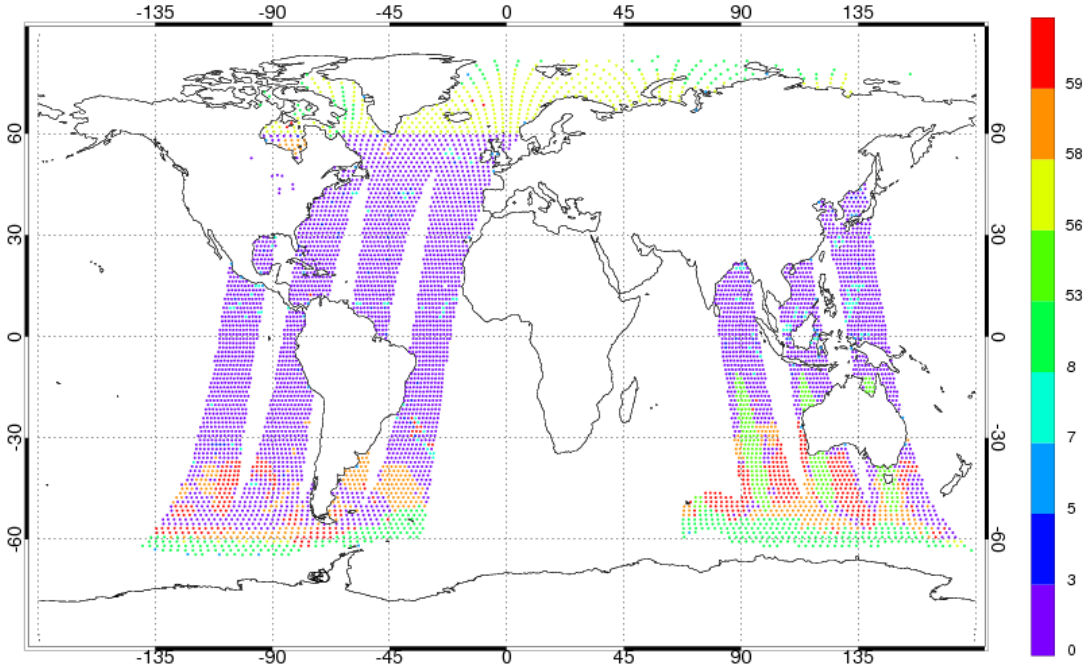


Column water vapor (kg/m^2)

Bias is likely caused by moisture and clouds. Cloud analysis hopefully will reduce the O-F here. Data are kept.

Small moisture and cloud contents lead to small jacobians, and thus little adjustments in hydrometers' analysis. As a result, bias information would be dumped at temperature analysis. Data are tossed out.

AMSR2 data quality control: Examples



59, Surface wind speed > 12 m/s

58, Model total column water vapor < 10 kg/m^2

56, Polar-ward of 60^o N or 60^o S.

53, Sun glint angle < 20^o

8, Emissivity check or cold SST (< 275 K).

7, Clouds > 1.0 kg/m^2

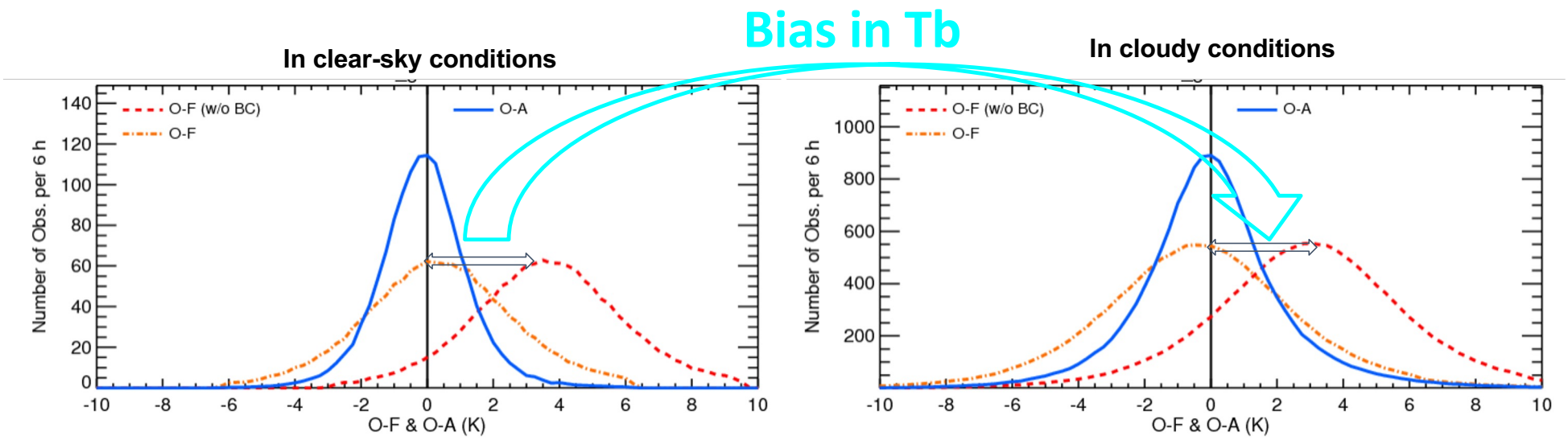
5, None-ocean surface

3, Out of gross-error range (2 x observation errors)

0, Pass QC

An example of data screening criteria between 03 hr – 09 hr, Aug 01, 2018 .
Data over land, ice or snow surfaces are not processed.

Bias corrections in the all-sky assimilation framework



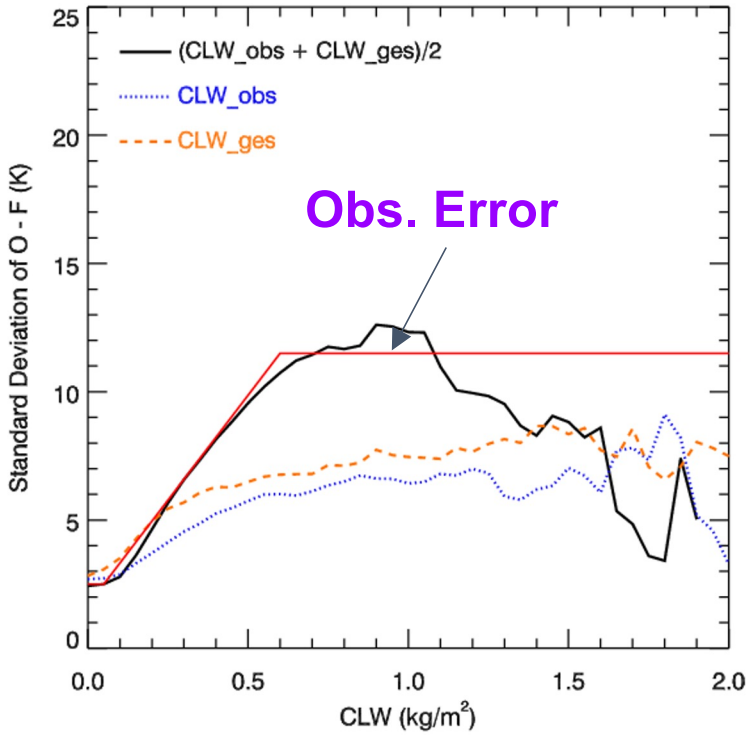
Histograms of Tb departure, O-F, before and after bias correction, and Tb O-A (ch 9, example)

Use the bias correction information from data in clear-sky conditions to correct data in both clear-sky and all-sky conditions.

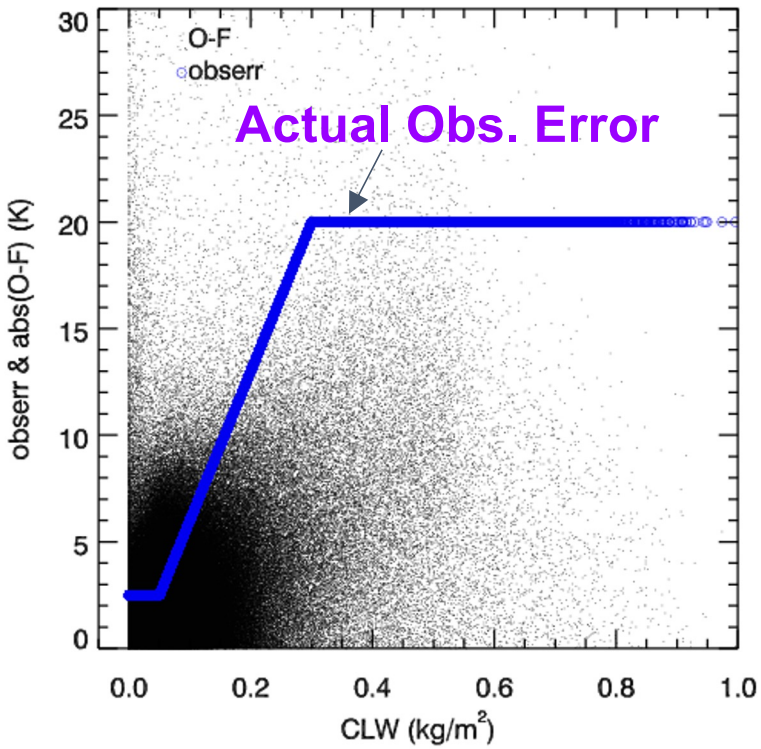
Note: Cloud amount is not a bias correction predictor within the all-sky assimilation framework.

Observation error: A function of symmetric clouds

STDV of O-F vs cloud amount



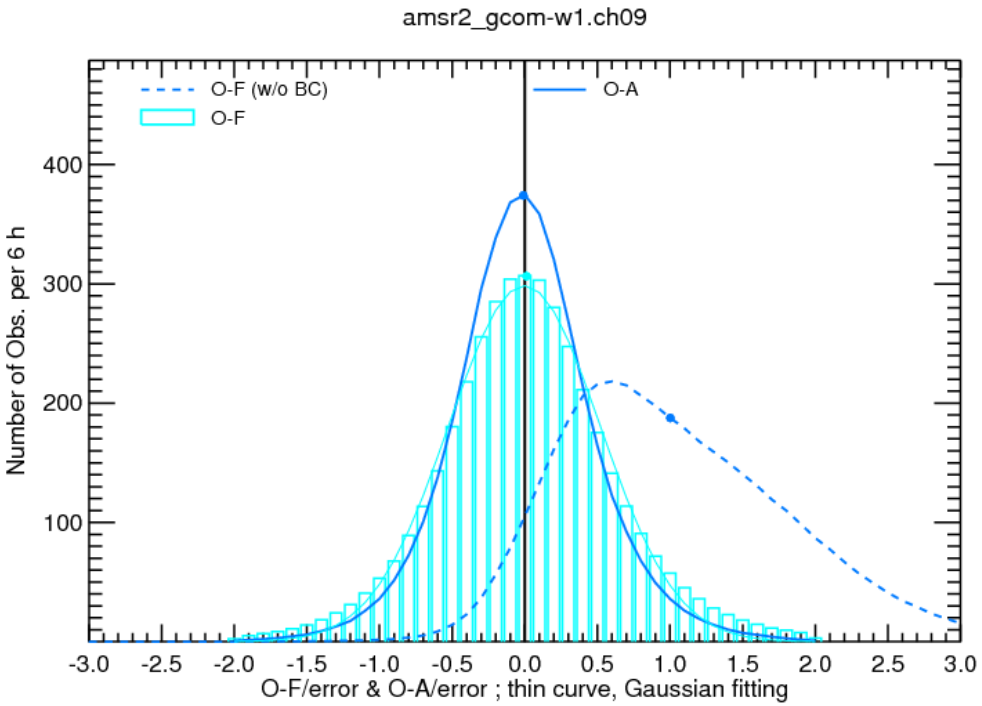
O-F vs (CLW_ges + CLW_obs)*0.5



- **Observational errors have to be largely inflated because there is a large inter-channel correlation between observational error covariances (not shown).**
- **Inflation may be not large enough at locations where there are small mean CLW between mis-matched clouds.**

An experiment to assimilate AMSR.

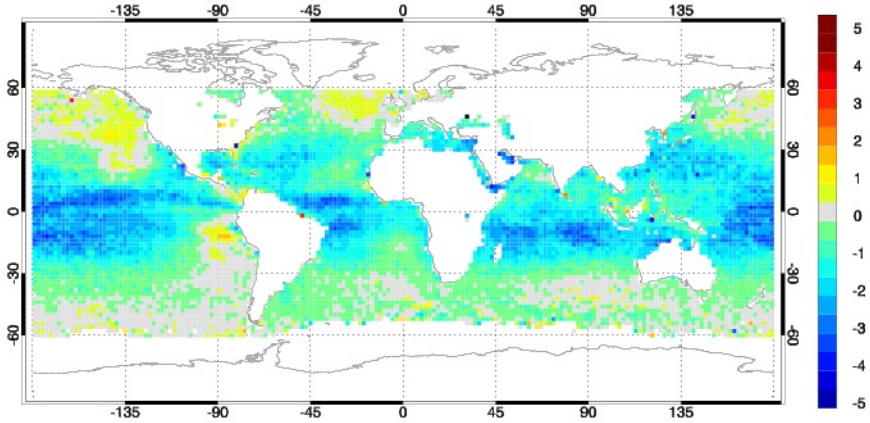
- Assimilate AMSR2 along with other observational data sets within GEOS in June-Aug 2018.
- **An Ensemble-replay experiment**: Use the ensemble in the control and only update central analysis. **Background errors for hydrometeors are derived from the ensemble analysis only.**
- Only assimilate AMSR2 channel 9 (23.8 GHz) and 11 (36.5 GHz).



Normalized O-F and O-A departures in July-Aug 2018

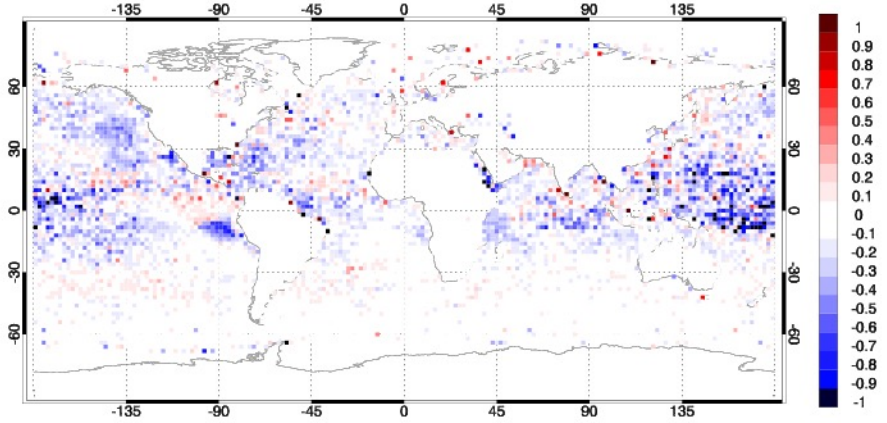
Impact on GEOS column water vapor analysis by AMSR2 data

GEOS Exp. – RSS, (kg/m^2)



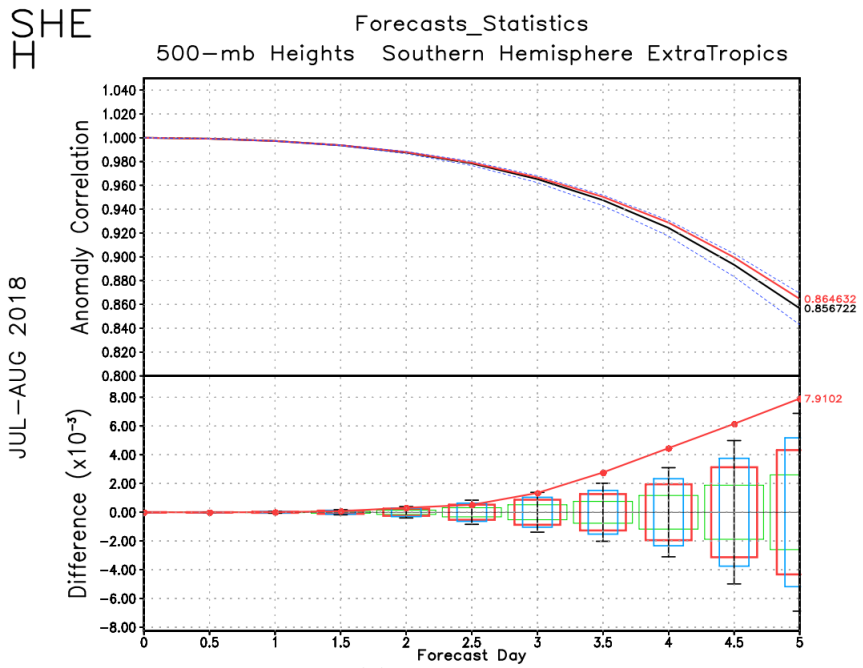
- Total column water vapor in GEOS analysis is generally smaller than retrievals made by Remote Sensing Systems, Inc. (RSS) from AMSR2 data during July-August 2018.

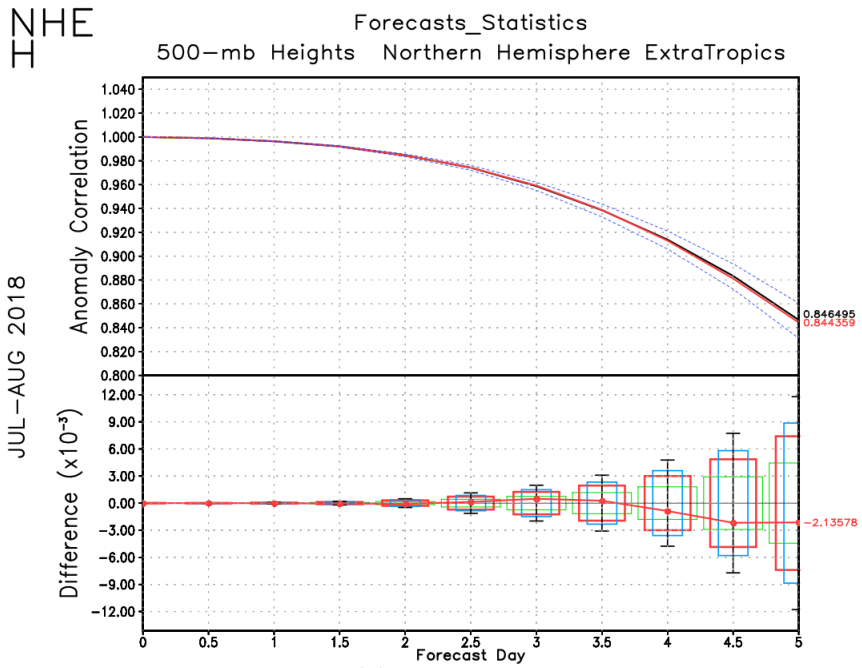
|Exp. – RSS| - |Control – RSS|, (kg/m^2)



- Assimilation of AMSR2 data brings the GEOS analysis closer to the retrievals in tropics and the east Pacific.

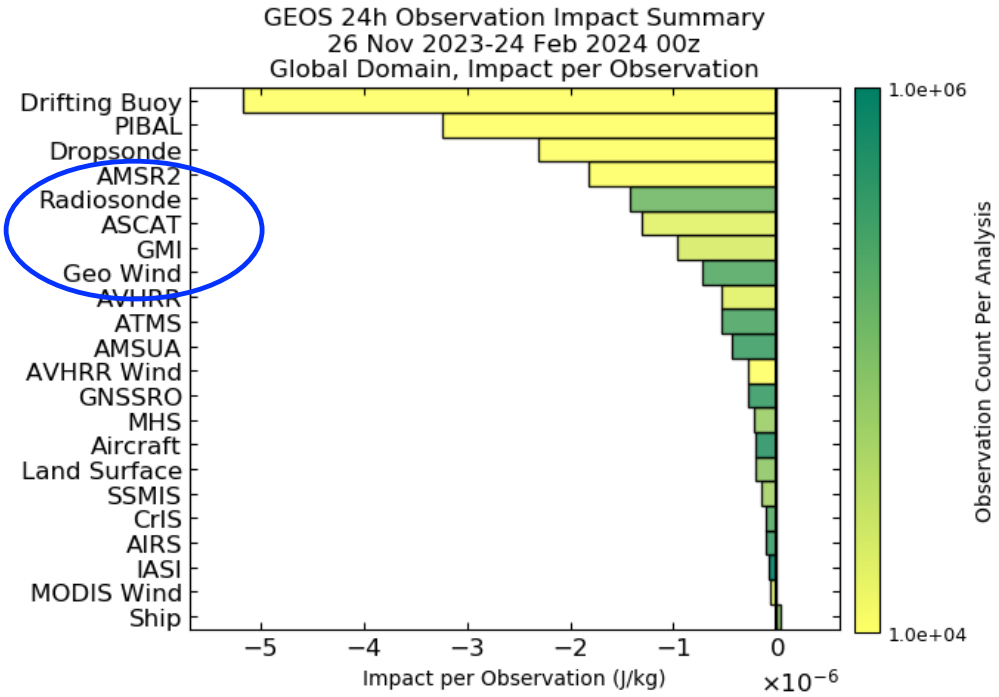
Impact of assimilating AMSR2 data in GEOS forecasts

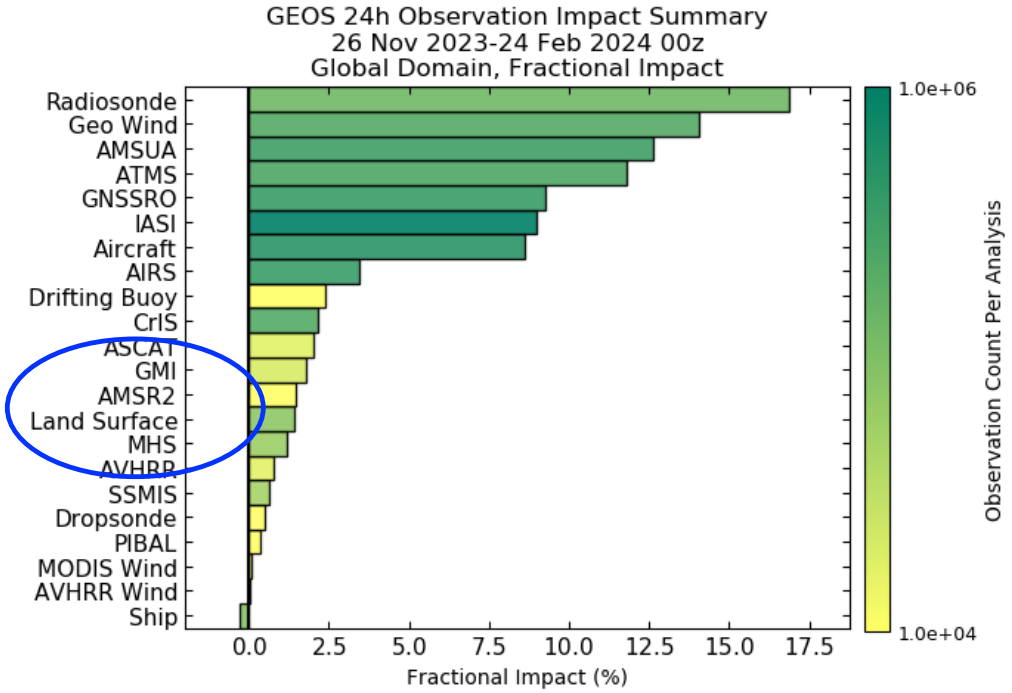




- Assimilating AMSR2 data improves GEOS forecasts in the southern hemisphere during July-August 2018 as shown in the left panel, but it has a neutral impact in the forecasts in the northern hemisphere as shown in the right panel.

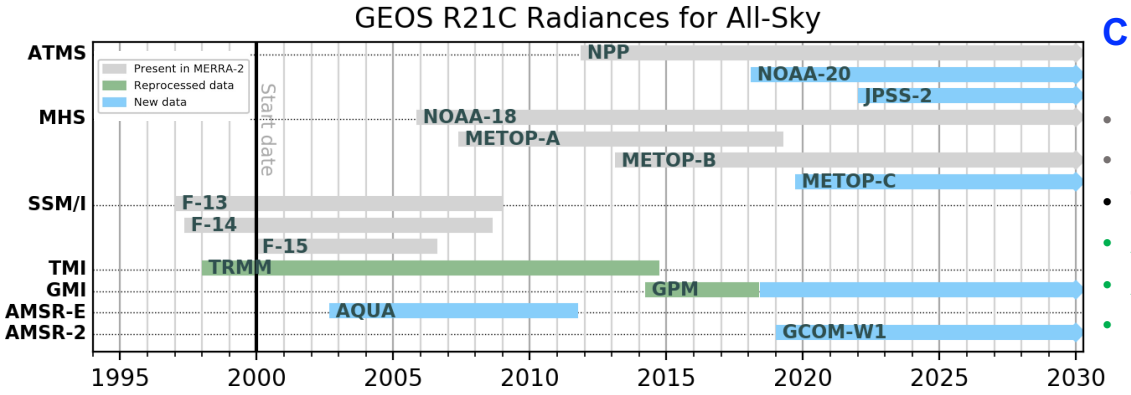
Impacts of assimilating GMI and AMSR2 in current GEOS





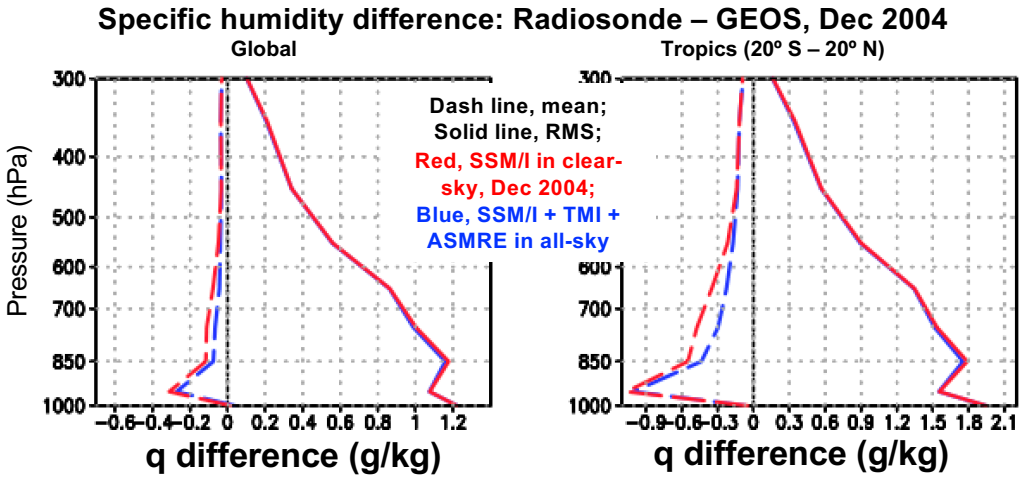
- AMSR2 and GMI have largest impact per observations among satellite radiance data but have overall smaller impact than many other MW or IR sounder **because of limited data are assimilated**.
- **Among these MW data, AMSR2 and GMI brightness temperature data at 23 GHz have larger impacts than data at other channels do.**

Microwave radiance all-sky data assimilation in GEOS-R21C



Changes from MERRA-2

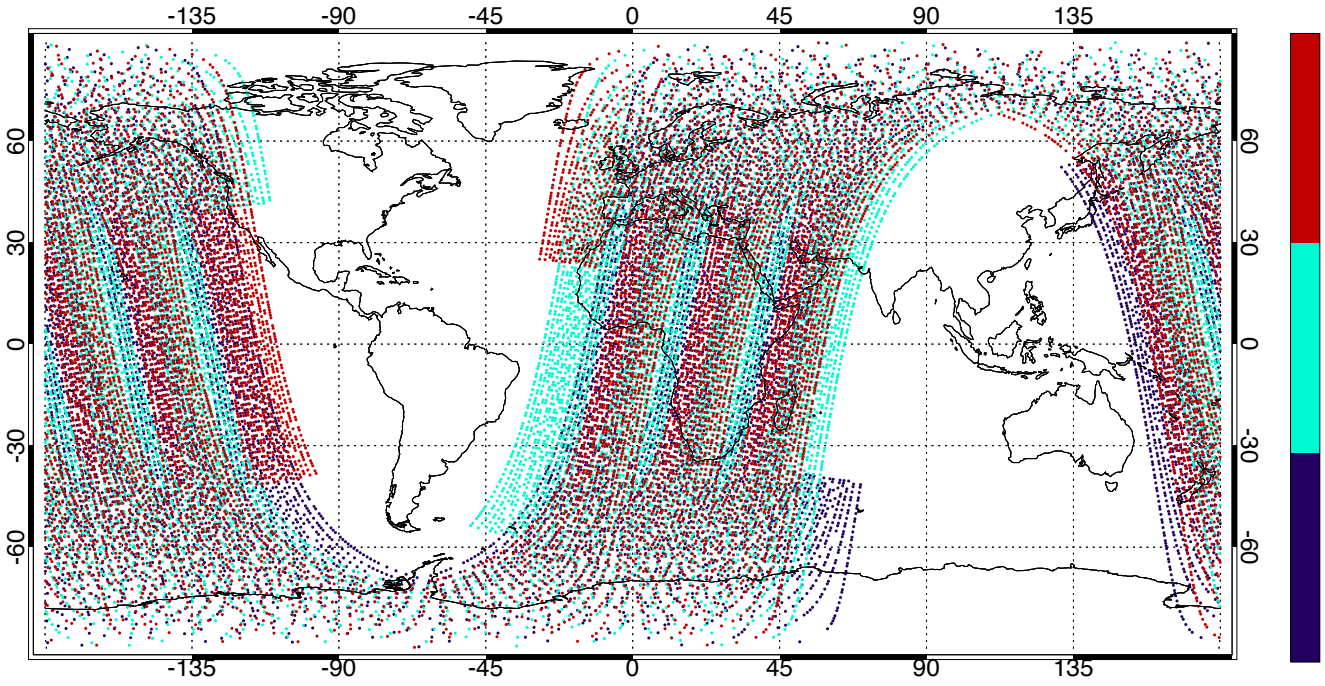
- MHS: clear-sky => all-sky
- SSM/I: clear-sky => all-sky
- TRMM: rain-rate => all-sky
- AMSR-E: not used => all-sky
- AMSR-2: not used => all-sky
- GMI: not used => all-sky



- GEOS humidity analysis is closer to radiosonde observations in tropical convection regions.

Assimilate New ATMS_NOAA 21 Observations

ATMS Suomi-NPP, NOAA-20, and NOAA-21 observation locations within a 6-hour window centered at 00hr 07/01/2023.

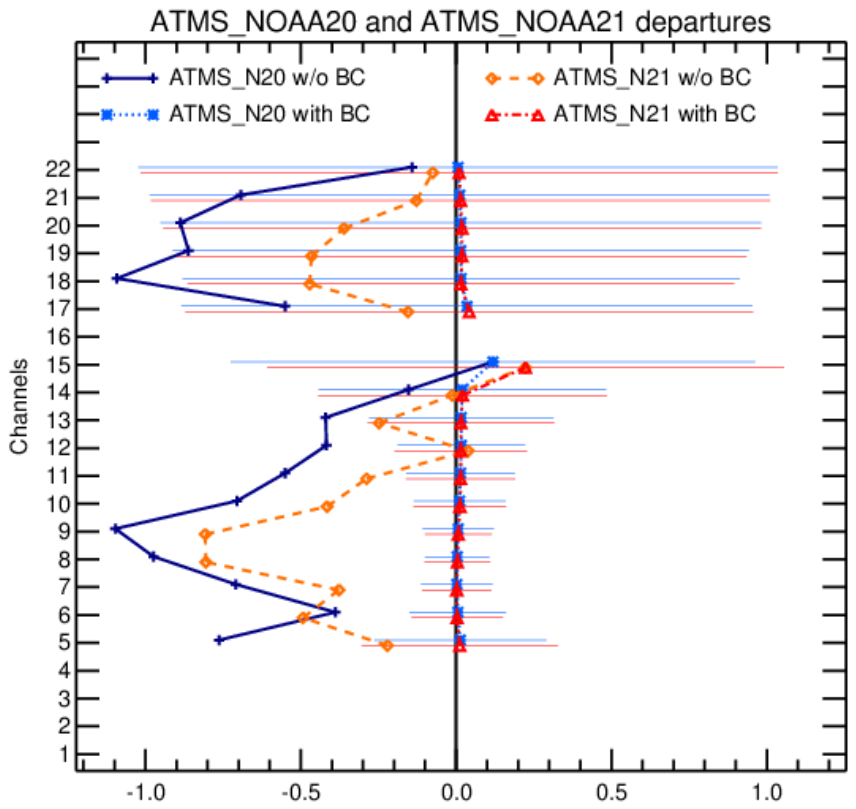


Each satellite crosses the equator at 1:30 PM (local time) in northern-bound direction at Sun-synchronous orbits.

The NOAA-21 is followed for about half of an orbit by NOAA-20, and Suomi-NPP is flying between them.

Data Selection

- Assimilate temperature sensitive channels 5-15, and moisture sensitive channels 17-22.
- Data are tossed over ice, snow, or mixed surface types. IFOV shapes are not considered when surface properties are interpolated. Data are also tossed at scan edges.
- ATMS data are assimilated in clear-sky and thin-cloud conditions within the clear-sky assimilation framework. Cloud effect is bias corrected.
- An experiment is conducted between mid-July – Aug 2023.



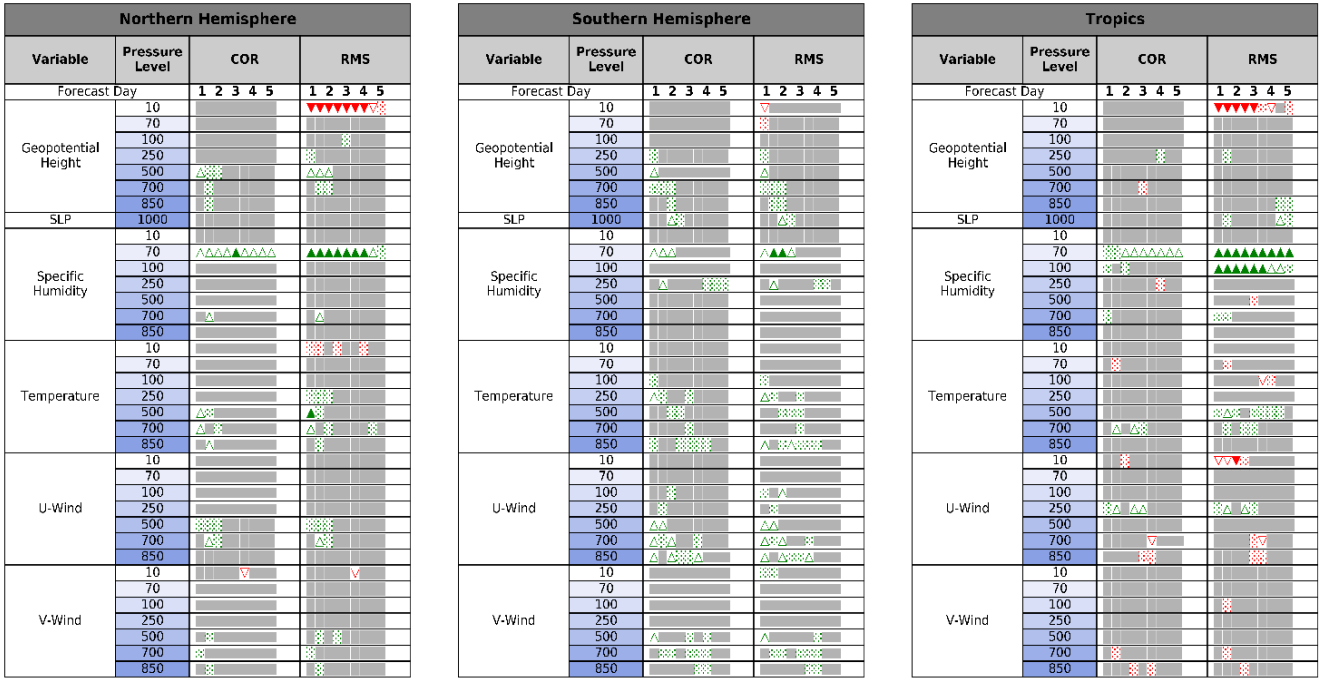
ATMS_NOAA20 and ATMS_NOO21 mean O-F w/o and with bias corrections in Aug 2023 (K). Error bars are standard deviations of O-F with BC.

Forecast impact

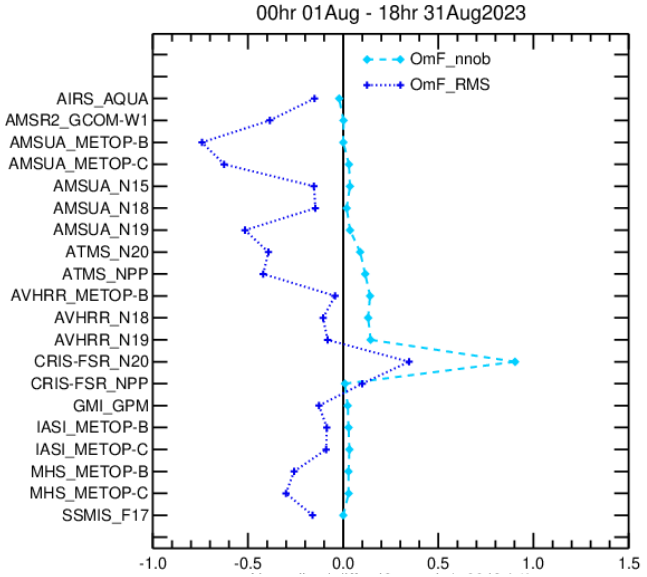
Legend

- ▲ far better, significant (99.99% confidence)
- △ better, significant (99% confidence)
- ⁘ slightly better, significant (95% confidence)
- ■ no significant difference
- ⁘ slightly worse, significant (95% confidence)
- ▽ worse, significant (99% confidence)
- ▼ far worse, significant (99.99% confidence)

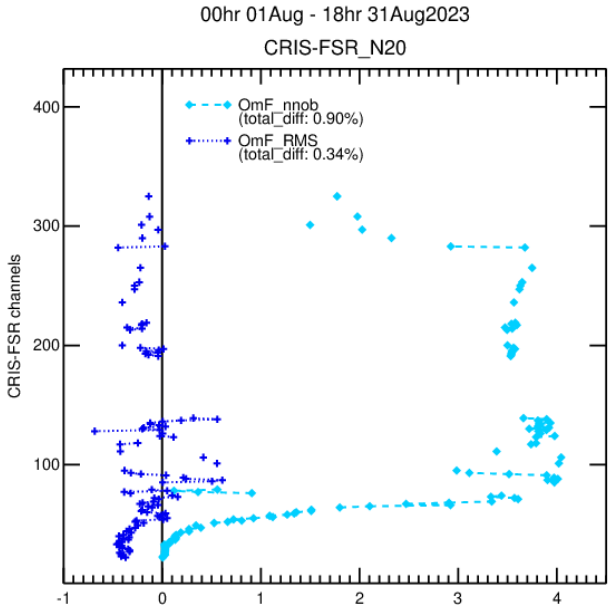
Forecast score card based on statistics verified against ERA5 in August 2023



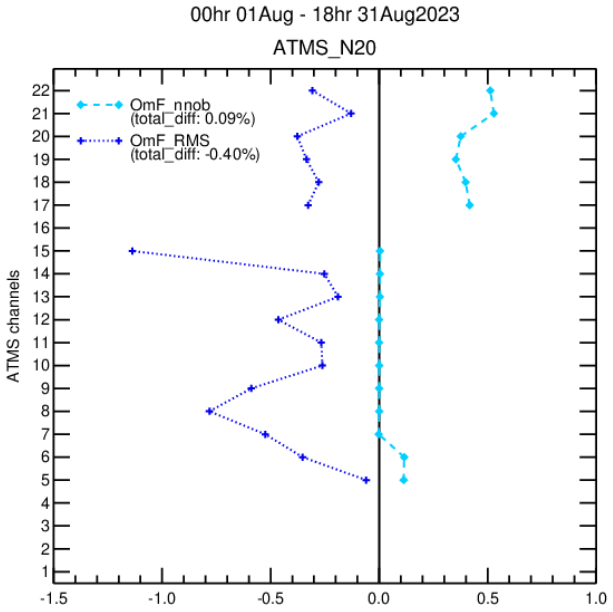
Compare O-F rms values and number of used data



Difference: Exp/control



Difference: Exp/control



Difference: Exp/control

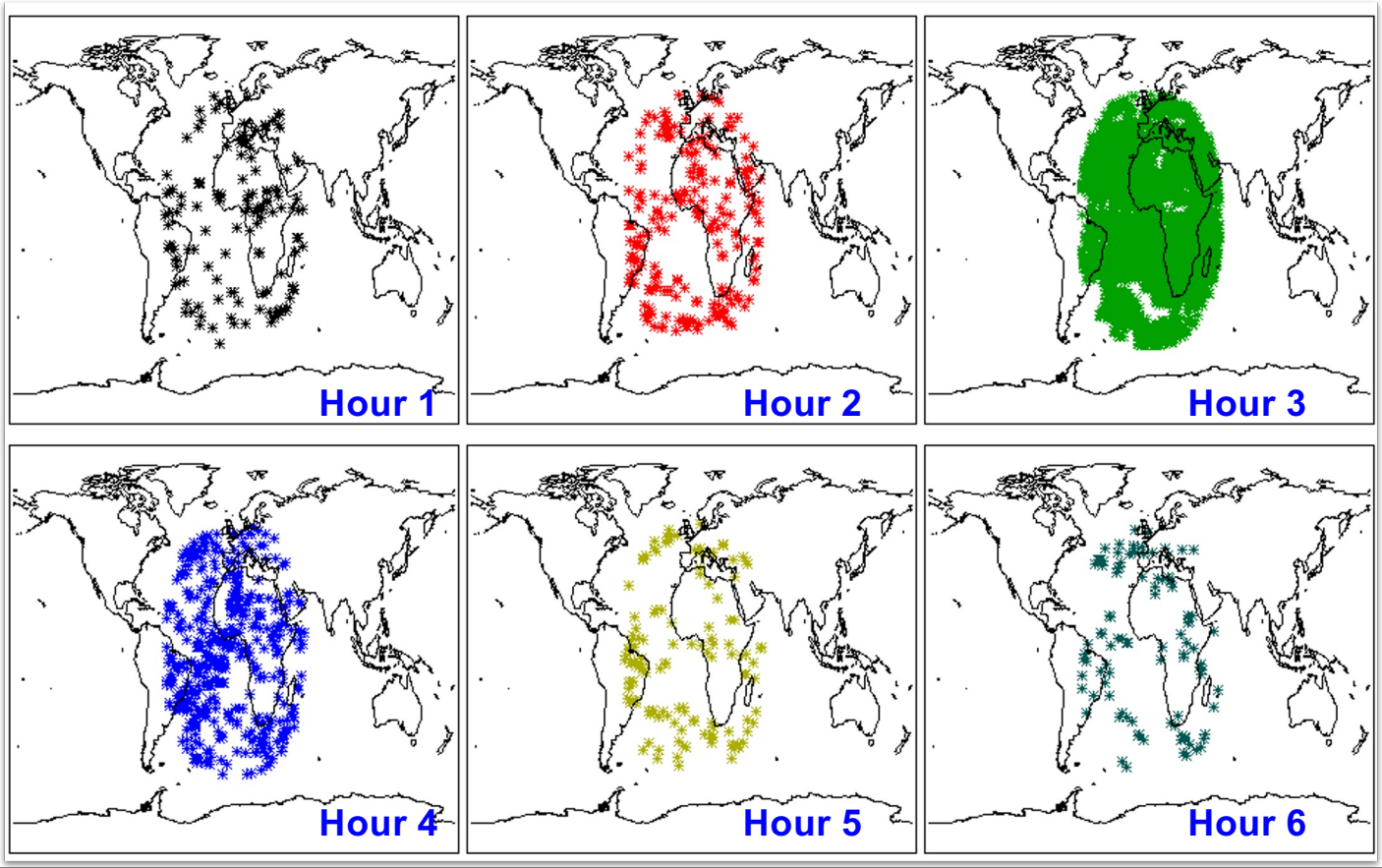
Positive impacts:

- O-F RMS values are generally reduced, **except for values for CRIS-FSR**.
- More CRIS-FSR_N20 observations are assimilated.
- Assimilation of ATMS_NPP and ATMS_N20 data is improved.

Improve Geostationary Radiance Data Selection

- Geostationary radiance data near the center of six-hour time-window were given preferences **during thinning** in a 3-D assimilation system.
- In current 4-D system, No time information is used during thinning. Therefore, observations are selected per the “first-come, first-selected” manner when they meet other data selection criteria. **More data are selected within the 1st hour because satellite data are saved and read sequentially.**
- New two-hourly-thinning for geostationary radiance data: Preference is given to observations at the beginning of the 1st two-hour period, the center time of the 2nd two-hour period, and the end of the 3rd two-hour period.

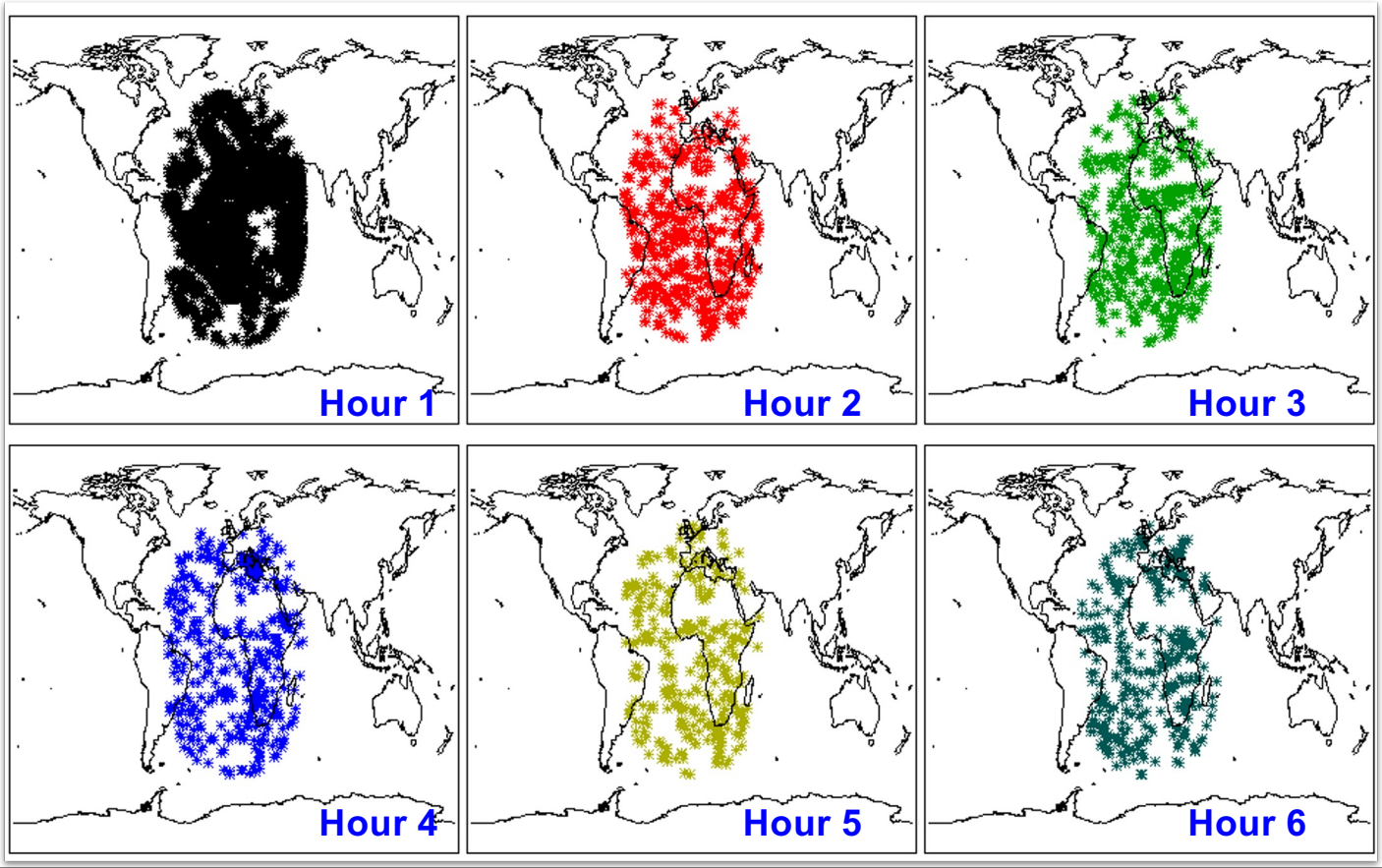
Maps of SEVIRI data after thinning within a 3-D assimilation framework



SEVIRI_M10 at 18 UTC, Jun 1, 2017.

More observations are selected within **hour 3** than other hours.

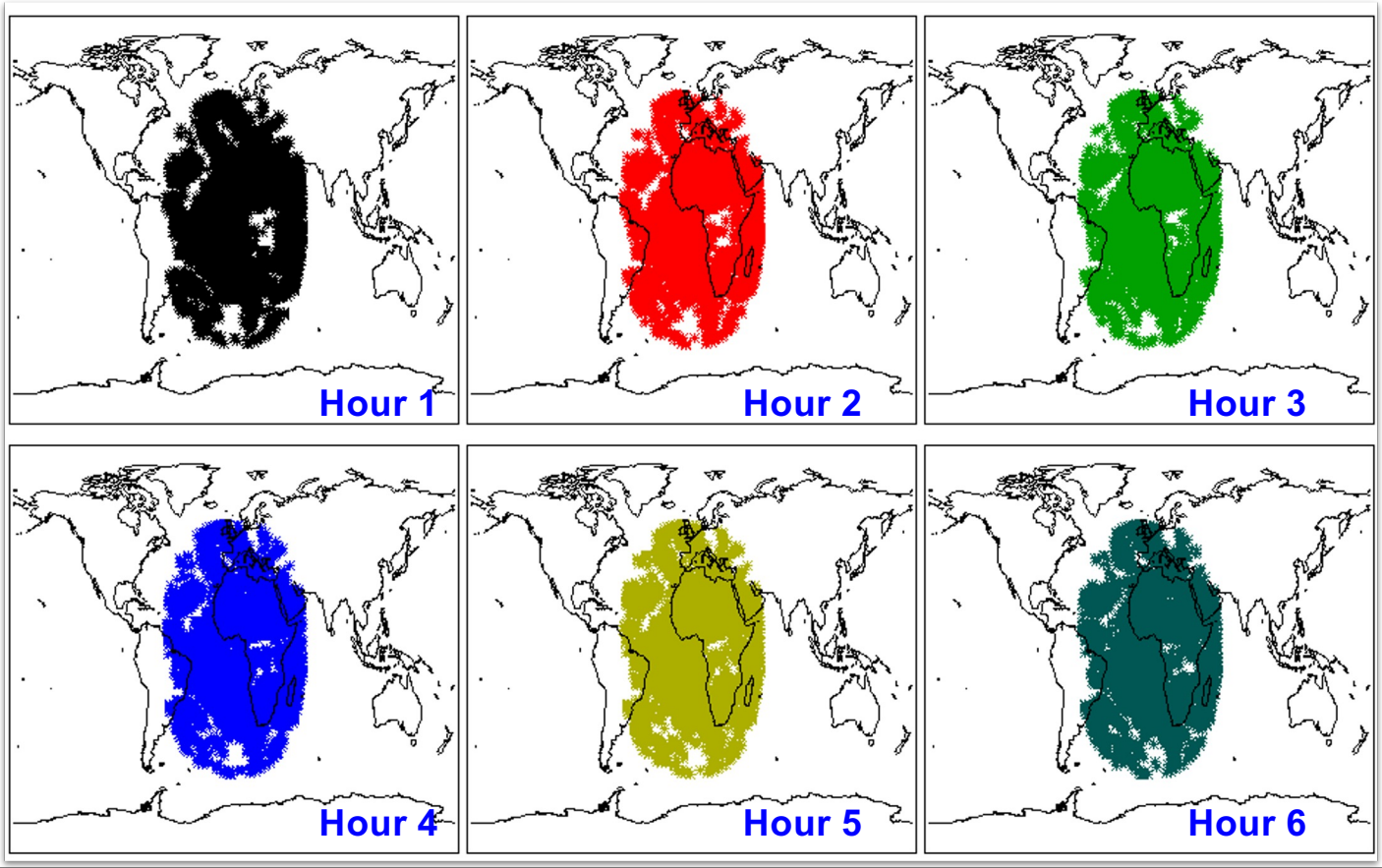
Maps of SEVIRI data after thinning in current 4-D system.



SEVIRI_M10 at 18 UTC, Jun 1, 2017.

More observations are selected within **hour 1** than other hours.

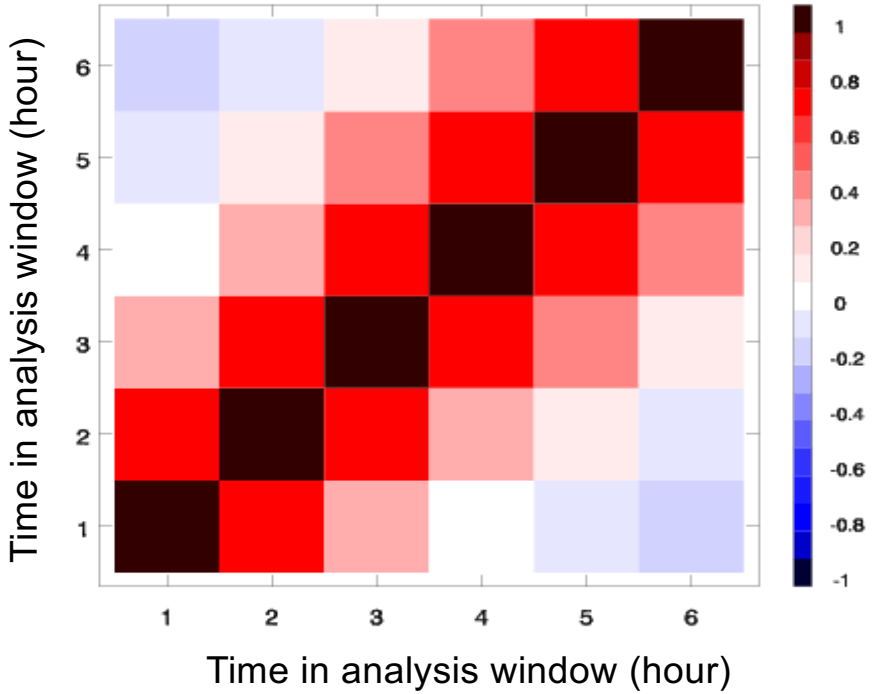
First attempt to fix the issue: Hourly-thinning.



SEVIRI_M10 at 18 UTC, Jun 1, 2017.

Set thinning time-window to be one hour. Nearly same number of data is selected within each hour after thinning.

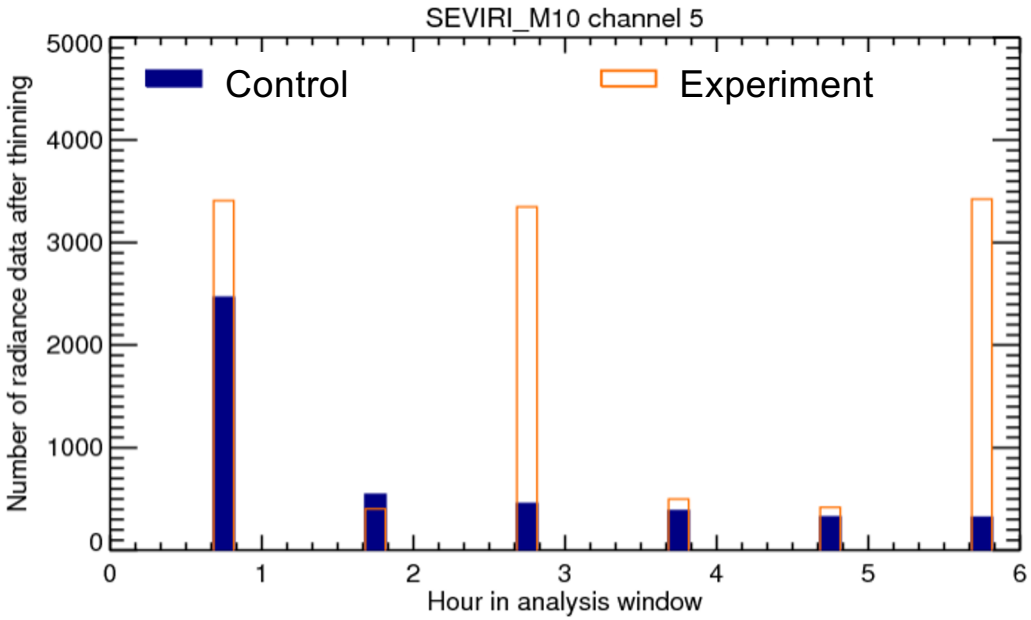
Correlations of observational error SEVEIRI_M10, cha 5.



- **Hourly-thinning has a slightly negative impact in GEOS-5's forecast skills.**
- Time correlations of SEVIRI_M10 channel 5 (6.25 μm) observation error in Dec 2016.

- These correlations are derived from O-F and O-A covariance within the same six-hour analysis cycles.
- This figure shows large observation error correlations within 2-3 hours.

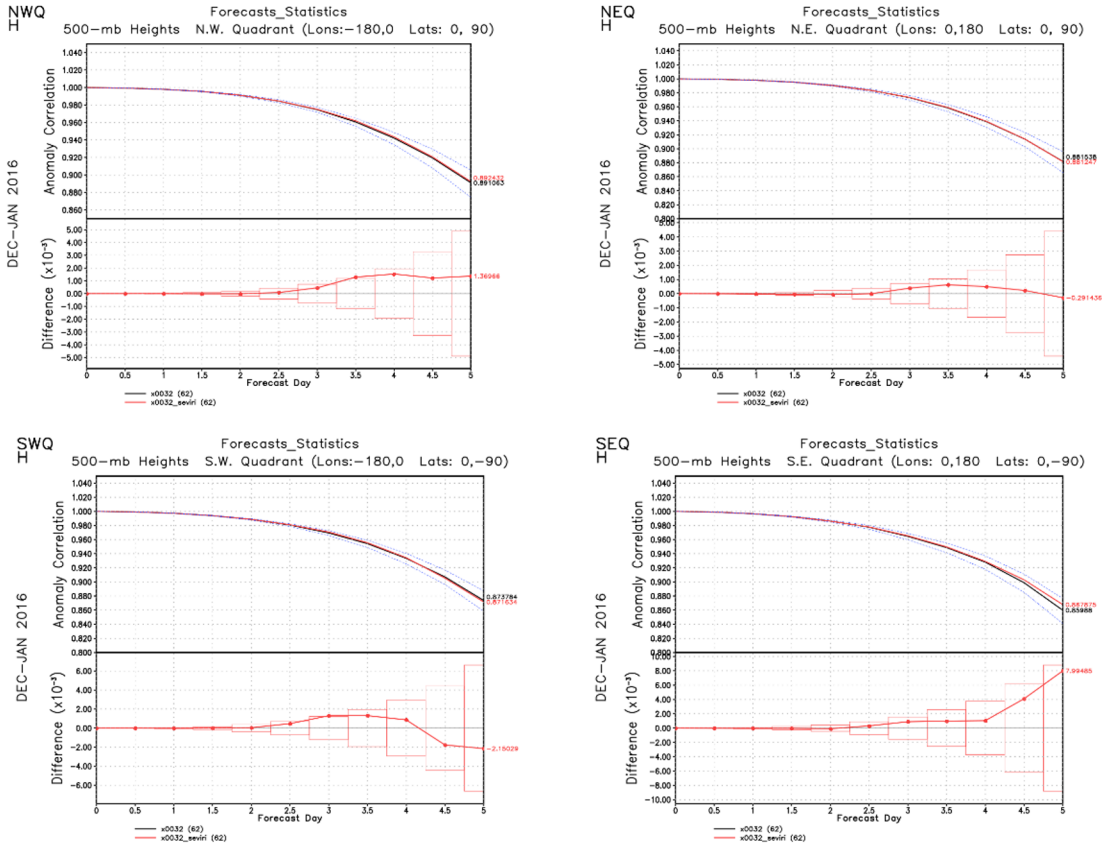
New solution: Two-hourly-thinning



Number SEVIRI_M10 data in control and the experiment (two-hourly-thinning) after thinning in Dec 2016

- **New two-hourly-thinning:** Preference is given to observations at the **beginning of the 1st two-hour period, the center time of the 2nd two-hour period, and the end of the 3rd two-hour period.**
- As a result, we can have nearly the same number of observations at the beginning, middle, and end of the six-hour time window for geostationary satellite observations.

Forecast impact: Anomaly correlation of forecasted GPH.



Experiment: Control + two-hourly-thing of SEVIRI data

- Slightly positive impact on forecasts in the Southeast Quadrant than in other regions. where most of SEVIRI_M10 observations are located in the tropical Atlantic Ocean.

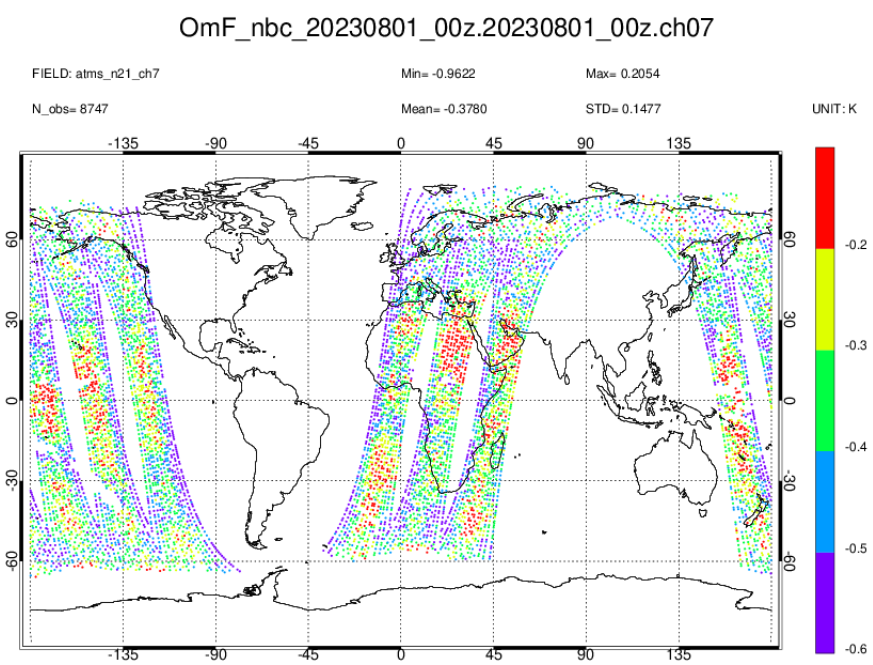
Summary and on-going work

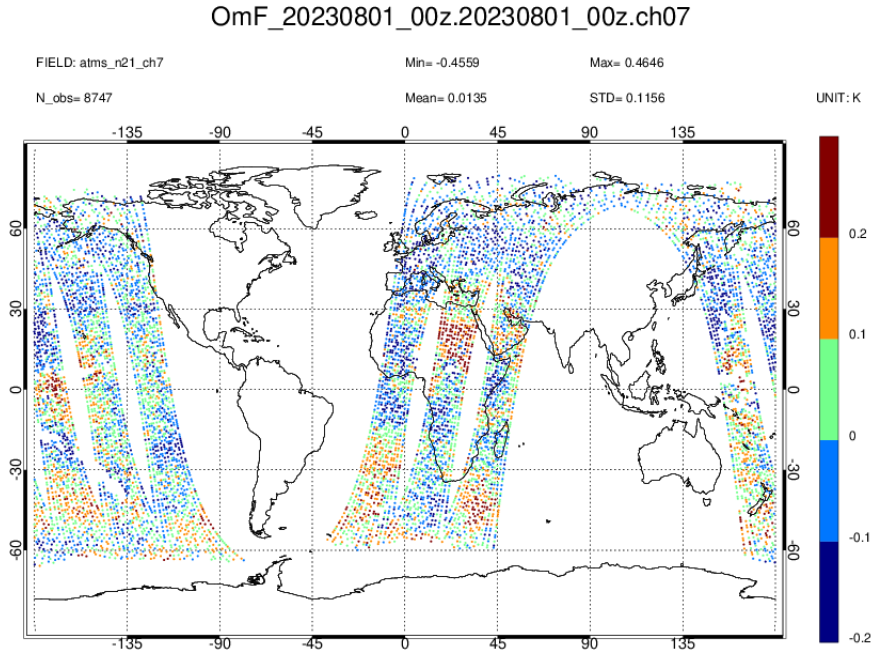
- All-sky microwave radiance data assimilation
  – Ver few low frequency and surface sensitive microwave radiance are assimilated over land, ice or snow surfaces.
  – Explore “all-sky-all-surface” assimilation of microwave radiance observations to improve planetary boundary analysis.
- Assimilate polar orbit infrared observations in all-sky conditions.
- Geostationary radiance
  – No geostationary radiance data are assimilated in GEOS. Will investigate the impact of assimilate those data over ocean.
- New NASA missions.

Thank you!

The end

ATMS NOAA21 ch7 O-F before and after bias correction





Horizonal Correlations In Wind Observational Errors

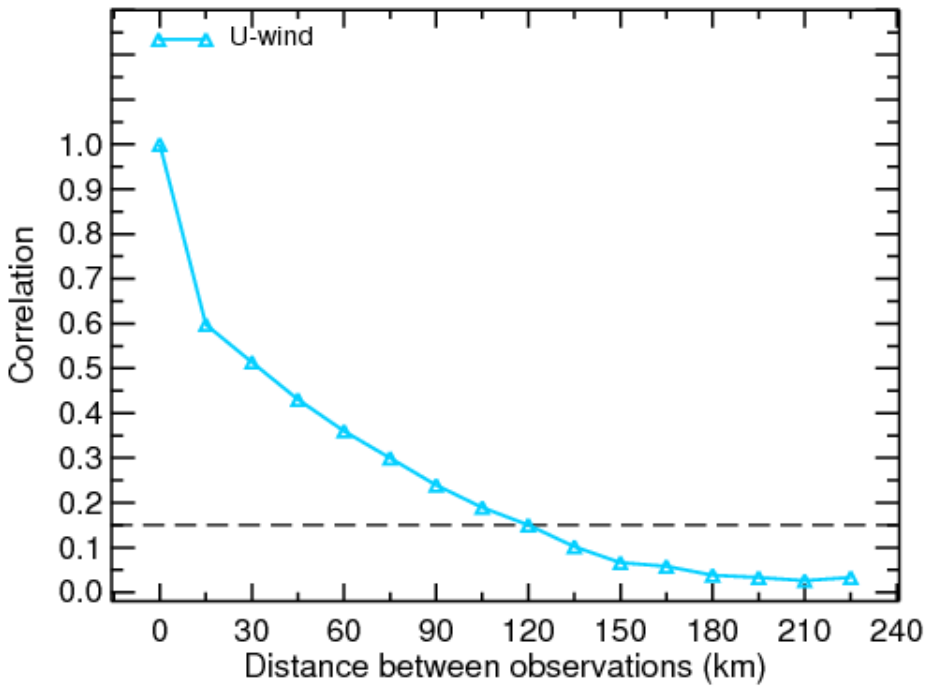
– In a DA system, observational error covariance can be (not perfectly) diagnosed as

covariance (Obs - Analysis, Obs – First guess)

– Correlation in observational errors, derived from the above covariance, decreases as distances between observations increase.

– We chose the horizontal distance where correlation is 0.15 as the new thinning grid size for AMV data.

Cloud track wind made by GOES-15

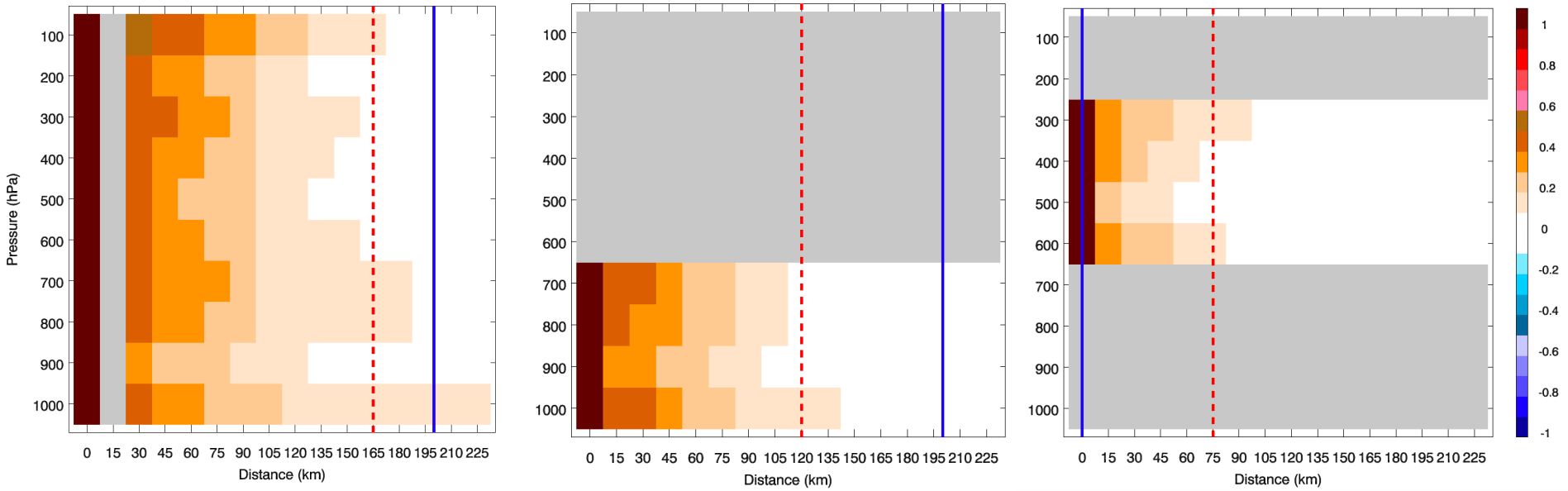


Horizontal Correlations In Observational Errors

For (IR) cloud track U-wind by Himawari

For (visible) U-wind by Meteosat-11

For (WV) high U-wind by GOES-R



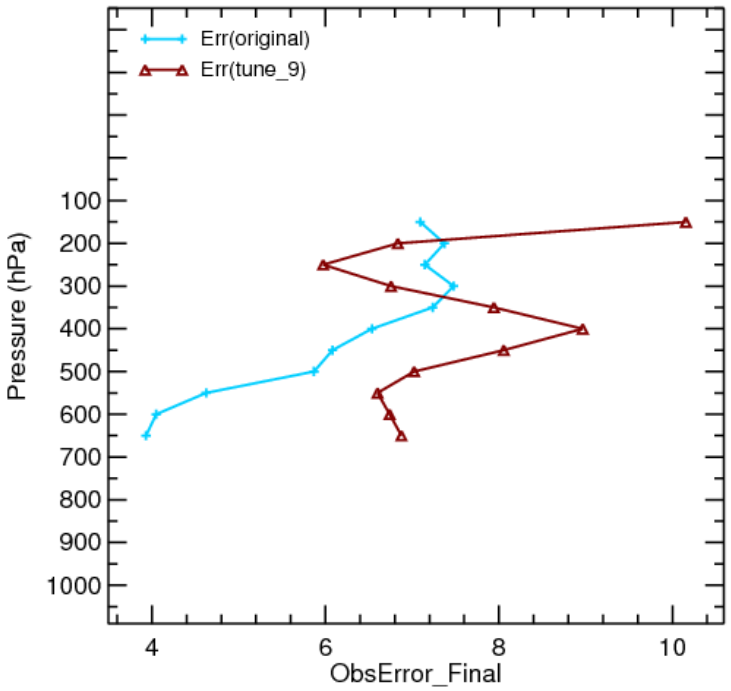
- Distances at blue lines: thinning grid sizes in the original configuration, 200 km or zero.
- Distances at red-dash lines: maximum distance where horizontal correlations is 0.15, **proposed as new thinning grid sizes**.
- Gray: No co-located observation.

➢ **AMV data are thinned in a scientifically consistent way.**

Tune Observational Error Inputs

Adjust observational error inputs in order to give similar weights (penalties) of AMV at different altitudes.

Observational errors for WV cloud top AMV by Meteosat-11.



Penalties for WV cloud top AMV by Meteosat-11.