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Developing Data Assimilated 4D Global Precipitation Products from the GEOS system in Support of the GPM Mission

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2. GESTAR, 3. SSAI

PMM Science Team Meeting, Nov 4-8, 2019

Introduction

- A significant number of satellite radiance data containing cloud and precipitation signal are discarded in NWP analysis systems due to various difficulties and the assumptions involving modern NWP data assimilation algorithms that were based on linearity and Gaussianity of error distributions.

- By enhancing GEOS analysis system with all-sky data assimilation capability, we extended radiance data usage to gain more information on atmospheric states in cloudy and precipitating regions.

- On **July 11th, 2018**, GPM Microwave Imager (GMI) observations were implemented into the NASA GMAO Forward Processing (FP) system
  - GMI radiance data are assimilated in GEOS in near-real-time
  - It was a big step. Direct radiance data assimilation under all-sky situations, eliminating previous limitation to those unaffected by clouds and precipitation

Project Objectives

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(1) Expanding the existing GEOS all-sky GPM microwave radiance data assimilation system to utilize all-sky microwave radiance from other microwave sensors on the GPM constellation satellites.

(2) Developing prototype of four-dimensional Level-4 global atmospheric and surface analysis data sets by assimilating all-sky microwave radiances from multiple sensors using the GEOS modeling and assimilation (at a spatial resolution ~ 25 km).

(3) Generating prototype of downscaled precipitation Level-4 datasets by extending the datasets developed in (2) to higher spatial resolutions (~ 7 km)

GEOS Atmospheric Data Assimilation System

The Goddard Earth Observing System (GEOS) atmospheric data assimilation system is a highly complex yet flexible global NWP system composed of **the GEOS Atmospheric General Circulation Model (AGCM)** and **the Gridpoint Statistical Interpolation (GSI) analysis algorithm.**

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- **AGCM**: The GEOS AGCM is a weather- and climate-capable model used for atmospheric analyses, weather forecasts, climate simulations and predictions at various horizontal resolutions, with 72 vertical layers to 0.01 hPa. Horizontal resolution of current GEOS FP forecasts and analyses are ~12 km and 25 km, respectively.
- **Analysis system**: The GSI algorithm combines information from irregularly distributed observations with the GEOS AGCM model state in such a way as to minimize a specified cost function.

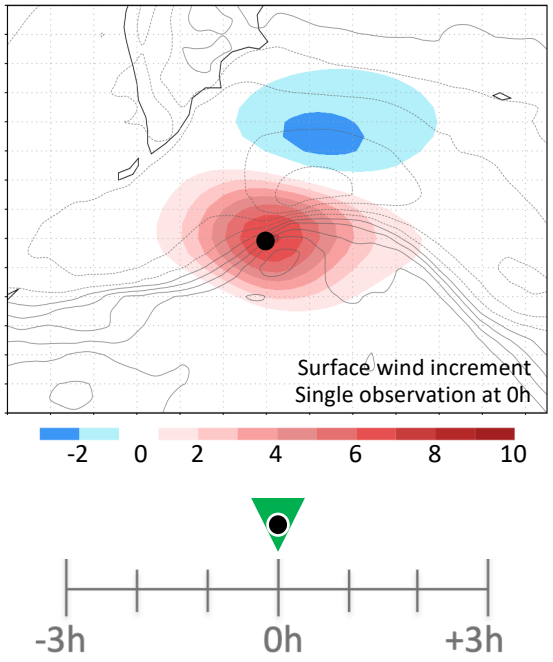
$$J(x_a) = (x_a - x_b)^T B^{-1} (x_a - x_b) + (H(x_b) - O)^T R^{-1} (H(x_b) - O)$$

Fit to model generated background fields **Fit to observations**

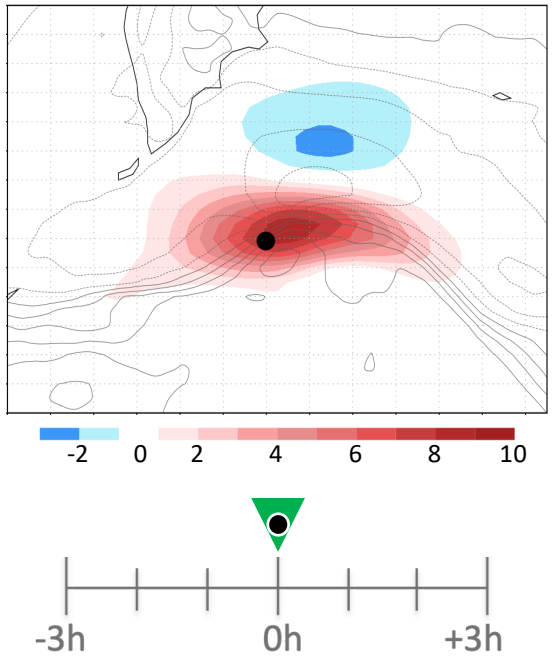
x_a= Analysis, x_b= Background (first guess field) , O= Observations ,B= Background error covariance, R = Observation Error covariance (= instrument error + representativeness error + forward operator error), H = Observation operator

Evolution of the GEOS data assimilation methodology

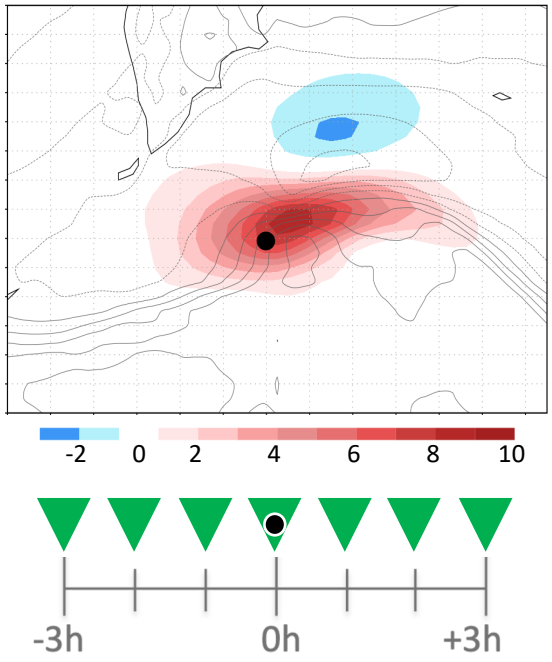
...2012
3D-Var
No flow dependence
No time dependence



2015
Hybrid 3D-Var
Flow dependence
No time dependence



2017
Hybrid 4D-EnVar
Flow dependence
Time dependence



Data Currently Assimilated In GEOS FP System

- AMSU-A (in NOAA 15, 18, 19, Aqua, METOP-A & B)
- MHS (in NOAA 18, 19, METOP-A & B)
- ATMS (in NPP)
- SSMIS (in DMSP F17, F18)
- **All-sky GMI (in GPM)**

Passive Microwave Radiometers

- AIRS (in Aqua)
- IASI (in METOP-A & B)
- HIRS (in METOP-A, NOAA 18,19)
- CrIS (in NPP)
- AVHRR in Metop-A, NOAA 18)
- SEVIRI (in METEOSAT-10)
- GOES

Passive Visible/Infrared Radiometers

- Conventional Data : Sonde, Buoy, Ship data, Aircraft data
- GPS Radio Occultation : refractivity
- OMI, MLS ozone data
- SatWind retrieved wind vectors

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- **All-sky GMI (in GPM)** **In GEOS-FP since July 2018!!**

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Data Currently Assimilated In GEOS FP System

All-sky data assimilation development completed. Currently NWP impact experiments are in progress to get ready for the future GEOS upgrades

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- MHS (in NOAA 18, 19, METOP-A & B)
- ATMS (in NPP)
- SSMIS (in DMSP F17, F18)

Development for all-sky DA in progress

- **All-sky GMI (in GPM)**

In GEOS-FP since July 2018!!

Passive Microwave Radiometers

- AIRS (in Aqua)
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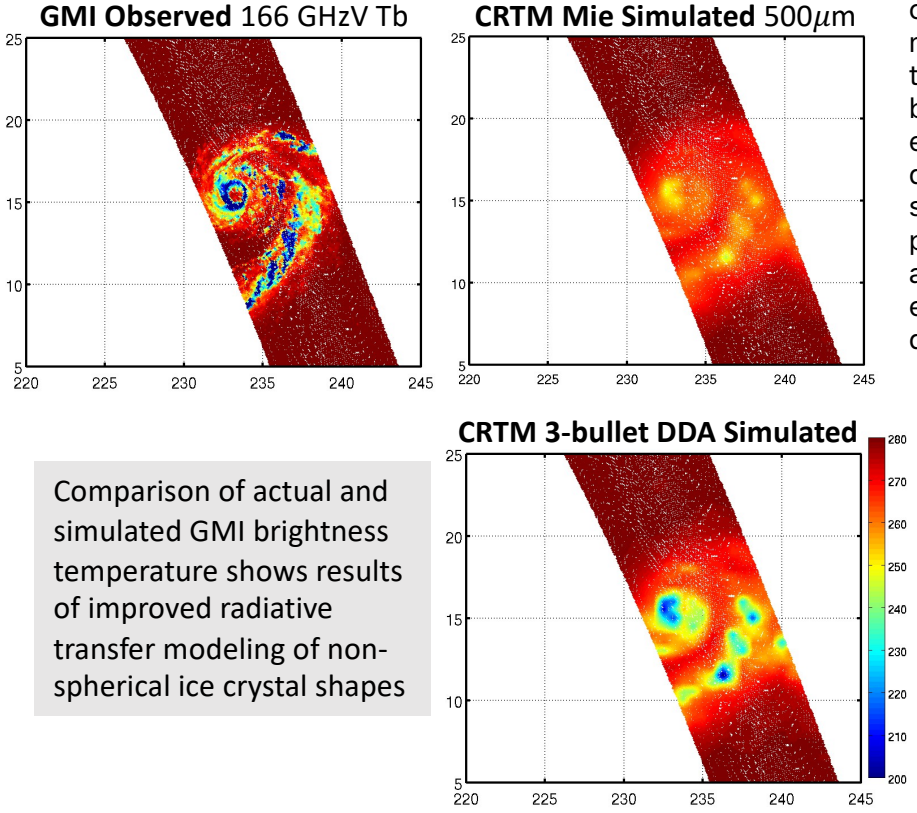
Assimilation of cloud- and rain-affected radiances

More enhancements made in GEOS ADAS:

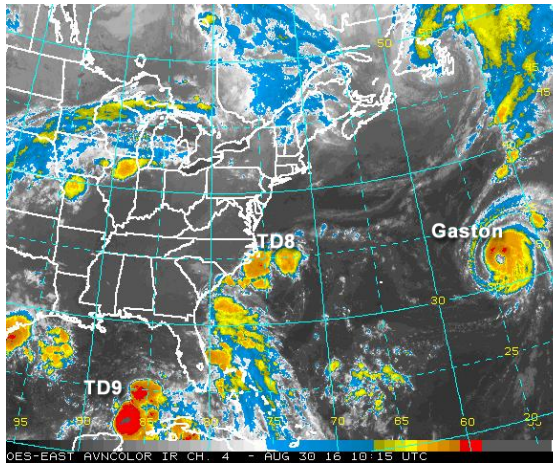
- Significant changes were made in GEOS ADAS to include **new analysis variables**: Hydrometeors such as **liquid cloud, ice cloud, rain, and snow** are analyzed using all-sky satellite data in GEOS.
- **Background error (hybrid) and observation error models (symmetric)** were built and tuned.
- **Bias correction methods** and **quality control procedures** for all-sky microwave radiance data were developed.
- **Enhancing cloud and precipitation optical properties in the Community Radiative Transfer Model (CRTM)** which plays a role as observation operator converting GEOS model fields to radiances measurable by GPM Microwave Imager.



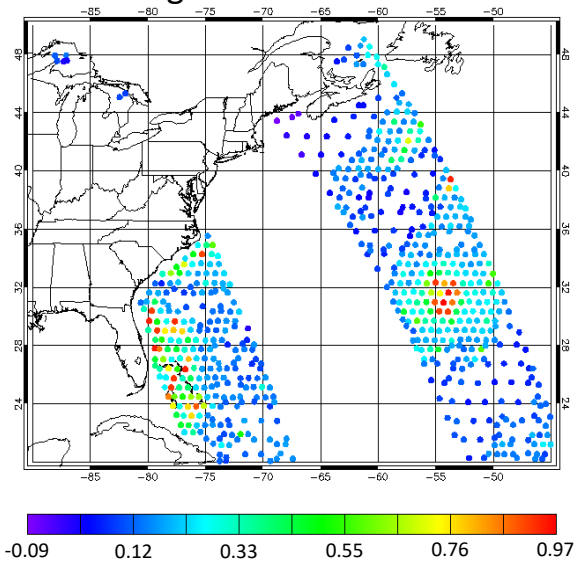
Comparison of actual and simulated GMI brightness temperature shows results of improved radiative transfer modeling of non-spherical ice crystal shapes

Dynamic adjustments in precipitating regions

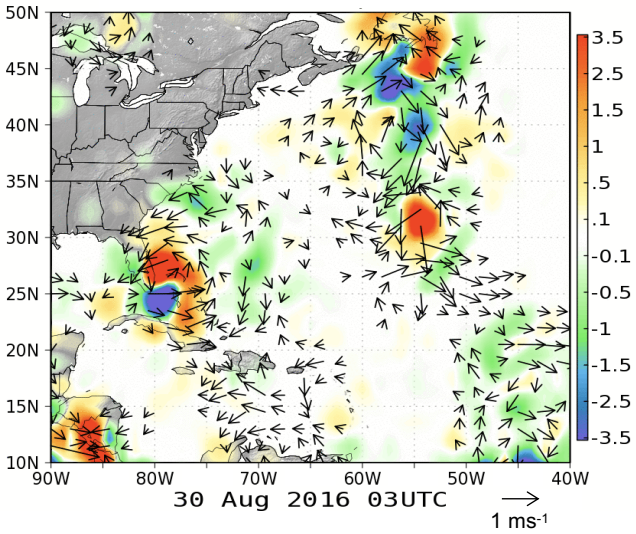
GOES East IR Imagery
30 Aug 2016 1015 UTC



GMI 37-GHz Tb Polarization Diff
30 Aug 2016 0300-0900 UTC



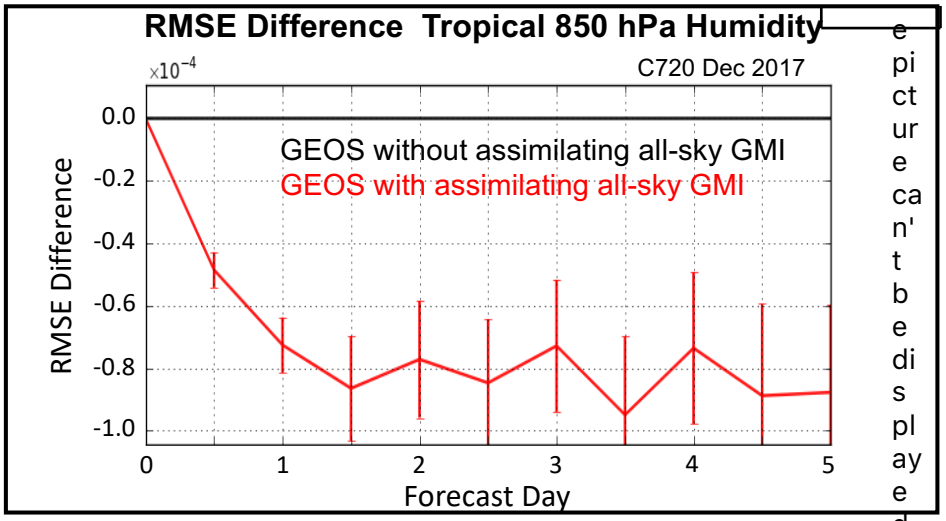
Analysis Increments 850hpa wind, rain
30 Aug 2016 0300-0900 UTC



- In addition to hydrometeors, dynamic variables such as wind, temperature and surface pressure are adjusted by assimilation of all-sky microwave radiances in hybrid 4D-EnVar.
- These changes in both the analyzed moisture and dynamic variables through assimilation of microwave radiance data contribute to GEOS forecast improvements.

Impact of GMI all-sky radiances on forecast skill

The red curve in the upper figure shows the Root Mean Square Error difference between humidity forecasts in Tropics with and without all-sky GMI analysis forcing. Here, negative RMSE difference means that all-sky GMI data assimilation system reduces the forecast errors. Adding GMI all-sky radiances improves the initial states for humidity, wind, and temperature and leads to reduced error, especially in the Tropics.



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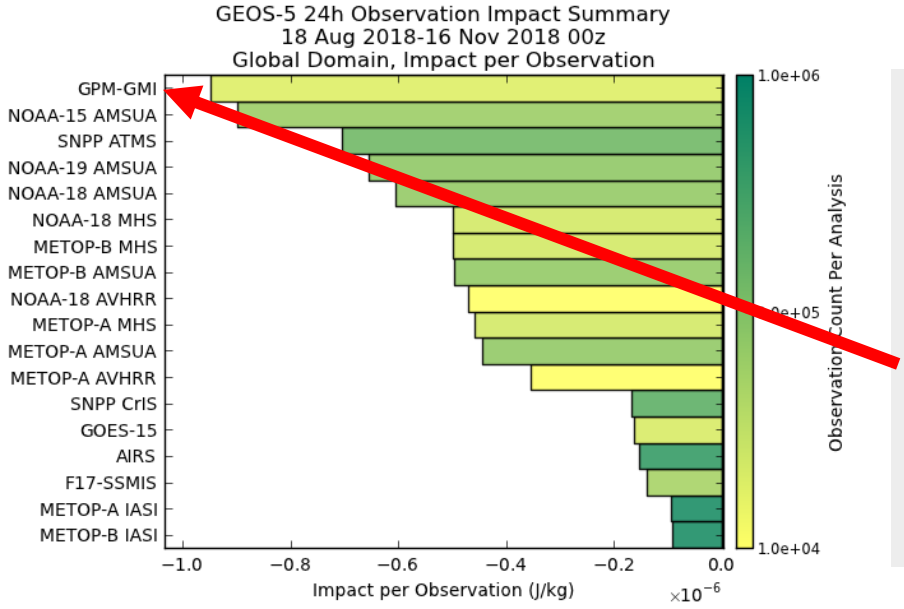
Forecast Sensitivity and Observation Impact (FSOI)



- The GMI improvement is consistent with results seen via the FSOI metric which is a matric of how each observation contributes to the reduction (negative) or increase (positive) of the 24 hour forecast error.
- GMI is seen to have the highest impact per observation of all the radiance observation types despite their relatively low number of observations.

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Delivered All-sky GMI DA system to NOAA NCEP

NOAA NCEP asked us to share the all-sky GMI data assimilation system. We sent all-sky GMI data assimilation system to NOAA NCEP 2 months ago.

(1) GMI data bufrization codes
(2) GSI analysis algorithm codes for all-sky GMI data
(3) CRTM cloud coefficient files

The All-sky GMI analysis system has been merged to NCEP Global Data Assimilation System (GDAS) trunk last month. The merged GDAS will go through NWP experiments to get ready for the NWS operational implementation soon.

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Expansion of all-sky system to utilize all-sky data from other microwave sensors

Extending All-sky Data Assimilation System to Utilize Other Satellite Microwave Sensors' Data

ct

Status of All-sky MW data assimilation developments in GEOS

Satellite	Sensor (Scanner)	# of Channels (Frequency)	Clear sky		Cloudy/Precipitating sky	
			Ocean sfc	Non-Ocean	Ocean sfc	Non-Ocean
GPM	**GMI** (conical)	13 channels (10GHz~190GHz)	●	■	●	■
GCOM-W1	**AMSR-2** (conical)	7 channels (6.9 GHz ~ 89 GHz)	■	■	▲	
DMSP F16, F17, and F18	**SSMIS** (conical)	24 channels (19.35 GHz ~ 190GHz)	●	●	▲	▲
NOAA-18 & 19, METOP-A &B	**MHS** (cross-track)	5 channels (89GHz ~ 190GHz)	●	●	■	■
NOAA-18 & 19, METOP-A &B	**AMSU-A** (cross-track)	11 channels (23.8 GHz ~ 89 GHz)	●	●	■	■
SNPP, NOAA-20	**ATMS** (cross-track)	22 channels (23.8 GHz ~ 190GHz)	●	●	■	■
Megha-Tropiques	**SAPHIR**	6 channels (183.2 GHz ~ 194.3GHz)	▲	▲	▲	▲

● : Currently assimilated in GEOS

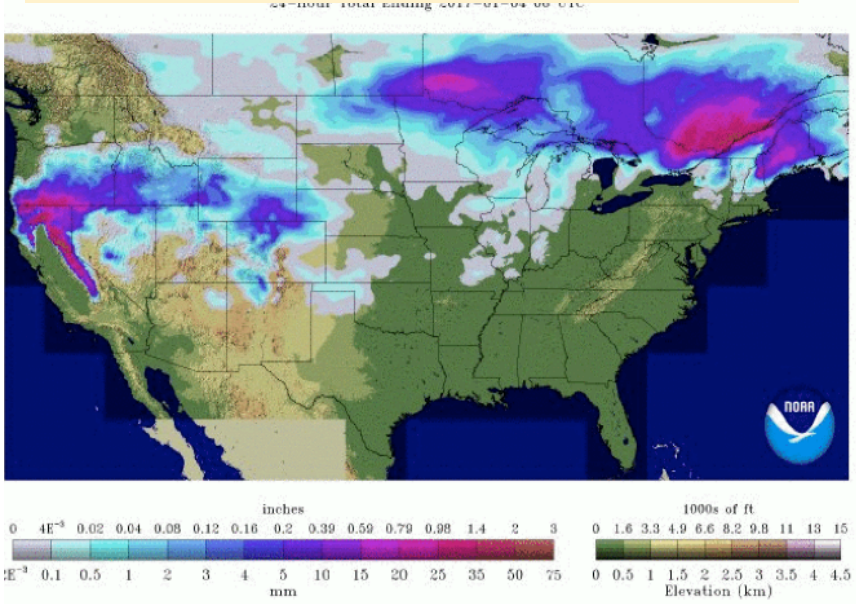
■ : Development almost completed and NWP experiments in progress.

▲ : Currently under development GEOS

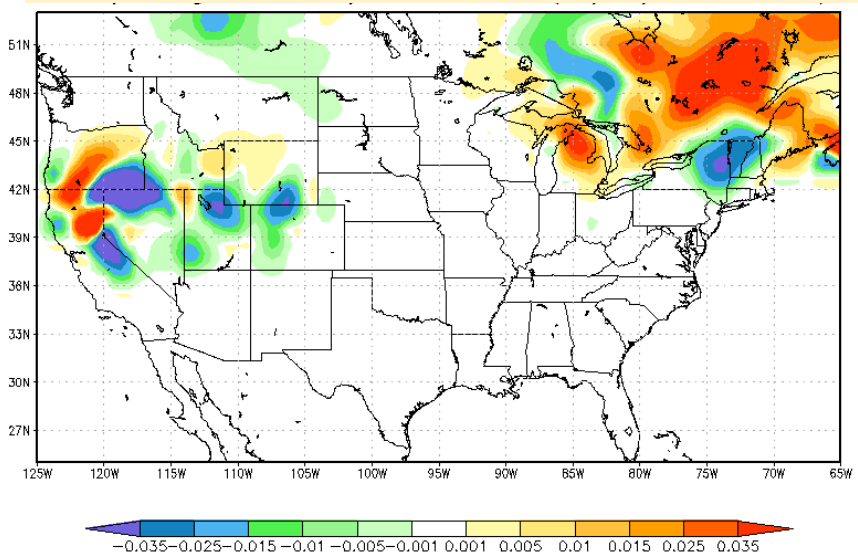
GEOS analysis changes made by assimilating all-sky microwave data from GMI and MHS from NOAA and METOP-A&B satellites

Early January 2017 North American Winter Storm

Observed Snow Precipitation



Snow Precipitation Changes in GEOS Analysis by Assimilating all-sky GPM + MHS data

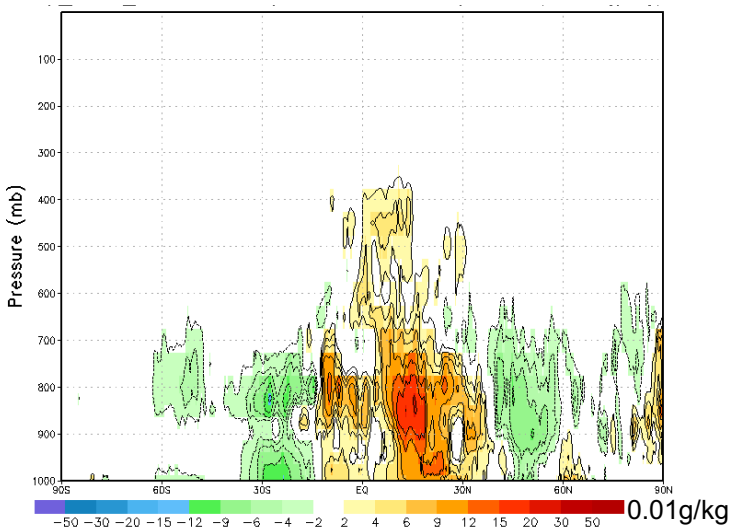


- Left Figure: Observed 24 hourly snowfall accumulation during the 2017 January North America Winter Storm that affected large are of US from west to south to east.
- Right Figure: Falling snow precipitation changes by assimilating all-sky data from GMI and several MHS sensors. These extended all-sky data usage can adjust snow precipitation in the analysis to be much closer to the observations.
- Other atmospheric parameters like water vapor and surface pressure are also adjusted physically-consistent manner. Therefore, we expect to see further improvements in GEOS forecast skills by this enhanced all-sky system.

Impact of MHS all-sky radiances on GEOS analyses and forecasts

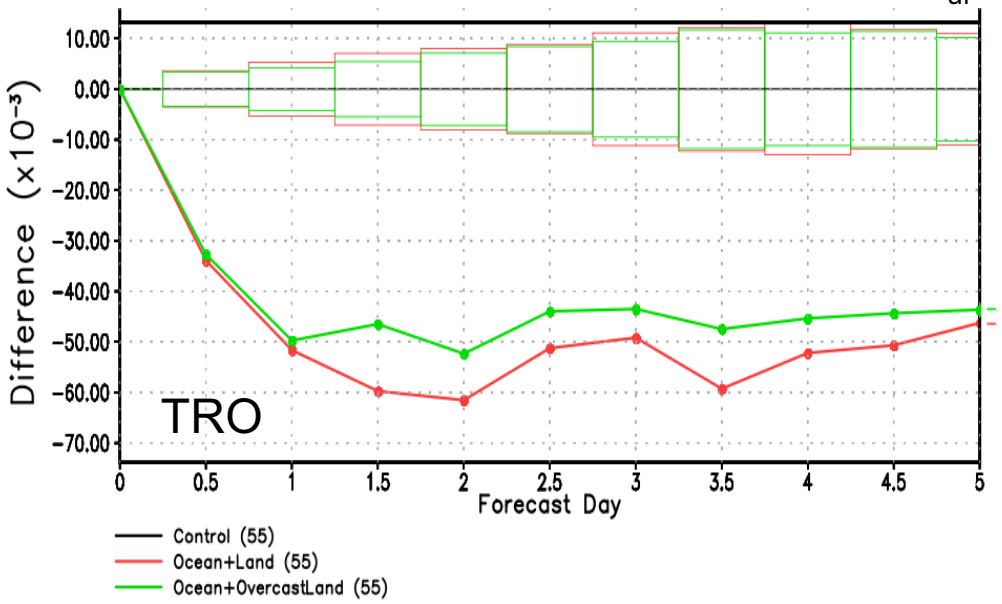
July 2018, Monthly Mean Qv Analysis Difference

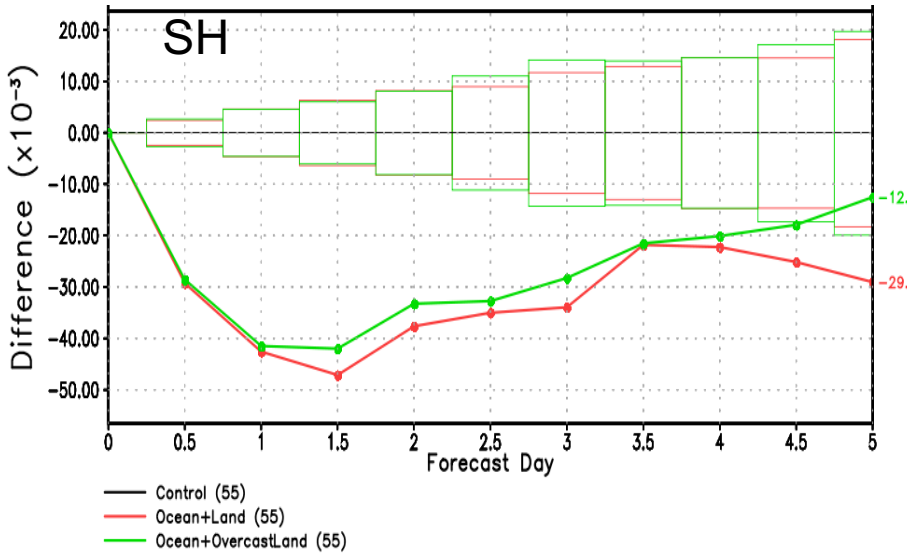
AllskyMHS – CNTL

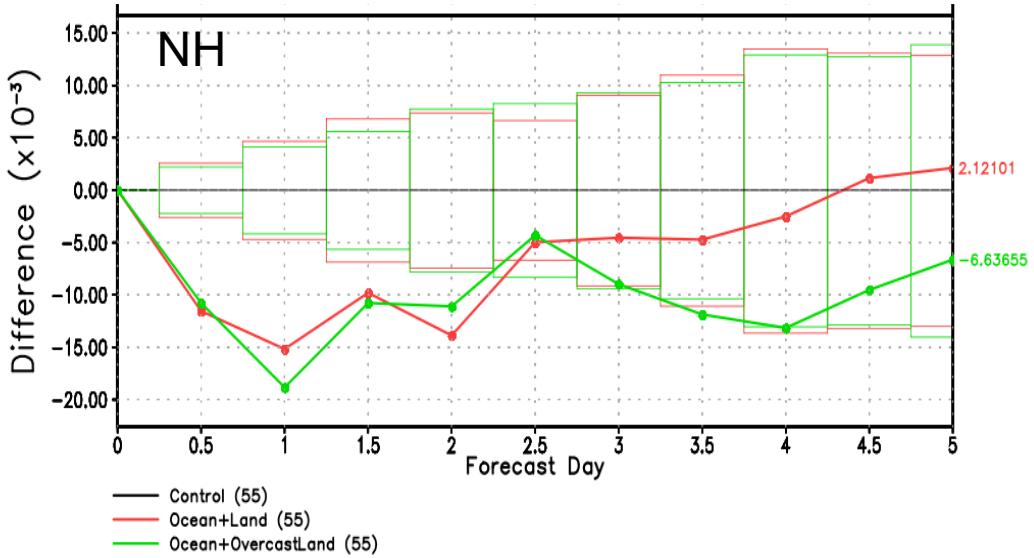


Forecast Error Reduction

850 hPa Humidity RMSE Difference



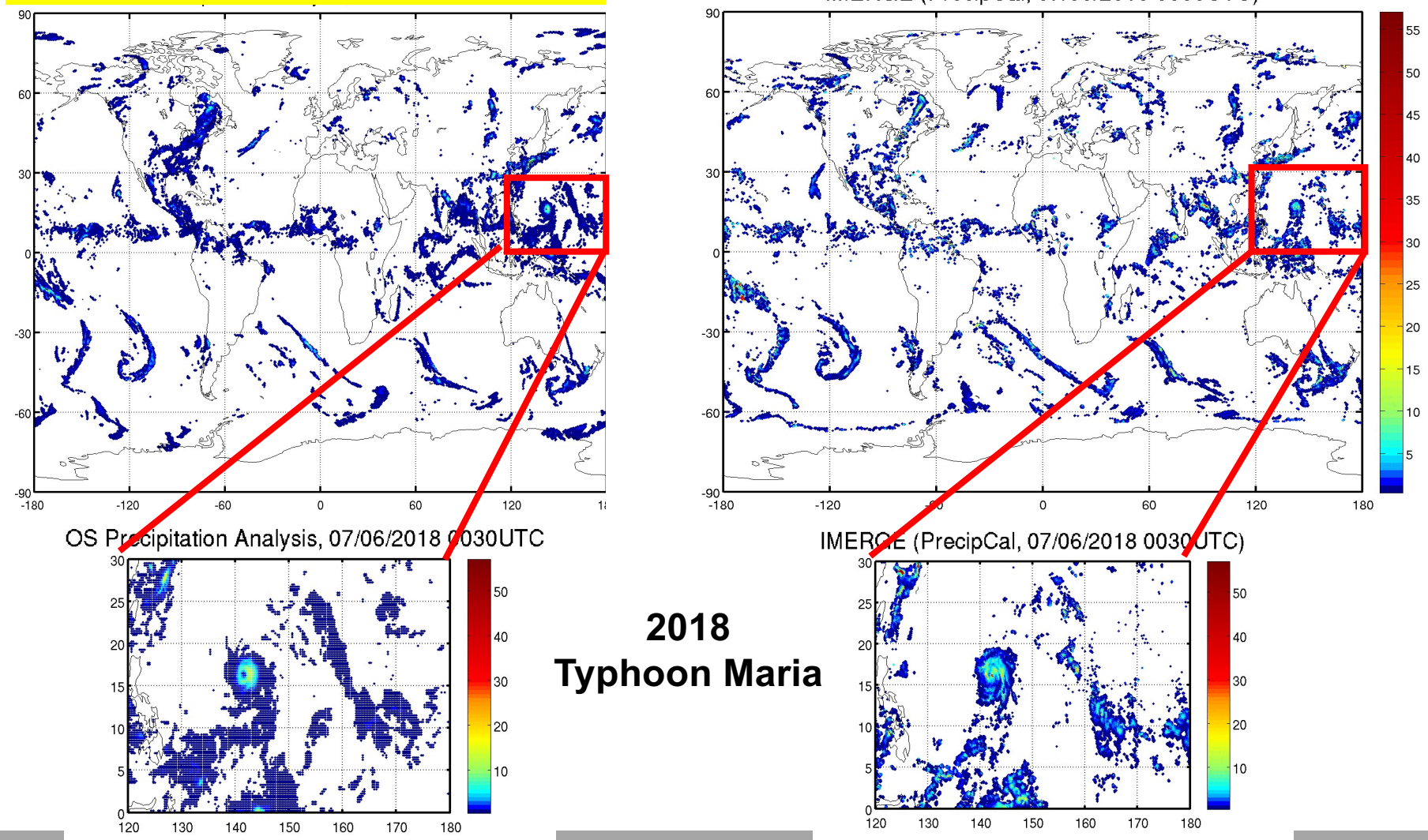




Prototype of Multi-Satellite Data Assimilated Global Atmospheric & Surface Analysis Products from GEOS

GEOS Analyzed Surface precip (mm/hr)
(Conventional, IR/MW clear sky data +
all-sky GMI and all-sky MHS data assimilated)

IMERGE
precipCal (mm/hr)



2018
Typhoon Maria

Final Remarks

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- GMAO has implemented all-sky GPM Microwave Imager (GMI) in GEOS FP, increasing not only the number of satellites observations assimilated but also the types of variables analyzed.
- All-sky GMI data made significant positive Impacts on GEOS forecasts especially for lower tropospheric water vapor, temperature, and winds.
- All-sky system developments were made to be able to share the codes with NOAA NWS.
- All-sky techniques in GEOS have been extended for MHS, AMSU-A and ATMS data. Further extension for other microwave sensors' data such as all-sky SSMIS, all-sky SAPHIR, and all-sky AMSR-2 data are in progress.
- We will work on generating downscaling precipitation products by applying all-sky microwave radiance data assimilated analyses and comparisons with IMERG data.
- We plan to utilize TMI, AMSR-E, GMI, and other all-sky observation from microwave sensors for next NASA GMAO reanalysis data production.

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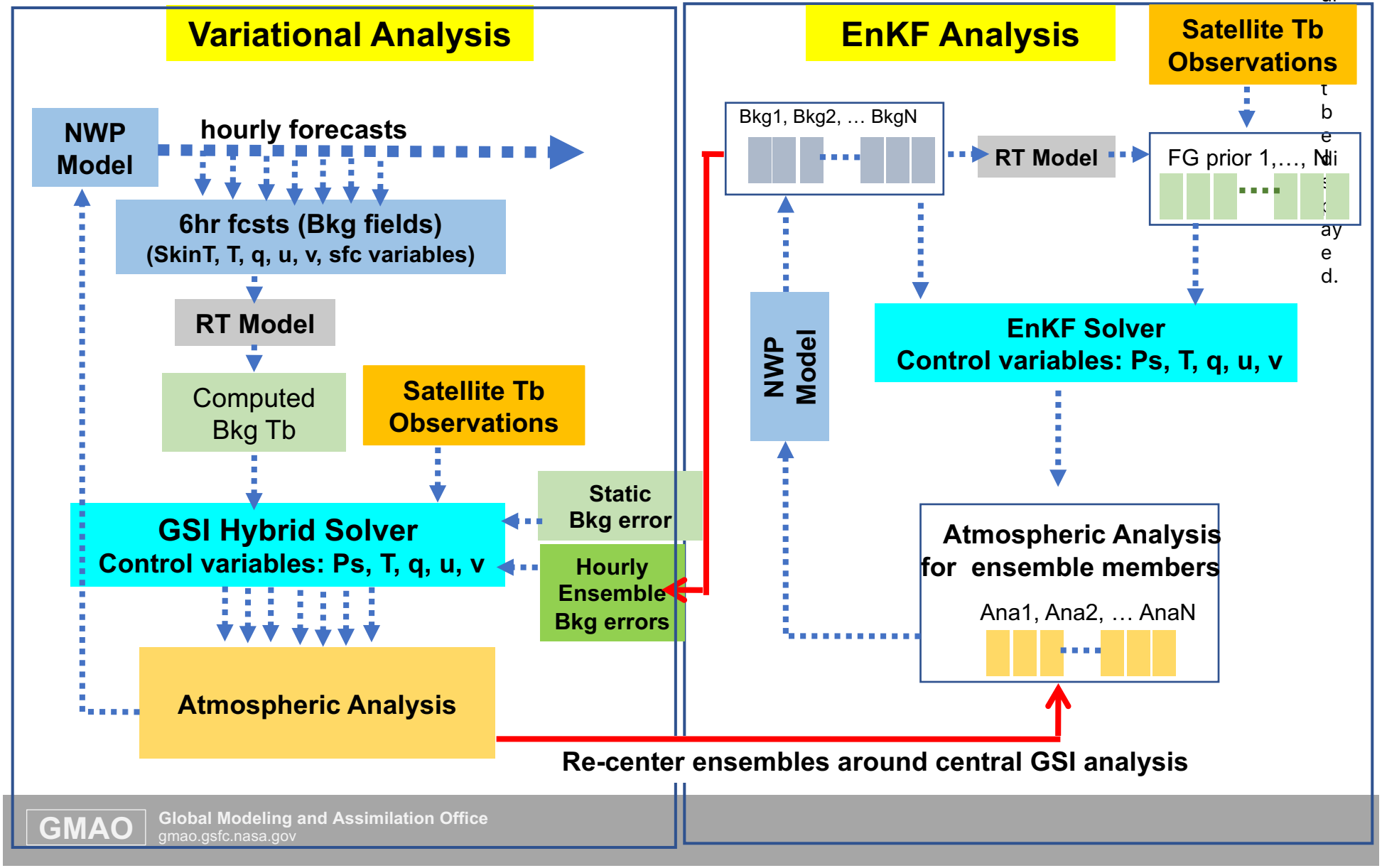
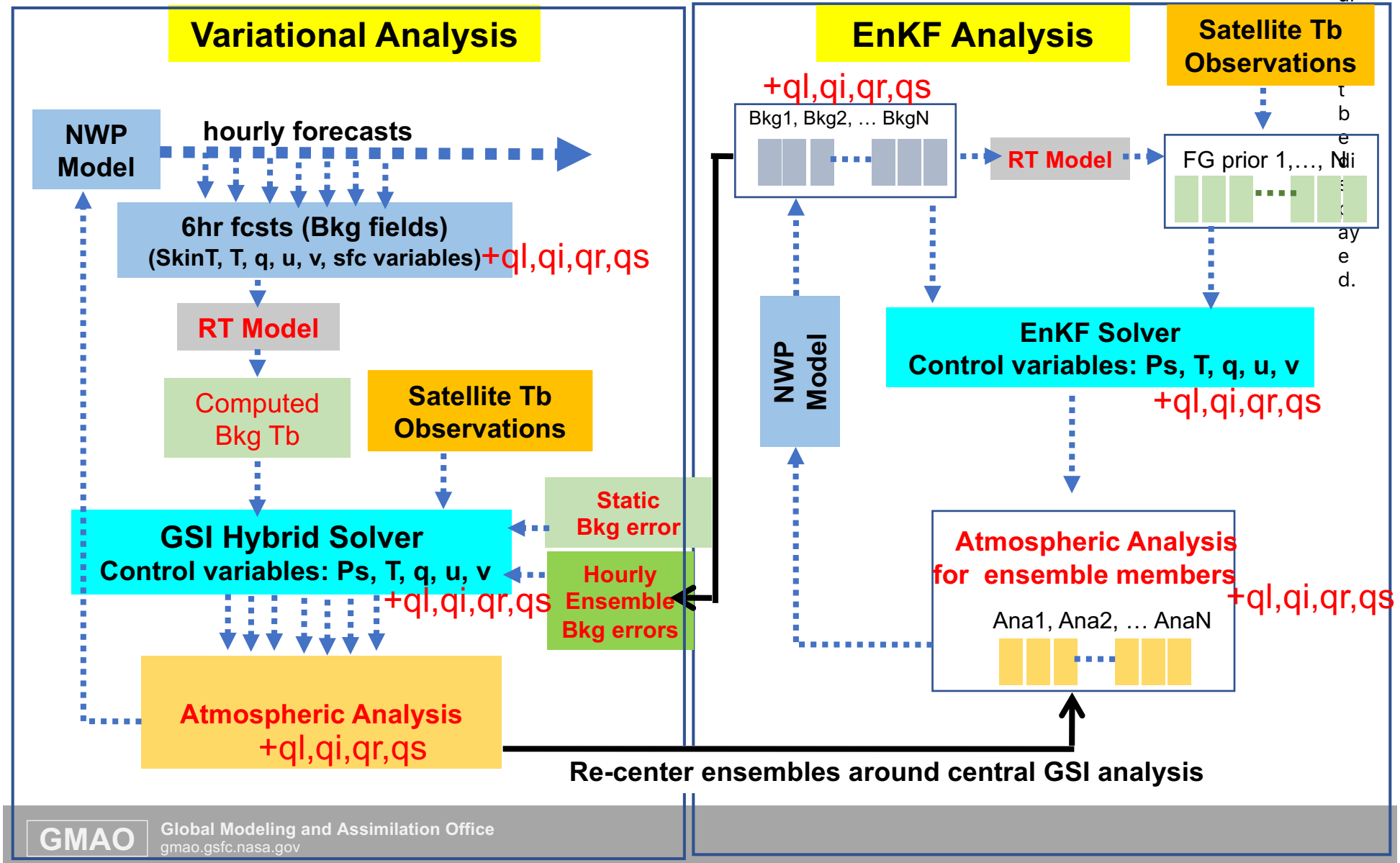
Backup slides

Hybrid 4D-EnVar Data Assimilation System

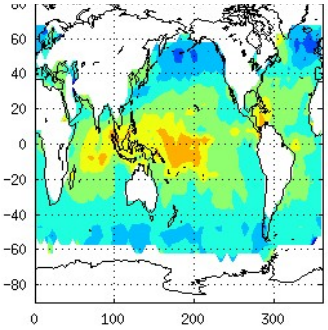


From Clear radiance DA to All-sky radiance DA

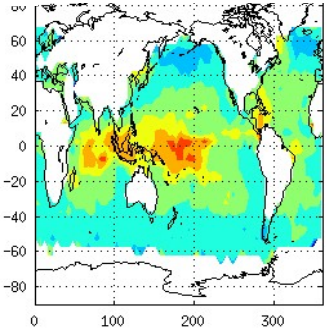


Monthly Mean of TB_{obs}-TB_{model} : GMI CH10

CRTM 2.2.3(MIE, reff=500μm)

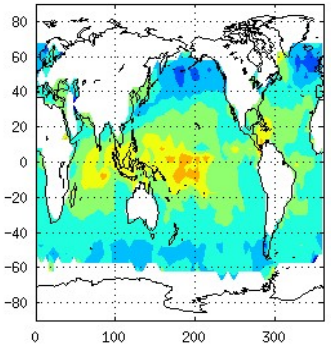


CRTM 2.2.3 (DDA, reff=500μm)

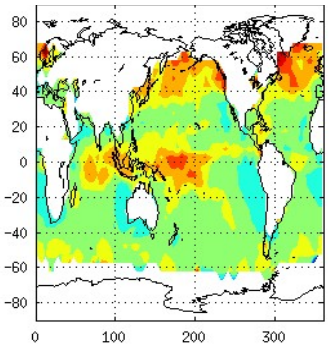


DDA : Liu(2008)

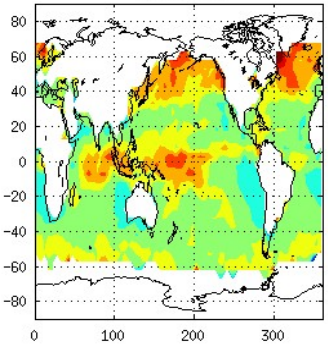
Soft Sphere



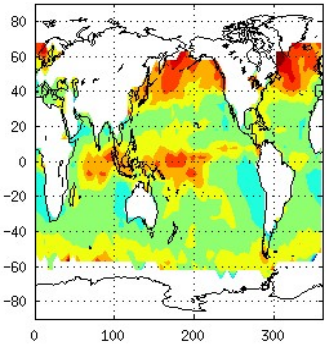
Long column



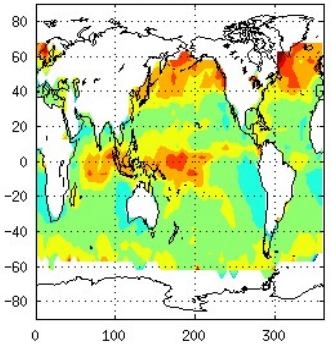
Short column



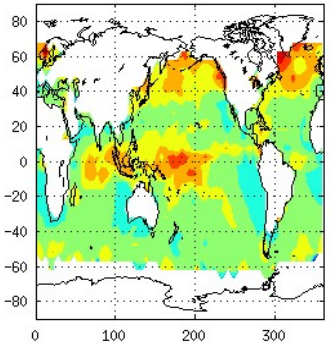
Block column



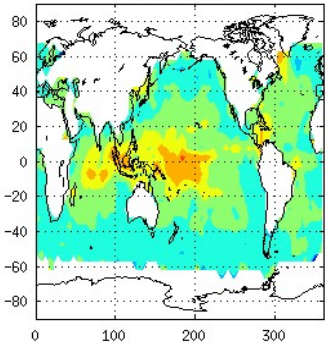
Thick Plate



Thin Plate



3-bullet



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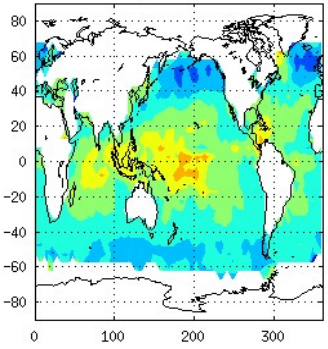
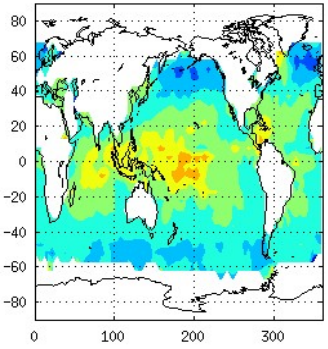
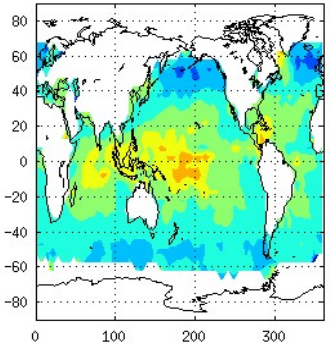


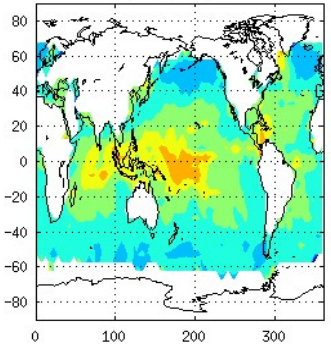
5-bullet



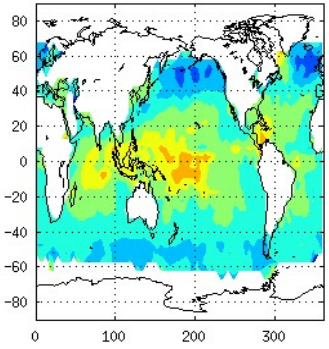
6-bullet

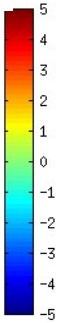


Sector Snowflake



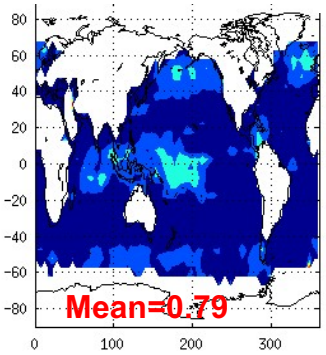
Dendrite



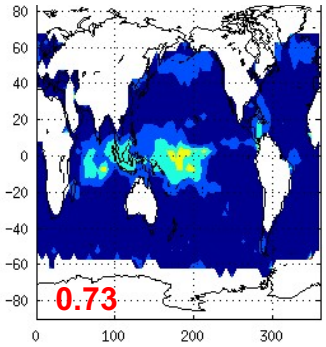


Monthly RMS of TB_{obs}-TB_{model} : GMI CH10

CRTM 2.2.3(MIE, reff=500μm)

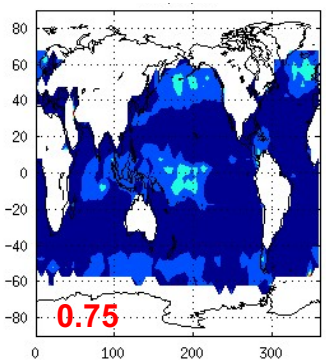


CRTM 2.2.3 (DDA, reff=500μm)

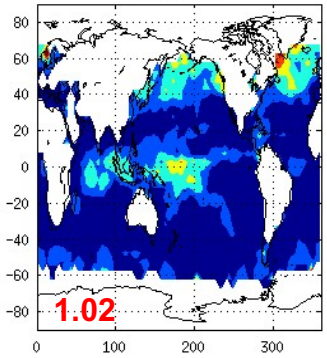


DDA : Liu(2008)

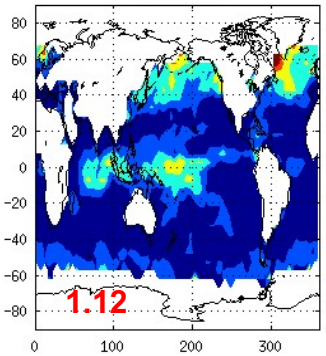
Soft Sphere



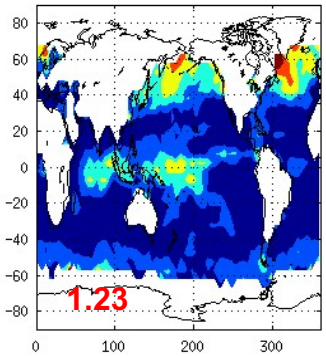
Long column



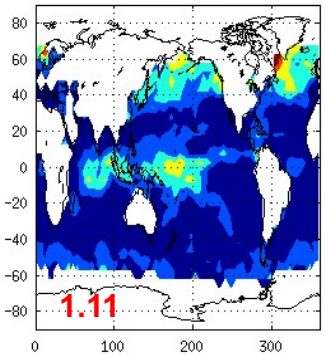
Short column



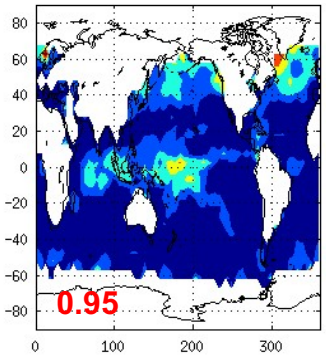
Block column



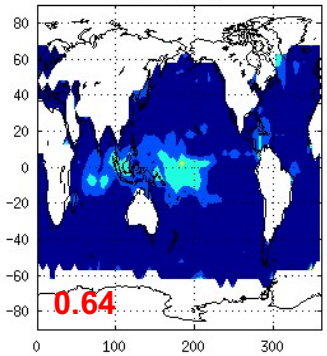
Thick Plate



Thin Plate



3-bullet



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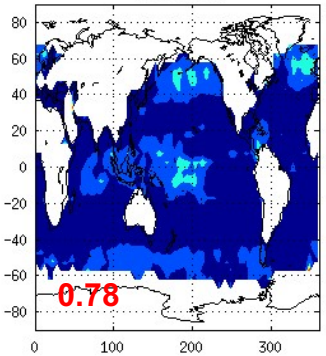

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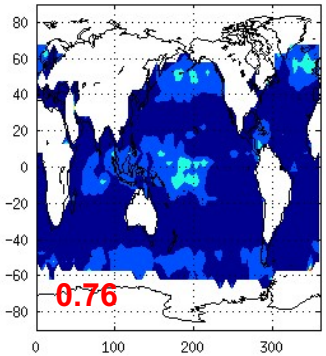
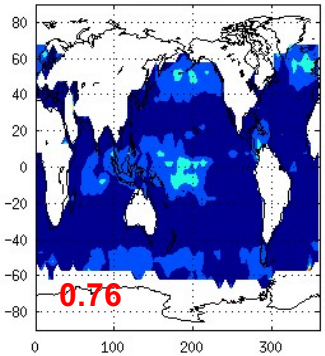
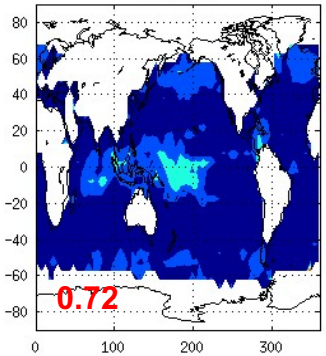


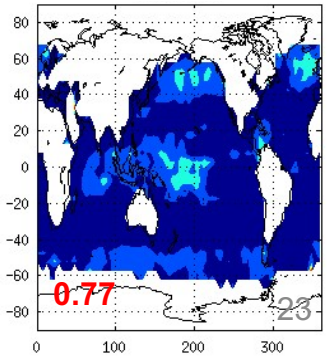
6-bullet

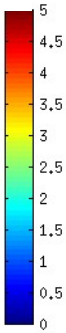


Sector Snowflake



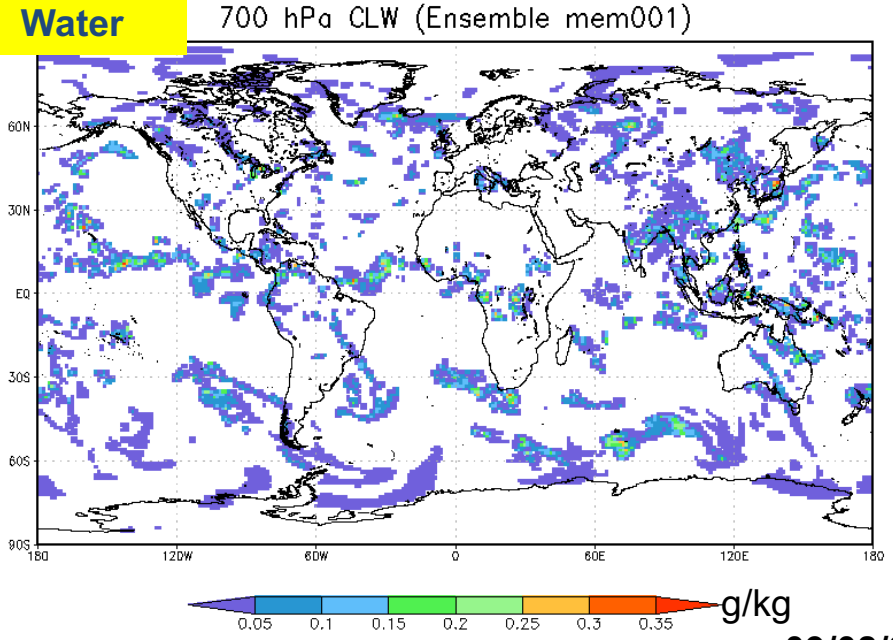
Dendrite



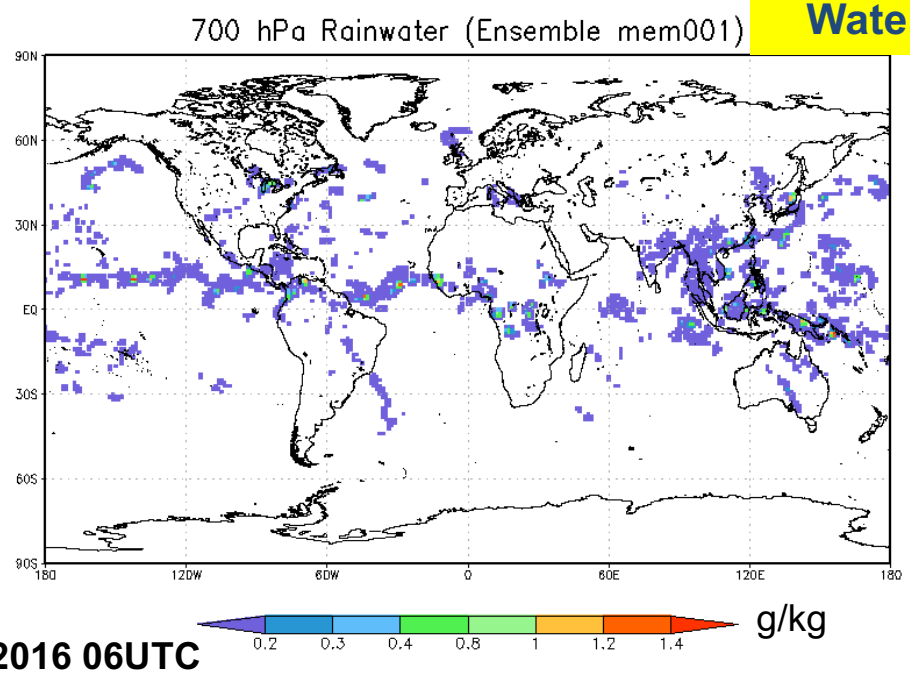


Background Errors

Cloud Liquid Water



Rain Water



09/08/2016 06UTC

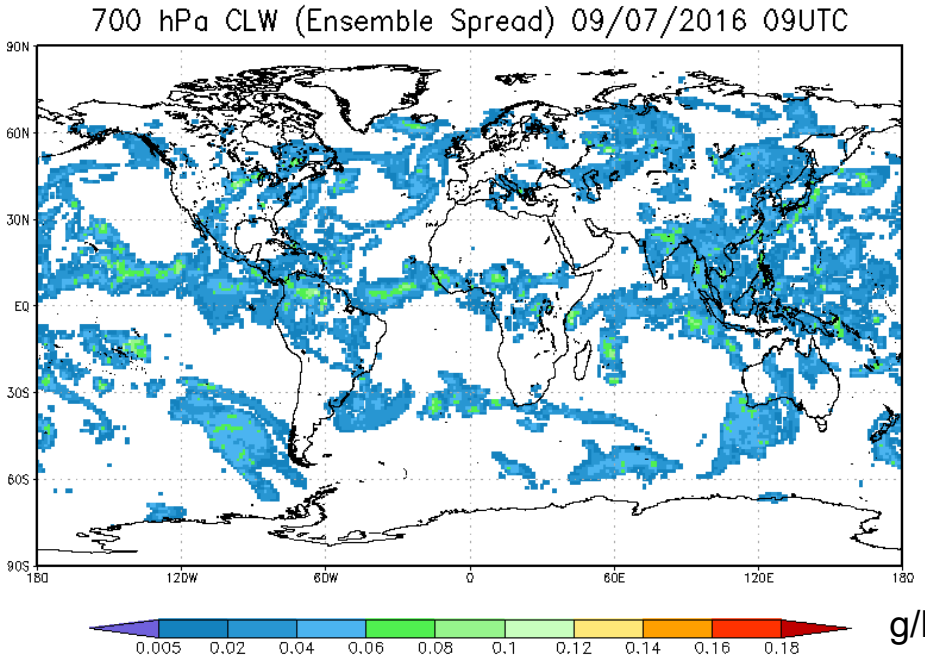
- 32 ensemble members from NASA GMAO's GEOS-5 system
- Horizontal: 0.5 deg (Ensemble member forecasts)

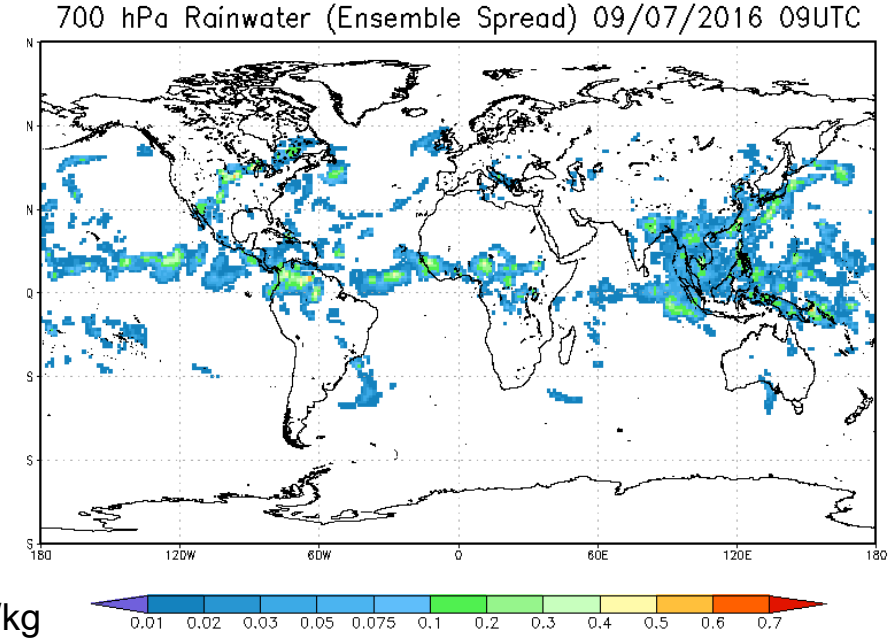
  12.5 km (central GEOS forecasts)
- Vertical: 72-levels

Background Errors

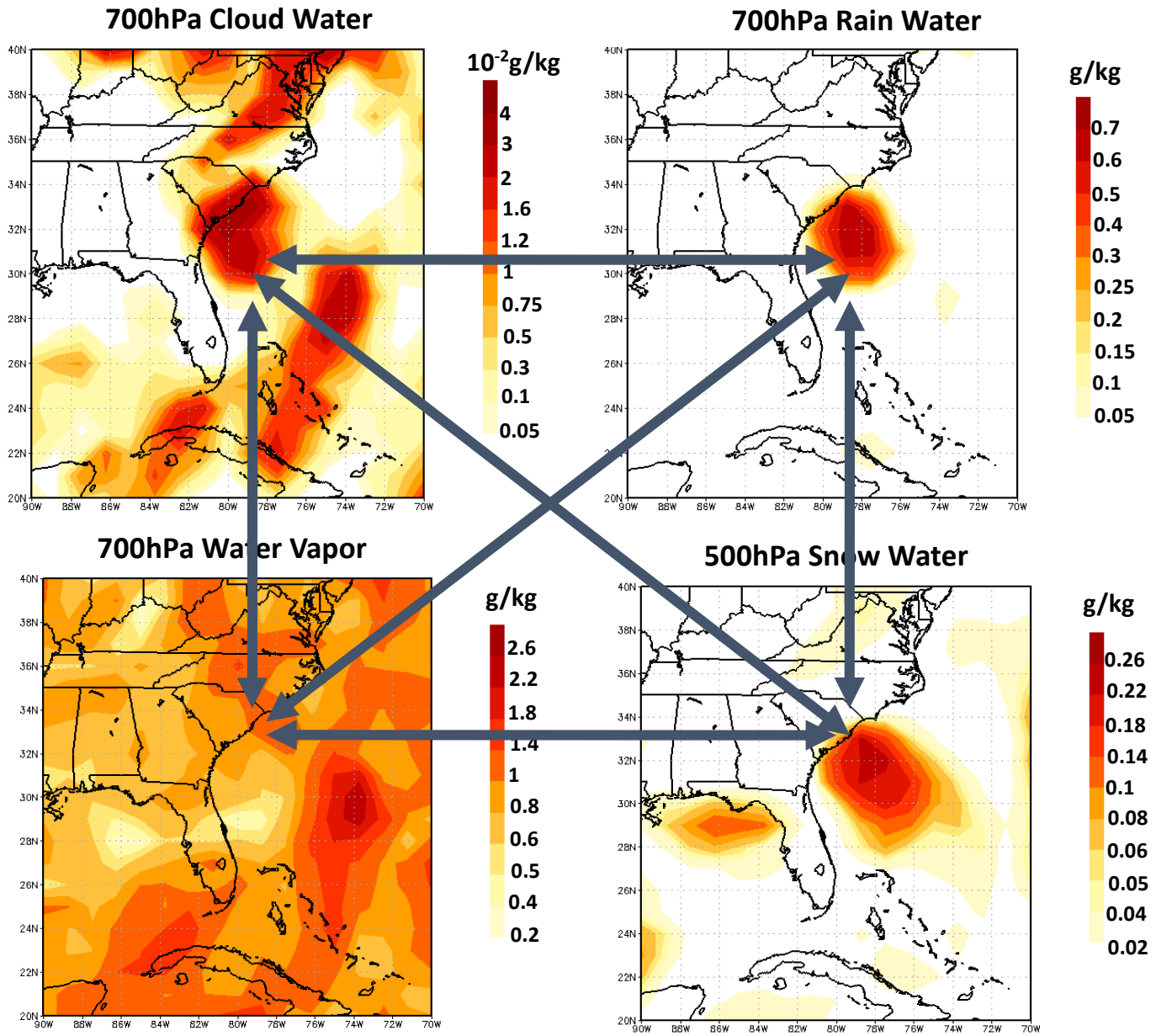
Hybrid 4D-EnVar Atmospheric Data Assimilation System

: Flow dependent background errors changing with time





Correlated Background Errors between Variables



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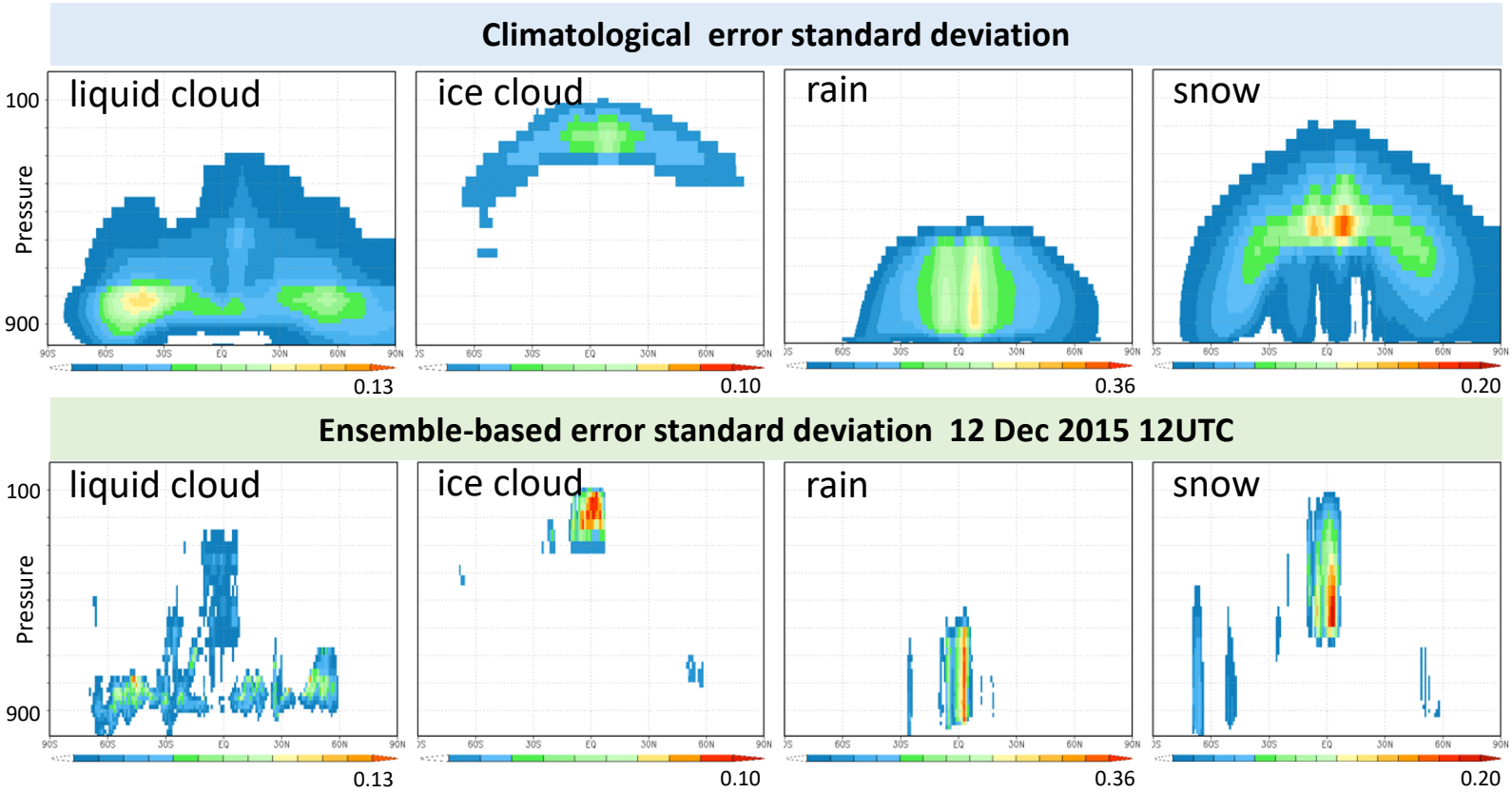
Hybrid background errors for hydrometeors



Products from current GEOS FP System

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GEOS Forward-Processing (FP) System

INPUT DATA

Background (First guess)	GEOS Forecasts	2D: sfc pressure, skin T, soil moisture, soil T, snow depth, fractions of ice, land, lake and ocean, sfc roughness, 2m, 10m, 50m winds,… 3D: pressure, thickness, virtual T, ozone, water vapor, cloud liquid, cloud ice, rain water, and snow water mixing ratios, …
Observations	AEROSOLS	Terra & Aqua Atmospheric Optical Depth
	TEMP. & PRESSURE	Radiosonde, Aircraft, Dropsonde, Drifting Buoy, METAR, Land Station
	RADIANCES	AIRS, AMSU-A, HIRS4,GOES Sounder, IASI, CRIS, SEVIRI, SSMIS, MHS, ATMS, and all-sky GPM Microwave Imager (GMI)
	WINDS	Radiosonde, PIBAL, WIND profiler, NEXRAD, Aircraft, Dropsonde, Surface Marine, ASCAT, AVHRR, IR/VIS Cloud Drift, PILOT
	MOISTURE	Radiosonde, Surface Marine, Surface Land, Dropsonde, Buoy, METAR, Aircraft
	GPS Radio Occultation	GRACE-A, TerraSAR-X, METOP-A, COSMIC-1,2,5,6, TANDEM-X, METOP-B
	OZONE	AURA OMI, MLS

OUTPUT PRODUCTS

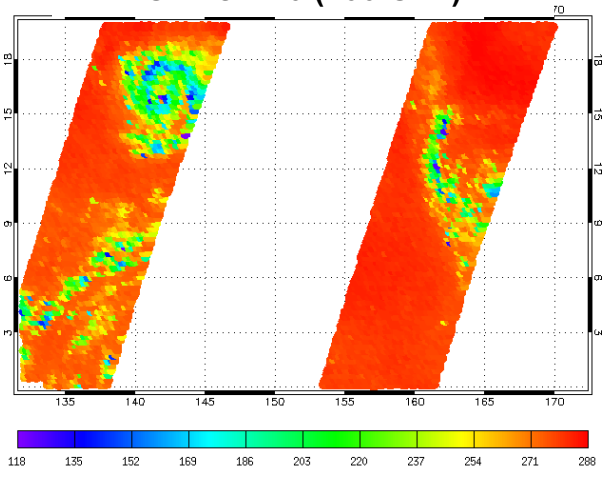
1. GEOS near-real time assimilation products at every 00UTC, 06UTC, 12UTC, and 18UTC
2. GEOS 10-day forecast products at every 00UTC
3. GEOS 5-day forecast products at every 12UTC

- Horizontal grid: 5/16x1/4 degree lon-lat grid
- 3D data are available in 42 pressure levels or 72 model grid layers
- 2D data every hour, 3D data every 3 hours
- Detailed information of assimilation products are available in https://gmao.gsfc.nasa.gov/products

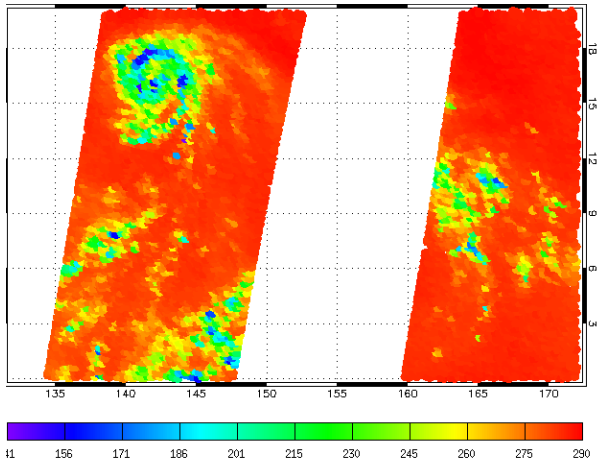
Developments of multi-satellite, all-sky MW radiance data assimilated precipitation products of this project builds upon the existing GEOS “Forward processing (FP)” stream. This table shows inputs and output products of the GEOS Forward-processing (FP) stream, which generates forecasts as well as assimilation products using the most current GEOS system used for real-time production at NASA GMAO.

Extension of All-sky GPM Microwave Imager (GMI) Data Assimilation System to Utilize Other Satellite Microwave Sensors' Data

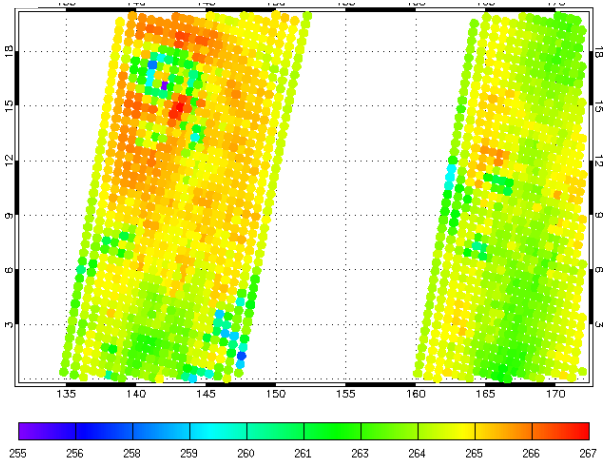
GMI CH 10 (166 GHz)



MHS CH2 (150 GHz)



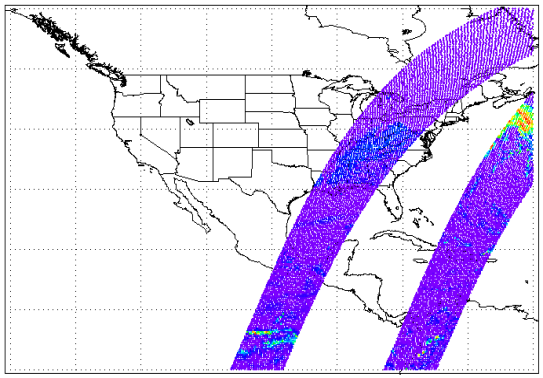
AMSU-A CH4 (53 GHz)



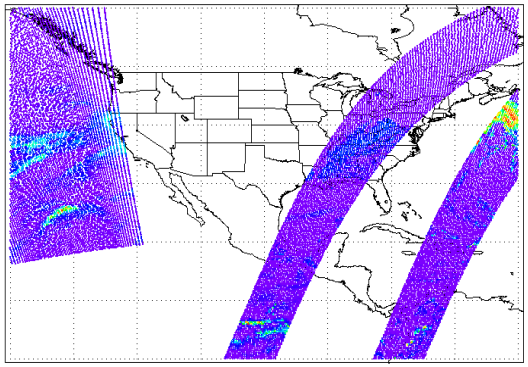
GMI and MHS both have channels near 183 GHz water vapor absorption band therefore provide us similar information about storms. However, MHS sensors are in multiple satellites (better temporal resolution) and has better spatial due to its wider swath width.

AMSU-A has channels near oxygen absorption band and sensitive to temperature.

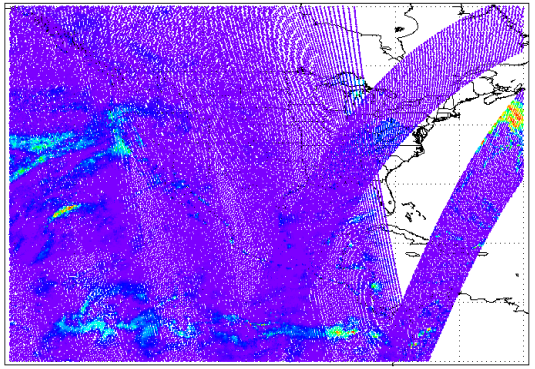
GMI Only



GMI + N18 MHS



GMI + N18 MHS+METOP-A MHS + METC



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Observation Error Model