Radiance Assimilation at NOAA/NCEP/EMC

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With help from Emily Liu, John Derber, Yanqiu Zhu and many others!

Talk Outline

- Current and future Global NWP configurations
- Near Sea Surface Temperature
- Cloudy Radiances
- CrIS
- Monitoring

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Current NWP Configuration

- The NCEP Global Forecast System (GFS) comprises the Global Spectral Model (GSM) run with the Gridpoint Statistical Interpolation (GSI) data assimilation system.
- Four cycles are run daily at 00Z, 06Z, 12Z and 18Z out to 16 days with a shorter 9 hour delayed forecast run which is used to initialize the data assimilation runs.

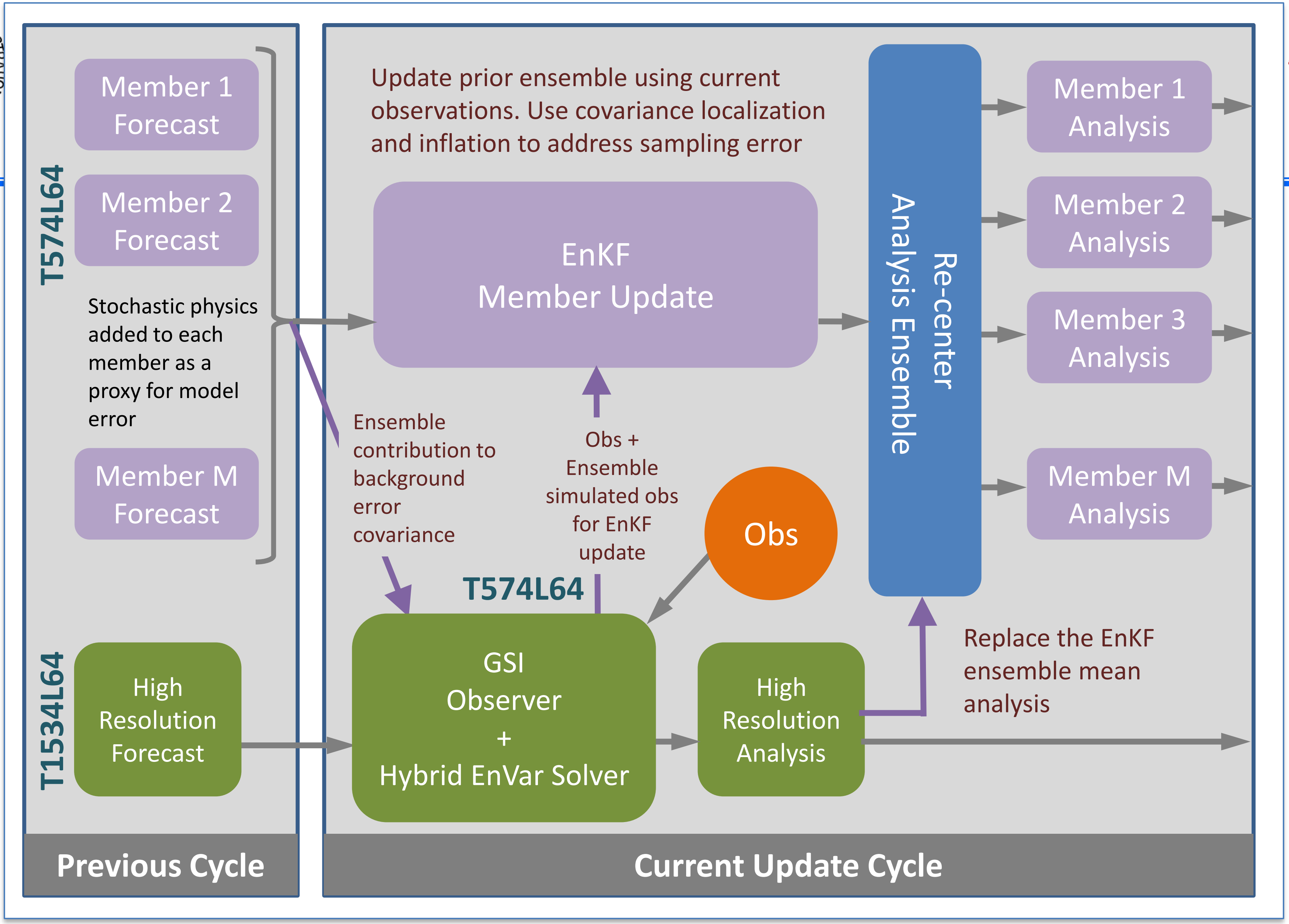
Current NWP Configuration (GSM)

- The GSM is a spectral model with spherical harmonic basis functions. It is run at a resolution of T1534 (~13km at the equator) out to ten days and continues at T574 (~34km) out to day 16.
- In the vertical there are 64 hybrid sigma-pressure layers with the top layer centered around 0.27 hPa (approximately 55 km).
- The current operational dynamical core of the GFS/GSM is based on a two time-level semi-implicit semi-Lagrangian discretization.

Current NWP Configuration (GSI)

- The GSI data assimilation system is a 4D Ensemble Var Hybrid System run at T574 (both deterministic and ensemble components).
- In the Ensemble Var hybrid system the background error covariances includes both ensemble and static terms. In the current system the ensemble part is given a weight of 87.5% with 12.5% given to the static term.
- The ensemble is comprised of 80 members.
- The 3D Ensemble Var system became operational at NCEP in May 2012 and was replaced by the 4D Ensemble Var System in May 2016.

Hybrid Assimilation Workflow



Satellite Data Usage in Global and Regional Models

Radiances:

GOES-15	Sounder	Channels 1-15
SEVIRI	Met-10	Channels 5-6
AMSU-A	NOAA-15	Channels 1-10, 12-13, 15
	NOAA-18	Channels 1-5, 6, 7, 10-13, 15
	NOAA-19	Channels 1-6, 9-13, 15
	Metop-A	Channels 1-6, 8-13, 15
	Metop-B	Channels 7-13
	Aqua	Channels 6, 8-13
MHS	NOAA-18	Channels 1-5
	NOAA-19	Channels 1,2,4,5
	Metop-A	Channels 1-5
	Metop-B	Channels 1-5
ATMS	SNPP	Channels 1-14, 16-22
AIRS	Aqua	93 Channels
IASI	Metop-A	120 Channels
	Metop-B	120 Channels
CrIS	SNPP	84 Channels
SSMIS	DMSP-17	Channels 1-3, 5-7, 24

AMVs:

GOES-13/15:	IR & WV cloud top
Himawari-8:	IR, WV, VIS cloud top
Meteosat-8/10:	IR, WV, VIS cloud top
Aqua/Terra MODIS:	IR & WV cloud top & WV clear sky
NOAA-15,18,19 & Metop-A/B AVHRR:	Infrared cloud top

Scatterometers:

Metop-A ASCAT

Ozone:

NOAA-19 SBUV; AURA OMI

GPSRO Bending Angle:

Cosmic-1 FM1/FM6

GRAS (Metop-A/B)

TerraSAR-X

Major Changes in 2016 global upgrade

- Introduction
- Current Global NWP Configuration
- Major Changes in 2016 global upgrade
- Major Changes in 2017 global upgrade
- NGGPS and FV^3
- Conclusions

Highlights of the May 2016 Model Upgrade

- 3D Ensemble Var extended to 4D Ensemble Var
- Assimilation of all-sky radiances for AMSU-A
- Assimilation of AVHRR AMVs
- Update CRTM. Bug fixes plus improvements to the microwave sea-surface emissivity model.
- Improved aircraft bias correction.

Highlights of the July 2017 Model Upgrade

- Mostly an improvement to infrastructure:
  - Upgrading to the NOAA Environmental Modeling System (NEMS) infrastructure
- Near Sea Surface Temperature Analysis
- Turn on VIIRS AMVs.
- Introduce Log-Normal wind QC for AMVs.
- Use GOES clear-air water vapour winds.
- Inclusion of extra GNSS-RO observations.

NGGPS and FV^3

- The Next Generation Global Prediction System (NGGPS) will eventually consolidate all the disparate NOAA prediction systems into one model framework.
- As part of this process a new dynamic core has been identified to replace (in the global) the GSM.
  - The rationale for doing this is the approach of the need for non-hydrostatic, convection resolving global models and to have more scalable solutions.
- Multiple candidate models were considered and eventually the GFDL Finite-Volume on the cubed-sphere (FV^3) model was selected.

NGGPS and FV^3

- The FV^3 dynamical core is scheduled to be implemented in the NCEP global system by FY19.
- As a results there is a major effort to incorporate the model into the NEMS infrastructure and to produce a fully cycling system that includes all the current sub-systems.
  - Implement FV^3 dynamic core in NEMS
  - Implement Common Community Physics Package
  - Implement data assimilation (4DEnVar with 4D incremental analysis update and stochastic physics)
  - Implement community model environment
- For data assimilation the initial implementation will transform from the cube-sphere to the Gaussian grid that is current used in the GSI.
  - Eventually we hope to be able to do data assimilation directly on the cube-sphere grid.
- We also plan to increase the number of model levels from 64 to 128 in this timeframe.

Timeline for next few upgrades

- Jan.-Feb. 2018: Monitor and then actively switch on AMVs from GOES-16 and CrIS & ATMS from JPSS-1.
  - Data will be used as closely as possible to current GOES-13 AMVs and S-NPP CrIS & ATMS
- May 2018: FV3-GFS operational in “beta-mode”. Current GFS remains the official NCEP global model.
  - Science changes to satellite data usage possible at this stage including addition of Saphir, GMI, OMI plus introduction of correlated obs errors and more use of cloudy radiances.
- Spring 2019: FV3-GFS promoted to operational status.
  - COSMIC-2 should be included at this point.

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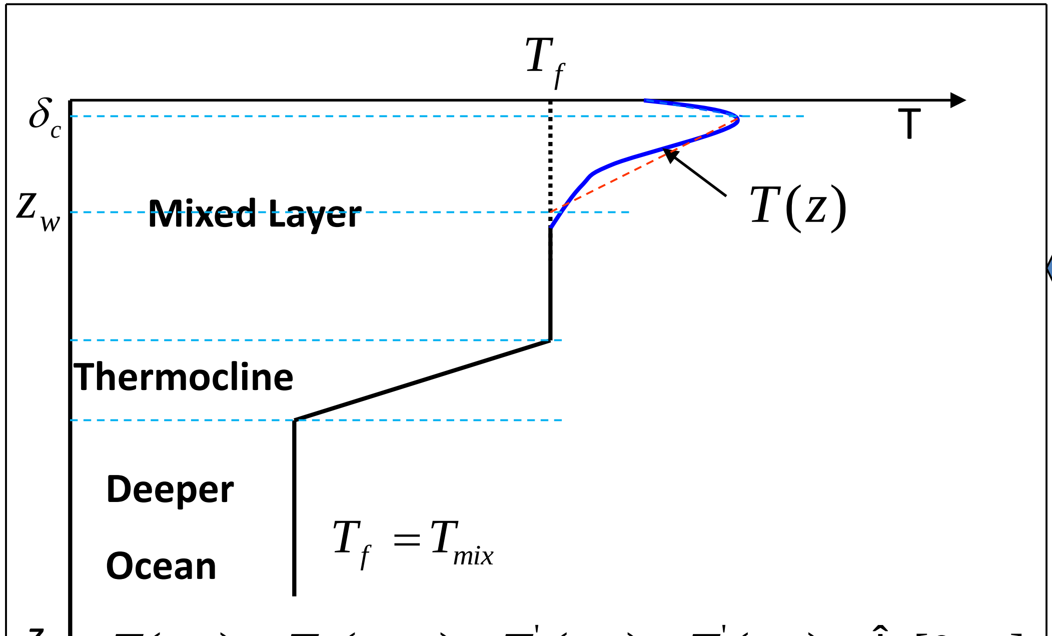
Direct Analysis of Sea Surface Temperature in the GSI (NSST)

- Previously, like many centers, the sea surface temperature was supplied to the GSI via an independent analysis. Many centers use OSTIA (from the Met Office), we use the RTG analysis produced at EMC.
- We have now moved to directly analyzing the SST in the GSI through the assimilation of in-situ sea surface temperature measurements as well as through the assimilation of radiance observations.
- The advantages to this are:
  - By simultaneously analyzing SST along with the atmospheric variables, a more consistent analysis may be achieved.
  - Through the NSST model (next slide) the forward calculation for radiances will have a skin temperature valid for the appropriate penetration depth
  - We can explicitly take account of the diurnal cycle

What is NSST
(Near-Surface Sea Temperature)?

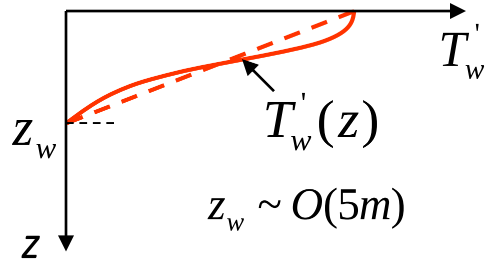
NSST is a **T-Profile** just below the sea surface.
Here, only the vertical thermal structure due to
diurnal thermocline layer warming
and **thermal skin layer cooling** is resolved.



$$T(z,t) = T_f(z_w,t) + T_w'(z,t) - T_c'(z,t),\ z \in [0, z_w]$$

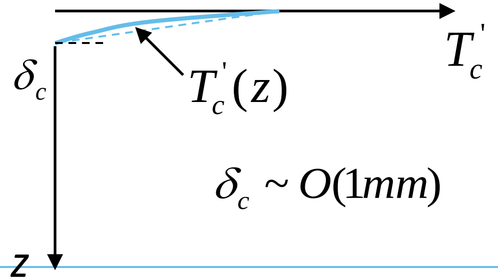
Diurnal Warming Profile

$$T_w'(z) = (1 - z/z_w)T_w'(0)$$

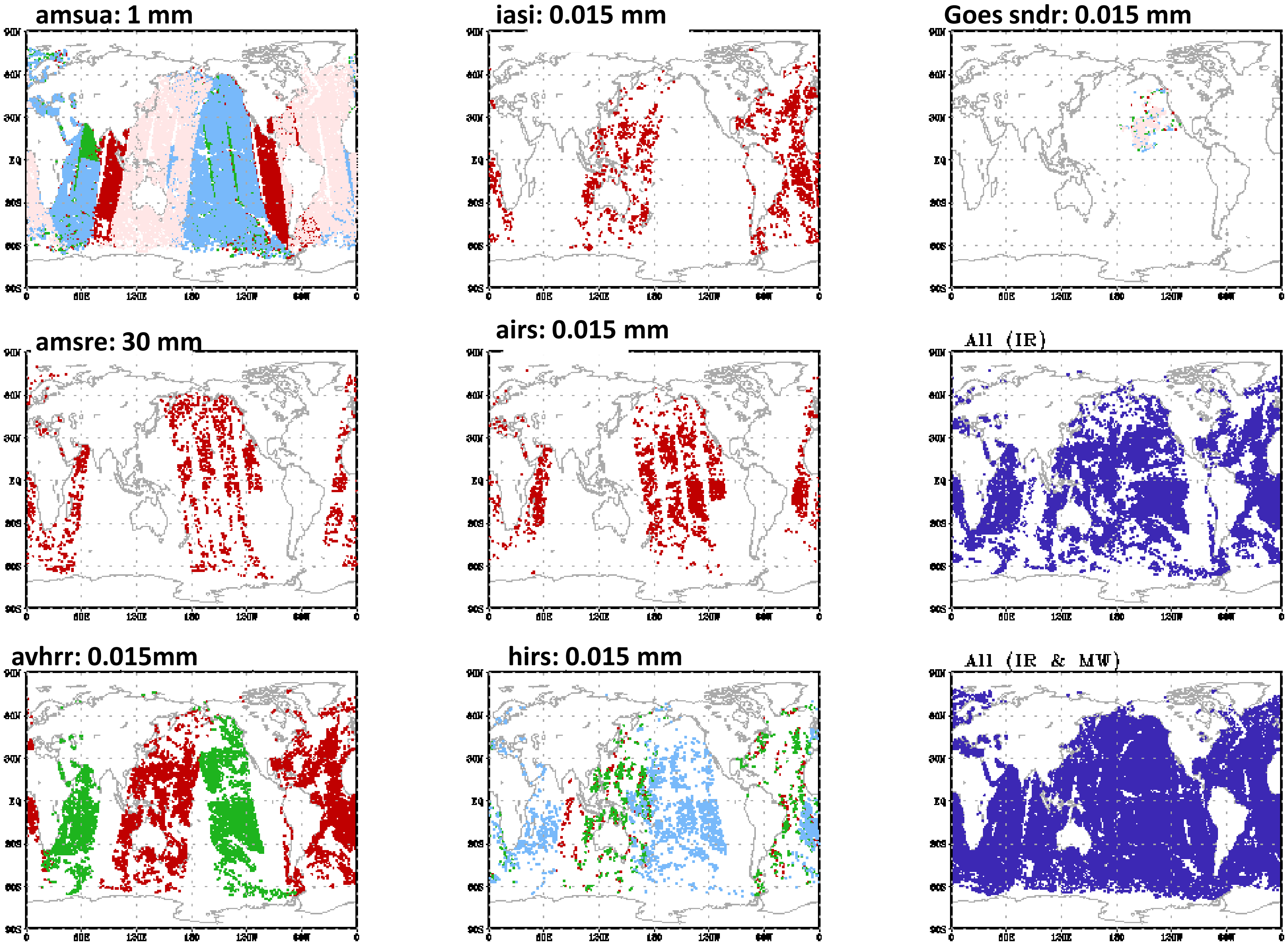


Skin Layer Cooling Profile

$$T_c'(z) = (1 - z/\delta_c)T_c'(0)$$



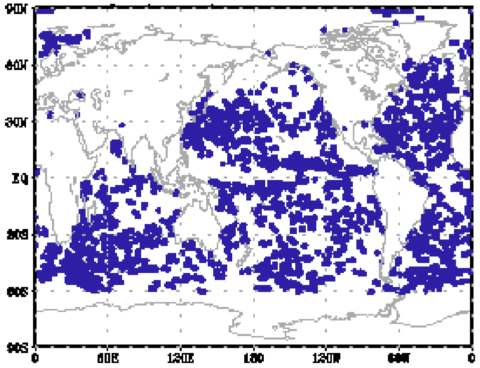
6-hour time window centered at 00Z, 05/22/2010



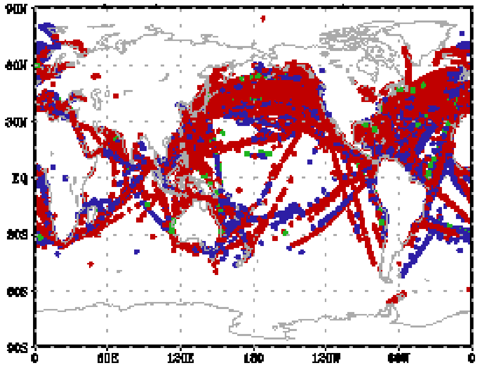
Satellite observations: coverage and skin-depth

13 days period in May 2010

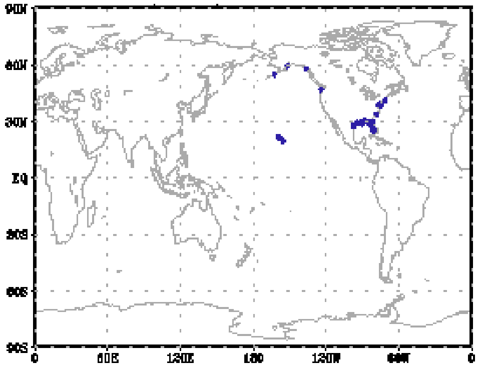
Drifting Buoy: 0.2 m



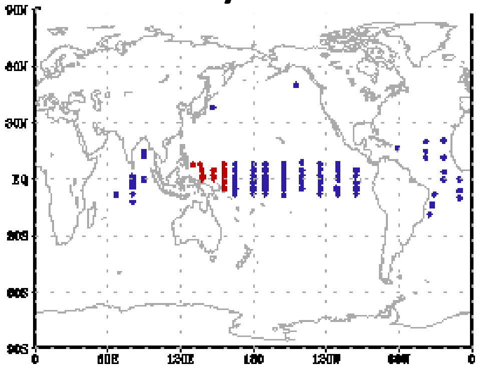
Ships: 1.0 – 3.0+ m



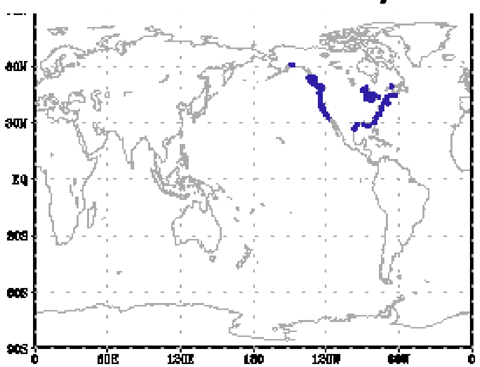
LCMAN: 1.0 m



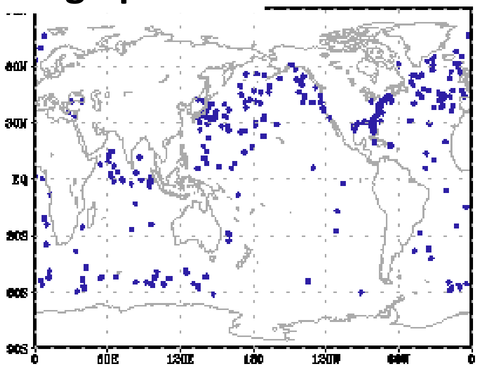
Fixed Buoy: 1.0 or 1.5 m



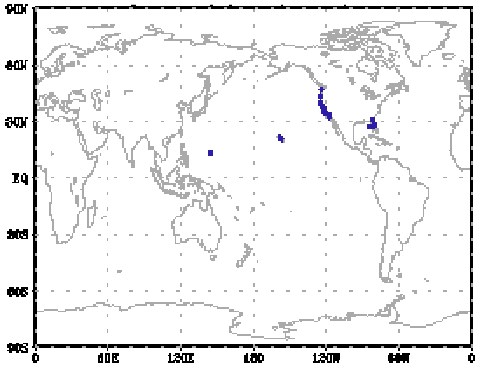
Some Moored Buoy: 0.6 m



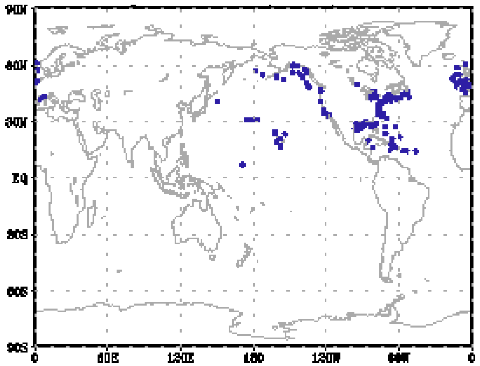
Argo profile: 1.0 or 5.0 m



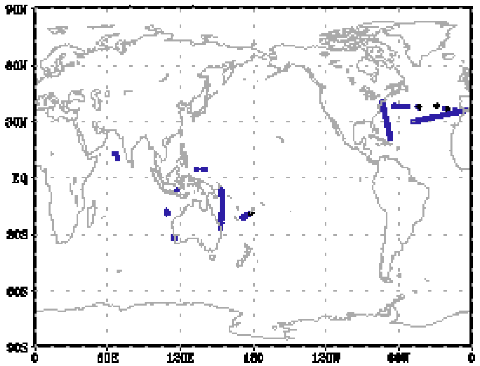
Scripts Mbuoy: 0.45m



Other Mbuoy: 1.0 m



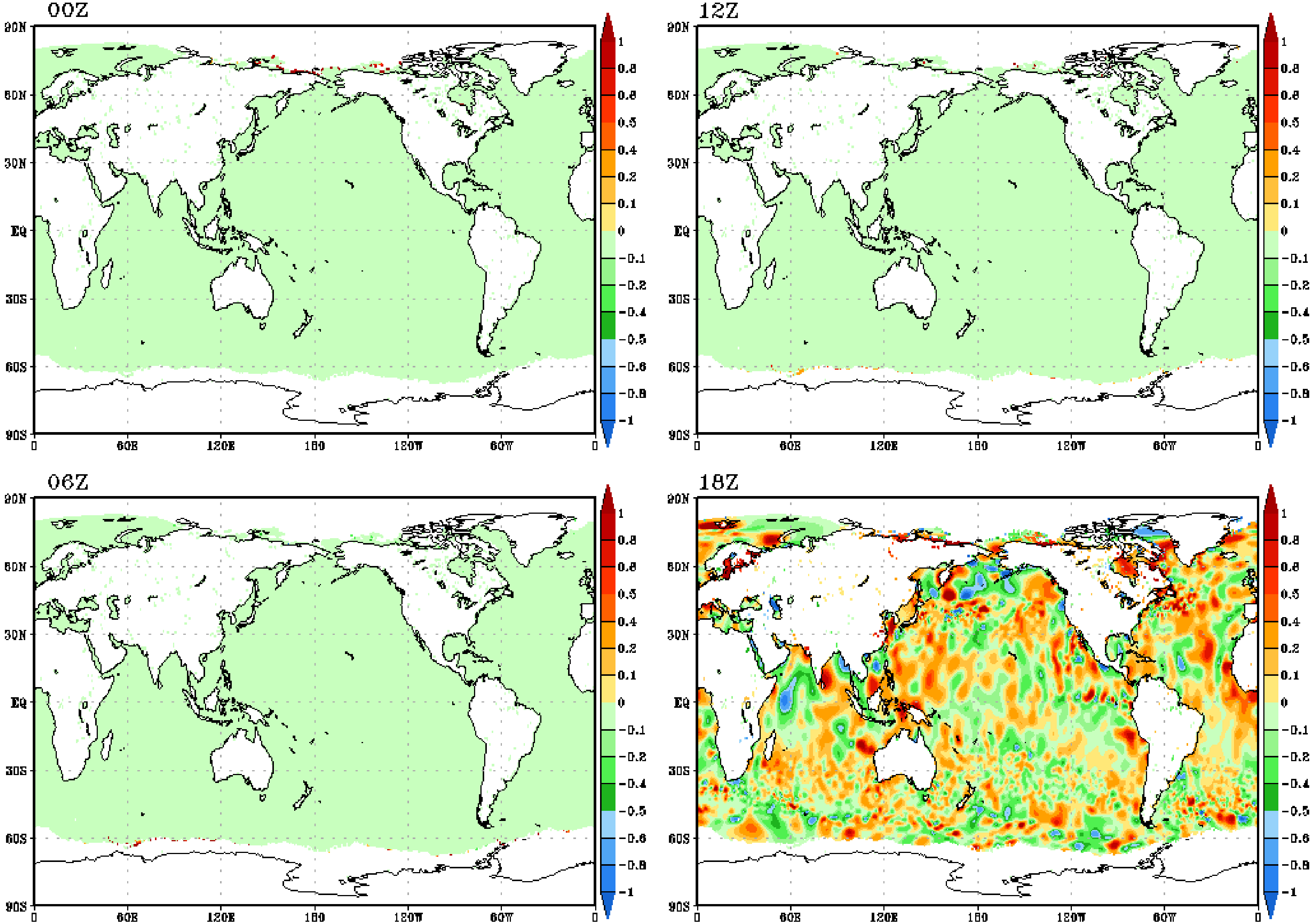
XBT: 1.5 – 5.0 m



In Situ sea temperature observations: coverage and depth

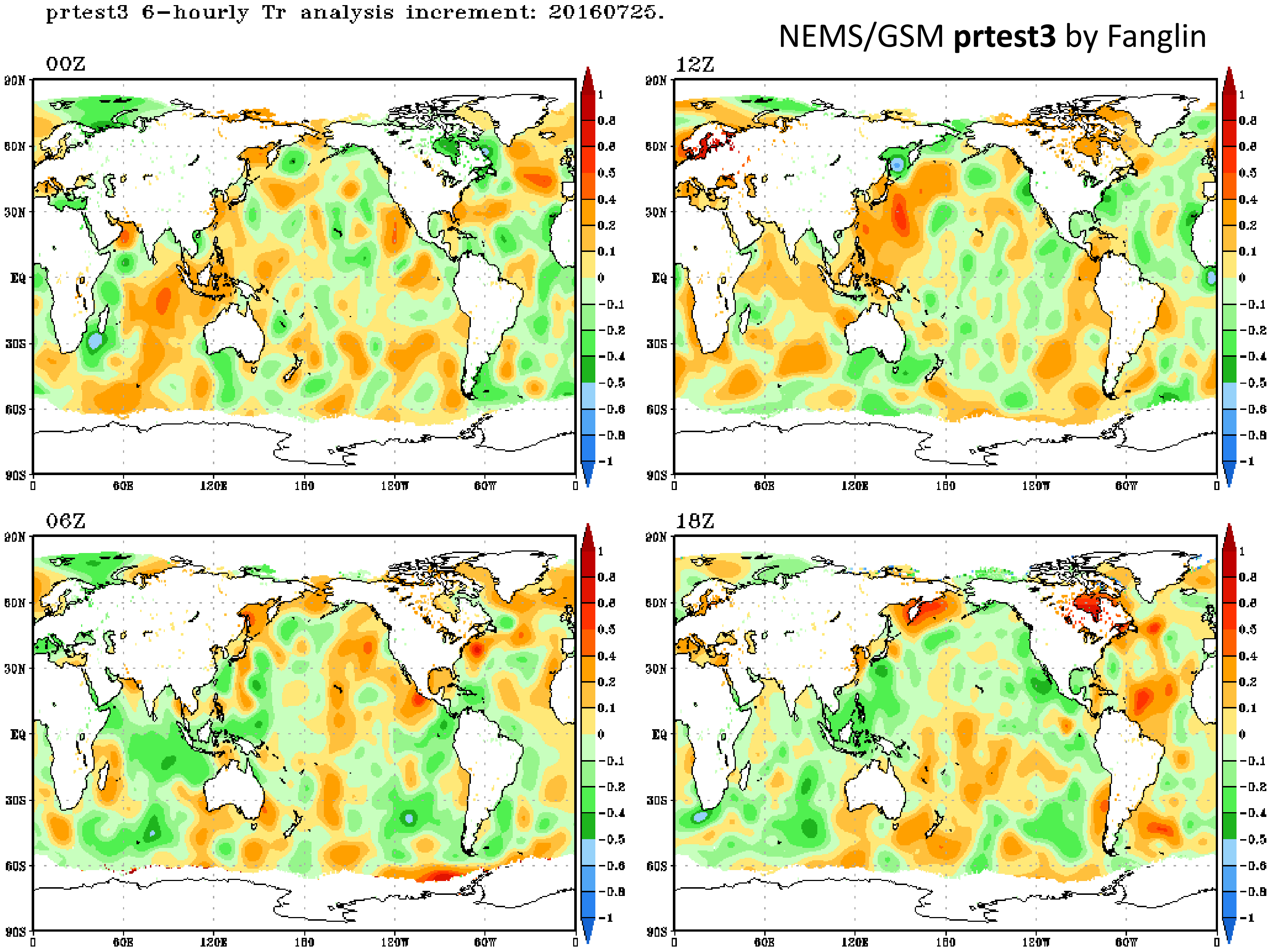
6-hourly tmpsfc analysis & increment: 20160725.

NEMS/GSM **prnemsr** by Fanglin



Current GFS SST (RTG) increment at 4 cycles for July 25, 2016

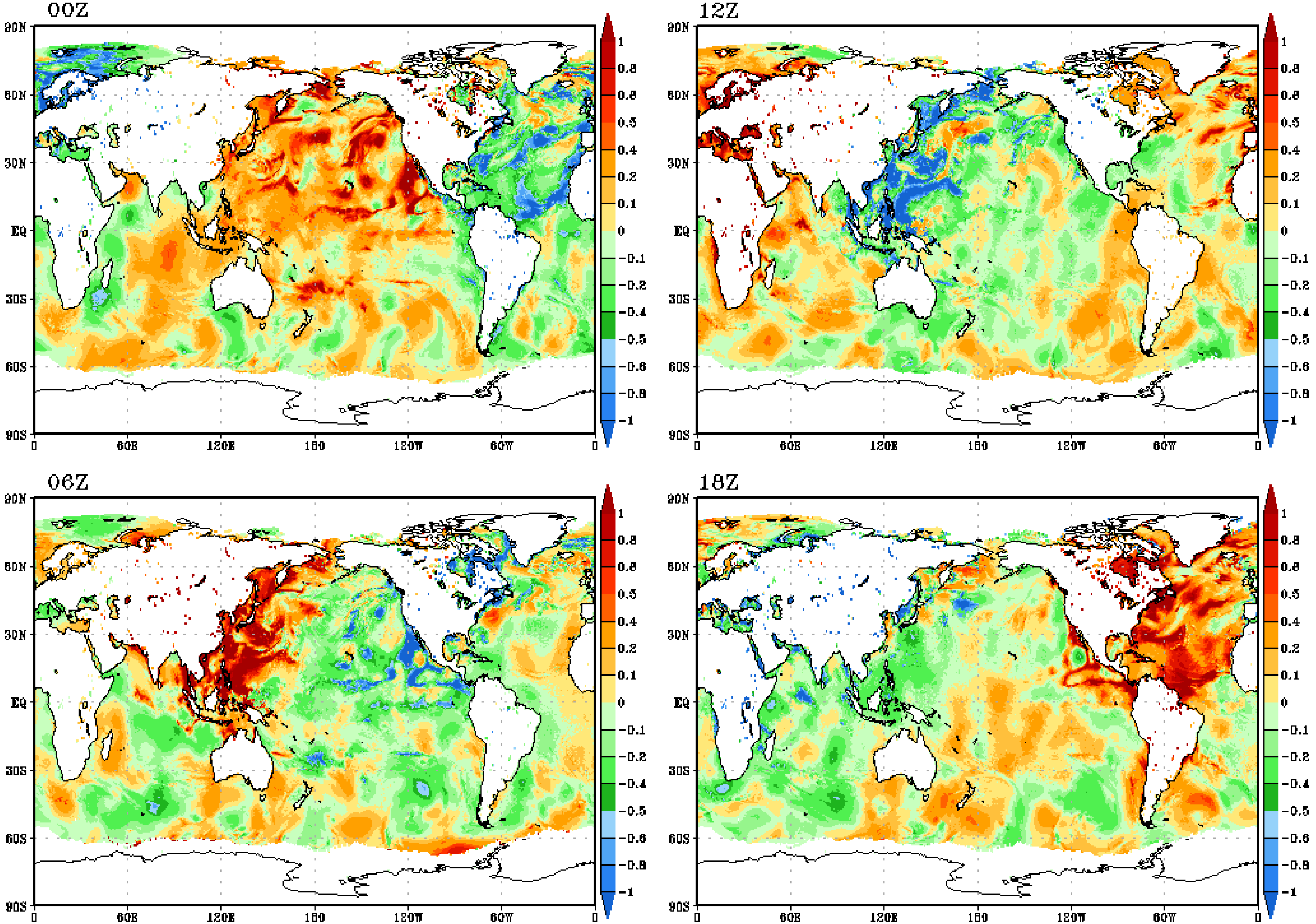
NEMS/GSM **prtest3** by Fanglin



NSST *Tf* analysis increment at 4 cycles for July 25, 2016

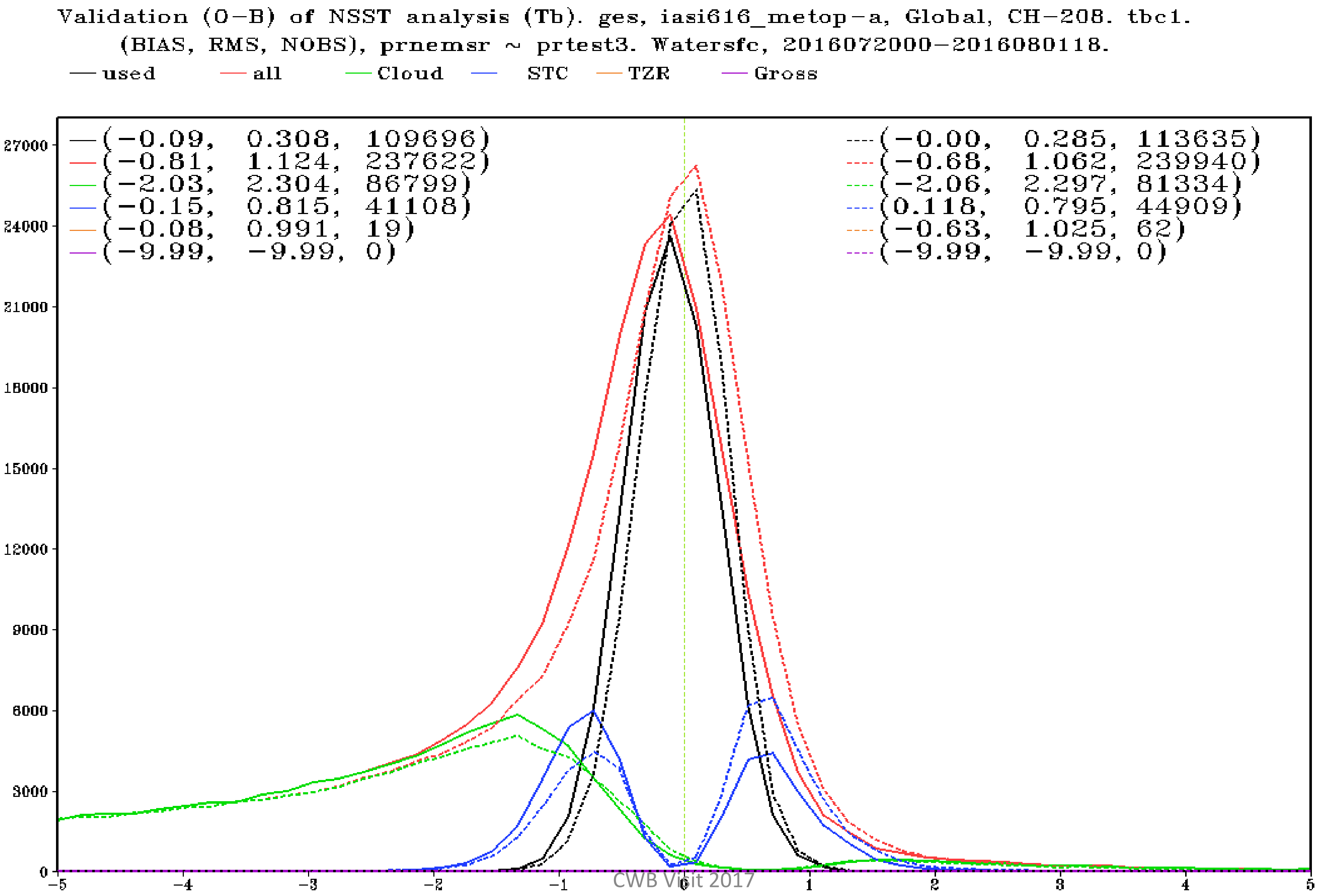
6-hourly tmpsfc analysis & increment: 20160725.

NEMS/GSM **prtest3** by Fanglin

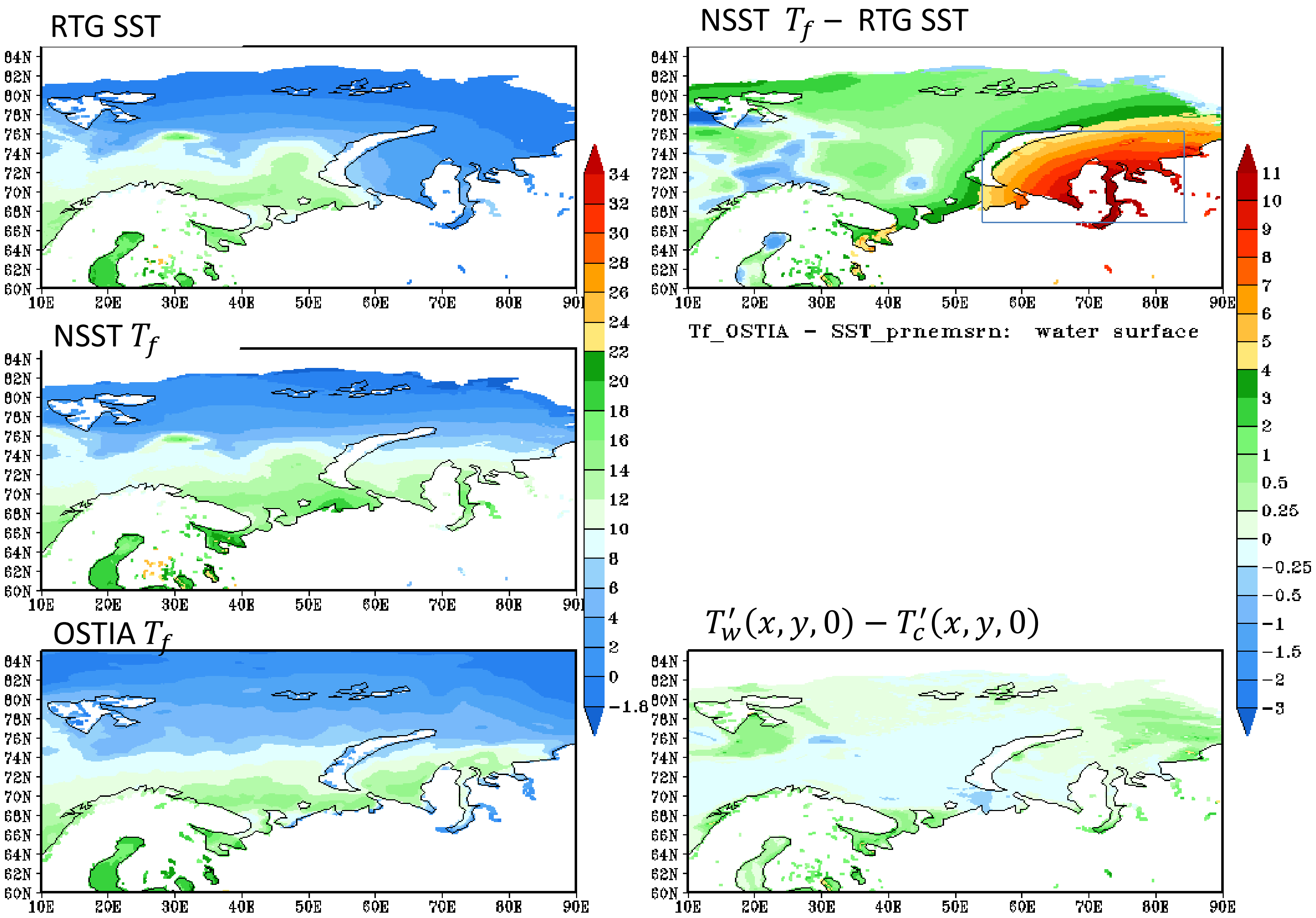


NSST SST increment at 4 cycles for July 25, 2016

Improved satellite data use by NSST. Based on 13-day (O-B) statistics, with NEMS/GSM and GSI



Comparison of RTG SST, NSST T_f and OSTIA T_f, Northern European area. 12 Z, July 26, 2016



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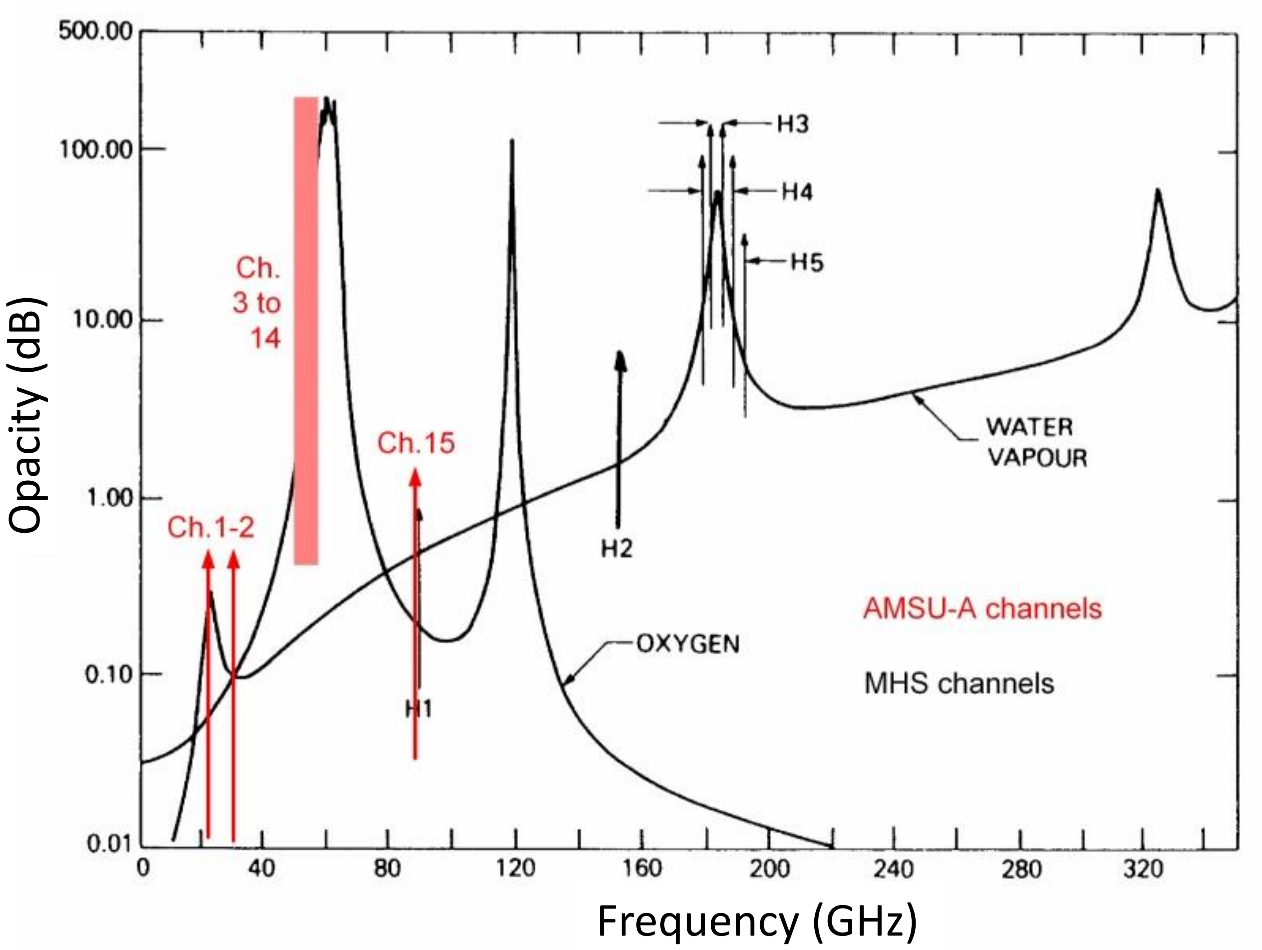
Cloudy Radiance Assimilation

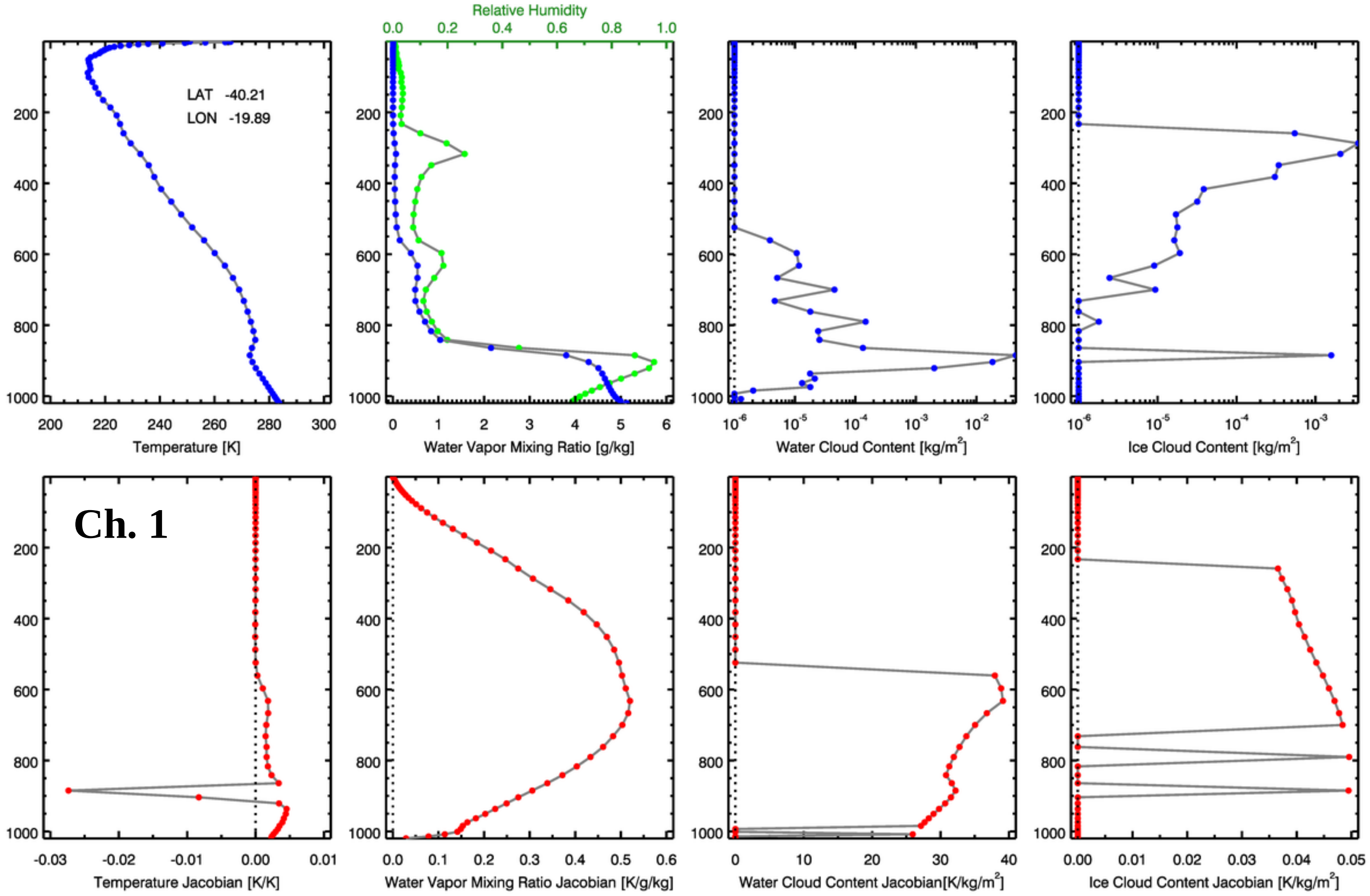
- We are currently operationally assimilating cloudy radiances from AMSU-A and are working towards extending this to ATMS, MHS and also to infrared sensors (initially IASI and SEVIRI)
- Challenges are:
  - Background Error Specification
  - Observation Error Specification
  - Bias Correction
  - Model spin-down

Atmospheric Opacity in the Microwave Spectrum



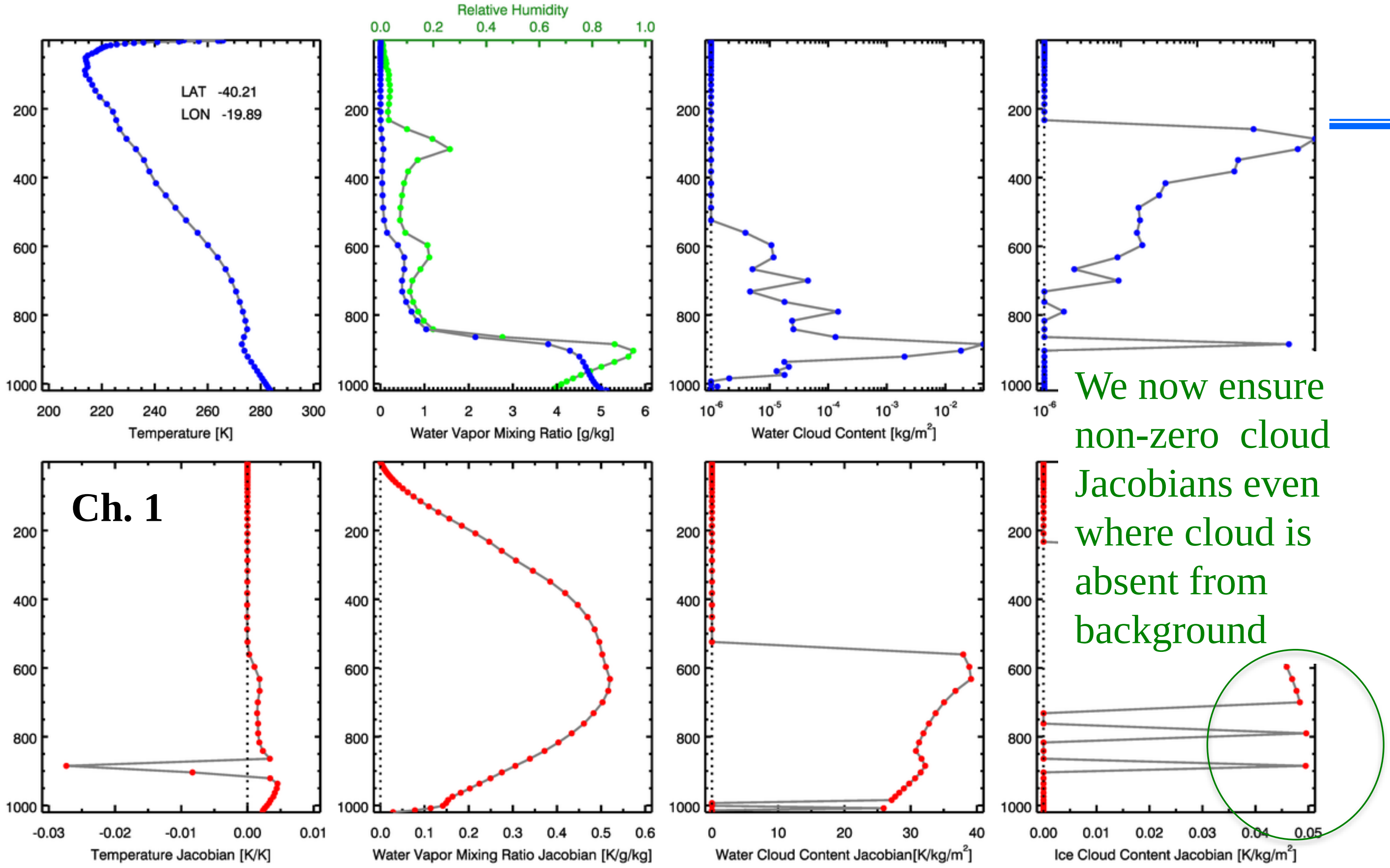
Sensitivity to cloud and/or precipitation increases as frequency increases

Properties of AMSU-A Radiances



- AMSU-A sensors see deep into the clouds, giving information on temperature, moisture and cloud structure. Much less sensitive to ice clouds
- Large temperature sensitivity where the cloud peaks

Properties of AMSU-A Radiances

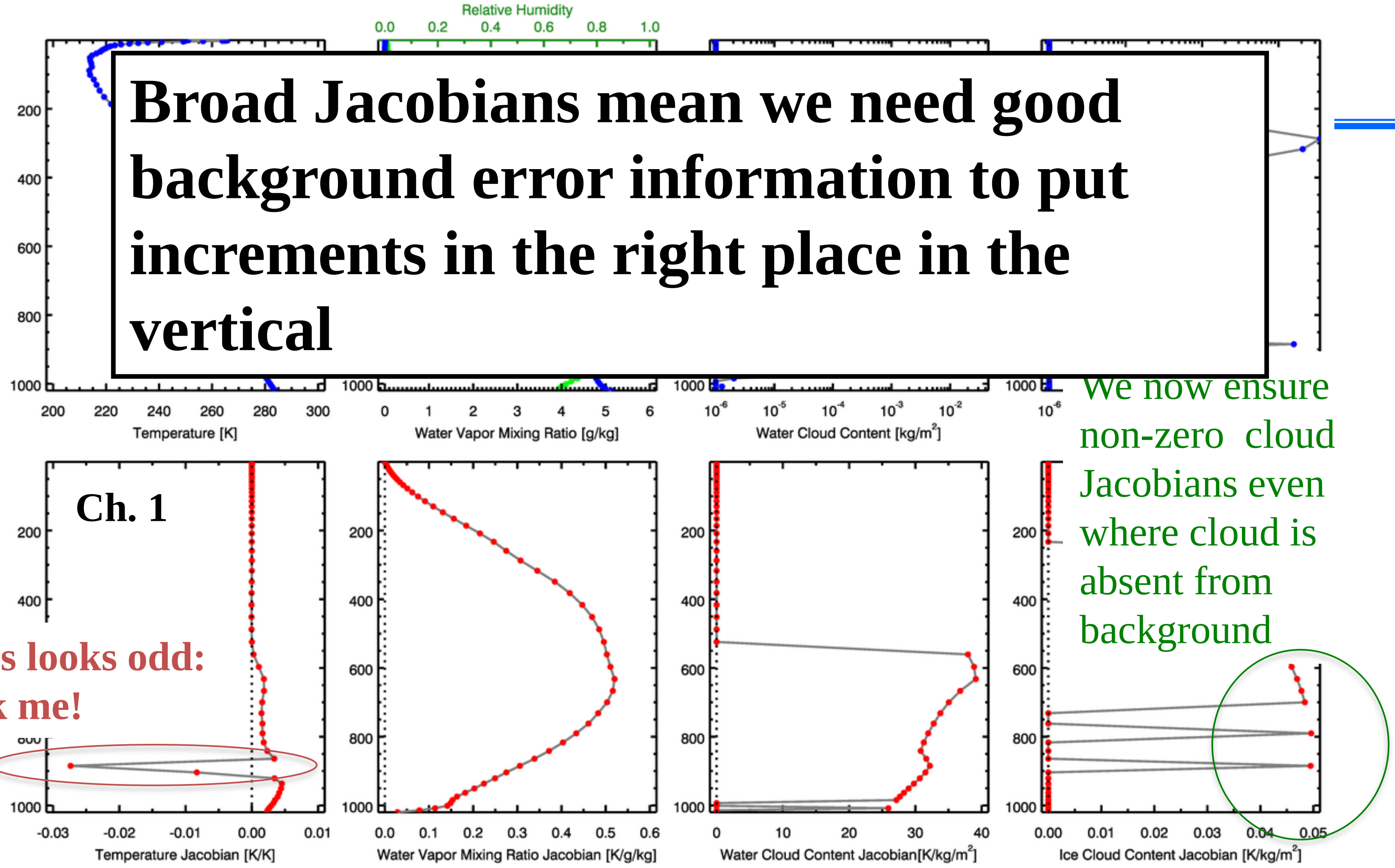


We now ensure non-zero cloud Jacobians even where cloud is absent from background

- AMSU-A sensors see deep into the clouds, giving information on temperature, moisture and cloud structure. Much less sensitive to ice clouds
- Large temperature sensitivity where the cloud peaks

Properties of AMSU-A Radiances

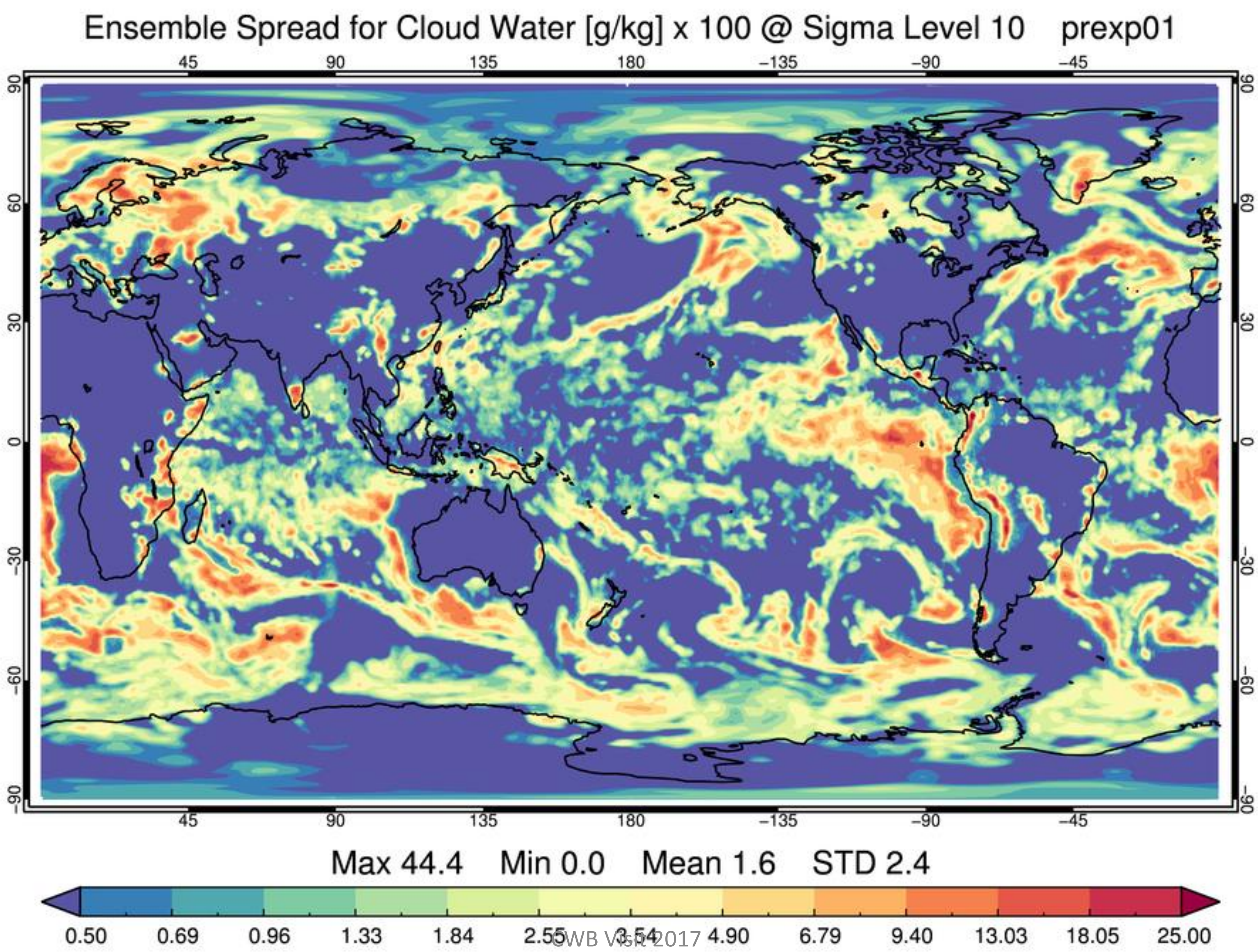
Broad Jacobians mean we need good background error information to put increments in the right place in the vertical

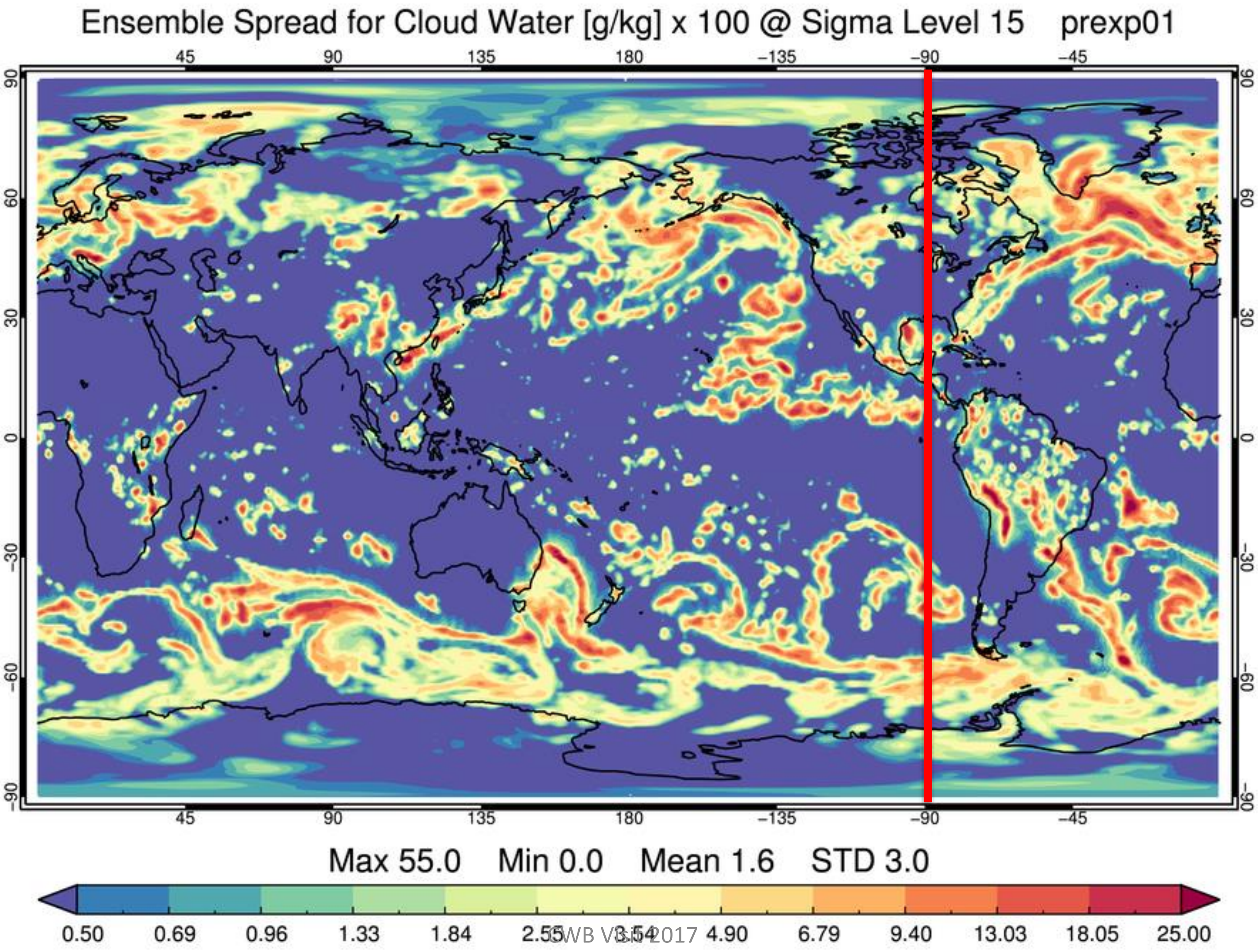


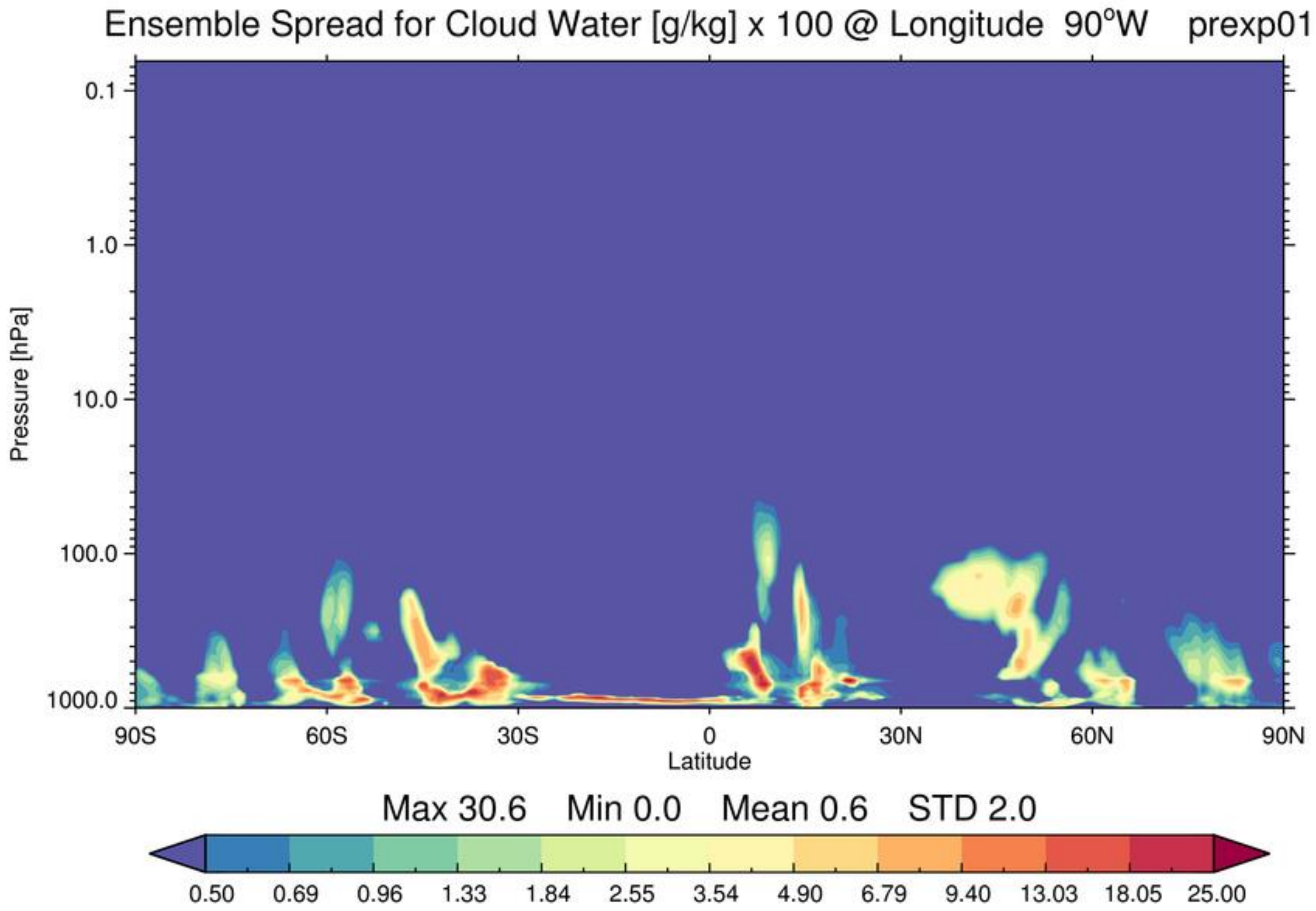
This looks odd: Ask me!

We now ensure non-zero cloud Jacobians even where cloud is absent from background

- AMSU-A sensors see deep into the clouds, giving iinformation on temperature, moisture and cloud structure. Much less sensitive to ice clouds
- Large temperature sensitivity where the cloud peaks


Ensemble Spread for Cloud Water [g/kg] x 100 @ Sigma Level 10 prexp01
Max 44.4 Min 0.0 Mean 1.6 STD 2.4
0.50 0.69 0.96 1.33 1.84 2.55 3.54 4.90 6.79 9.40 13.03 18.05 25.00


Ensemble Spread for Cloud Water [g/kg] x 100 @ Sigma Level 15 prexp01
45 90 135 180 −135 −90 −45
90 60 30 0 −30 −60 −90
Max 55.0 Min 0.0 Mean 1.6 STD 3.0
0.50 0.69 0.96 1.33 1.84 2.55 3.54 4.90 6.79 9.40 13.03 18.05 25.00


Ensemble Spread for Cloud Water [g/kg] x 100 @ Longitude 90°W prexp01
Pressure [hPa]
0.1
1.0
10.0
100.0
1000.0
90S
60S
30S
0
30N
60N
90N
Latitude
Max 30.6 Min 0.0 Mean 0.6 STD 2.0
0.50
0.69
0.96
1.33
1.84
2.55
3.54
4.90
6.79
9.40
13.03
18.05
25.00

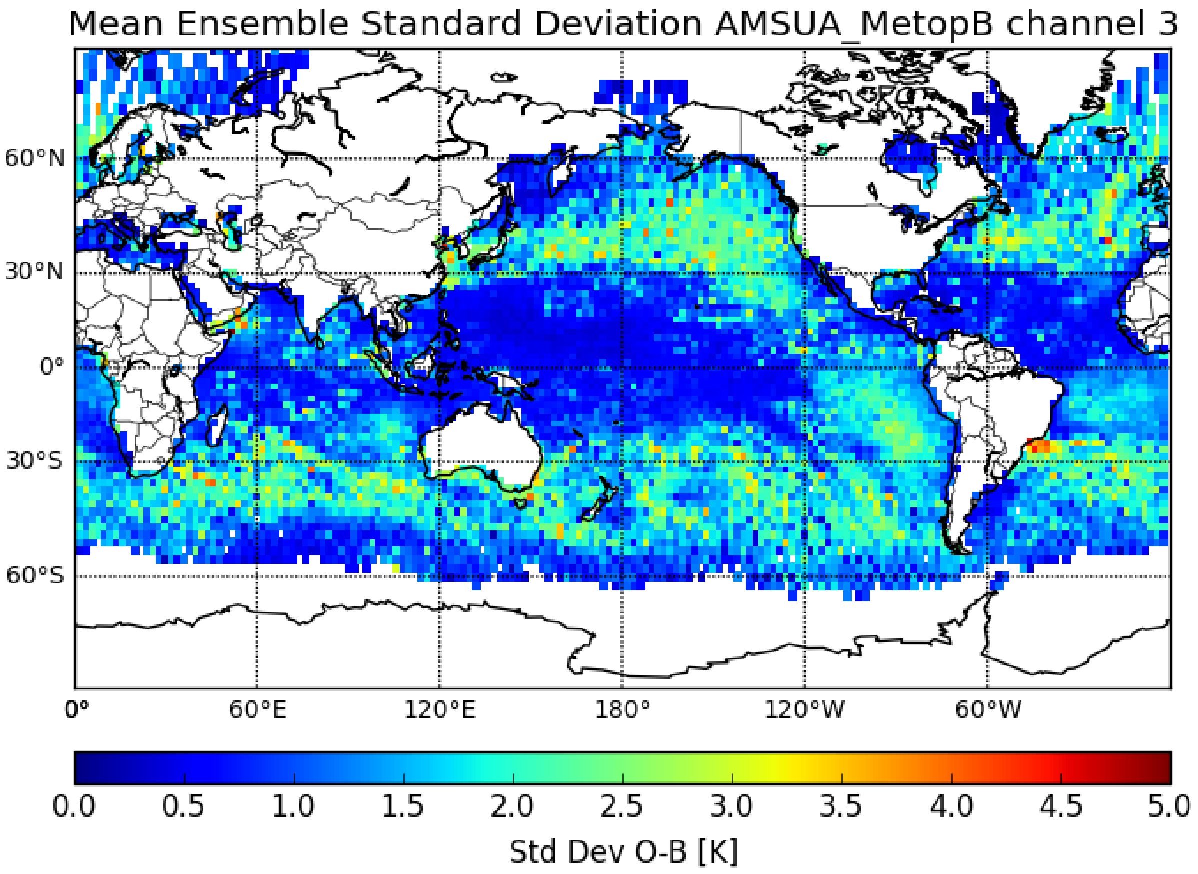
Ensemble Spread

- How can we validate the ensemble spread?
  - Compare to observations

Background Errors are mostly determined by the Ensembles…

Here are the mean errors from the ensembles in radiance space for AMSU-A on Metop-B averaged over ten days.

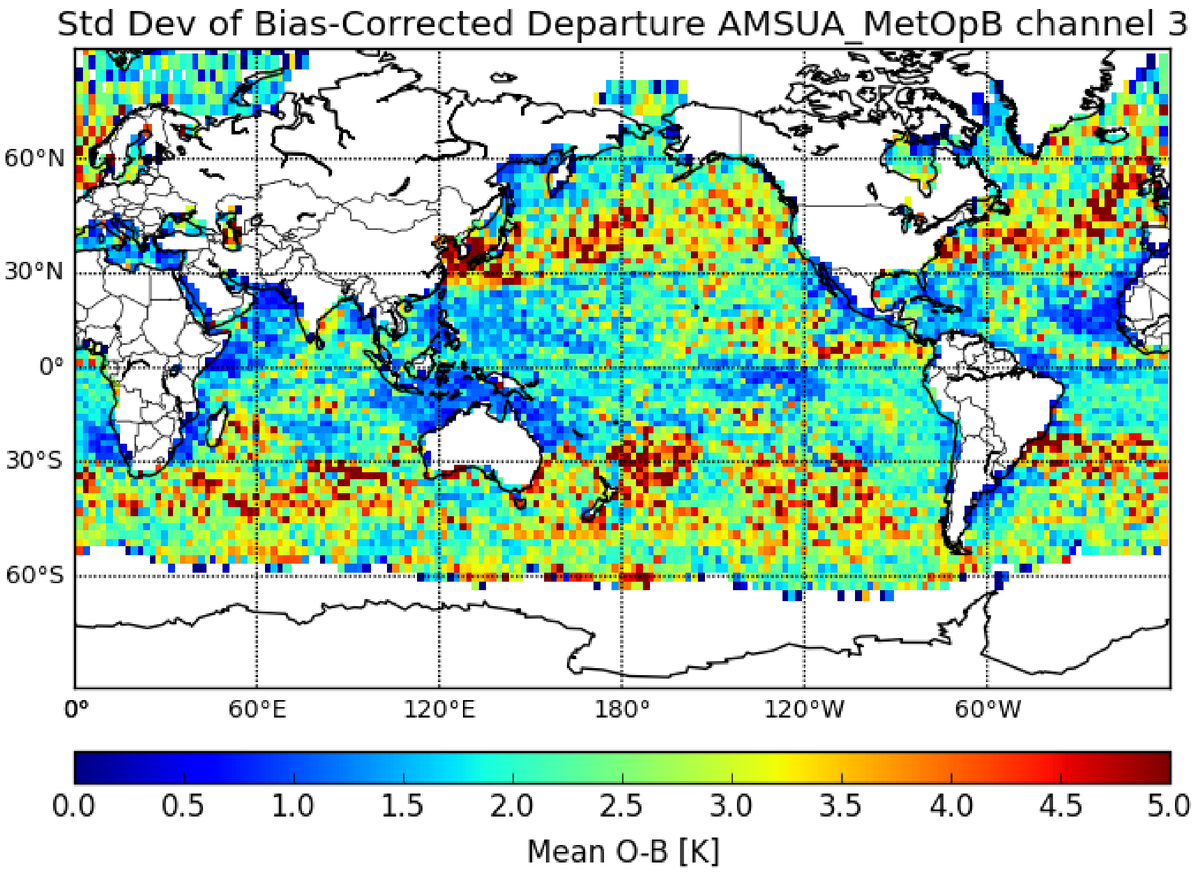
We can compare this to…..



Standard Deviation of First Guess Departures

… the standard deviation of first guess departures over the same period.

Of course, in addition to the background error, this also includes contribution from instrument noise, representivity error and forward model error.



Observation Error

- The appropriate error to assign to an observation should consider
  - Instrument noise
  - Forward Model Error
  - Representivity Error
  - Linearity Error
- The last two terms are expected to be most significant in cloudy regions
- Often in the past these have been approximated by the first guess departure, O-B
- Can we do this for cloudy radiances?

Cloudy Observation Errors

Function of observed cloud or model cloud ?

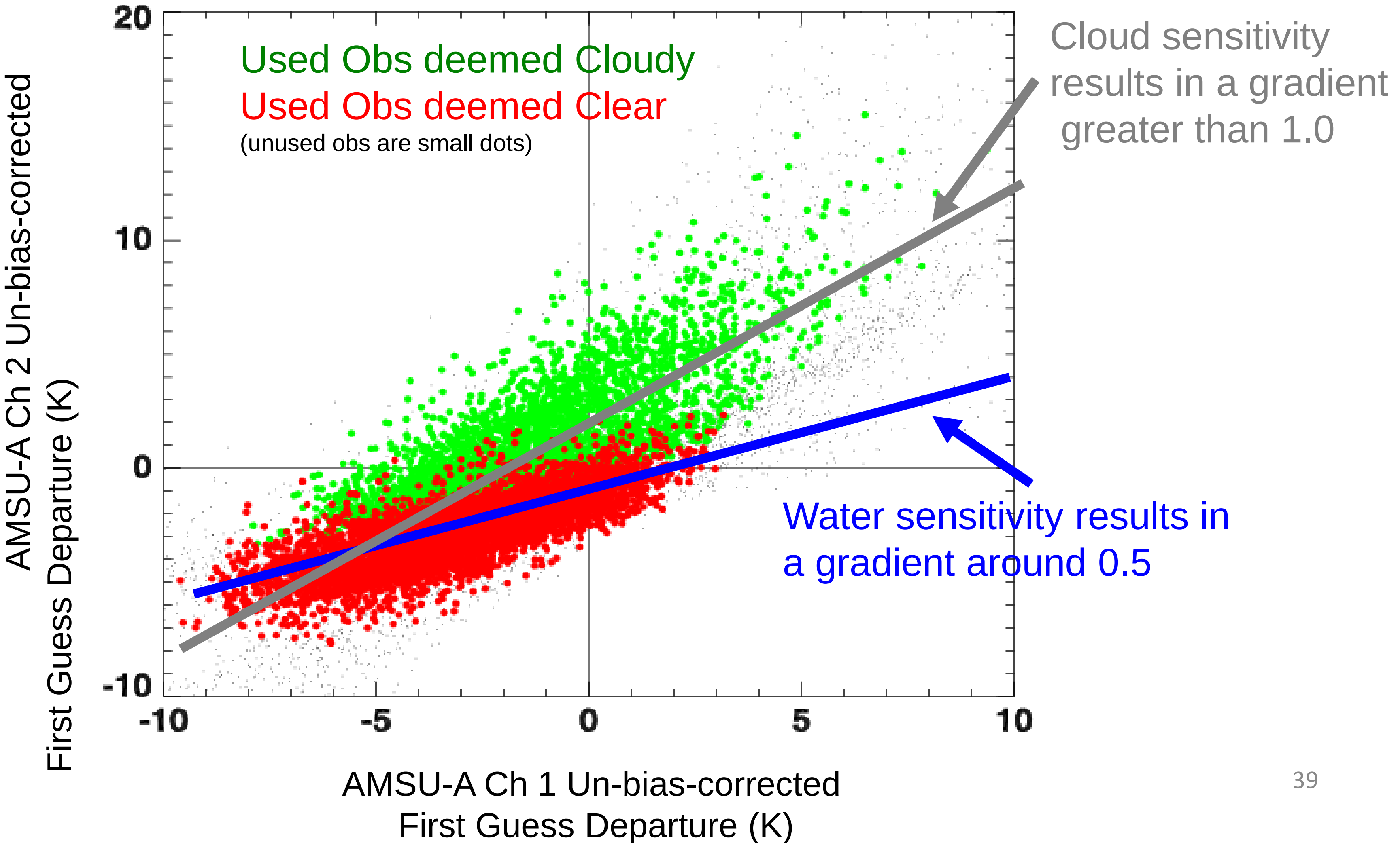
Geer et al. (2010)

Obs: Cloudy sky Model: Clear	Obs: Clear sky Model: Cloudy

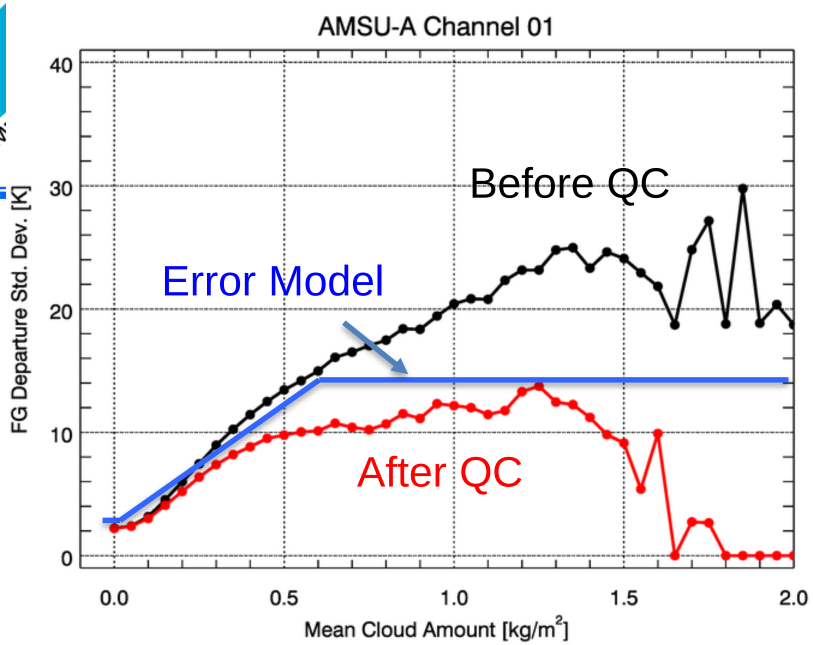
Obs error function of Obs cloud → Large obs errror (Small weight) | Small obs errror (Large weight) → Dry model atmosphere

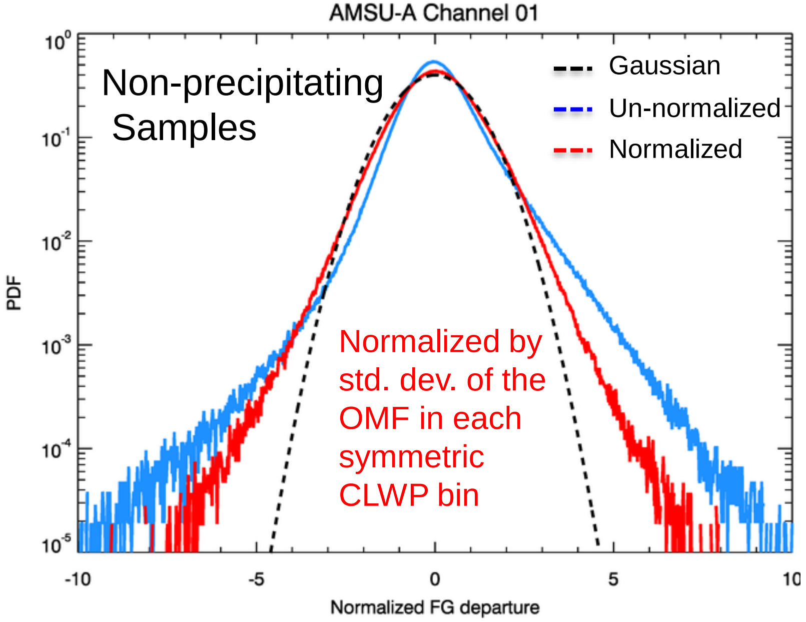
Obs error function of Model cloud → Small obs errror (Large weight) | Large obs errror (Small weight) → Moisten model atmosphere

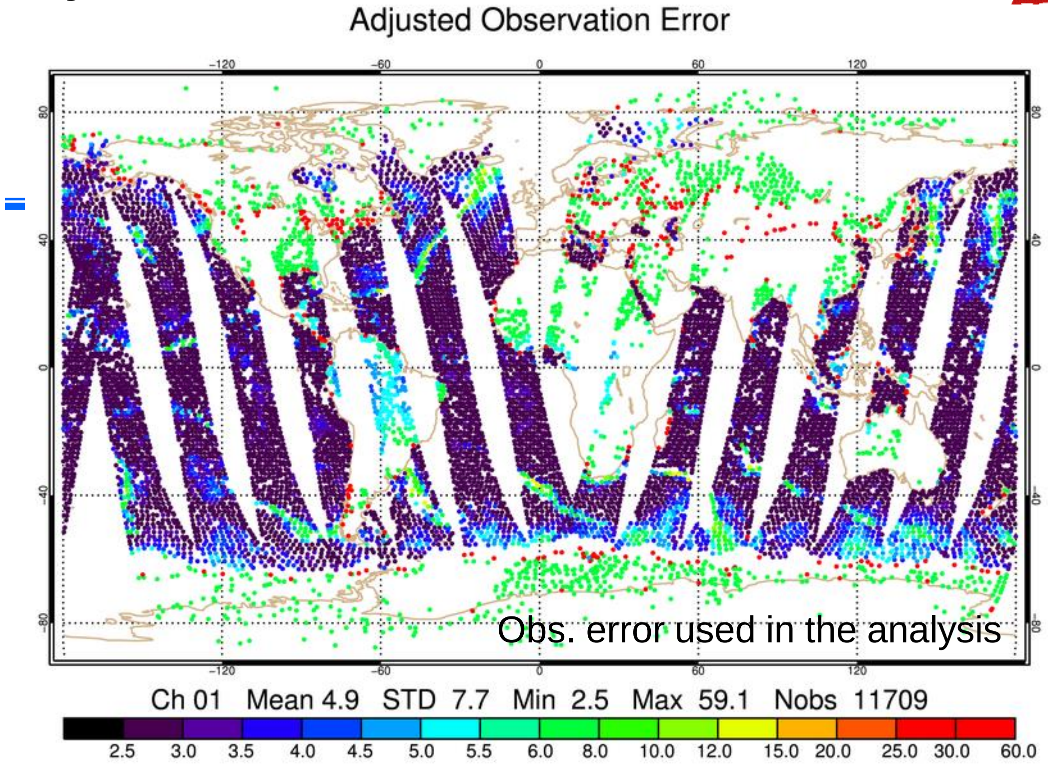
Cloud detection in the microwave



Observation Error for AMSU-A under All-sky Conditions



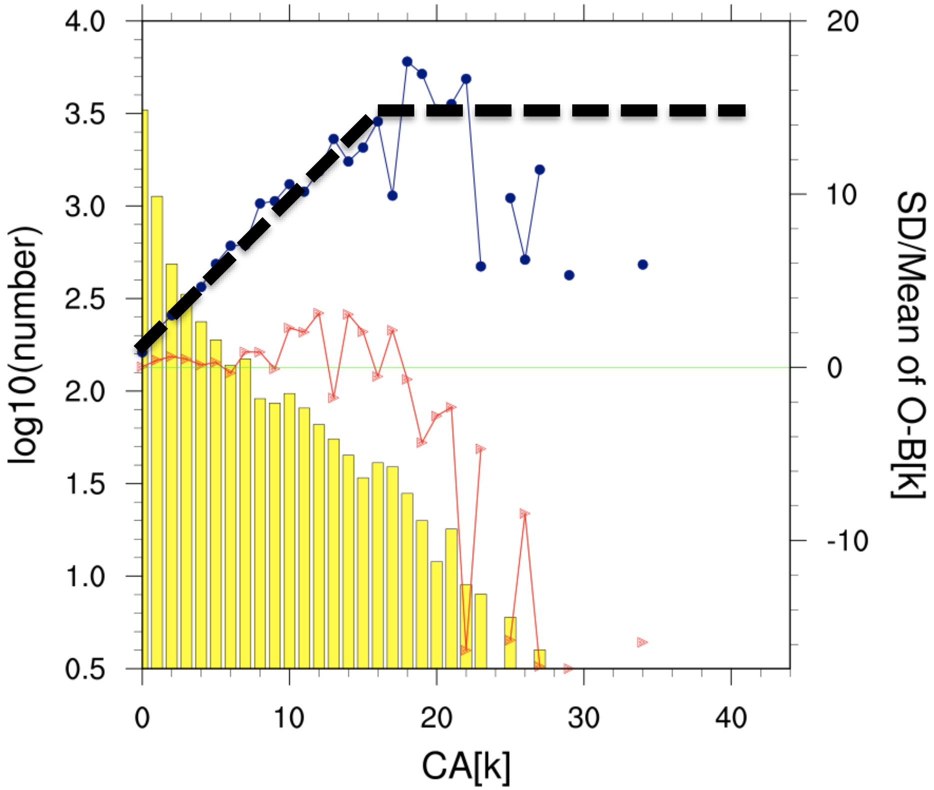




- Observation error is assigned as a function of the symmetric cloud amount
- Gross check ±3 of the normalized FG departure (accept Gaussian part of the samples)

Infrared Error Model Based on Radiative Cloud Effect (CE)

$$CE_i = (|OB_i - FG_{clr,i}| + |FG_i - FG_{clr,i}|)/2$$



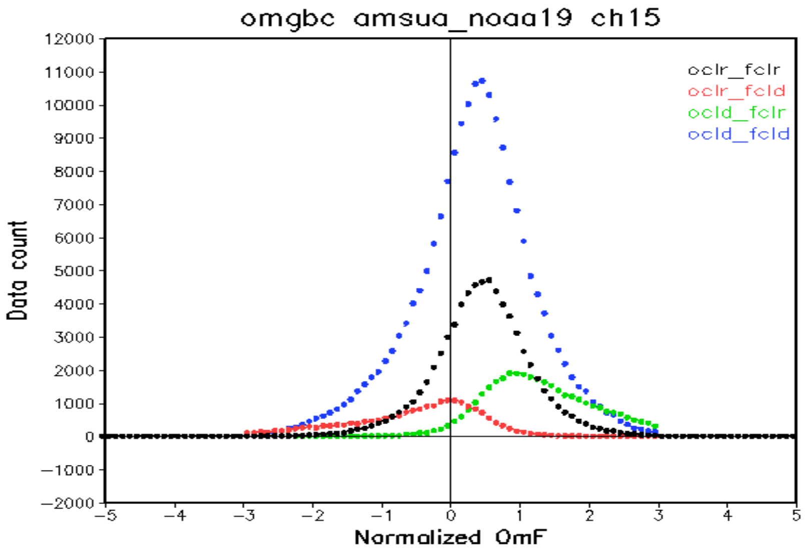
Bias

Standard Deviation

Counts

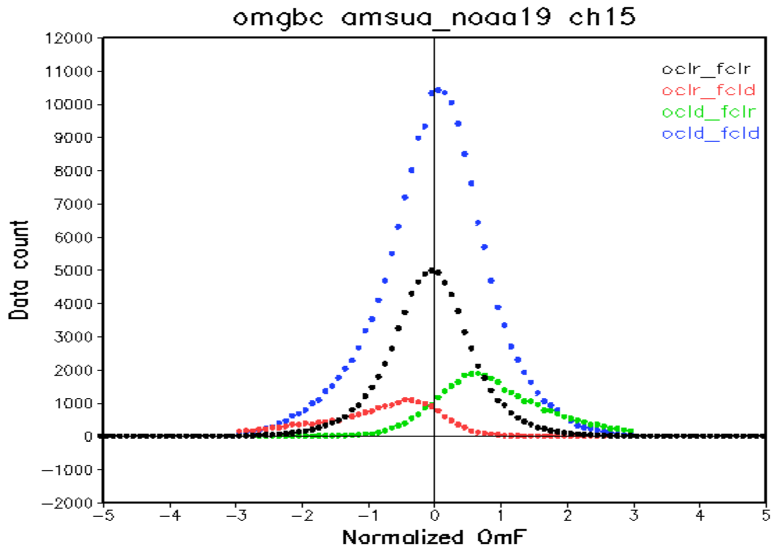
Dashed = Error Model

All-sky Radiance Bias Correction (Zhu et al. 2014)



Using all observations

Normalized OmF w/ BC



Using observations where cloudiness inferred from observations and model agree

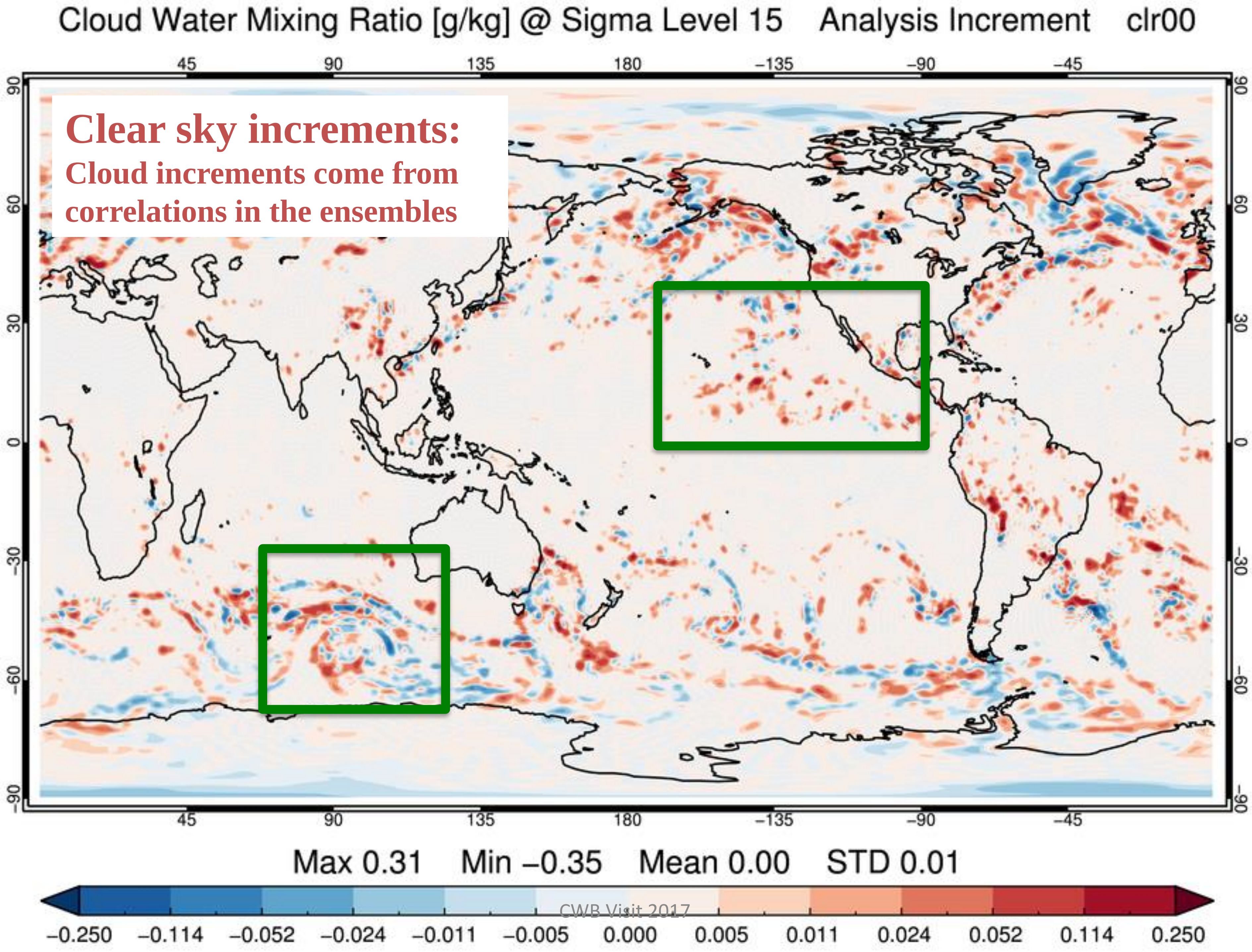
Normalized OmF w/ BC

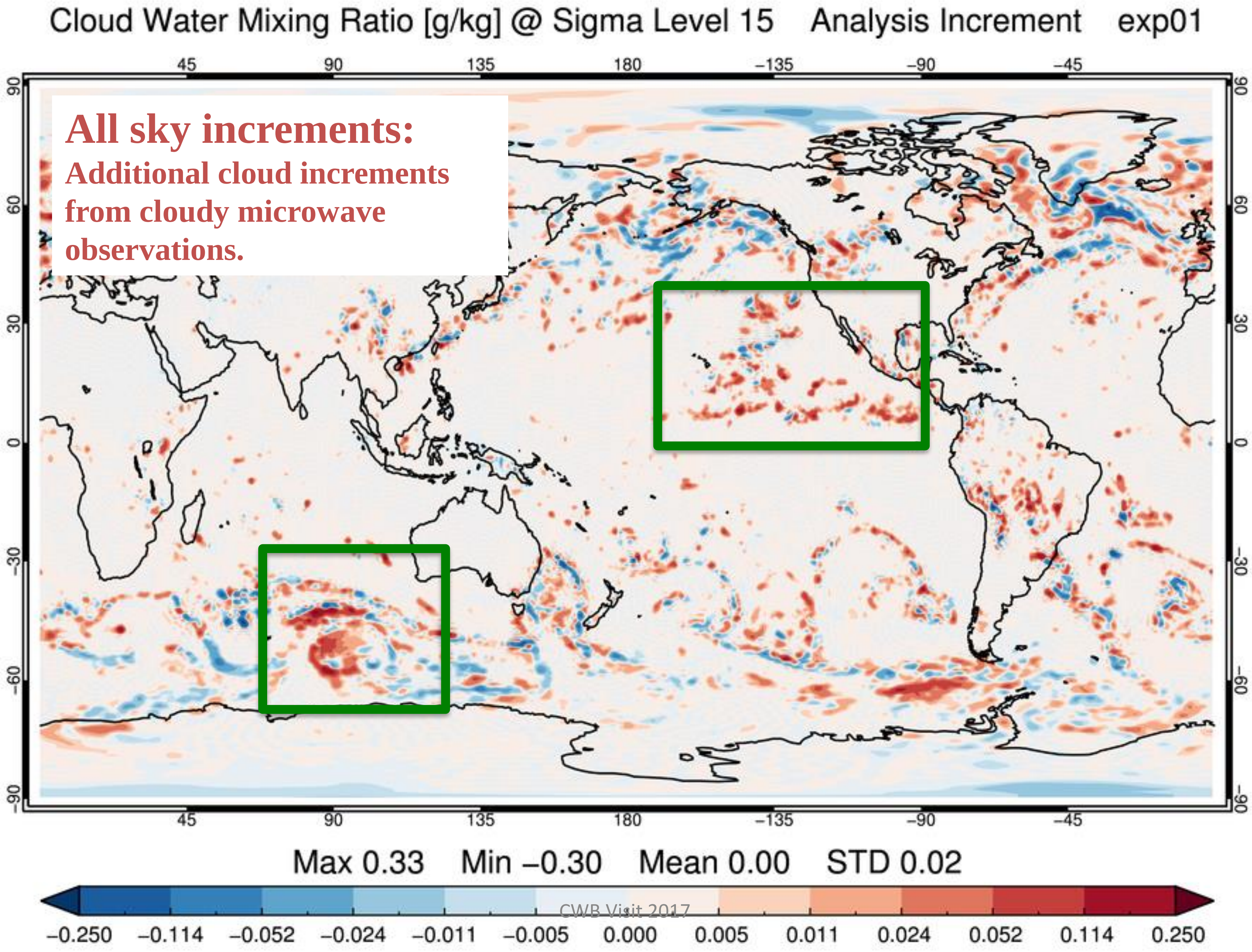
Analysis Increments and Spindown

- Most of the increment to the cloud fields in the analysis comes from the ensembles.
- The cloud increments produced are not always in balance with other model fields
  - Spin down remains a problem

Clear sky increments:

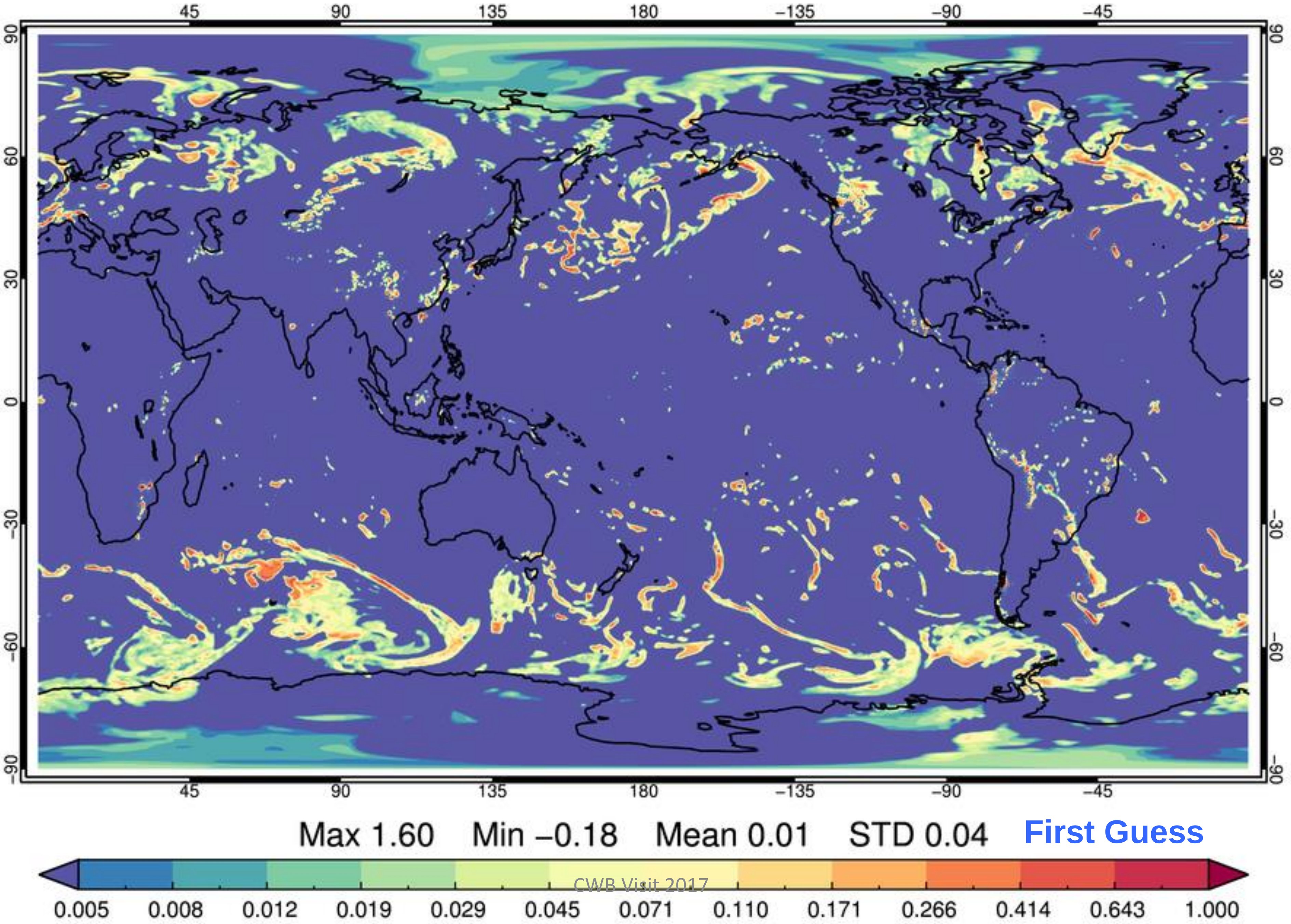
Cloud increments come from correlations in the ensembles





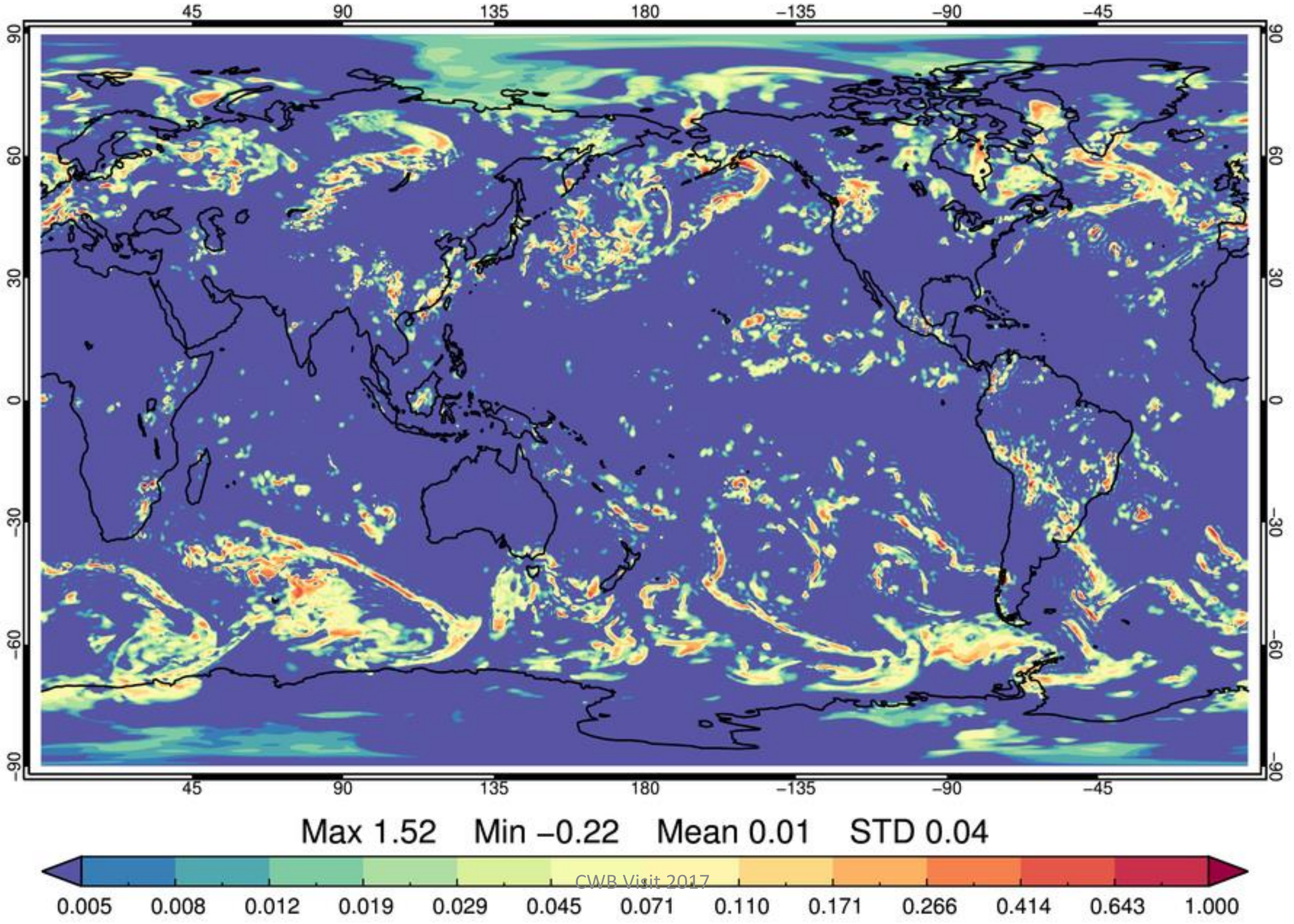
Cloud Water Mixing Ratio [g/kg] @ Sigma Level 15 Analysis Increment exp01
All sky increments:
Additional cloud increments from cloudy microwave observations.
Max 0.33 Min –0.30 Mean 0.00 STD 0.02
–0.250 –0.114 –0.052 –0.024 –0.011 –0.005 0.000 0.005 0.011 0.024 0.052 0.114 0.250

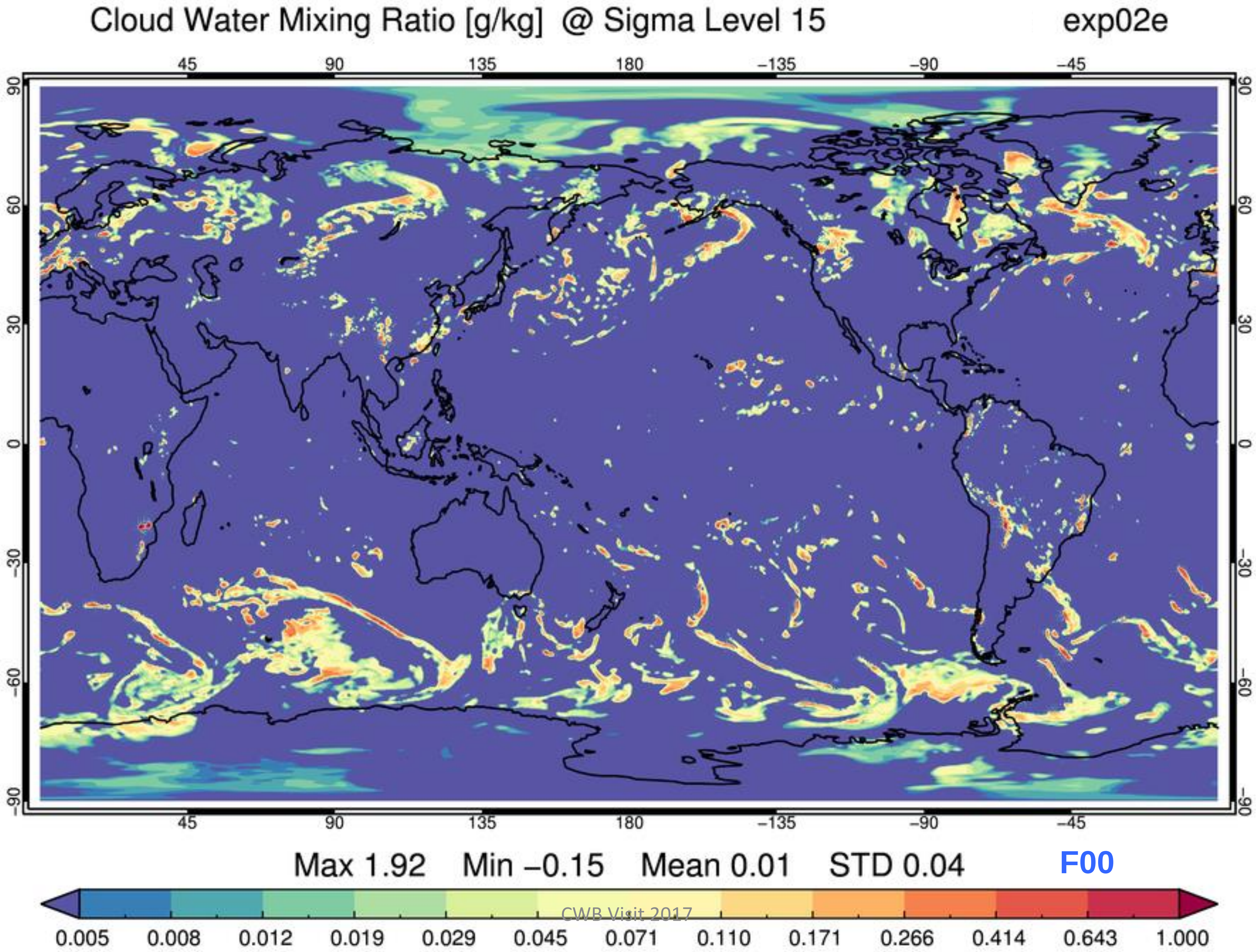
Cloud Water Mixing Ratio [g/kg] @ Sigma Level 15 exp02e



First Guess

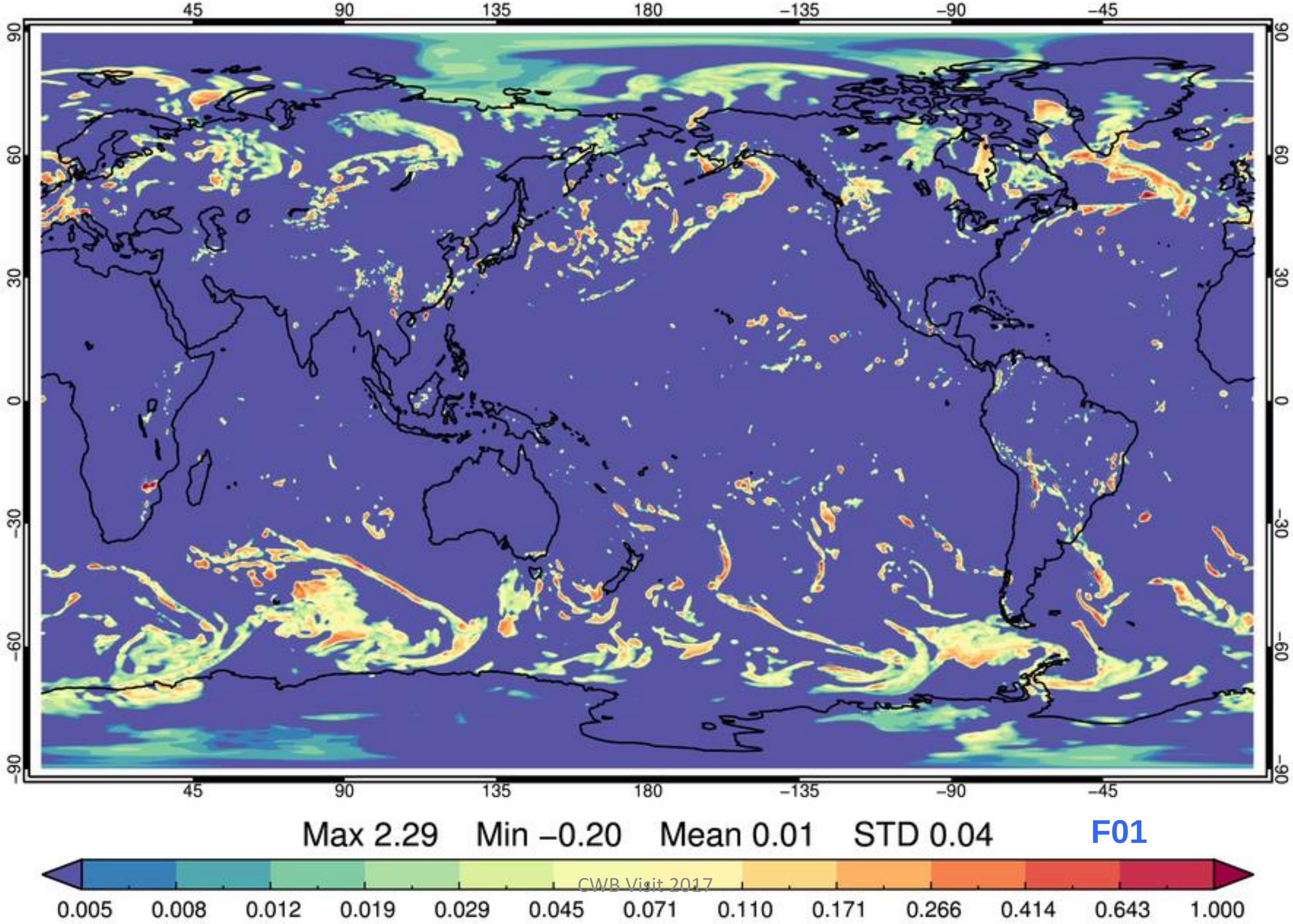
Cloud Water Mixing Ratio [g/kg] @ Sigma Level 15 exp02e





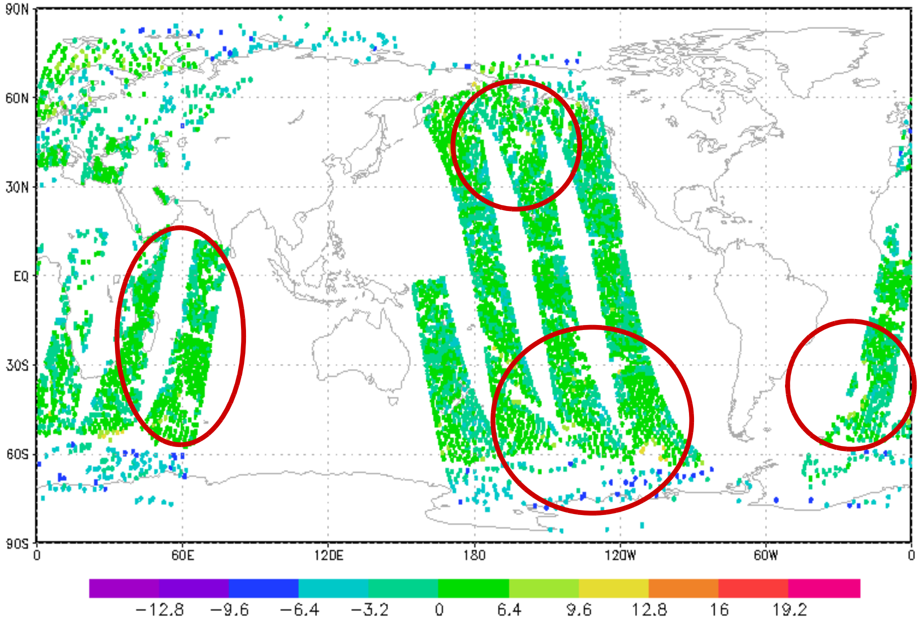
Cloud Water Mixing Ratio [g/kg] @ Sigma Level 15
exp02e
45
90
135
180
−135
−90
−45
90
60
30
0
−30
−60
−90
Max 1.92 Min −0.15 Mean 0.01 STD 0.04
F00
0.005 0.008 0.012 0.019 0.029 0.045 0.071 0.110 0.171 0.266 0.414 0.643 1.000

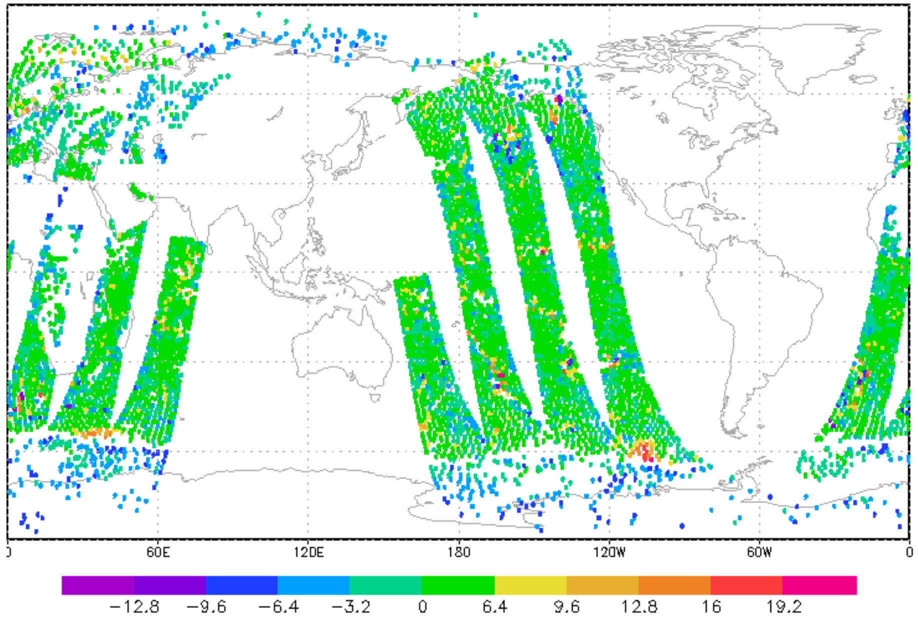
Cloud Water Mixing Ratio [g/kg] @ Sigma Level 15 exp02e



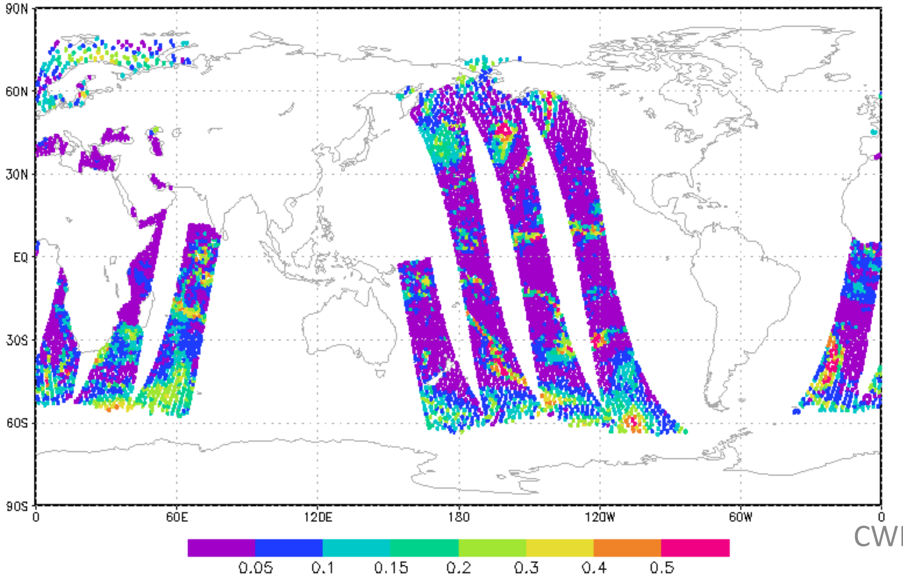
Cloudy Radiance Impact

Clear-sky OmF vs. All-sky OmF





CLW



- More data coverage: Thick clouds that are excluded from clear-sky assimilation are now assimilated under all-sky condition
- Rainy spots are excluded from both conditions

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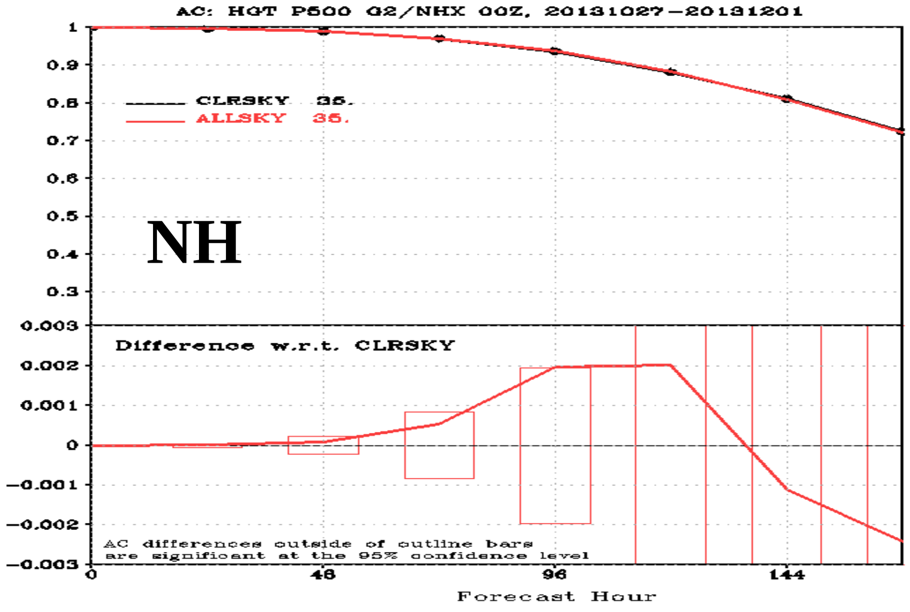
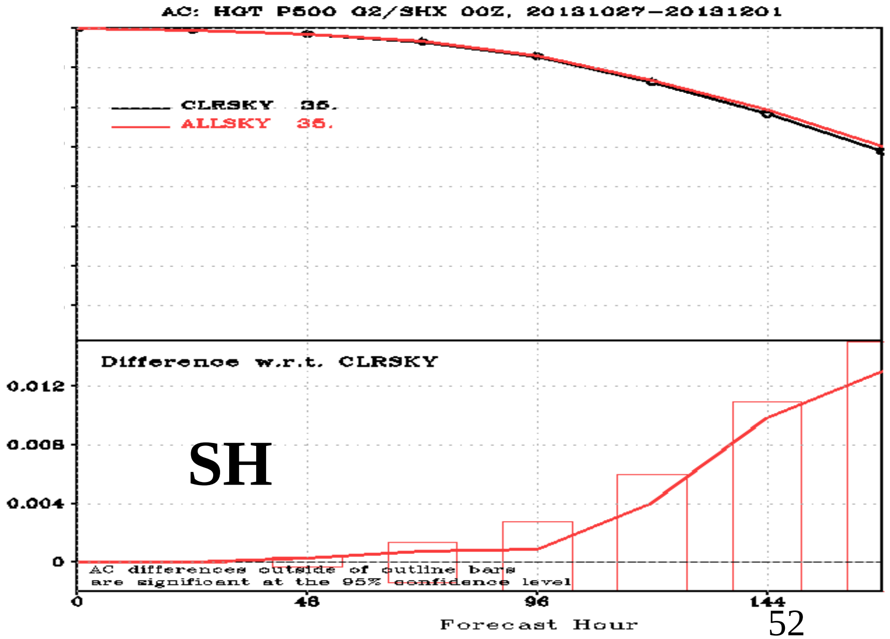
T670/T254 All-sky Microwave Radiance Assimilation in 3D EnVar



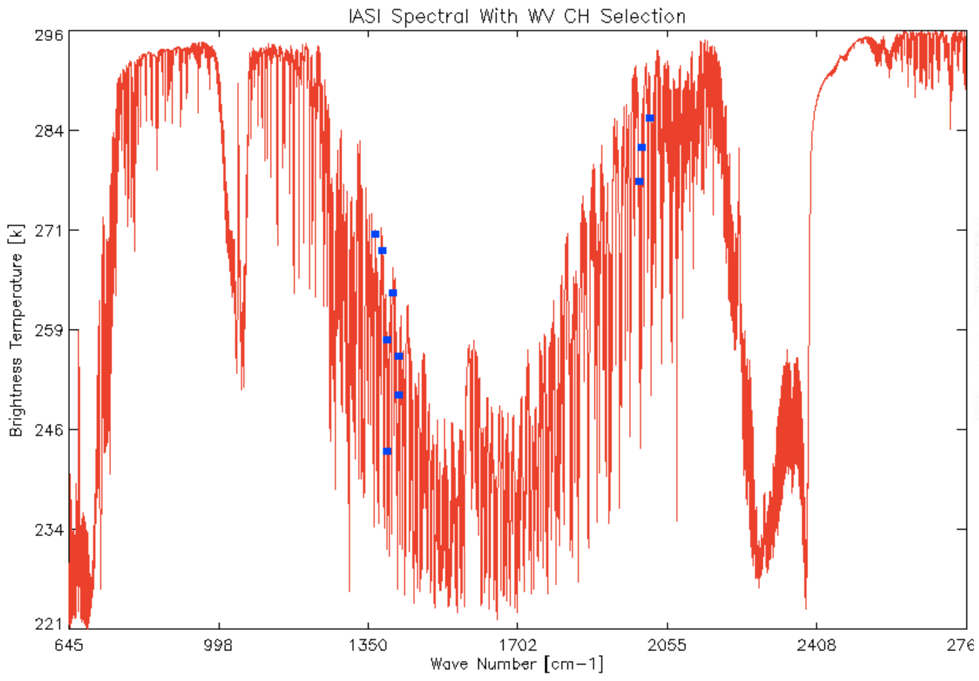
Anomaly Correlation at 500 hPa

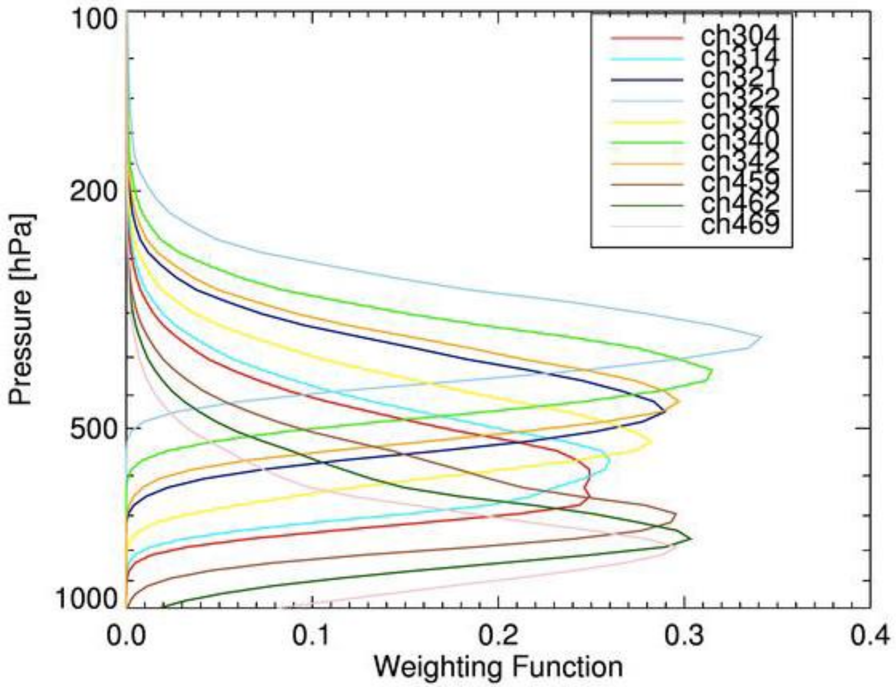


All-Sky Improves Forecast

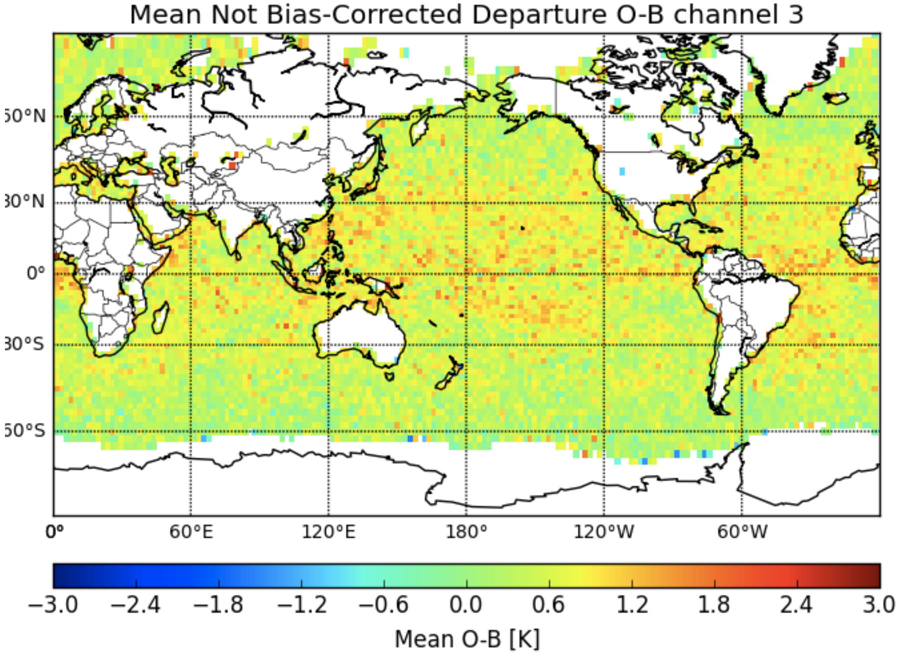
All-Sky Degrades Forecast

Humidity Channels used and their Jacobians



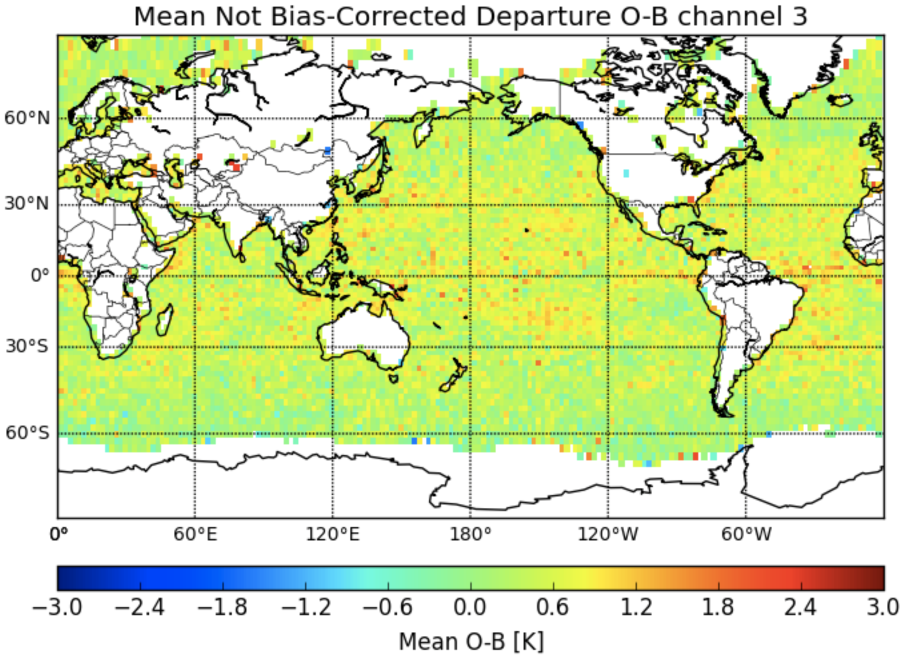


MHS channel 3 unbias-corrected mean first-guess departure



No cloudy IASI

With cloudy IASI



Latitudinal dependence of first-guess departure is reduced when cloudy IASI radiances are used

Talk Outline

- Current and future Global NWP configurations
- Near Sea Surface Temperature
- Cloudy Radiances
- CrIS
- Monitoring

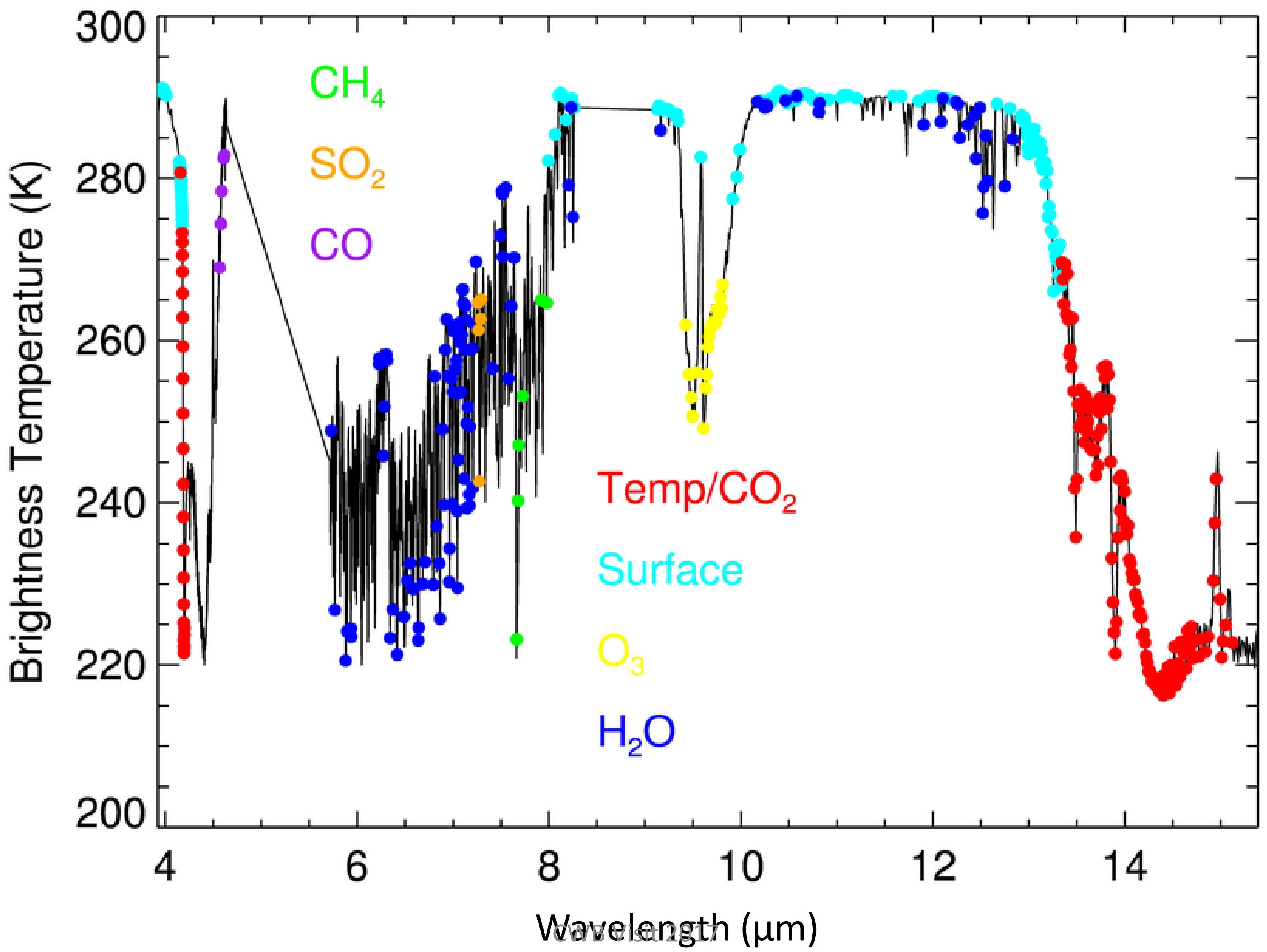
S-NPP CrIS Data Assimilation Configuration

- We receive a subset of 399 channels (Gambacorta et al., 2013) in BUFR format.
- We assimilate those channels designated for temperature, cloud, CO_2 and surface that do not suffer from solar contamination. This totals 84 channels from 672.5cm^{-1} to 1095.0cm^{-1}.
  - This is similar to our IASI channel selection. We hope to extend to include water vapor channels when we switch to FSR for JPSS-1, although the additional impact is likely to be small.
- Forecast impact is small and positive.

JPSS-1 CrIS Data Assimilation

- For JPSS-1 we plan to receive the full FSR spectrum at NCEP – allowing us to be more flexible in our channel selection.
  - We aim to use more of the 15µm CO_2 band channels than is possible with the current selection.
  - We will also make use of channels from the water vapor band.
- A channel selection for NWP has also been produced with Antonia Gambacorta of NOAA-NESDIS
  - We consulted widely in the NWP community on this channel selection (mostly through the ITSC NWP Working Group)
  - This channel selection is suggested for direct broadcast and GTS distribution as well as being the default subset being distributed by NESDIS (the full spectrum is also being distributed).

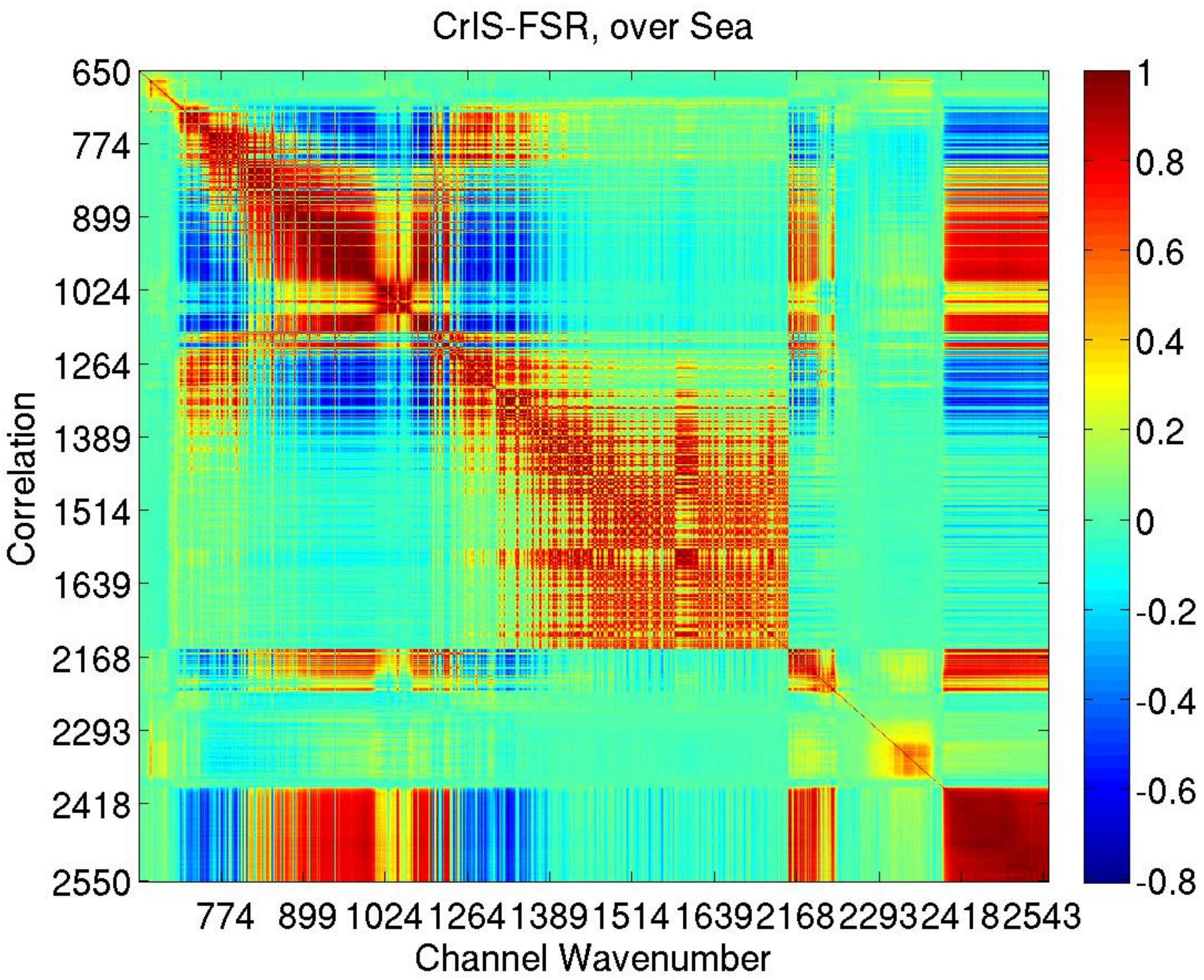
CrIS FSR Channel Selection



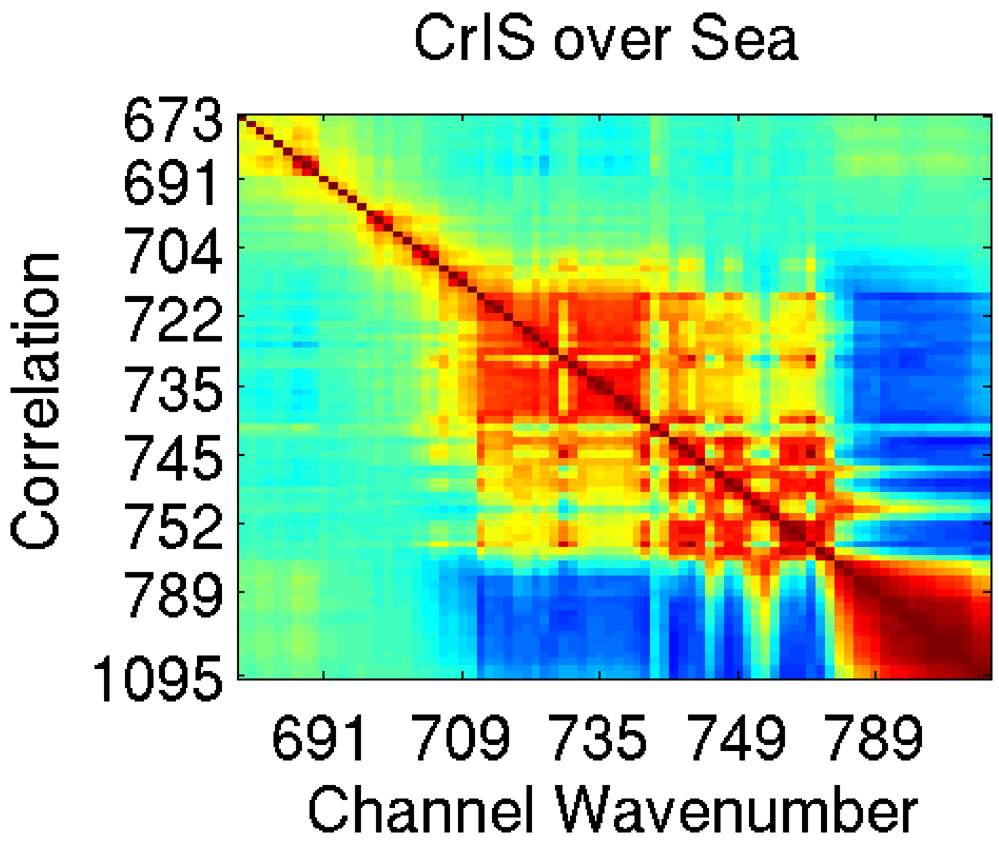
CrIS Correlated Observation Error

- The use of prescribed spectrally-correlated observation errors for CrIS is being tested and may be included with the JPSS-1 implementation.
- Correlated observation errors are important for hyperspectral sounders particularly in the water vapour and surface sensitive bands
- For interferometers we use apodised radiances which also introduce correlations – for CrIS using the correct correlated observation error is important in the 15μm band as otherwise information from the first resonance in the interferogram is being lost.

CrIS Observation Error Correlation Matrix



CrIS Observation Error Correlation Matrix (Detail)



Strong adjacent-channel correlations due to apodisation …
In addition to significant broader correlation structures (forward model/representivity error?)

Talk Outline

- Current and future Global NWP configurations
- Near Sea Surface Temperature
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- CrIS
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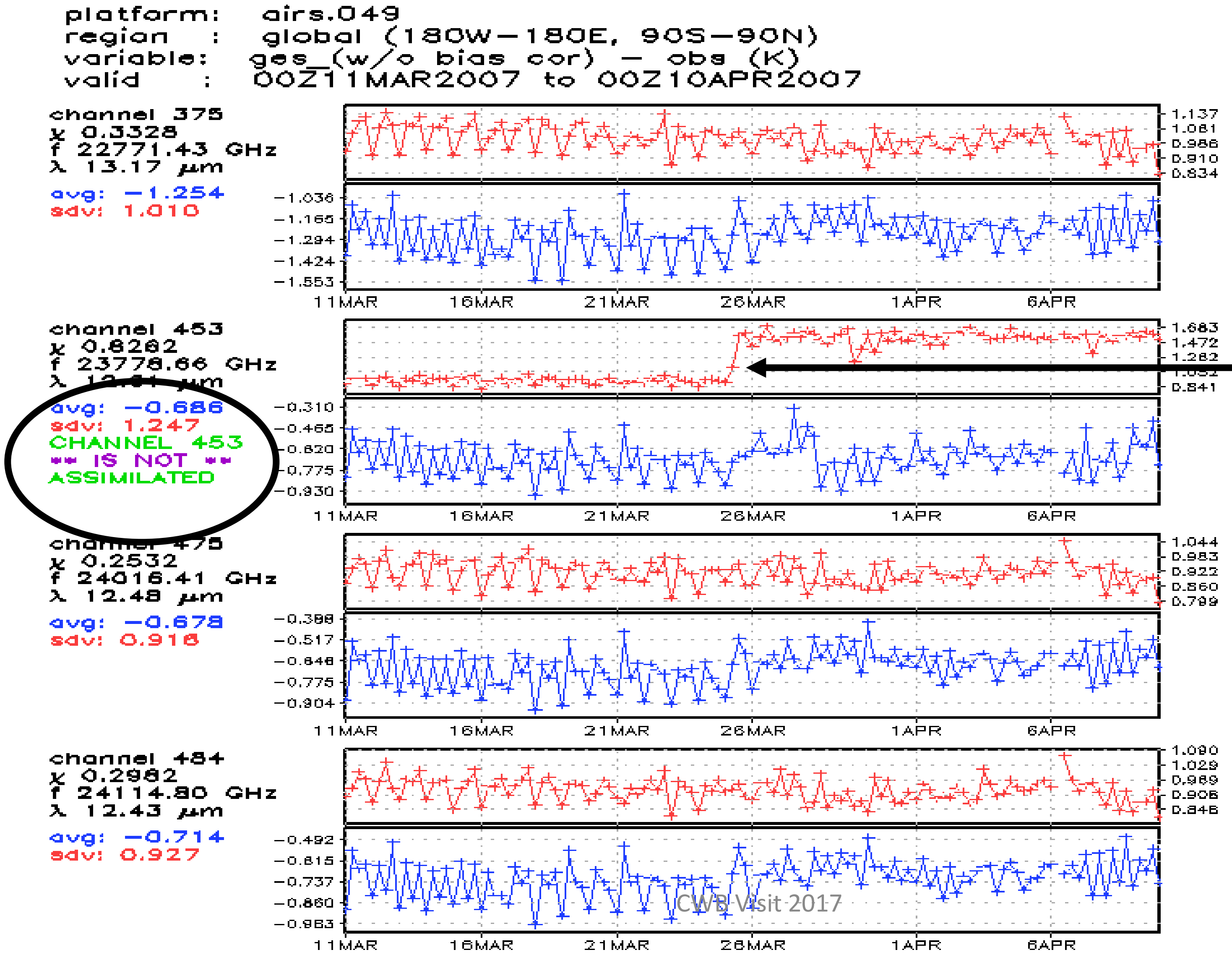
Data Monitoring

- It is essential to have good data monitoring.
- Usually the NWP centres see problems with instruments prior to notification by provider.
- The data monitoring can also show problems with assimilation systems.
- Needs to be ongoing/real time.
- Monitoring reports from most major NWP centers at:
  https://nwpsaf.eu/site/monitoring/
- NCEP data monitoring is at:
  http://www.emc.ncep.noaa.gov/gmb/gdas/

Quality Monitoring of Satellite Data

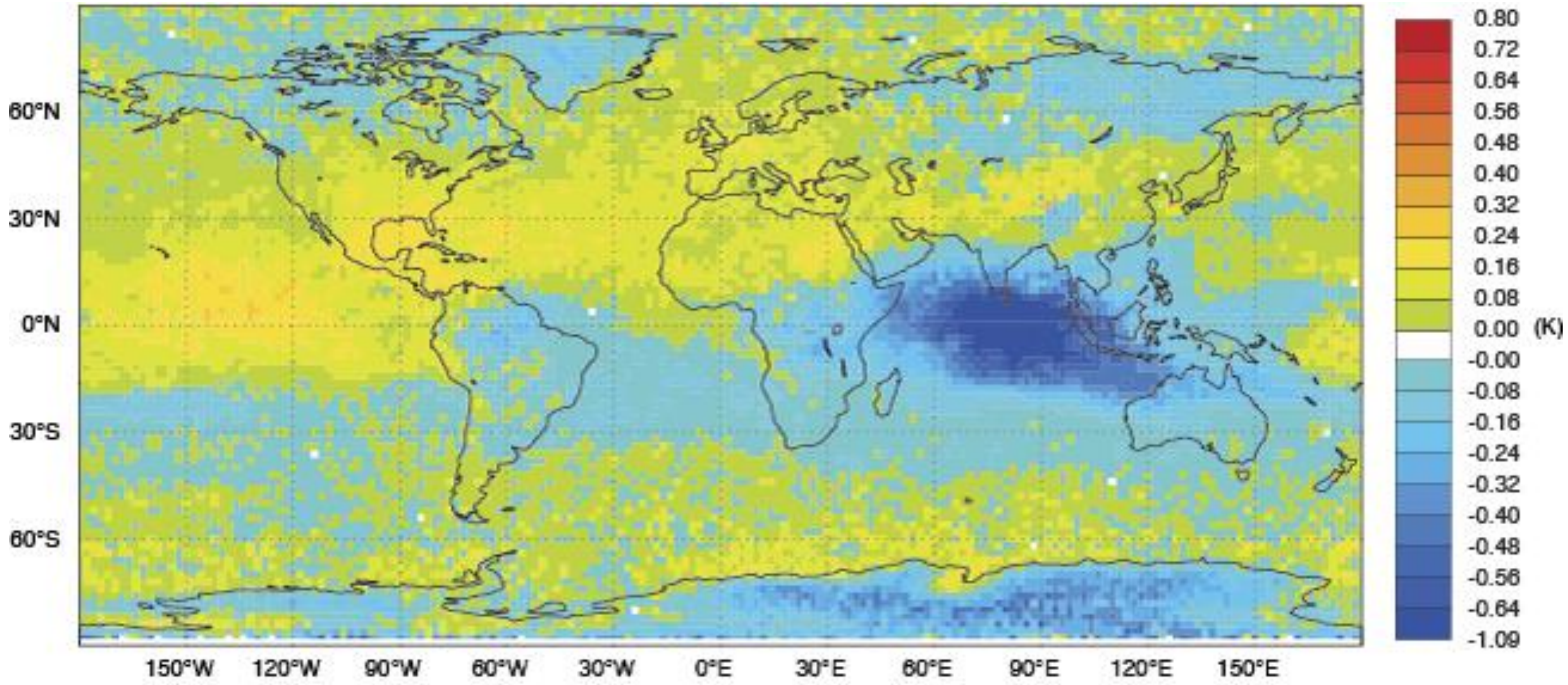
AIRS Channel 453 26 March 2007



Increase in SD Fits to Guess

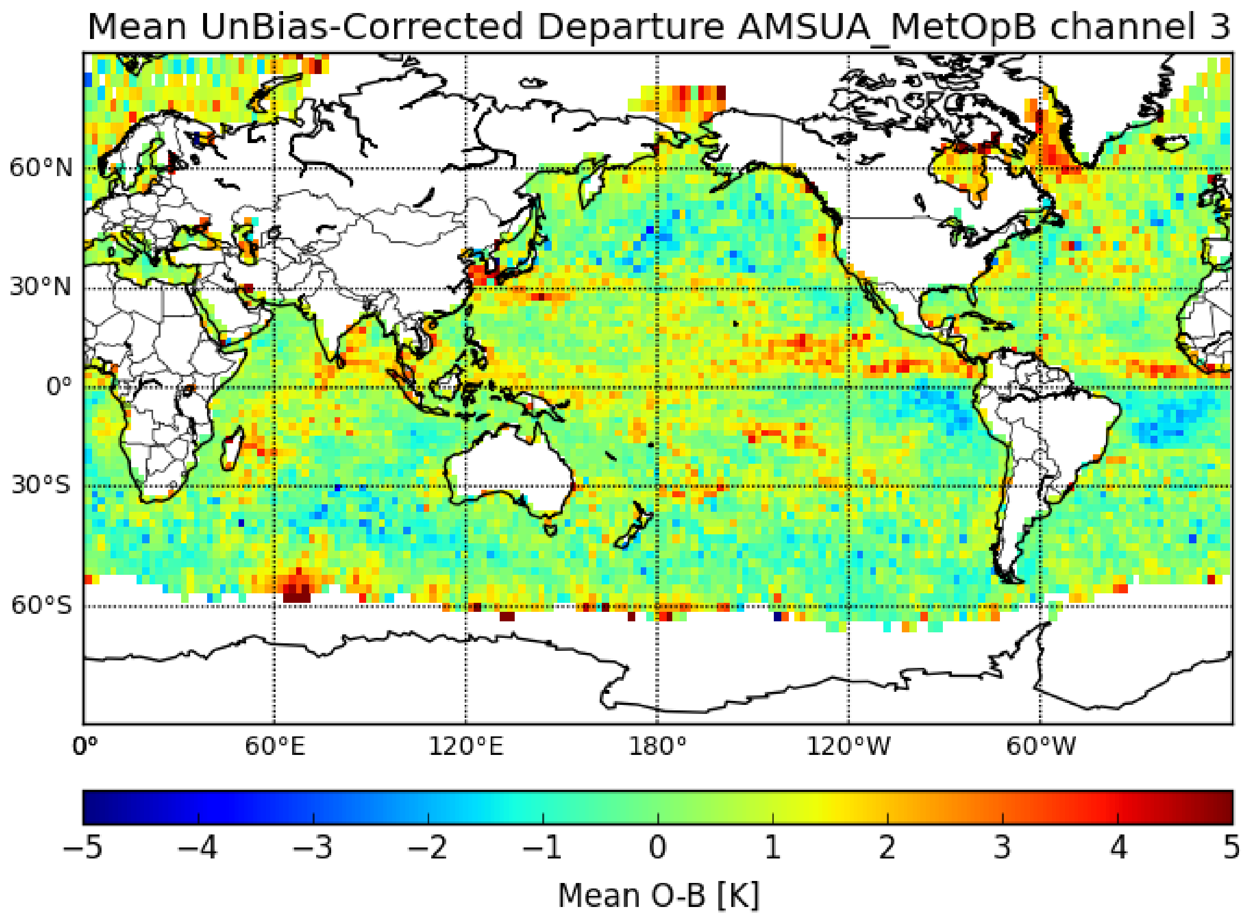
Unexpected HCN Signal

First guess departure at *713 cm*$^{-1}$



Maps of Mean First-Guess Departure …

… can help identify where the model or the radiative transfer are introducing biases.



Questions?

Backup Slides

GSI Code Flow

Get user input parameters

(resolution, static/hybrid, 3d/4d, constraints, data type, data thinning, … etc)

Get resource files*

anainfo: bkg/anl vars
satinfo : sensor/channel + obs error
locinfo : localization length
…etc

Initialization

*GSI advanced user's guide

Read in and distribute:
Observations
Bkg fields, Bkg errors Radiance bias correction info
Radiance diag. files (opt)

Initialize CRTM observation operator (call int_crtm)

- Sensor/channel spectral information
- Sensor/channel transmittance coefficients for gases
- Spectral coefficients for surface emissivity, cloud and aerosol optical properties

Outer Loop Iteration (glbsoi.f90)
Call setup routines: (e.g., setuprad.f90 for radiance)

- Compute simulated observation and Jacobian with associated observation operator (call_crtm provide and for radiance data)
- Compute radiance bias correction predictors
- Compute Hessian of J from radiance bias correction
- Compute observation innovations
- Quality control and adjust obs errors

Call **Inner Loop Iteration** (pcgsoi.f90)

- Compute gradient information
- Apply background error)
- Compute search direction and step size
- Update analysis increment
- Check convergence

Update guess fields
Estimate bias correction coefficients for passive channels

Write output files for analysis, radiance bias correction and obs diagnostic files

Important Input Files For Radiance Assimilation

USER PROVIDED FILES:

- OBS_INPUT namelist: Lists instruments, links to CRTM files, defines thinning etc.
- SATINFO*: Controls channel-by-channel data usage, observation errors quality control
- SCANINFO: Defines relation between scan position and scan angle plus usage at scan edges
- ANAVINFO: Defines state and control variables and their use within the CRTM.
- cloudy_radiance_info.txt*: Additional information of cloudy radiance observation error model.

FILES UPDATED BY THE GSI:

- SATBIAS: Contains bias-correction coefficients
- SATBIAS_PC: Preconditioning information for bias correction
- SATANGBIAS: Scan-dependent bias correction file if this is done offline (a depreciated feature in NCEP DA)

*There has been a restructuring of the way radiance assimilation is being done resulting in modifications to some files and addition of extra ones. The current release of the DTC GSI does not include these changes.