Satellite Radiance Assimilation

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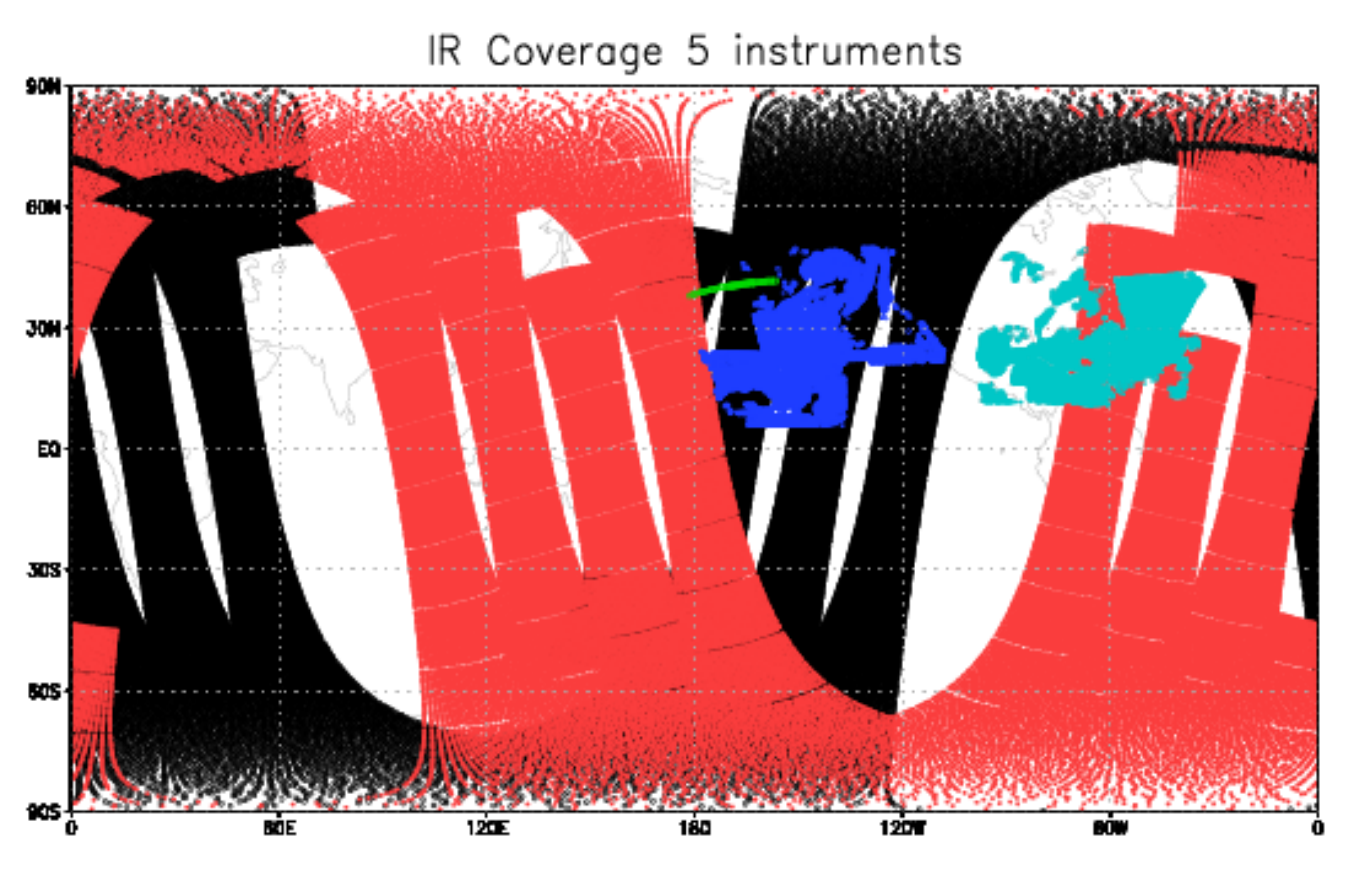
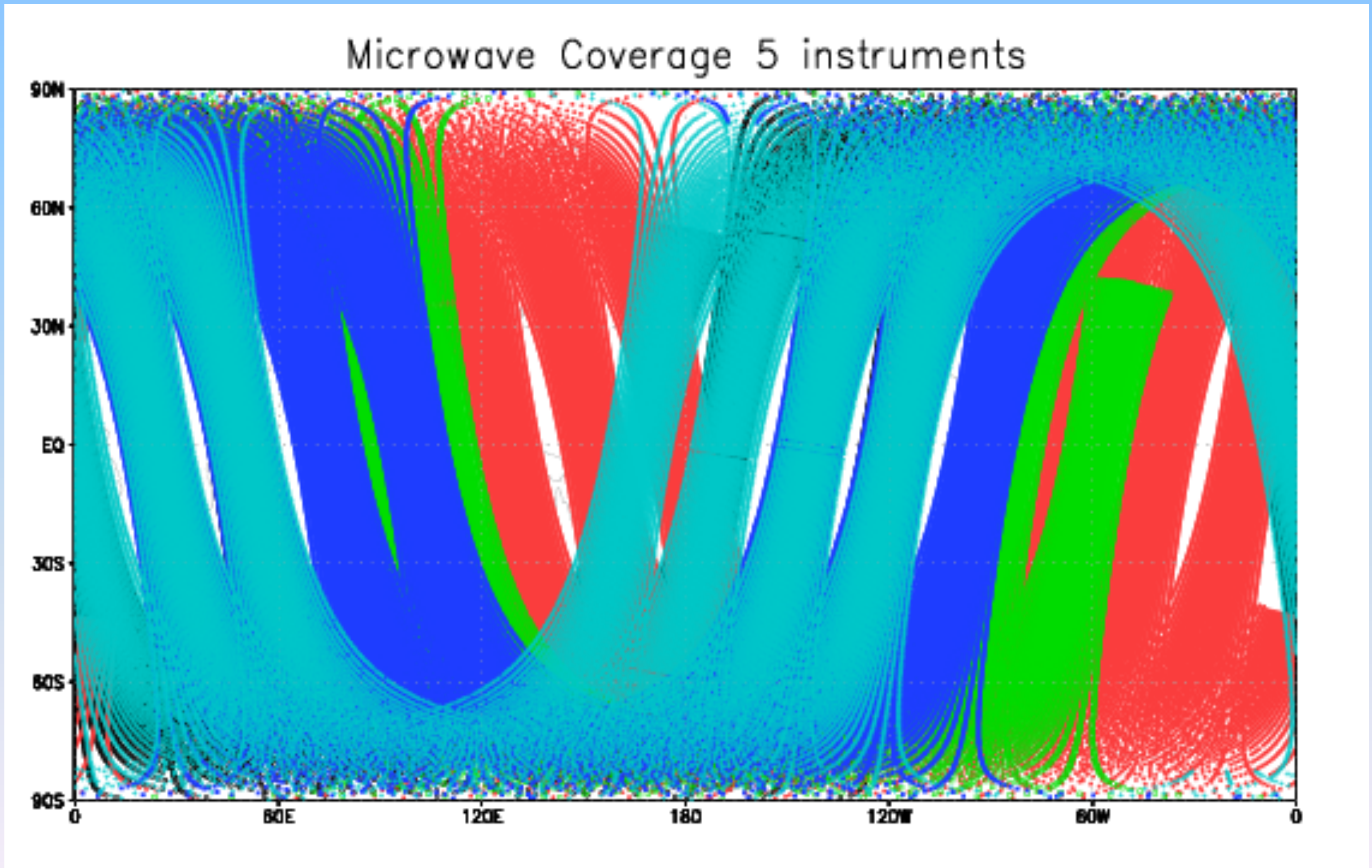
With input from:
Many others

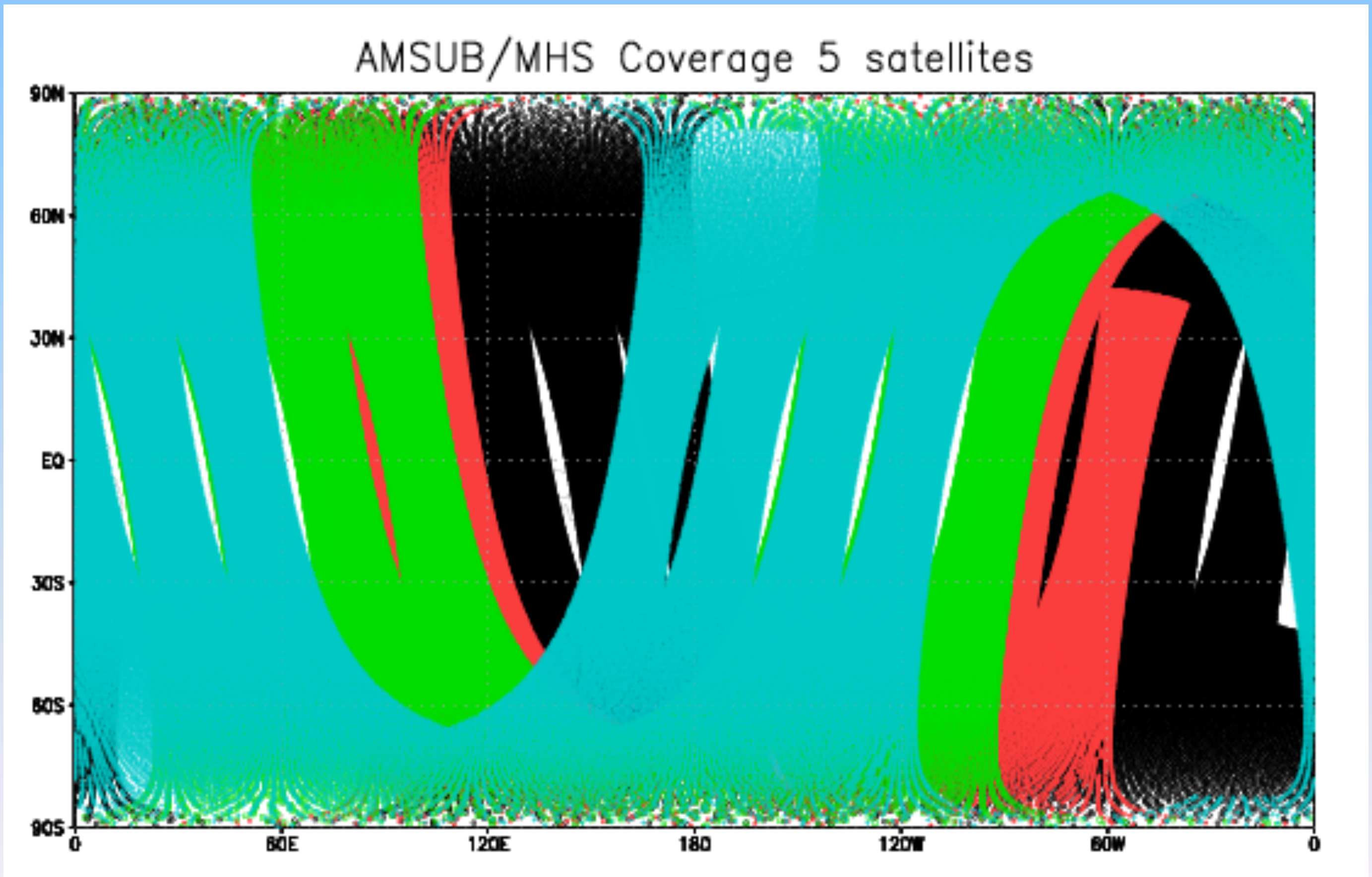
Coverage IR
AIRS, METOP, N-17, GOES-11/12



Coverage – Microwave AMSU-A AQUA,N-15,-16,-18, METOP



Coverage – Microwave AMSU-B/MHS N-15,-16,-17,-18,METOP



Atmospheric analysis problem (theoretical)

$$\mathbf{J = J_b + J_o + J_c}$$

$$\mathbf{J = (x-x_b)^T B_x^{-1}(x-x_b) + (\mathit{K}(x)-O)^T(E+F)^{-1}(\mathit{K}(x)-O) + J_C}$$

J = Fit to background + Fit to observations + constraints

$\mathbf{x}$ = Analysis
$\mathbf{x_b}$ = Background
$\mathbf{B_x}$ = Background error covariance
K = Forward model (nonlinear)
O = Observations
E+F = R = Instrument error + Representativeness error
$\mathbf{J_C}$ = Constraint term

Note!

- I will be talking about satellite radiances today. But everything I say today applies with other data sources. The problems may be different, but the problems of similar complexity exist with almost every data set.

Operational radiance data requirements

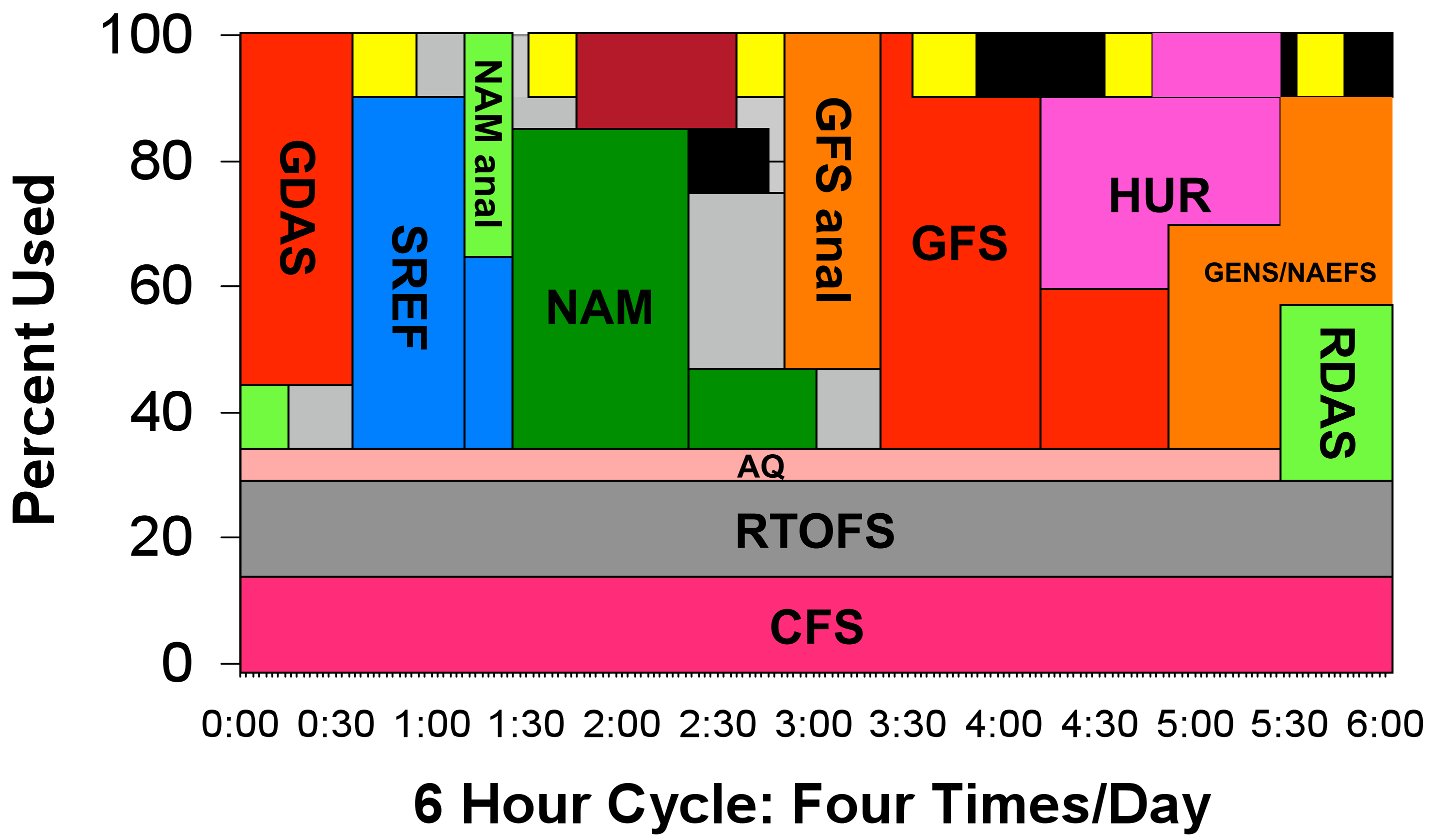
- Requirements for operational use of observations
  - Available in real time in acceptable format
  - Assurance of stable data source
  - Quality control procedures defined (conservative)
  - Observational errors defined (and bias removed if necessary)
  - Accurate forward model (and adjoint) available
  - Integration into data monitoring
  - Evaluation and testing to ensure neutral/positive impact

Data available in real time in acceptable format

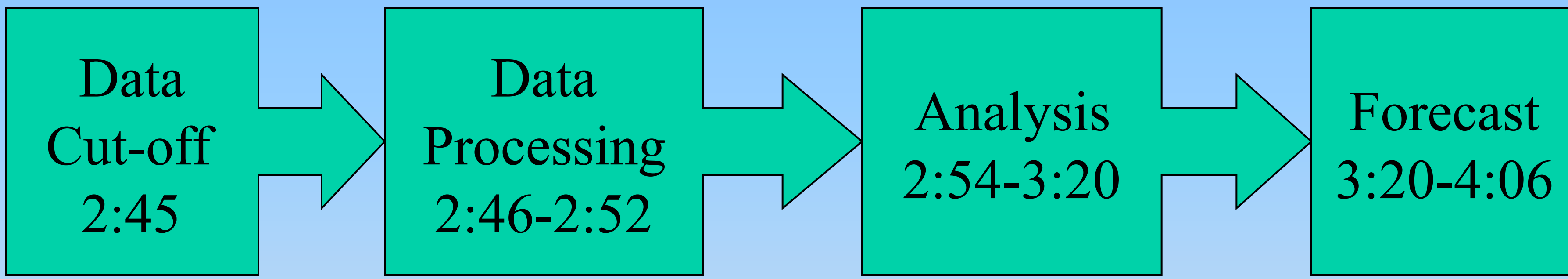
- Data formats
  - WMO acceptable formats – BUFR – CREX (not really relevant) – used by most NWP centers
  - Almost every satellite program uses a different format
  - Significant time and resources used understanding/ converting/developing formats
- If data is not available in time for use in data assimilation system – not useful

NCEP Production Suite
Weather, Ocean, Land & Climate Forecast Systems

2007

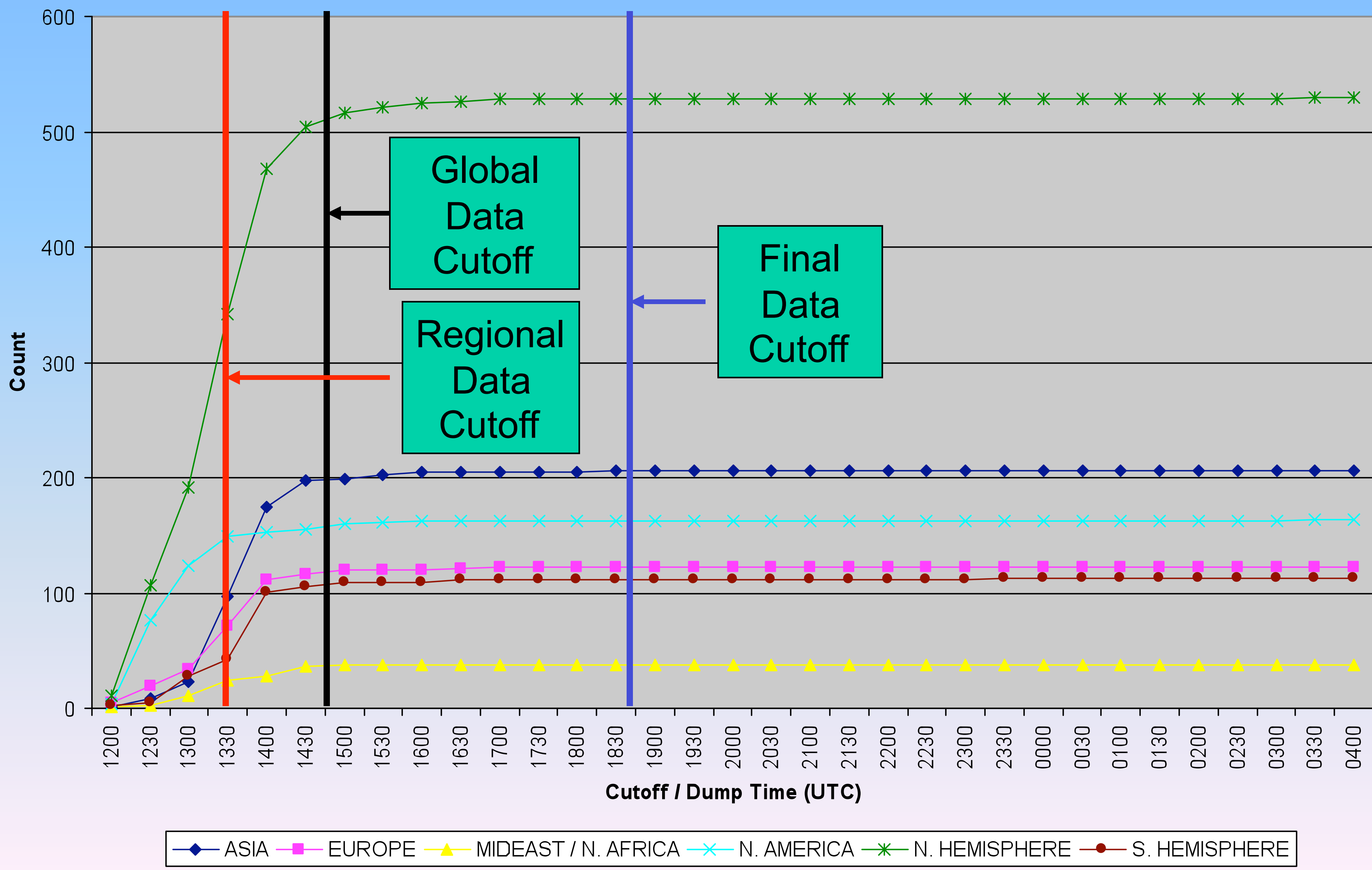


GFS analysis/forecast cycle

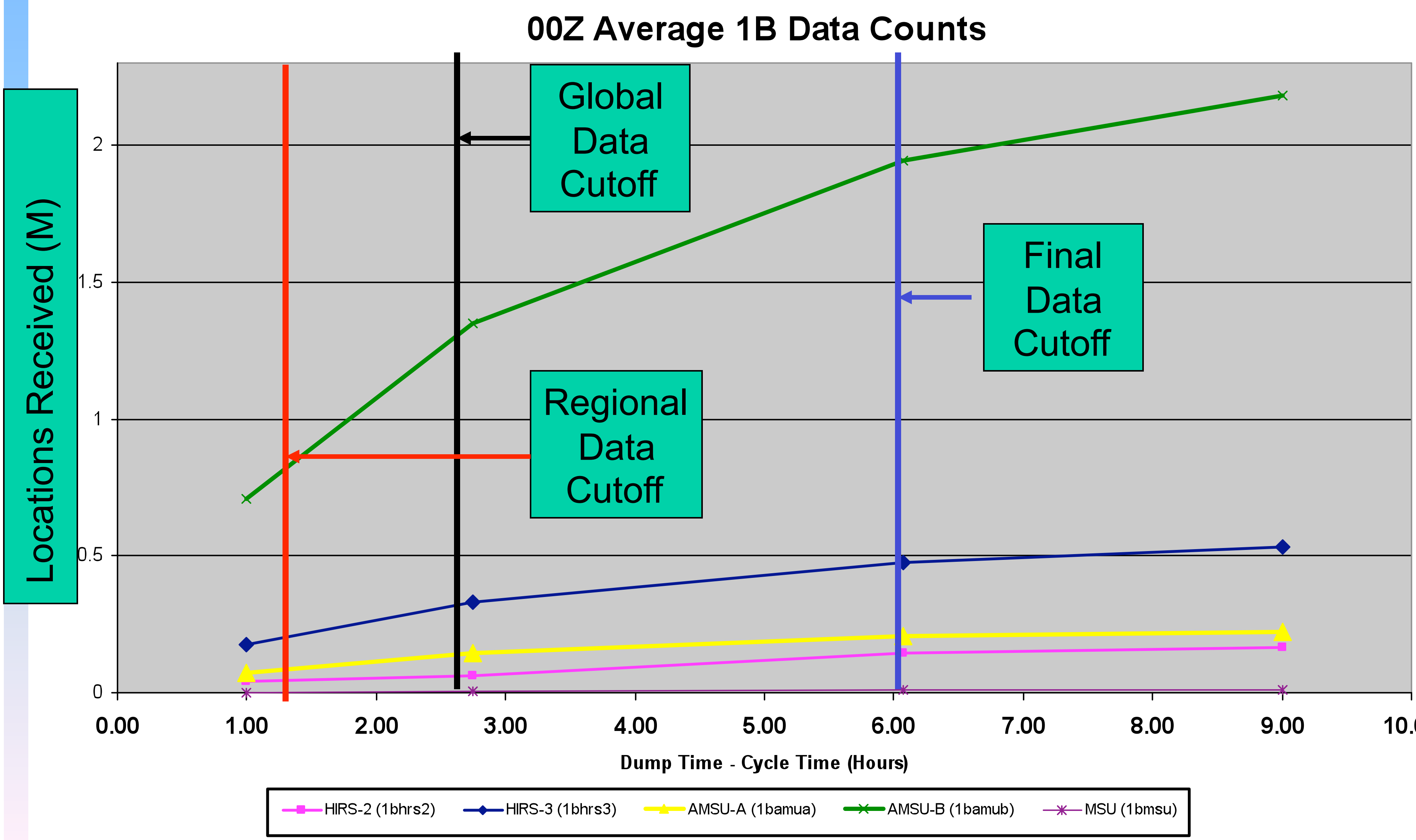


- Any data not available by Cut-off will not be used
- Later catch up cycle at +6:00

Rawinsonde Delivery

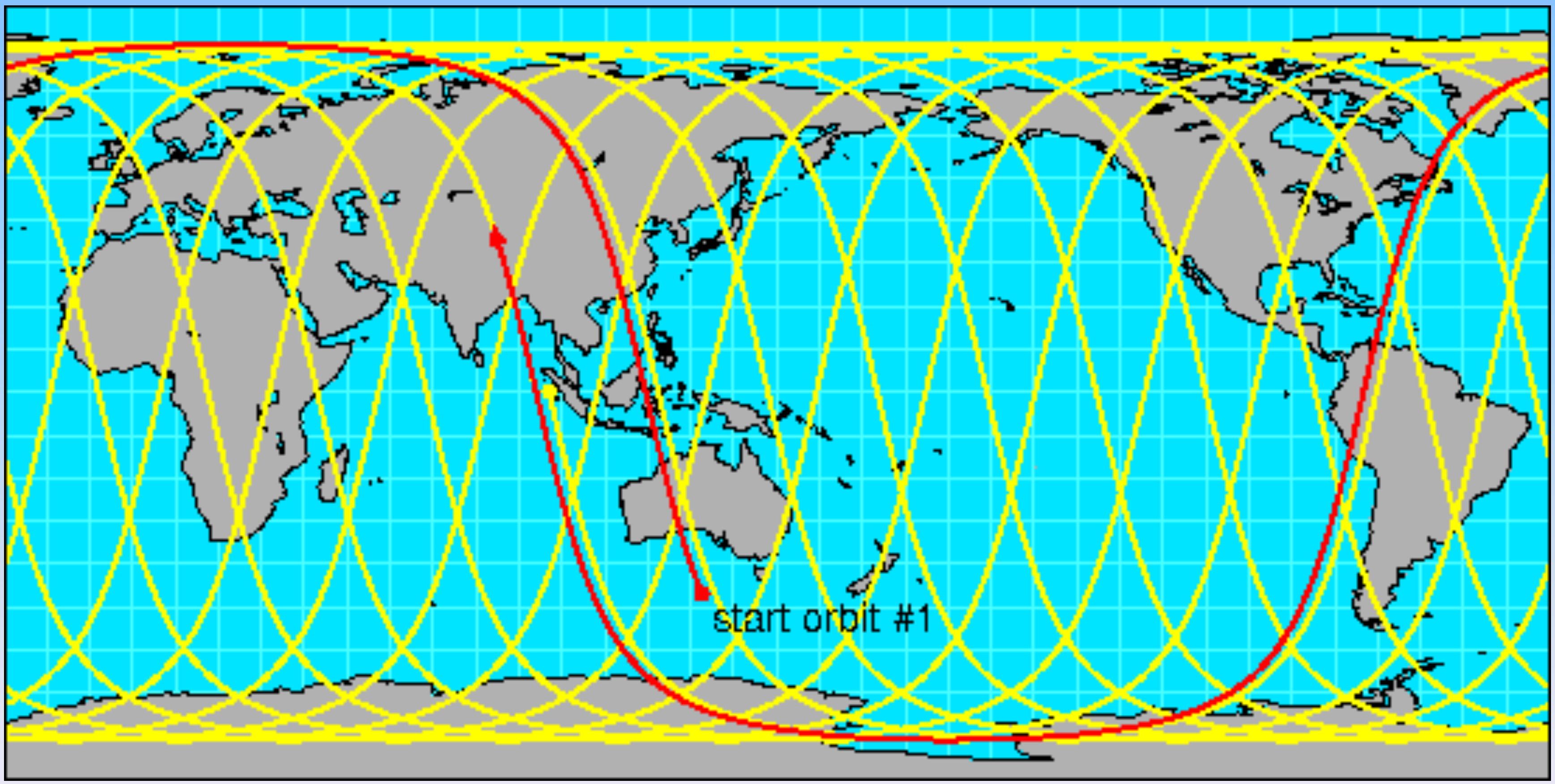


POES Data Delivery

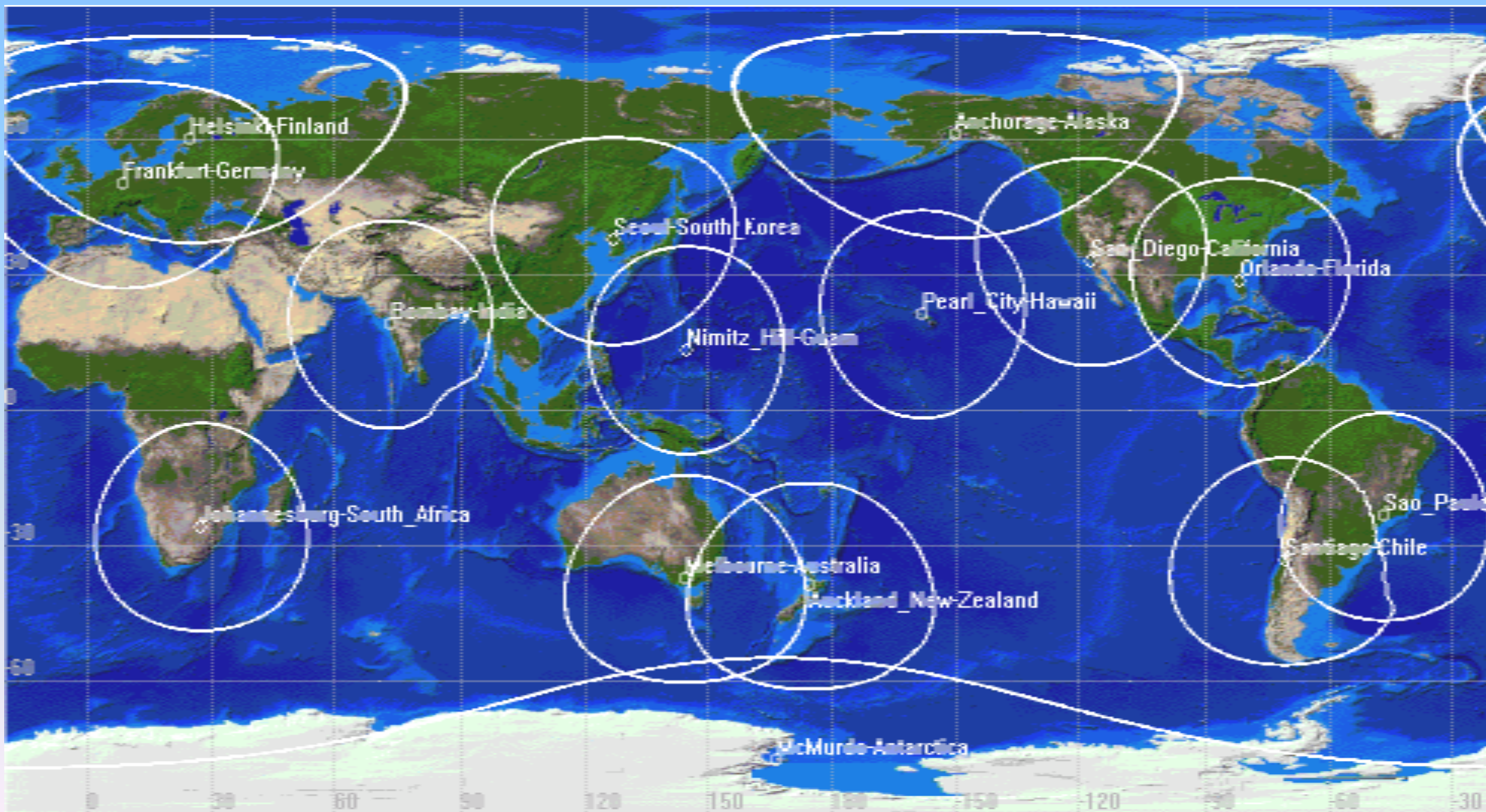


Satellite data delivery

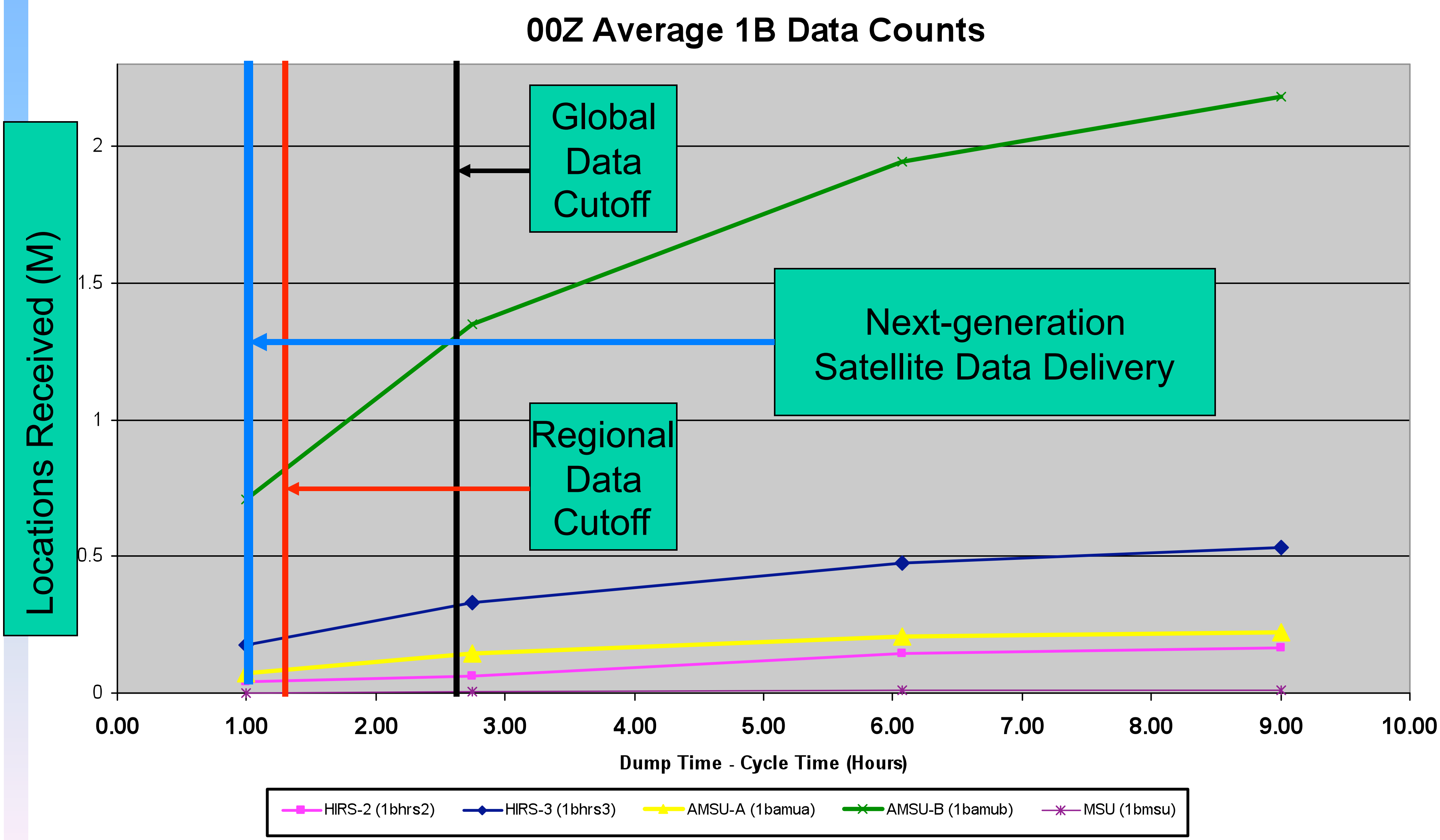
- Satellite data must wait until ground station within sight to download
- Conflicts between satellites
- Blind orbits
- Proposed NPOESS ground system (METOP currently left out)
  - **SafetyNet is a system of 15 globally distributed receptors linked to the centrals via commercial fiber, it enables low data latency and high data availability**


start orbit #1

NPOESS SafetyNetTM Architecture



POES Data Delivery



Assurance of stable data source

- Changes in data processing can result in changes in observation error characteristics
- Notification, testing and provision of test data sets essential prior to changes
- For operational satellites – situation OK
- For research satellites – means loss of control by instrument/program scientists

Accurate forward model

- One of the biggest data assimilation developments in the last 15 years was allowing the observations to be different from the analysis variables
  - In variational schemes this is done through the *K* operator
  - In OI, the same thing could be done – but was only rarely done.
  - The development allows us to use the observations as they were observed AND allows the use of analysis variables with nice properties.

Forward model - Satellite data

- Radiance data differ from many conventional data in that the observations are often indirect observations of meteorological parameters
  - If x is the vector of meteorological parameters we are interested in and
  - y is the observation,
  - then $y = K(x,z)$,
    - where z represents other parameters on which the observations is dependent
    - K is the physical relationship between x, z and y

Satellite data

- Example –
  - y are radiance observations,
  - x are profiles of temperature, moisture and ozone.
  - *K* is the radiative transfer equation and
  - z are unknown parameters such as the surface emissivity (dependent on soil type, soil moisture, etc.), CO2 profile, methane profile, etc.
- In general, *K* is not invertible – thus retrievals.
  - Physical retrievals – usually very similar to 1D variational problems (with different background fields)
  - Statistical retrievals – given y predict x using regression

Satellite data

- 3-4 D variational analysis can be thought of as a generalization of “physical retrieval” to include all types of data and spatial and temporal variability.
- To use data in 2 steps – retrieval and then analysis-- can be done consistently if K is linear and if one is very careful – but is generally suboptimal.

Satellite data

- Key to using data is to have good characterization of *K* – forward model.
- If unknowns in *K*(x,z) – either in formulation of *K* or in unknown variables (z) are too large data cannot be reliably used and must be removed in quality control.
  - example, currently we do not use radiances containing cloud signal
- Note that errors in formulation or unknown variables generally produce correlated errors. This is a significant source of difficulty.

Satellite data

- Additional advantages of using observations directly in analysis system
  - easier definition of observation errors
  - improved quality control
  - less introduction of auxiliary information
  - improved data monitoring

Forward Model Radiances

- Convert analysis variables to T, q, Ps, u, v, ozone
- Interpolate T profiles, q profiles, ozone profiles, u_1,$v_{1,}$ P_s and other surface quantities to observation location
- Reduce u_1 and v_1 to 10m values
- Calculate estimate of radiance using radiative transfer model (and surface emissivity model)
  - Tangent linear of calculation – inner iteration
  - Currently simulation does not include clouds
- Apply bias correction
- Compare observation to estimate

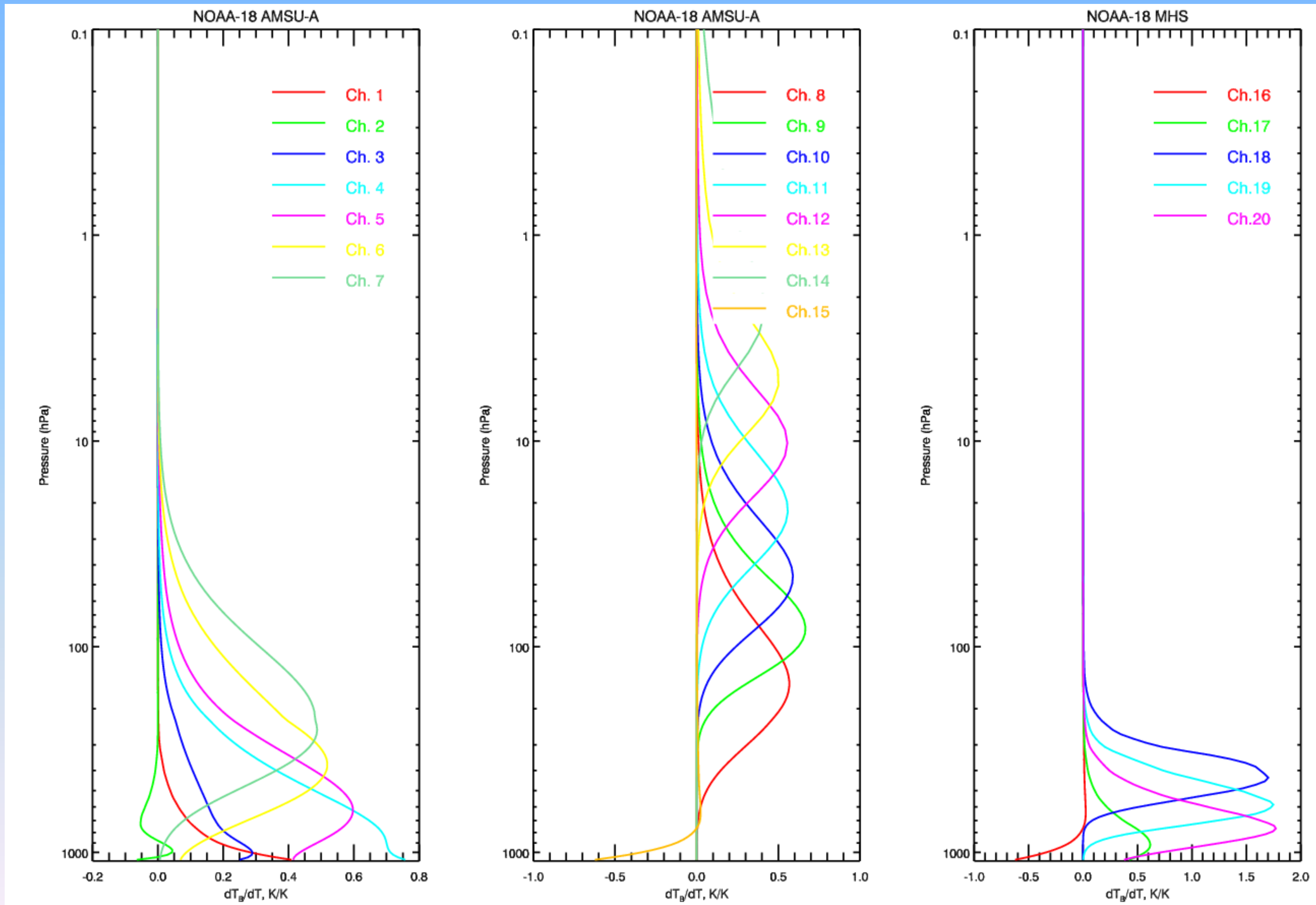
Satellite Radiance Observations

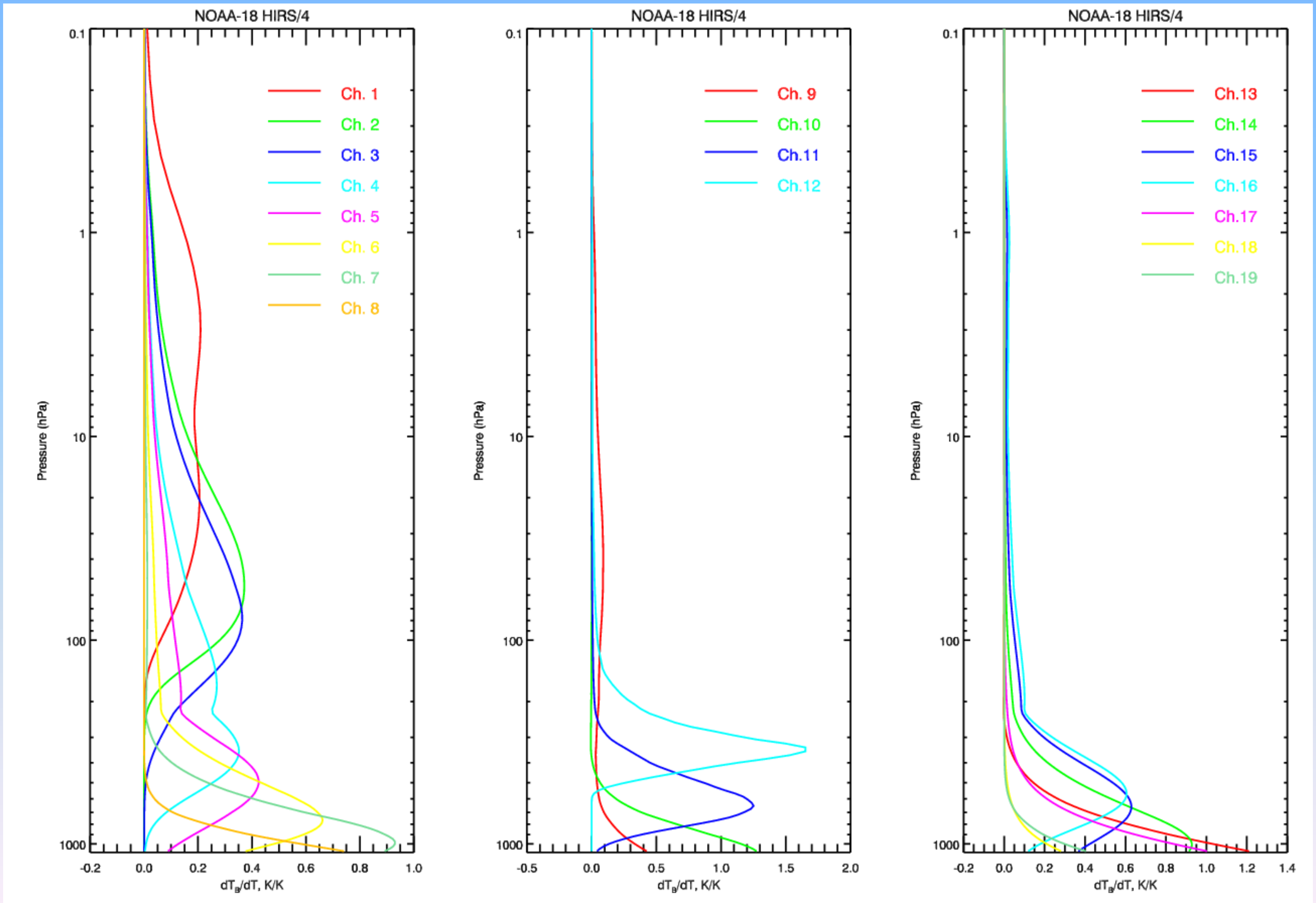
- Measure upwelling radiation at top of atmosphere
- Measure deep layers
  - IR not quite as deep as microwave
  - New IR instruments (AIRS, IASI, GIFTS) narrower, but still quite deep layers
  - Deep layers generally implies large horizontal scale

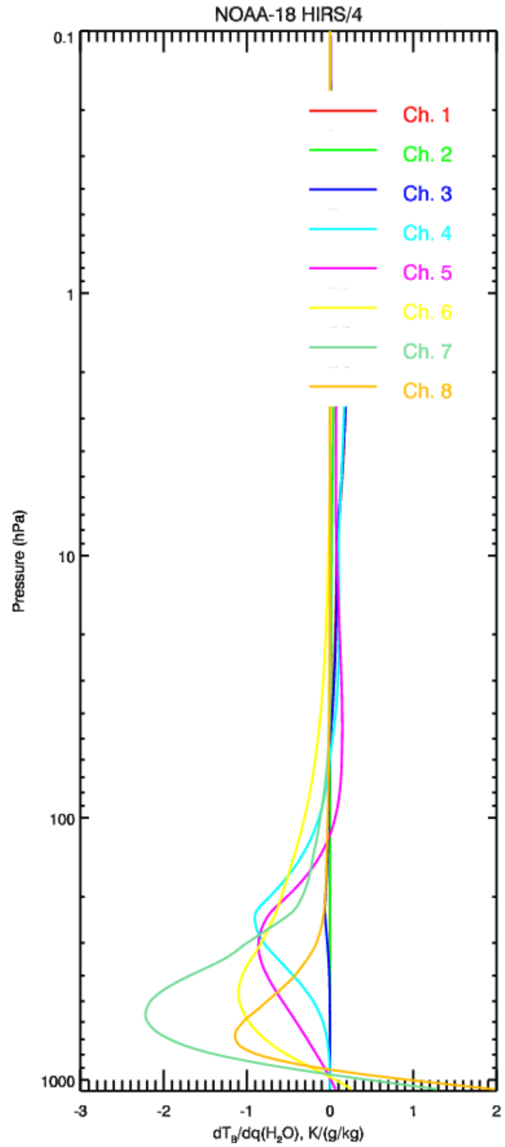
Forward model for RT

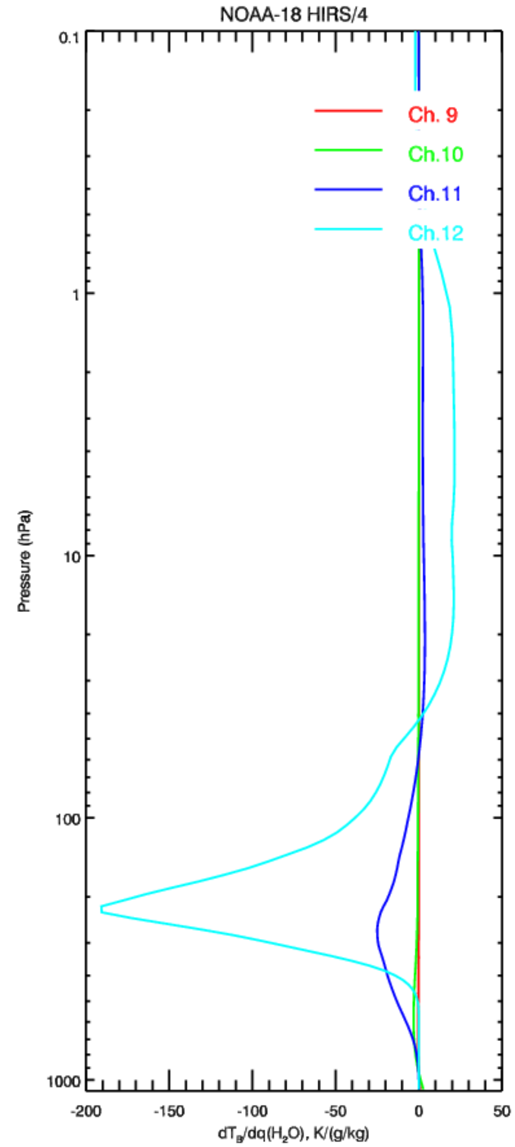
- RTTOV – CRTM two examples of fast forward models
- From CRTM get both simulated radiance and

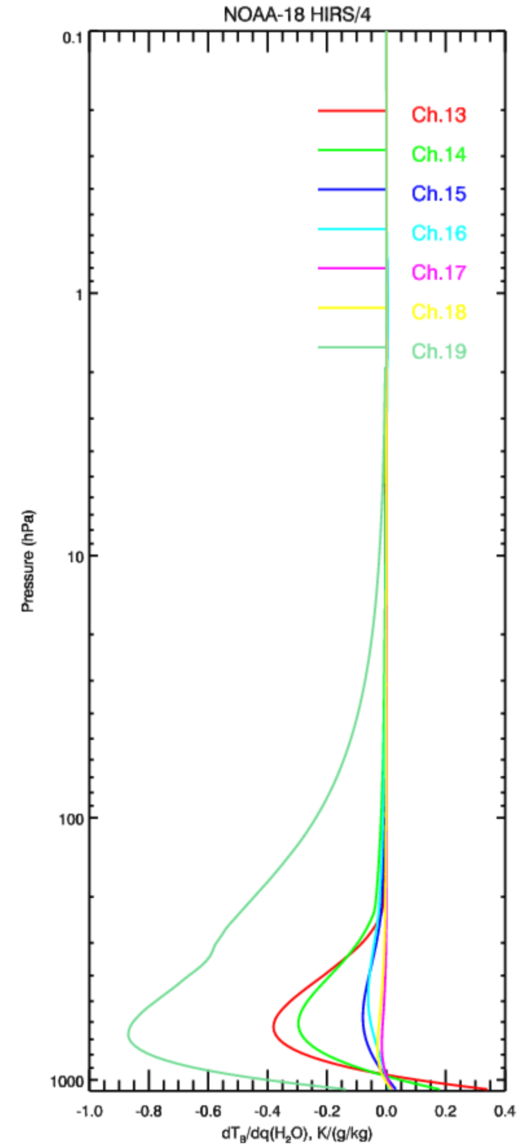
$$\frac{\partial R}{\partial T}, \frac{\partial R}{\partial q}, \frac{\partial R}{\partial q}, \frac{\partial R}{\partial O_3}, \ldots$$

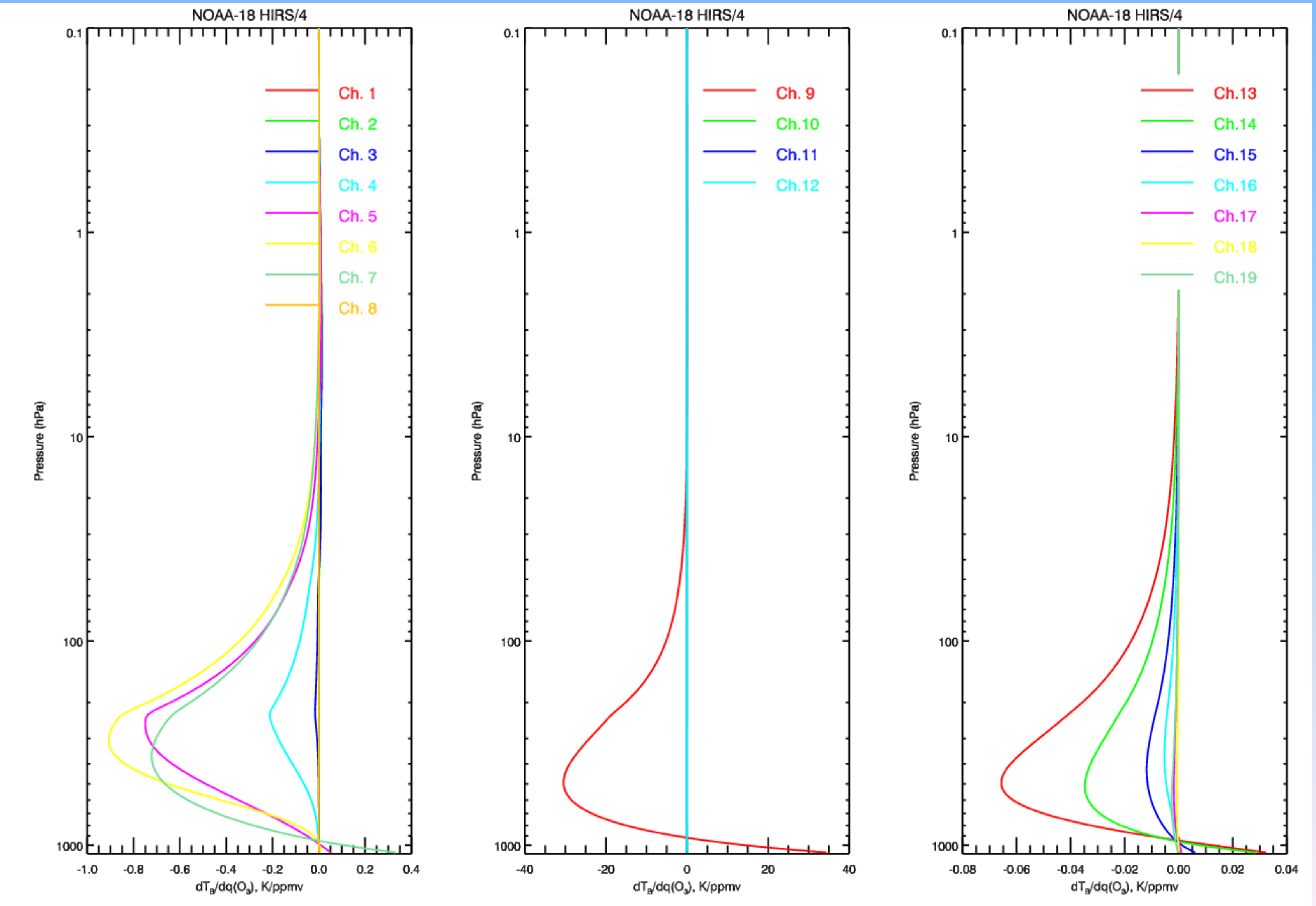

NOAA-18 AMSU-A
Ch. 1
Ch. 2
Ch. 3
Ch. 4
Ch. 5
Ch. 6
Ch. 7
Pressure (hPa)
0.1
1
10
100
1000
-0.2
0.0
0.2
0.4
0.6
0.8
dT_B/dT, K/K
NOAA-18 AMSU-A
Ch. 8
Ch. 9
Ch.10
Ch.11
Ch.12
Ch.13
Ch.14
Ch.15
Pressure (hPa)
-1.0
-0.5
0.0
0.5
1.0
dT_B/dT, K/K
NOAA-18 MHS
Ch.16
Ch.17
Ch.18
Ch.19
Ch.20
Pressure (hPa)
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
dT_B/dT, K/K


NOAA-18 HIRS/4
Ch. 1
Ch. 2
Ch. 3
Ch. 4
Ch. 5
Ch. 6
Ch. 7
Ch. 8
Pressure (hPa)
dT_B/dT, K/K
NOAA-18 HIRS/4
Ch. 9
Ch.10
Ch.11
Ch.12
Pressure (hPa)
dT_B/dT, K/K
NOAA-18 HIRS/4
Ch.13
Ch.14
Ch.15
Ch.16
Ch.17
Ch.18
Ch.19
Pressure (hPa)
dT_B/dT, K/K

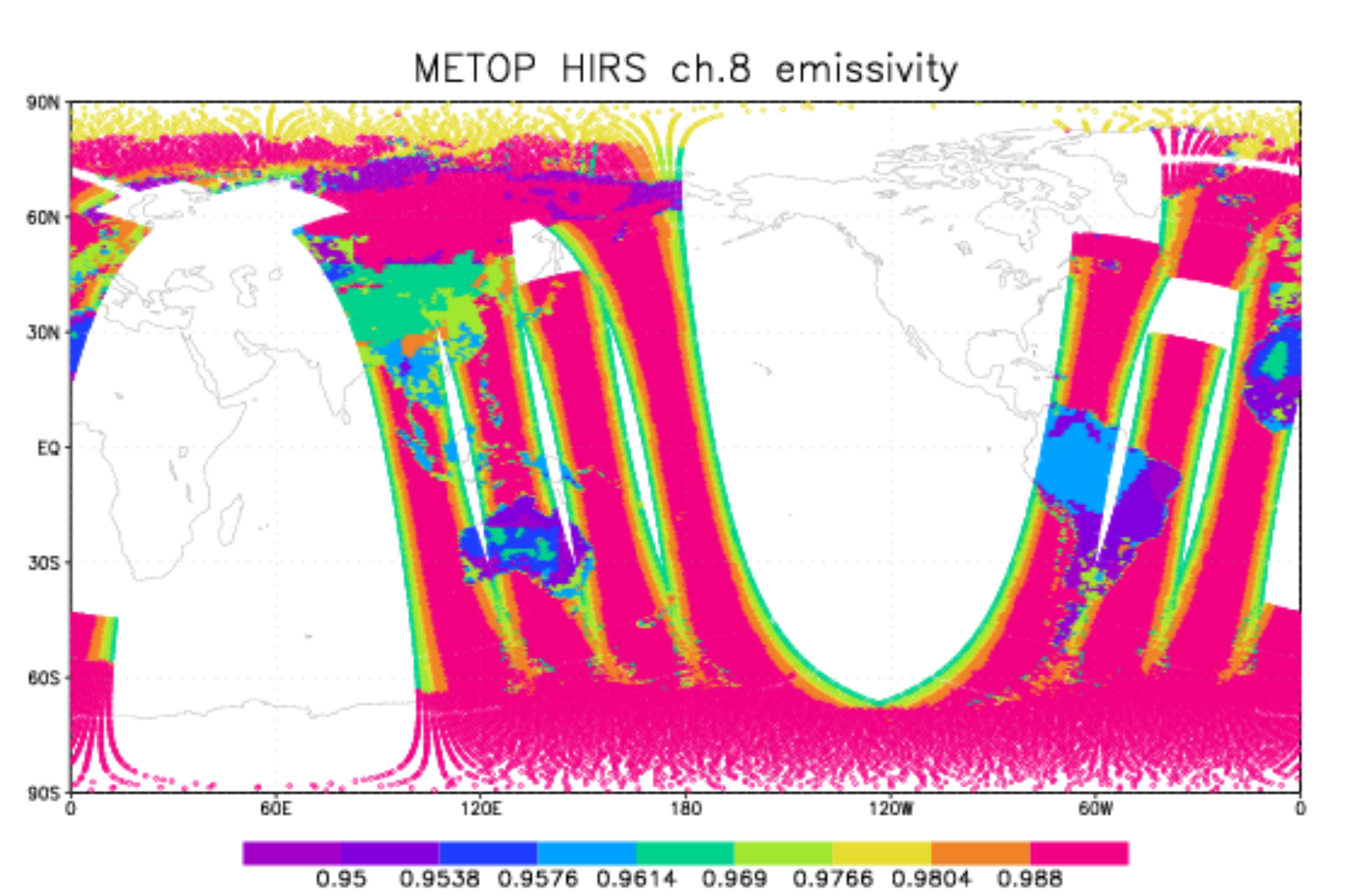

NOAA-18 HIRS/4
Pressure (hPa)
0.1
1
10
100
1000
-3
-2
-1
0
1
2
dT_B/dq(H_2O), K/(g/kg)
Ch. 1
Ch. 2
Ch. 3
Ch. 4
Ch. 5
Ch. 6
Ch. 7
Ch. 8


NOAA-18 HIRS/4
Pressure (hPa)
0.1
1
10
100
1000
-200
-150
-100
-50
0
50
dT_B/dq(H_2O), K/(g/kg)
Ch. 9
Ch.10
Ch.11
Ch.12

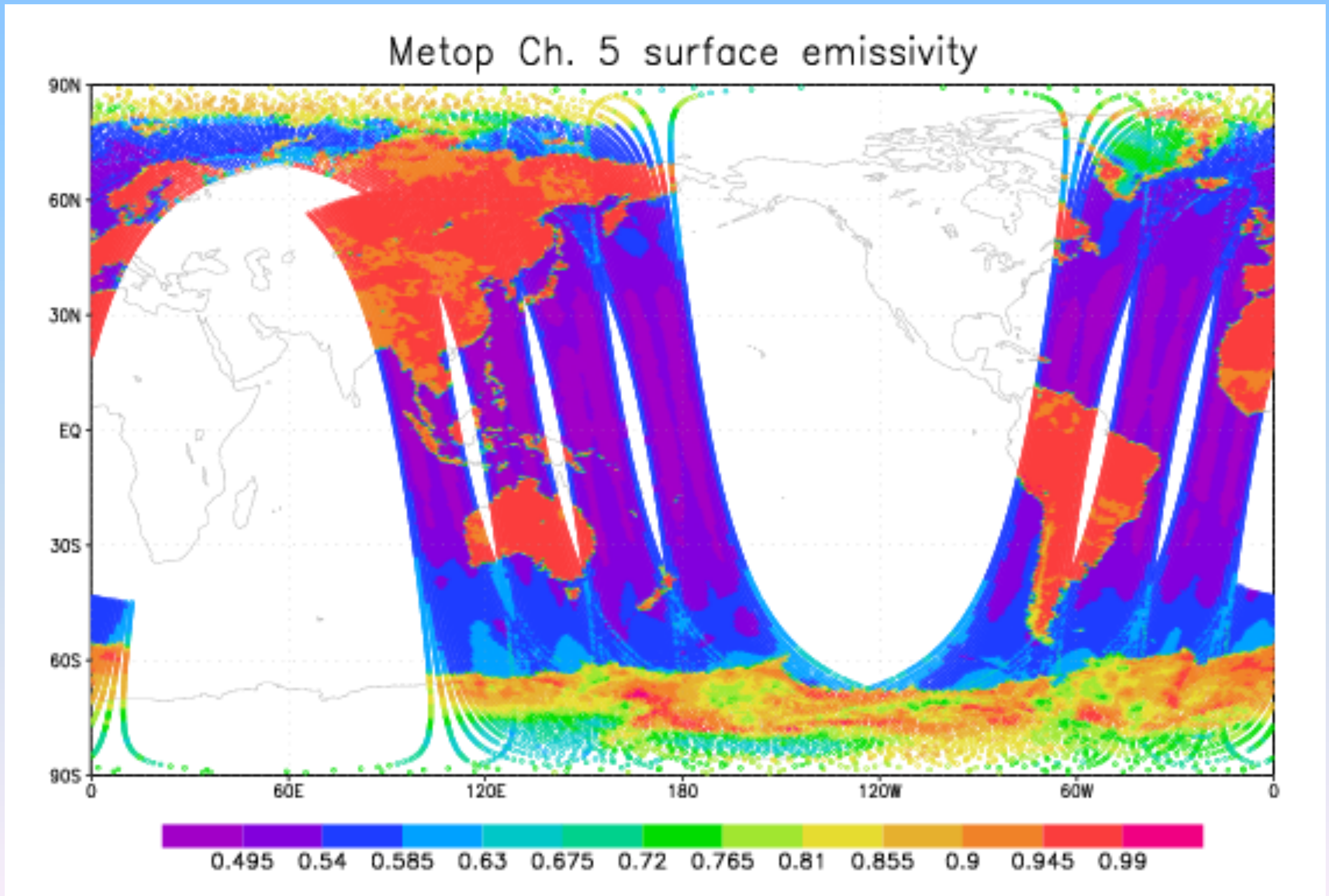

NOAA-18 HIRS/4
Pressure (hPa)
0.1
1
10
100
1000
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
dT_B/dq(H_2O), K/(g/kg)
Ch.13
Ch.14
Ch.15
Ch.16
Ch.17
Ch.18
Ch.19


NOAA-18 HIRS/4
Ch. 1
Ch. 2
Ch. 3
Ch. 4
Ch. 5
Ch. 6
Ch. 7
Ch. 8
Pressure (hPa)
dT_B/dq(O_3), K/ppmv
NOAA-18 HIRS/4
Ch. 9
Ch.10
Ch.11
Ch.12
Pressure (hPa)
dT_B/dq(O_3), K/ppmv
NOAA-18 HIRS/4
Ch.13
Ch.14
Ch.15
Ch.16
Ch.17
Ch.18
Ch.19
Pressure (hPa)
dT_B/dq(O_3), K/ppmv

Surface Emissivity
Infrared

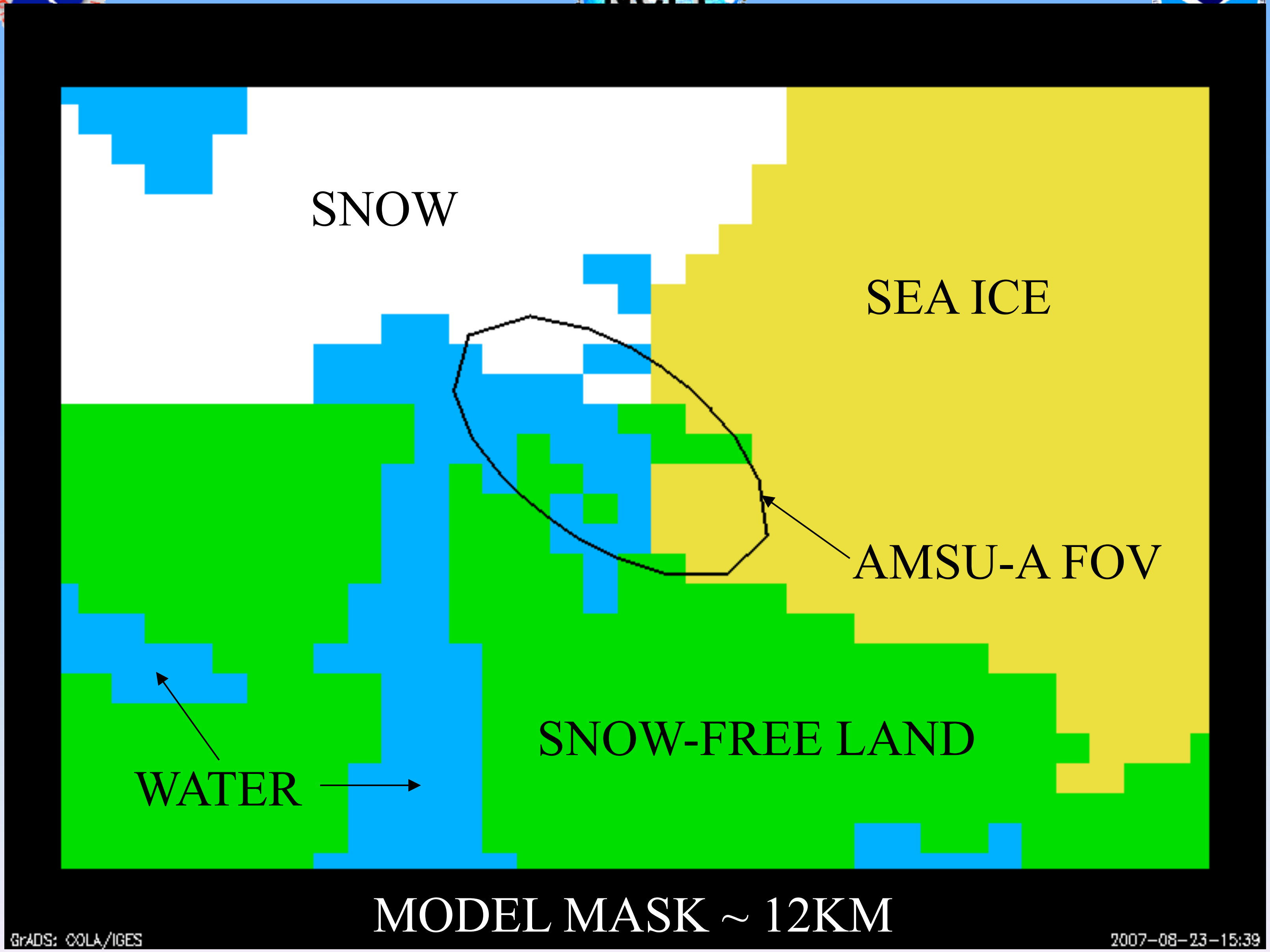


Surface Emissivity Microwave



Accounting for size and shap of Field of View

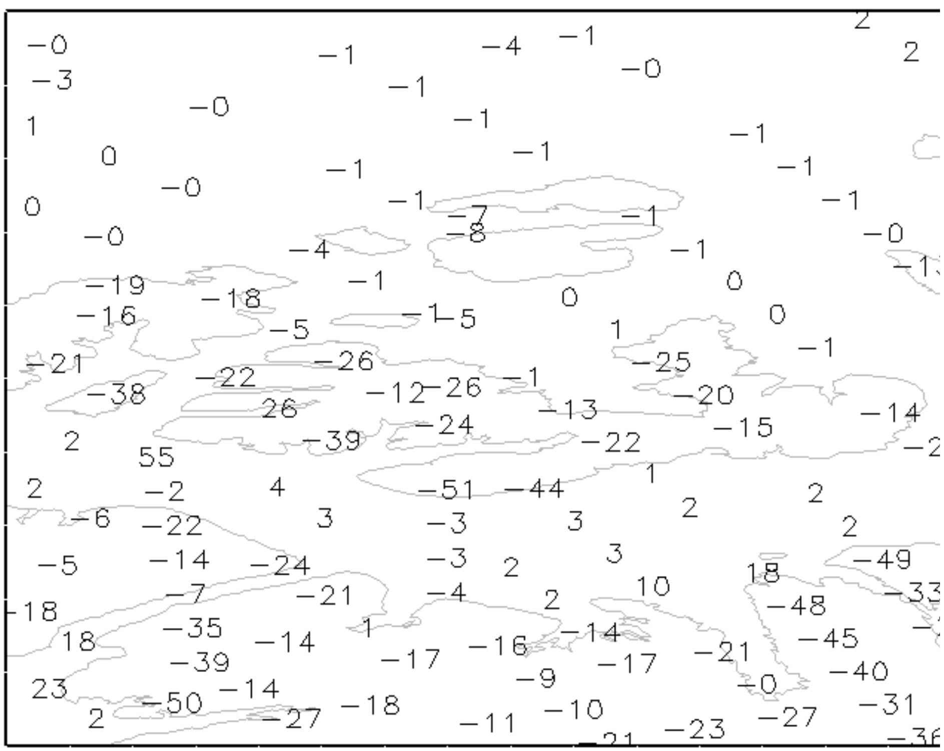
- Size and shape of FOV can have a large impact – especially when the FOV covers different surface types.
  - Emissivity of land and sea quite different so a mixture will give very different results
  - Power from any point of FOV also important
- Microwave FOVs tend to be much larger than IR FOVs
- Major problem knowing what you are looking at
  - Freezing and thawing of lakes
  - Flooding
  - Snowfall
  - Vegetation (leaf water content)
  - Dew
  - High enough resolution (in space and time) land use maps
- Ability to properly model % surface characteristics in radiative transfer important


SNOW
SEA ICE
AMSU-A FOV
SNOW-FREE LAND
WATER
MODEL MASK ~ 12KM
GrADS: COLA/IGES
2007-08-23-15:39

IMPACT: ACCOUNTING FOR FOV

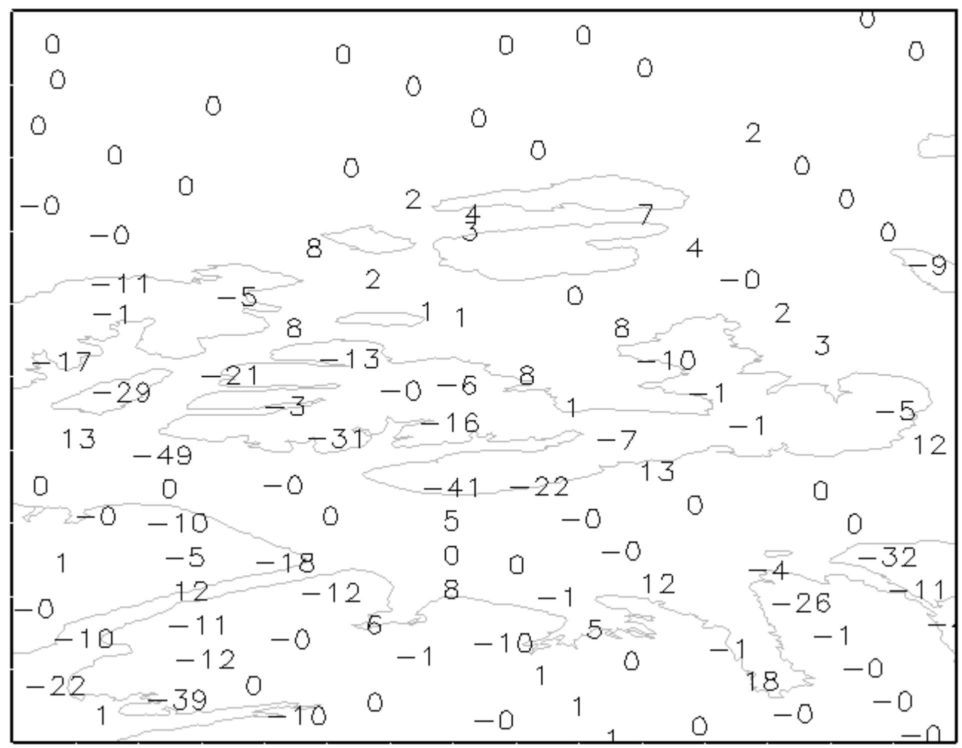
EX: NOAA-15 AMSU-A, CHANNEL 2

CONTROL:
OBS. MINUS GUESS T_b



NORTHERN CANADA

IMPACT: CHANGE IN
OBS. MINUS GUESS T_b



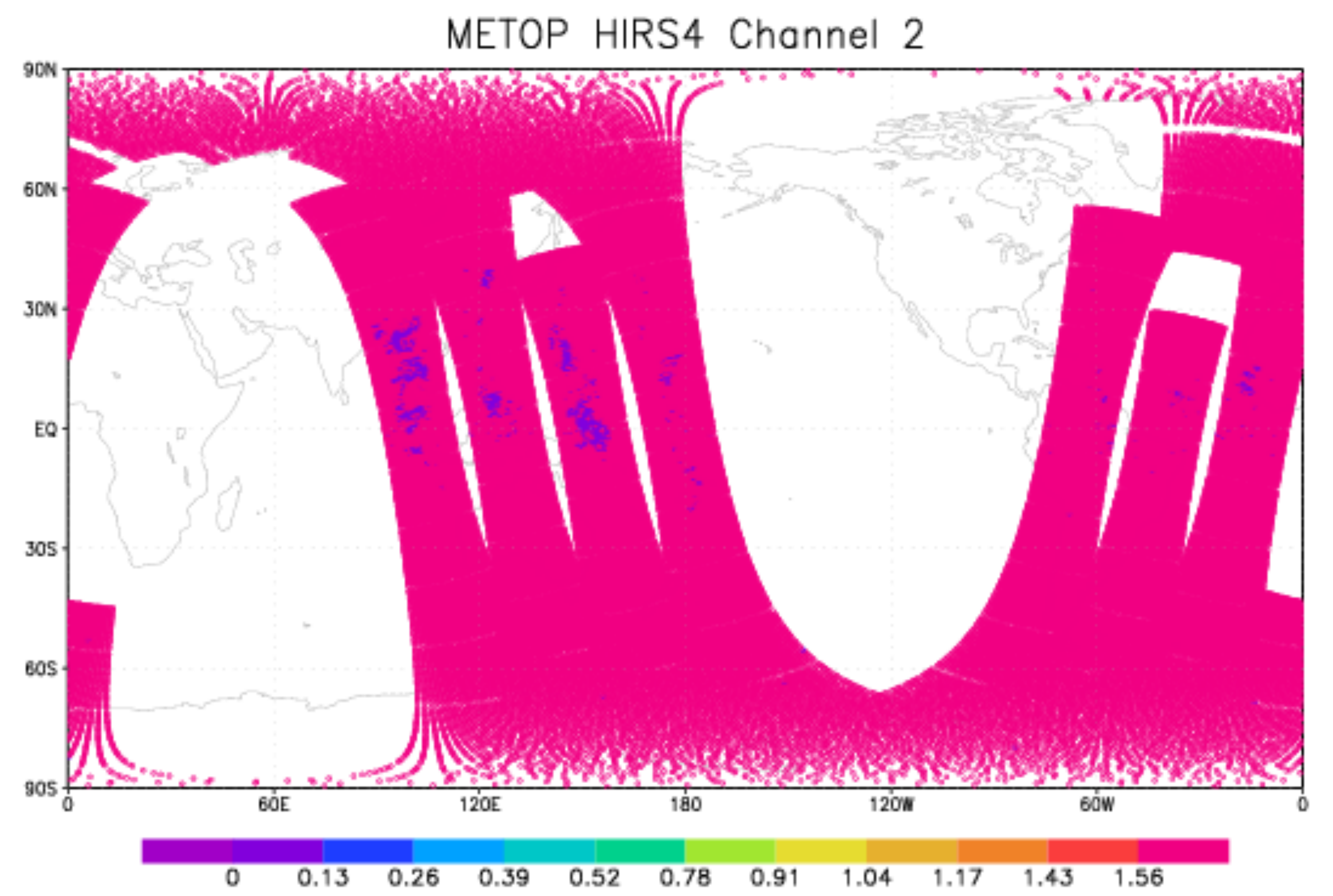
NEGATIVE IS IMPROVEMENT

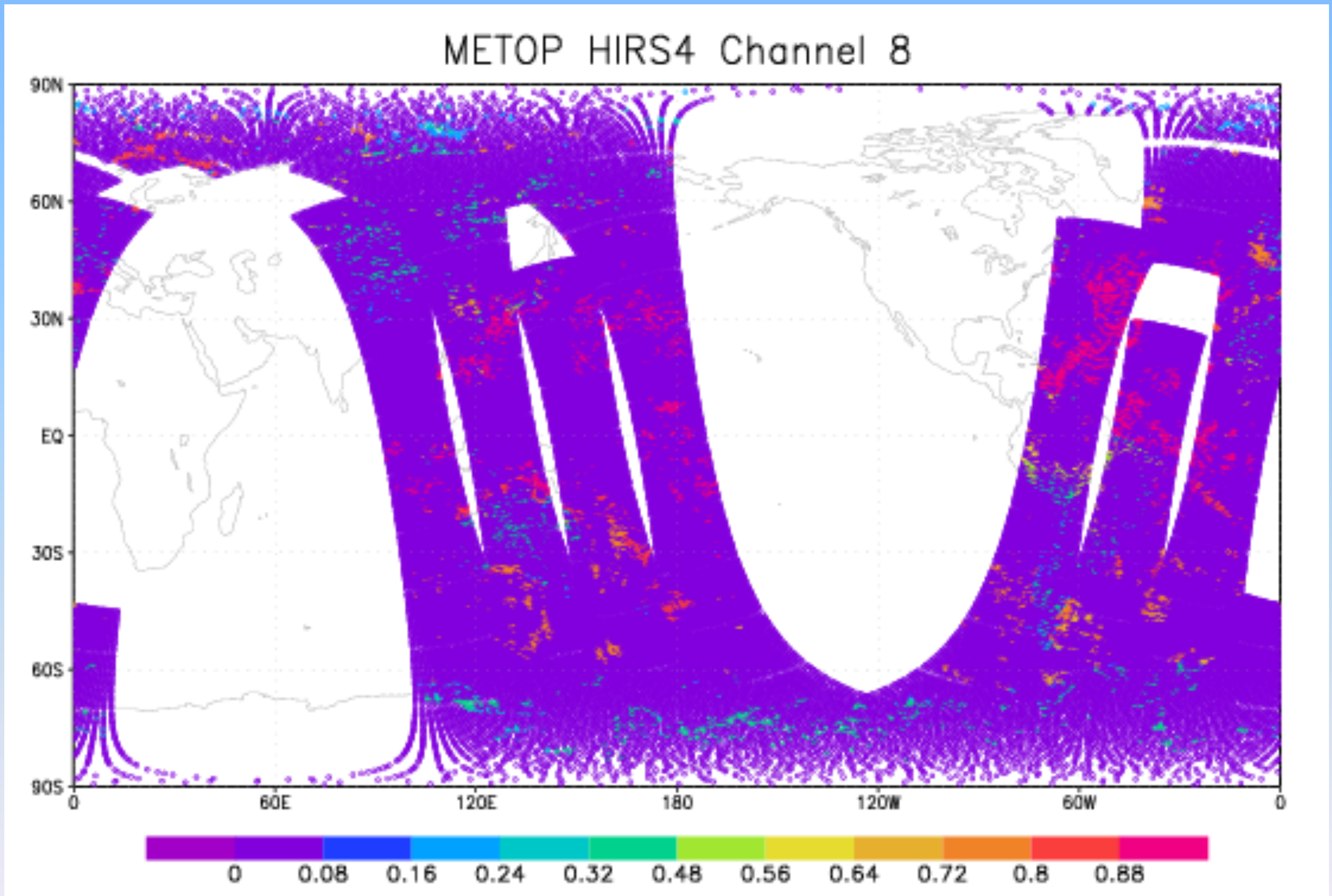
Quality control procedures

- The quality control step may be the most important aspect of satellite data assimilation
- Data must be removed which has gross errors or which cannot be properly simulated by forward model
- Most problems with satellite data come from 3 sources
  - Instrument problems
  - Clouds and precipitation simulation errors
  - Surface emissivity simulation errors

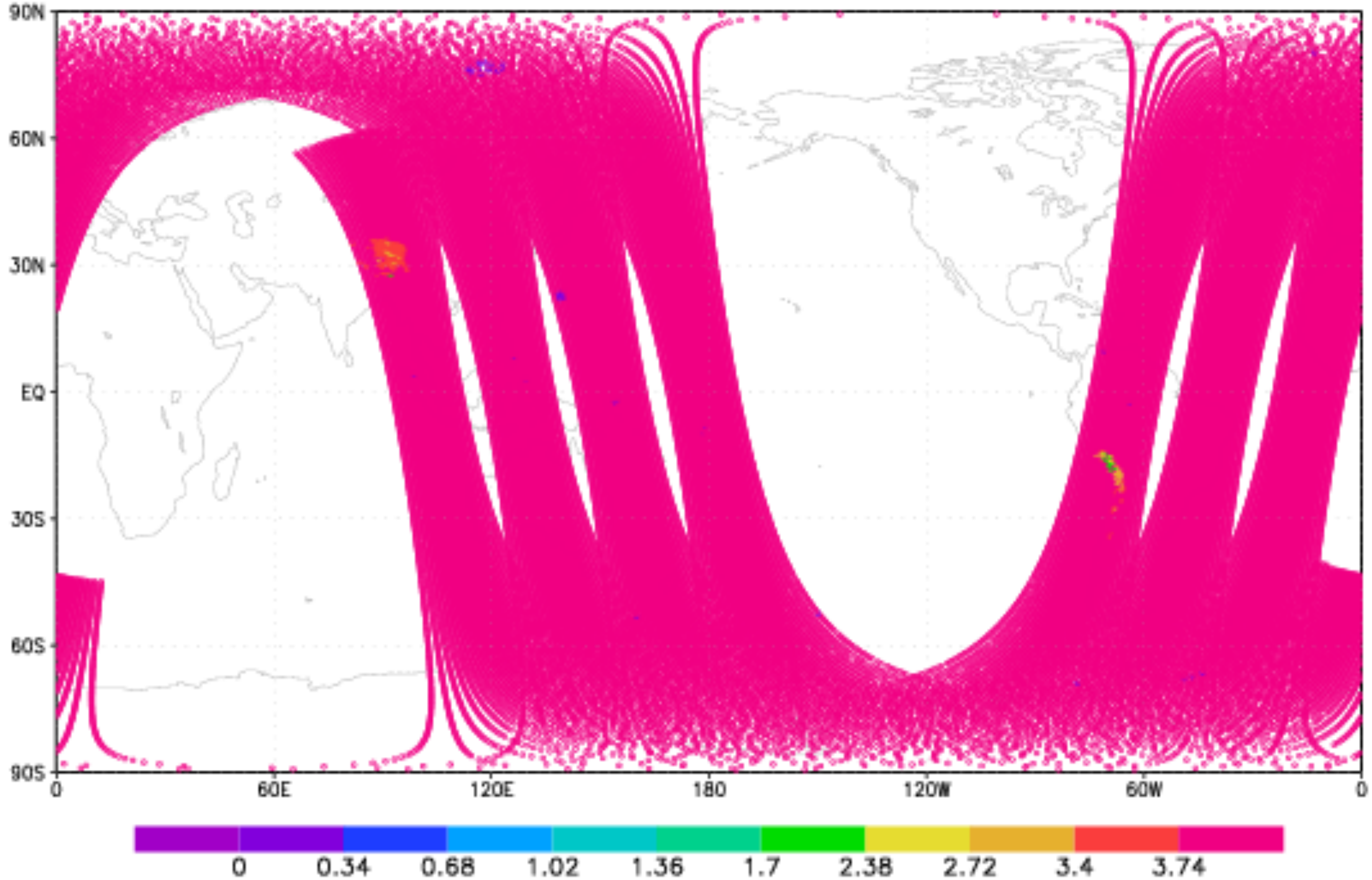
Quality control procedures

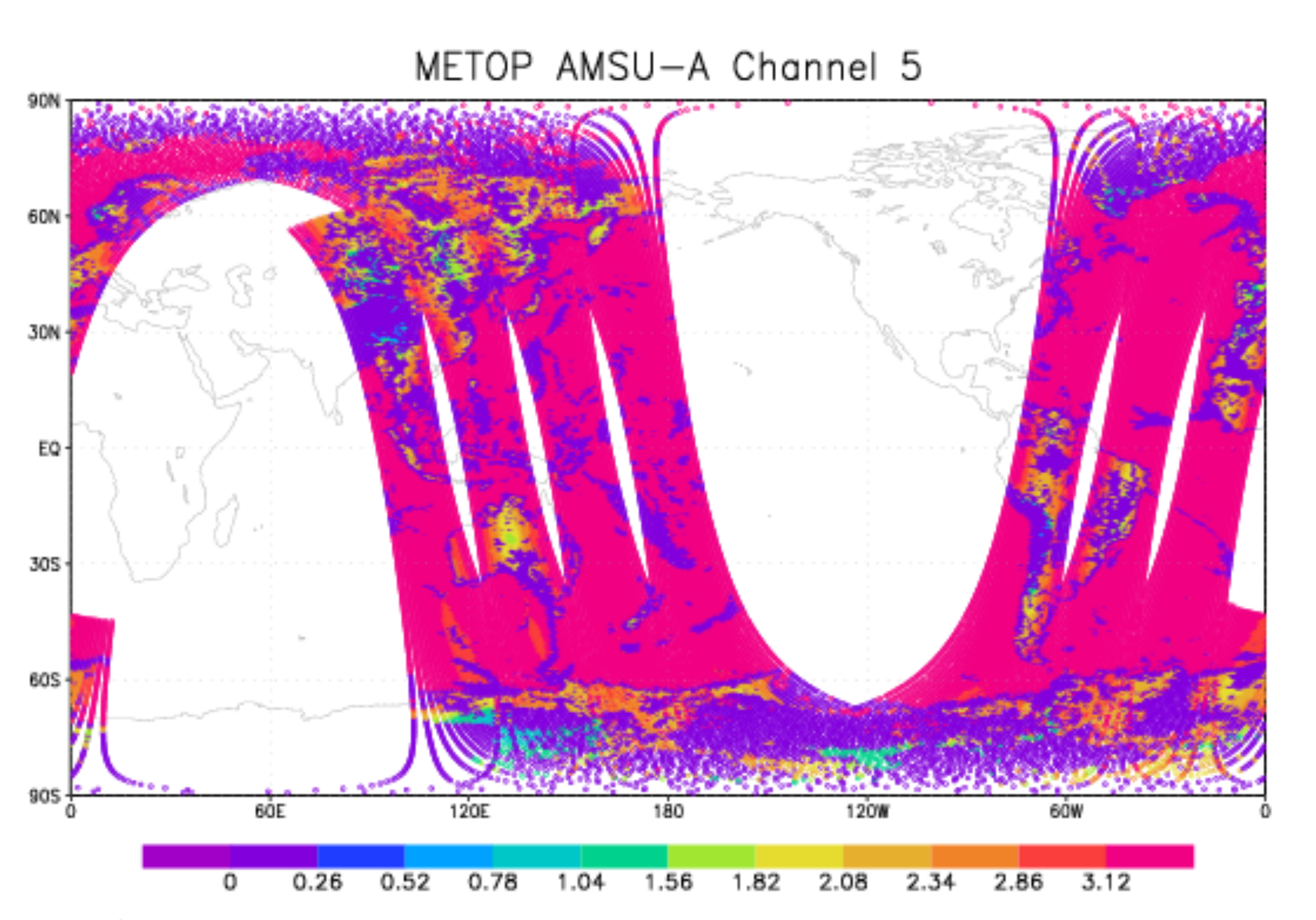
- IR cannot see through clouds
  - Since deep layers not many channels above clouds – cloud height difficult to determine
- Microwave impacted by clouds and precipitation but signal from thinner clouds can be modeled and mostly accounted for in bias correction
- Surface emissivity and temperature characteristics not well known for land/snow/ice
  - Also makes detection of clouds/precip. more difficult over these surfaces


METOP HIRS4 Channel 2
90N
60N
30N
EQ
30S
60S
90S
0
60E
120E
180
120W
60W
0
0
0.13
0.26
0.39
0.52
0.78
0.91
1.04
1.17
1.43
1.56


METOP HIRS4 Channel 8
90N
60N
30N
EQ
30S
60S
90S
0
60E
120E
180
120W
60W
0
0
0.08
0.16
0.24
0.32
0.48
0.56
0.64
0.72
0.8
0.88

METOP AMSU-A Channel 7



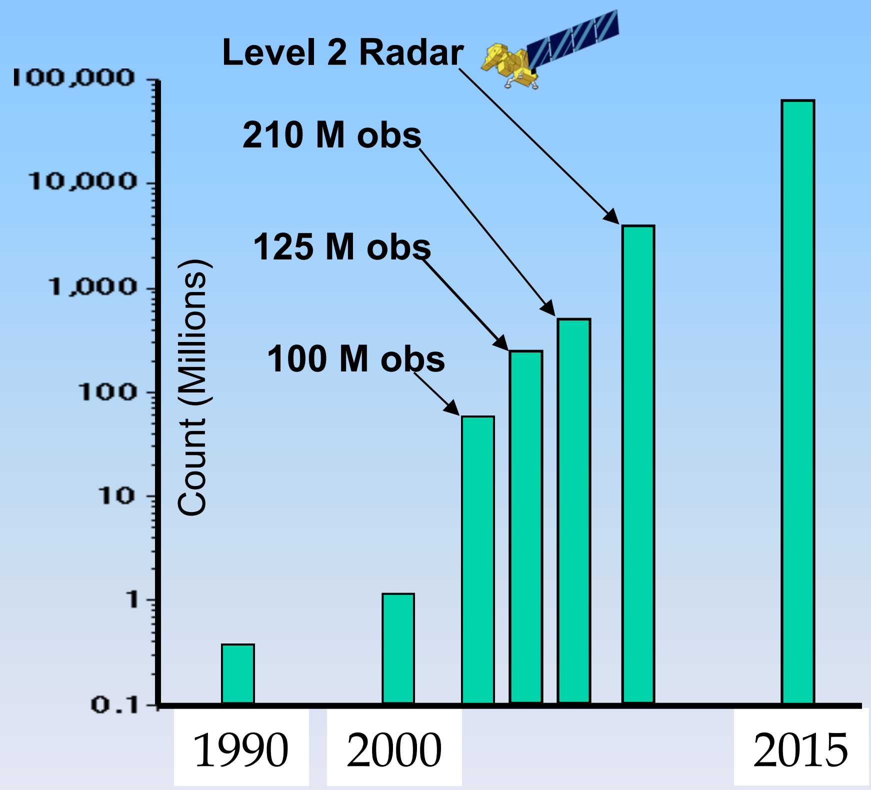

METOP AMSU-A Channel 5
90N
60N
30N
EQ
30S
60S
90S
0
60E
120E
180
120W
60W
0
0
0.26
0.52
0.78
1.04
1.56
1.82
2.08
2.34
2.86
3.12

Quality control procedures (thinning)

- Some data is thinned prior to using
- Three reasons
  - Redundancy in data
    - Radiances
    - AMWs
  - Reduce correlated error
    - AMWs
  - Computational expense
    - Radiances

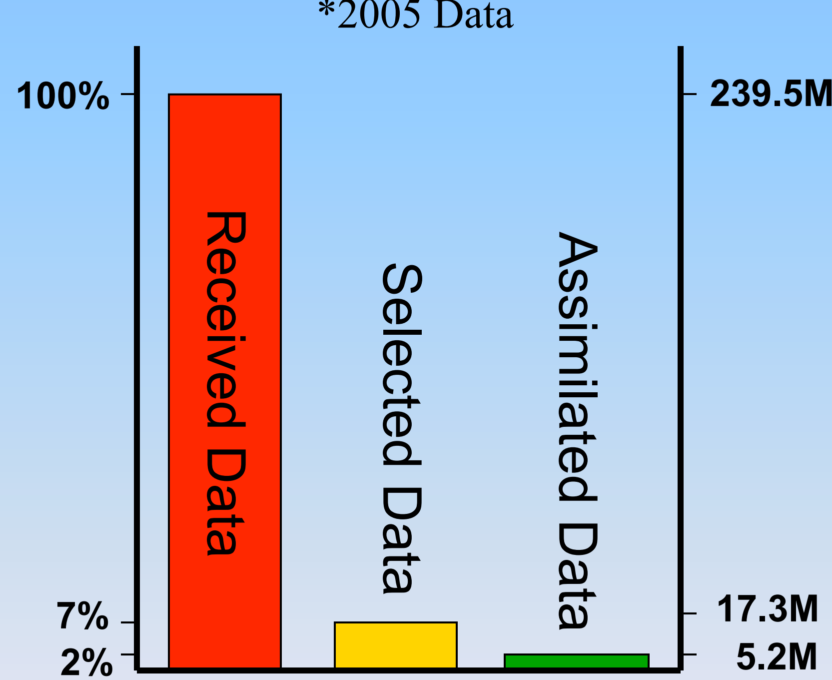
Satellite Data Ingest

Daily Satellite & Radar Observation Count



Five Order of Magnitude Increases in Satellite Data Over Fifteen Years (2000-2015)

Daily Percentage of Data Ingested into Models



Received = All observations received operationally from providers
Selected = Observations selected as suitable for use
Assimilated = Observations actually used by models

Observational errors

- Observation errors specified based on instrument errors and o-b statistics. Note difference between instrument errors and o-b statistics tend to be quite small. (see later slides)
- Generally for satellite data errors are specified a bit large since the correlated errors are not well known.
- Bias must be accounted for since it is often larger than signal

Satellite observations

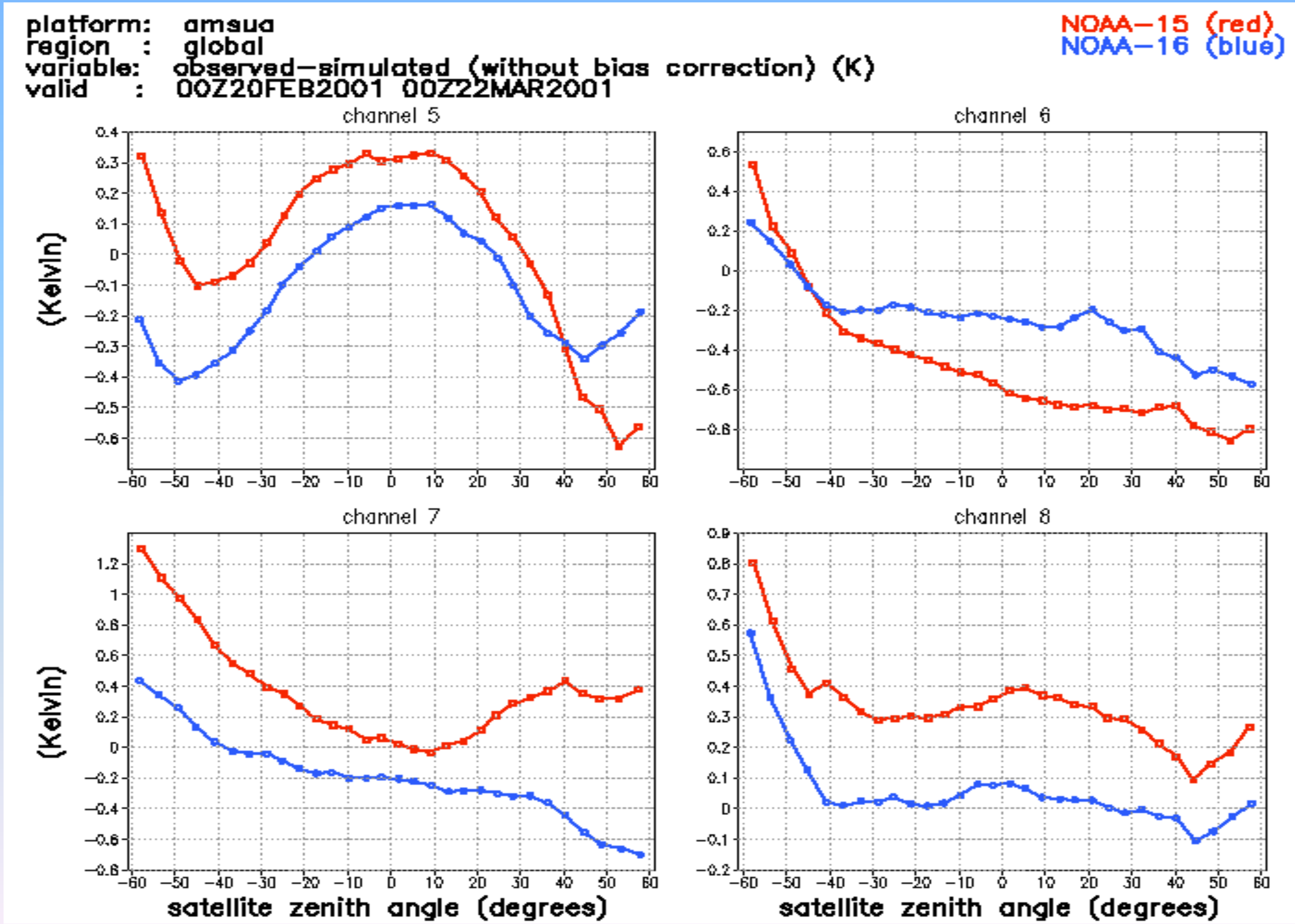
- Different observation and error characteristics
  – Type of data (cloud track winds, radiances, etc.)
  – Version of instrument type (e.g., IR sounders - AIRS, HIRS, IASI, GOES, GIFTS, etc.)
  – Different models of same instrument (e.g., NOAA-15 AMSU-A, NOAA-16 AMSU-A)

Bias Correction

- The differences between simulated and observed observations can show significant biases
- The source of the bias can come from
  - Biased observations
  - Inadequacies in the characterization of the instruments
  - Deficiencies in the forward models
  - Biases in the background
- Except when the bias is due to the background we would like to remove these biases

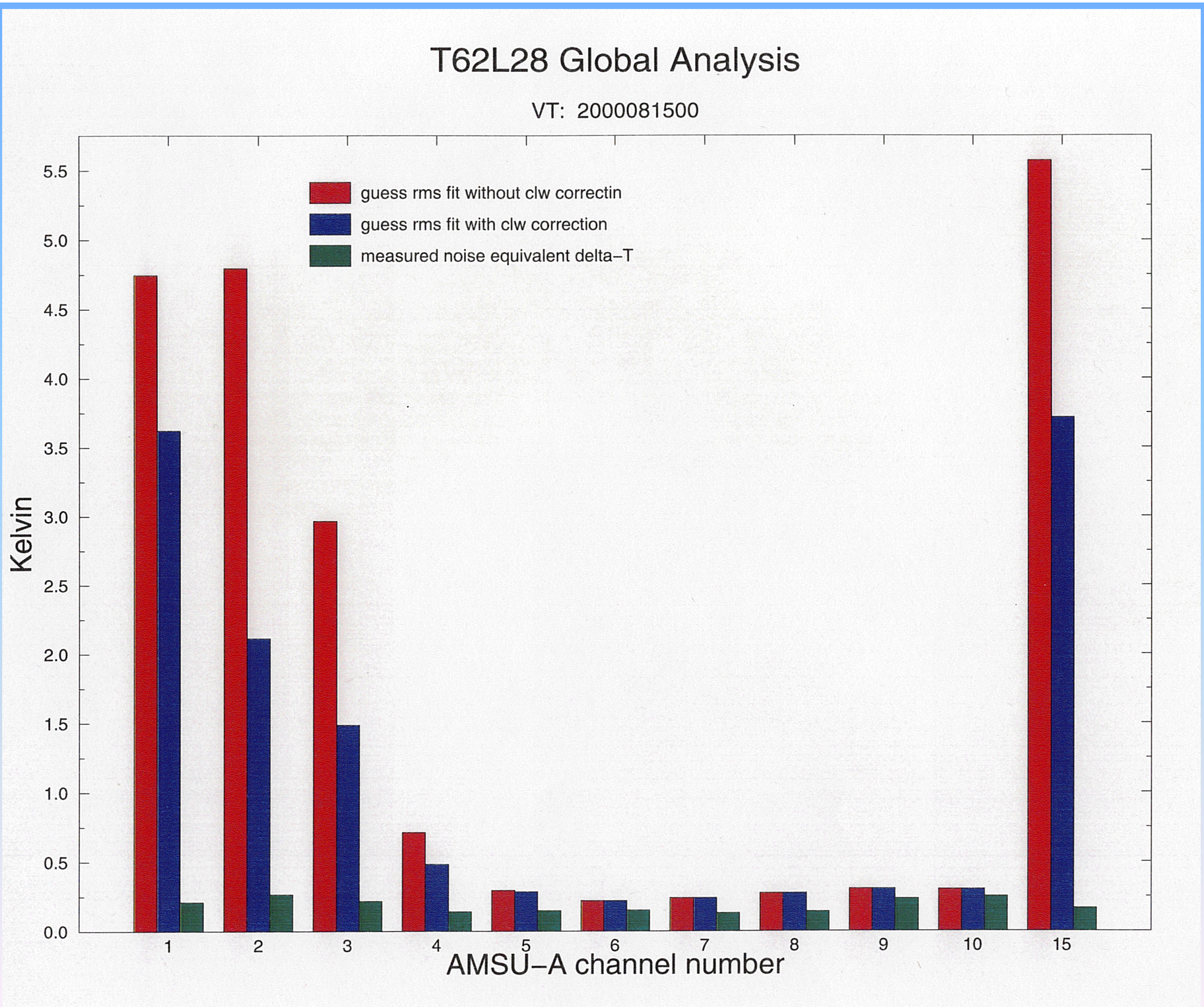
Bias Correction

- Currently we are only bias correcting, the radiances and the radiosonde data (radiation correction)
- For radiances, biases can be much larger than signal. Essential to bias correct the data
- NCEP uses a 2 step process for radiances (others are similar)
  - Angle correction (very slowly evolving – different correction for each scan position)
  - Air Mass correction (slowly evolving based on predictors)


platform: amsua
region : global
variable: observed-simulated (without bias correction) (K)
valid : 00Z20FEB2001 00Z22MAR2001
NOAA-15 (red)
NOAA-16 (blue)
channel 5
channel 6
channel 7
channel 8
(Kelvin)
satellite zenith angle (degrees)

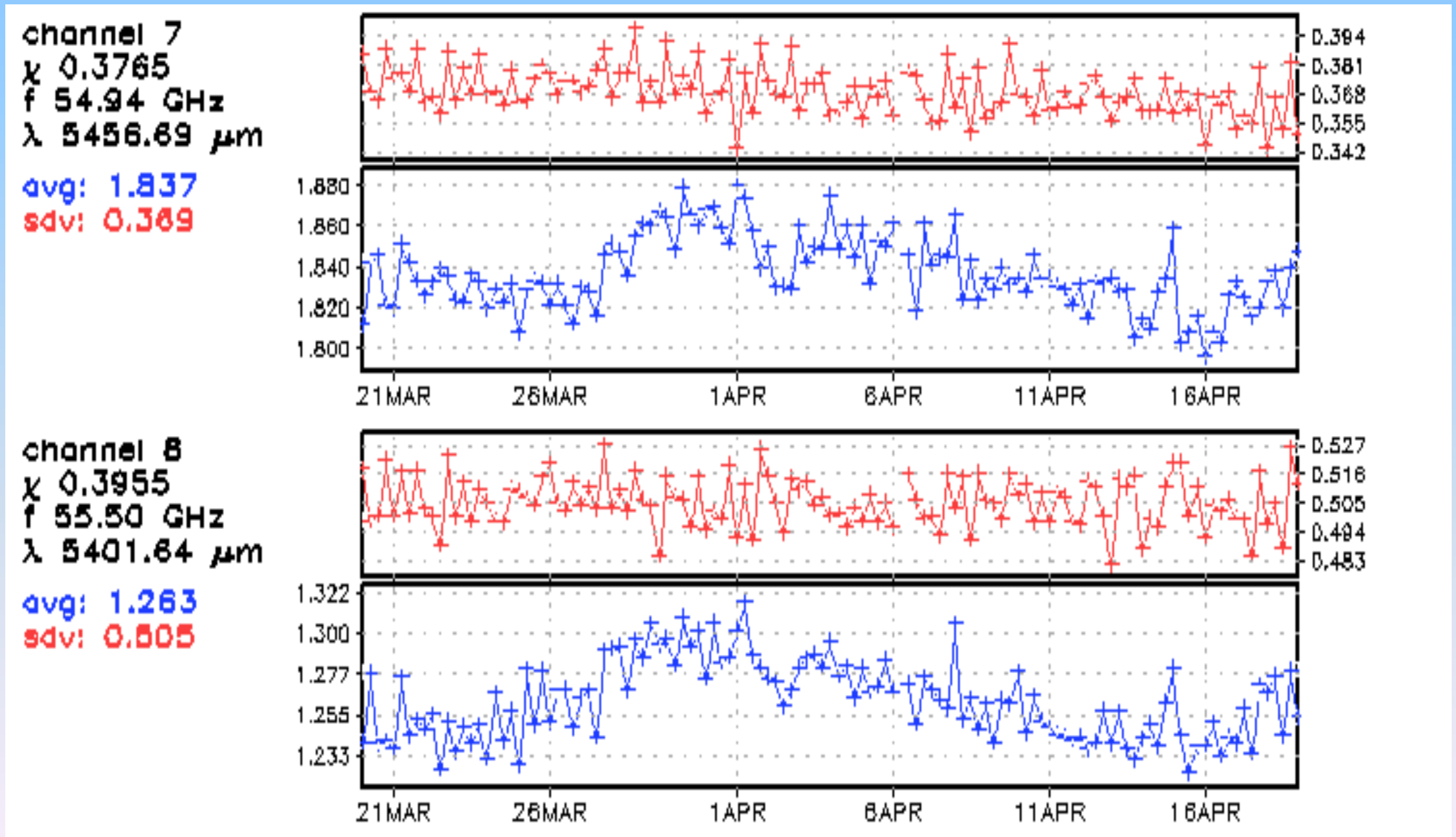
Satellite radiance observations Bias correction

- Air Mass prediction equation for bias
  - Coefficients in equation analysis variable w/ background (previous analysis) values
  - Predictors
    - mean
    - path length (local zenith angle determined)
    - integrated lapse rate
    - integrated lapse rate ** 2
    - cloud liquid water

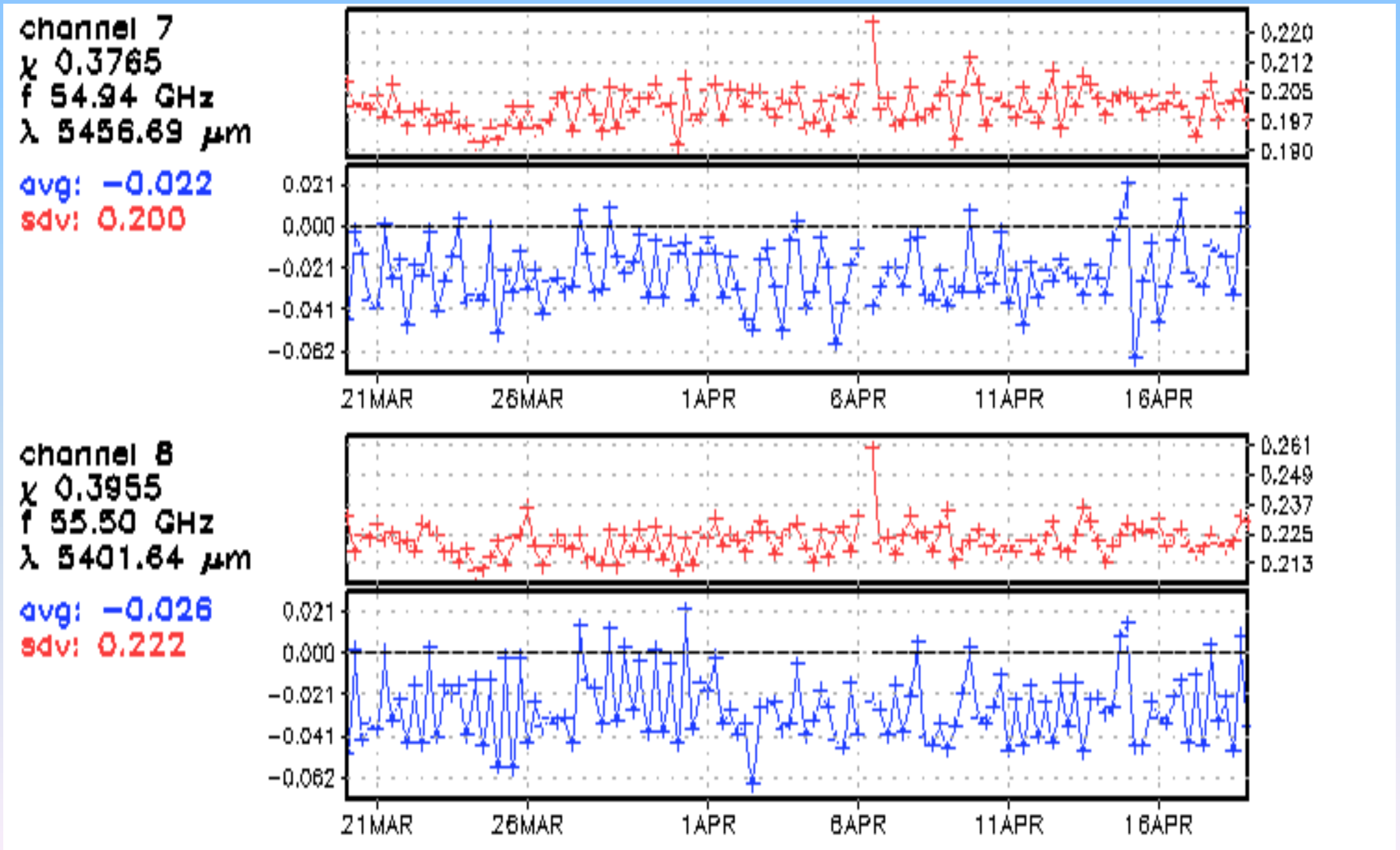


T62L28 Global Analysis
VT: 2000081500
guess rms fit without clw correctin
guess rms fit with clw correction
measured noise equivalent delta−T
Kelvin
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
1
2
3
4
5
6
7
8
9
10
15
AMSU−A channel number

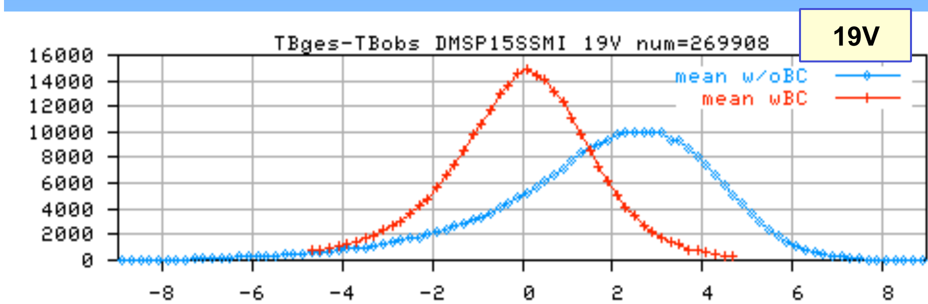
NOAA 18 AMSU-A
No Bias Correction

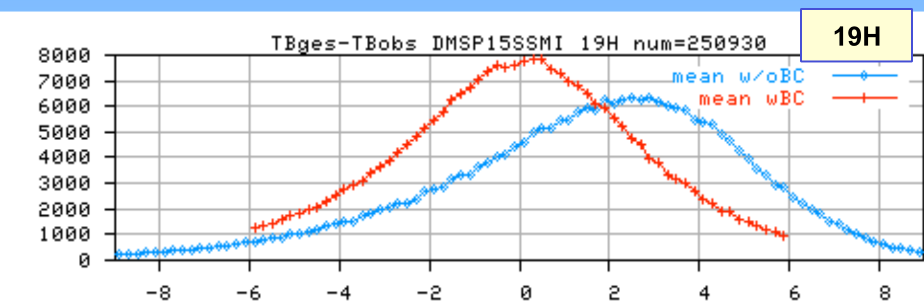


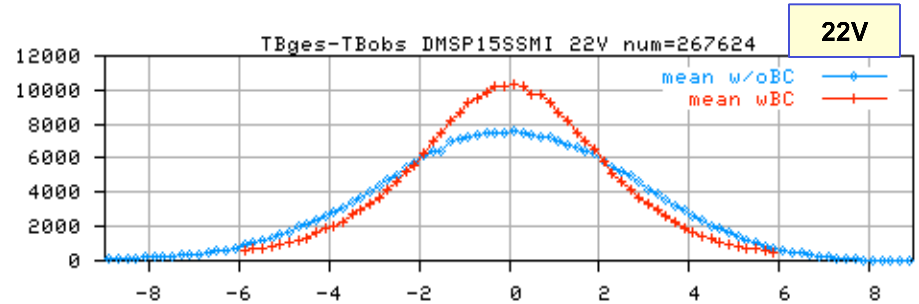
NOAA 18 AMSU-A
Bias Corrected

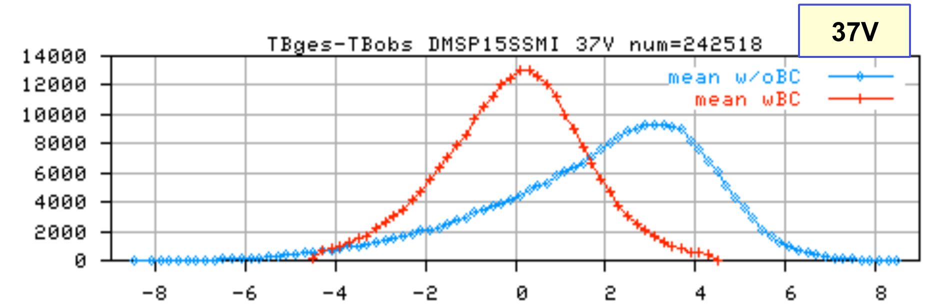


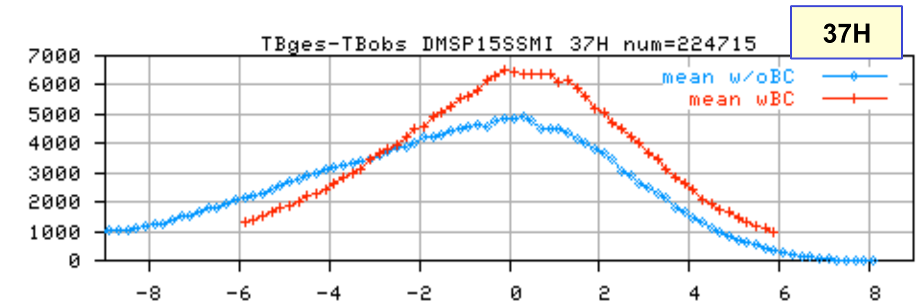
Observation - Background histogram

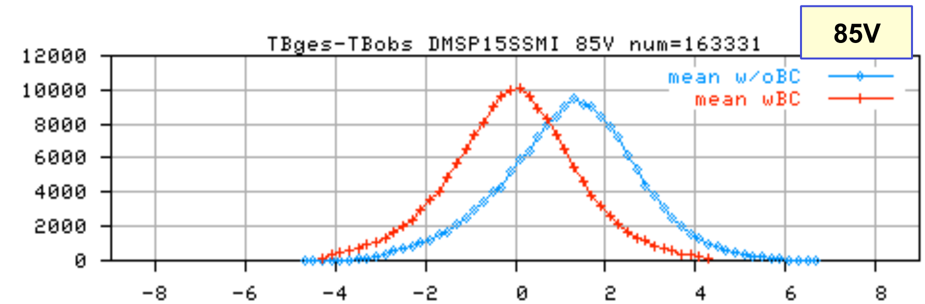


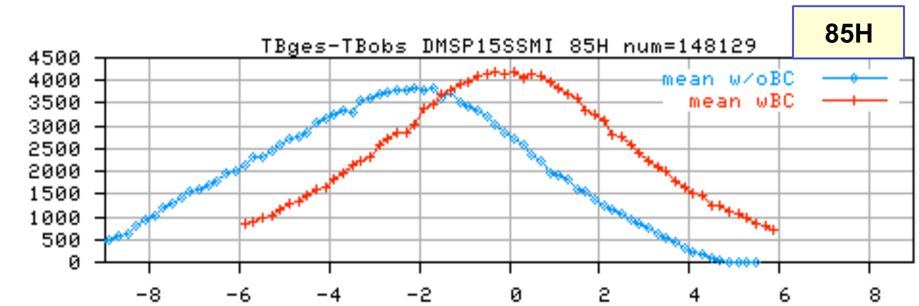












DMSP15 July2004 : 1month
before bias correction
after bias correction

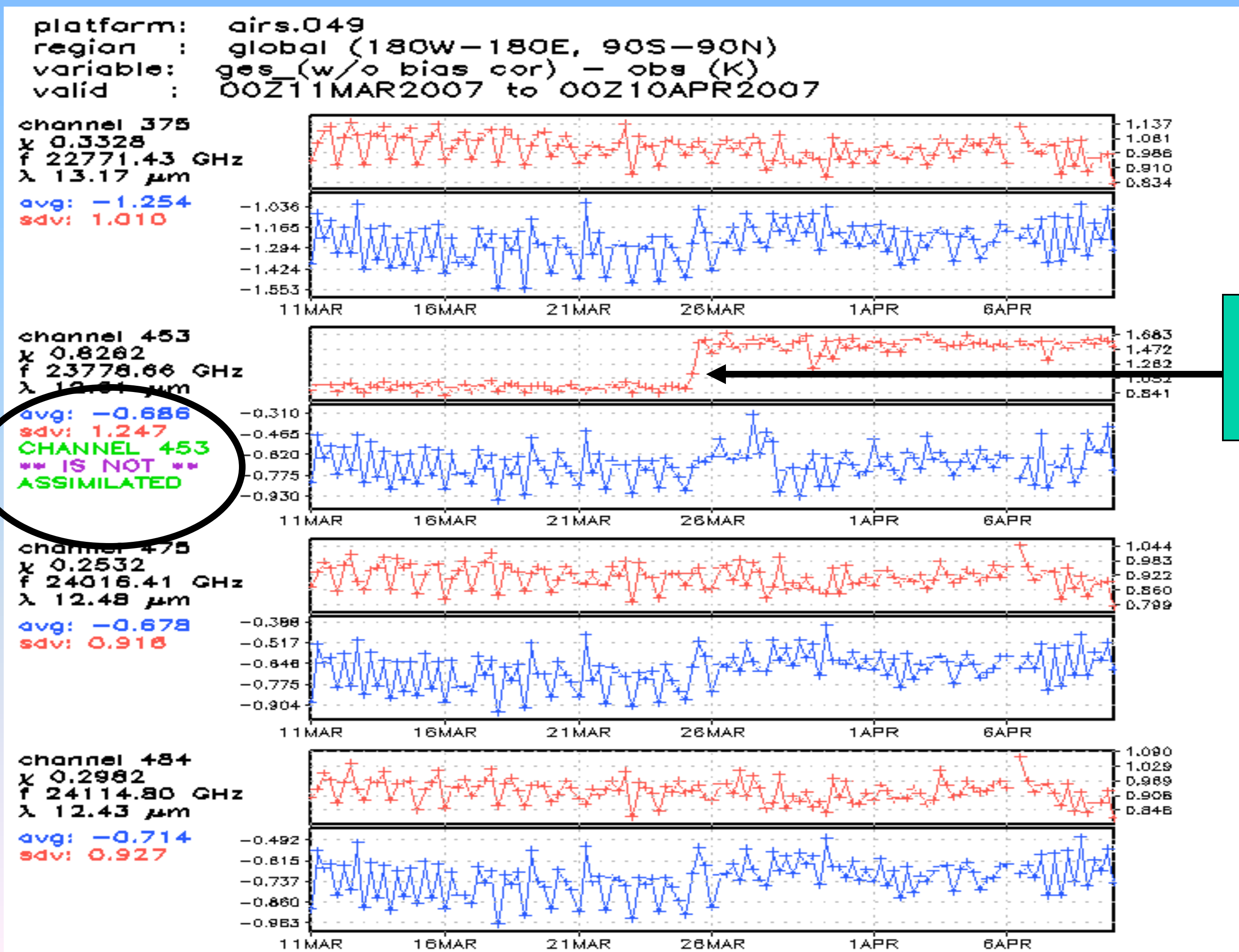
gl use 2004070200-073118(63cases)

Data Monitoring

- It is essential to have good data monitoring.
- Usually the NWP centres see problems with instruments prior to notification by provider (UKMO especially)
- The data monitoring can also show problems with the assimilation systems
- Needs to be ongoing/real time
- http://www.emc.ncep.noaa.gov/gmb/gdas/radiance/esafford/opr/index.html

Quality Monitoring of Satellite Data

AIRS Channel 453 26 March 2007



Increase in SD Fits to Guess

Data impact

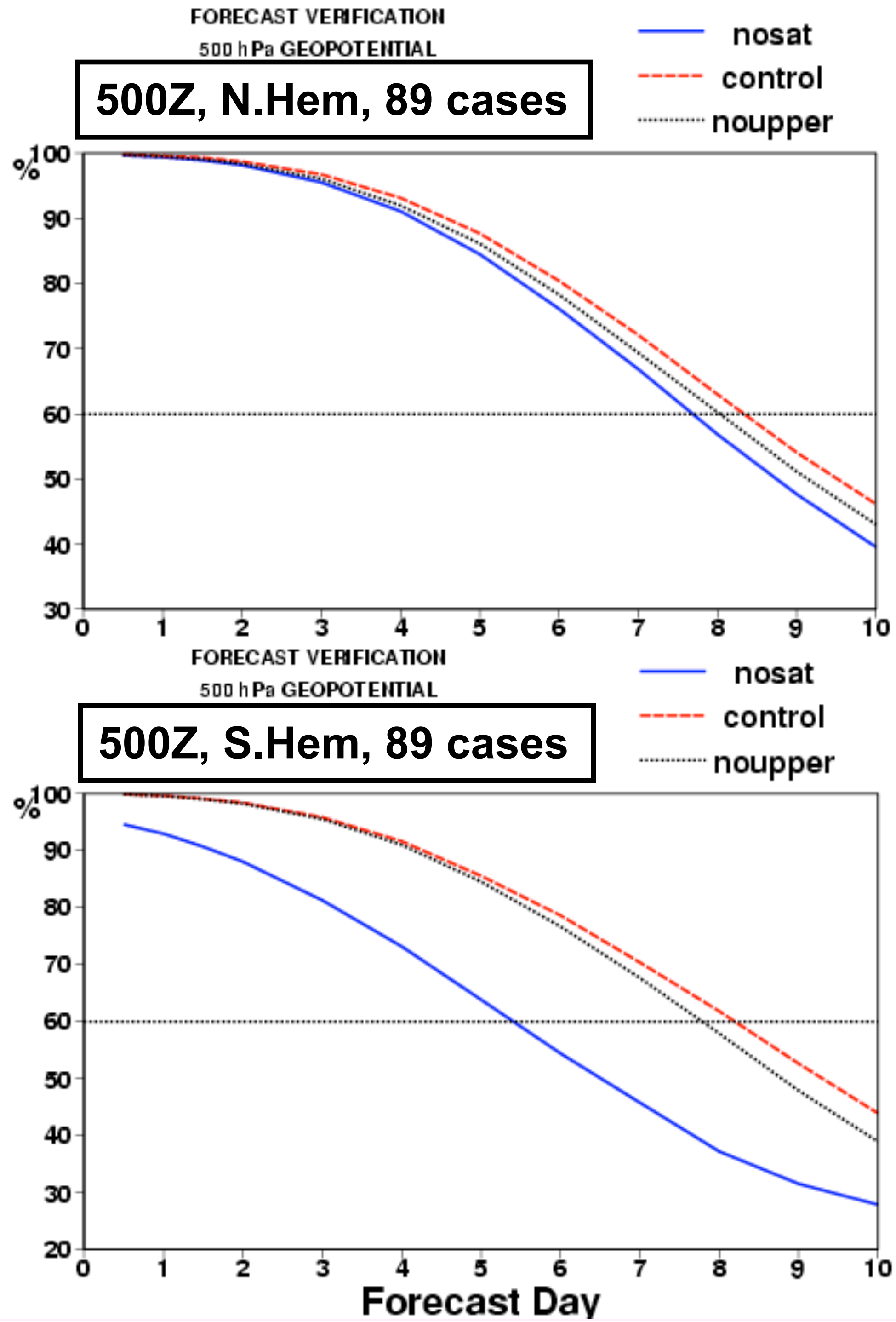
- Satellite data extremely important part of observation system.
- Much of the improvement in forecast skill can be attributed to the improved data and the improved use of the data
- Must be measured relative to rest of observing system – not as stand alone data sets
- Extremely important for planning ($$$$)

Observing System Experiments (ECMWF - G. Kelly et al.)

NoSAT= no satellite radiances or winds

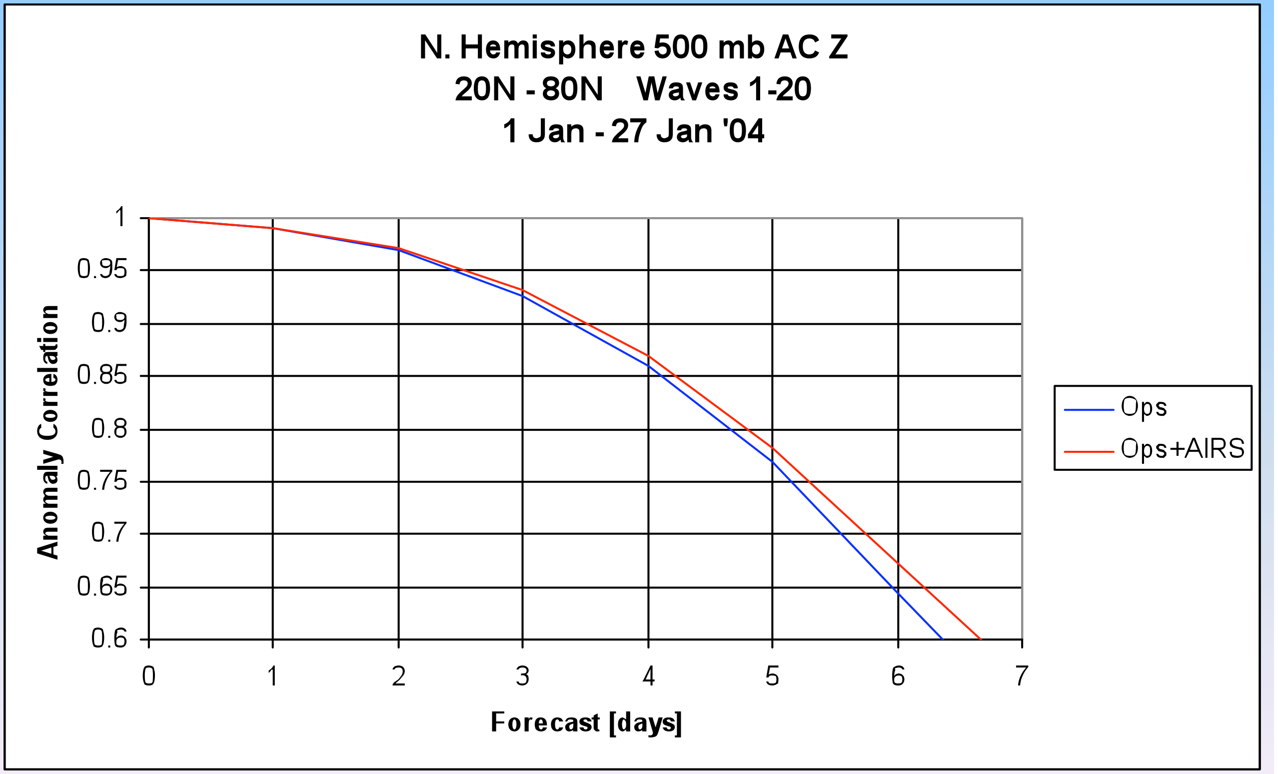
Control= like operations

NoUpper=no radiosondes, no pilot winds, no wind profilers



JCSDA AIRS Testing

- NCEP operational system
  - Includes first AIRS data use
- Enhanced AIRS data use
  - Data ingest includes all AIRS footprints
  - 1 month at 55 km resolution
  - Standard data selection procedure



Summary

- Operational data assimilation of radiance data requires:
  - Data available in real time in acceptable format
  - A stable data source
  - Quality control procedures to be defined
  - Bias correction and observational errors defined
  - An accurate forward model
  - Data monitoring
  - Evaluation and testing to ensure neutral/positive impact
  - All of the above are more important than assimilation technique.
- Lots more work to be done!

Keeping up with the observing system

- New data sets
  - GOES-13 and 14
  - SEVERI
  - SSM/IS
  - NPP and NPOESS (JPSS – Joint Polar Satellite System)
  - GOES-R

Improved use of radiance data

- Improved CRTM (v2.0)
- Inclusion of cloudy radiance
  - Forward model includes model physics and cloudy CRTM
- Improved surface temperatures and emissivities
- Improved geometry
- Trace gases and aerosols

Cloud/precipitation assimilation

- Developing tangent linear and adjoint of cloud/precipitation physics
  - Eliminating discontinuities – produces similar results to original physics
- Inclusion of Clouds and Precipitation in radiative transfer
  - Probably not accurate in all location (heavy precipitation – thick clouds)
  - Will need to pick and choose
- Inclusion of diabatic balance in analysis
  - Inclusion of cloud/precipitation/surface physics in strong constraint
  - 4dvar
  - Hybrid assimilation (background errors include more cross correlations)
- Choice of analysis variable
  - Consistency between water vapor, cloud water and precipitation
  - Met Office has chosen single analysis variable for moisture (total moisture
- Very difficult problem which will require years of development.

Useful References

- McNally, A.P., J.C. Derber, W.-S. Wu and B.B. Katz, 2000: **The use of TOVS level-1B radiances in the NCEP SSI analysis system.** Q.J.R.M.S., 126, 689-724.
- Derber, J. C. and W.-S. Wu, 1998: **The use of TOVS cloud-cleared radiances in the NCEP SSI analysis system**. Mon. Wea. Rev., 126, 2287 - 2299. .
- Kazumori, M; Liu, Q; Treadon, R; Derber, JC, **Impact Study of AMSR-E Radiances in the NCEP Global Data Assimilation System** Monthly Weather Review,Vol. 136, no. 2, pp. 541-559. Feb 2008.