# The Contribution of ATOVS data to operational NWP

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# Introduction

- The direct use of radiance data began with TOVS and ATOVS data.
- Many aspects of the assimilation of newer satellite sounding data are based on those from ATOVS.
- The current use of the ATOVS data remains the core of satellite radiance assimilation.

# Outline

- The TOVS and RTOVS Data
- Radiative Transfer modeling, TL and Adjoints
- Bias Correction
- Quality Control
- Observation Errors
- Monitoring
- Future Enhancements

# TOVS and ATOVS

- TIROS Operational Vertical Sounder (TOVS).
- Advanced TIROS Operational Vertical Sounder.
- Microwave data from these satellites extremely important – still best microwave instruments available (SSM/IS?).
- Similar Microwave instruments on METOP and AQUA.
- Infrared - newer higher spectral resolution data available (AIRS, IASI), but currently only single copies.

# TOVS and ATOVS

- NOAA-15, 16, 17, 18 currently available – but some instruments have failed
  - http://www.oso.noaa.gov/poesstatus/
- METOP and AQUA have microwave instruments that are similar to ATOVS.
- METOP and GOES geostationary sounders have instruments similar or the same as the HIRS part of ATOVS.

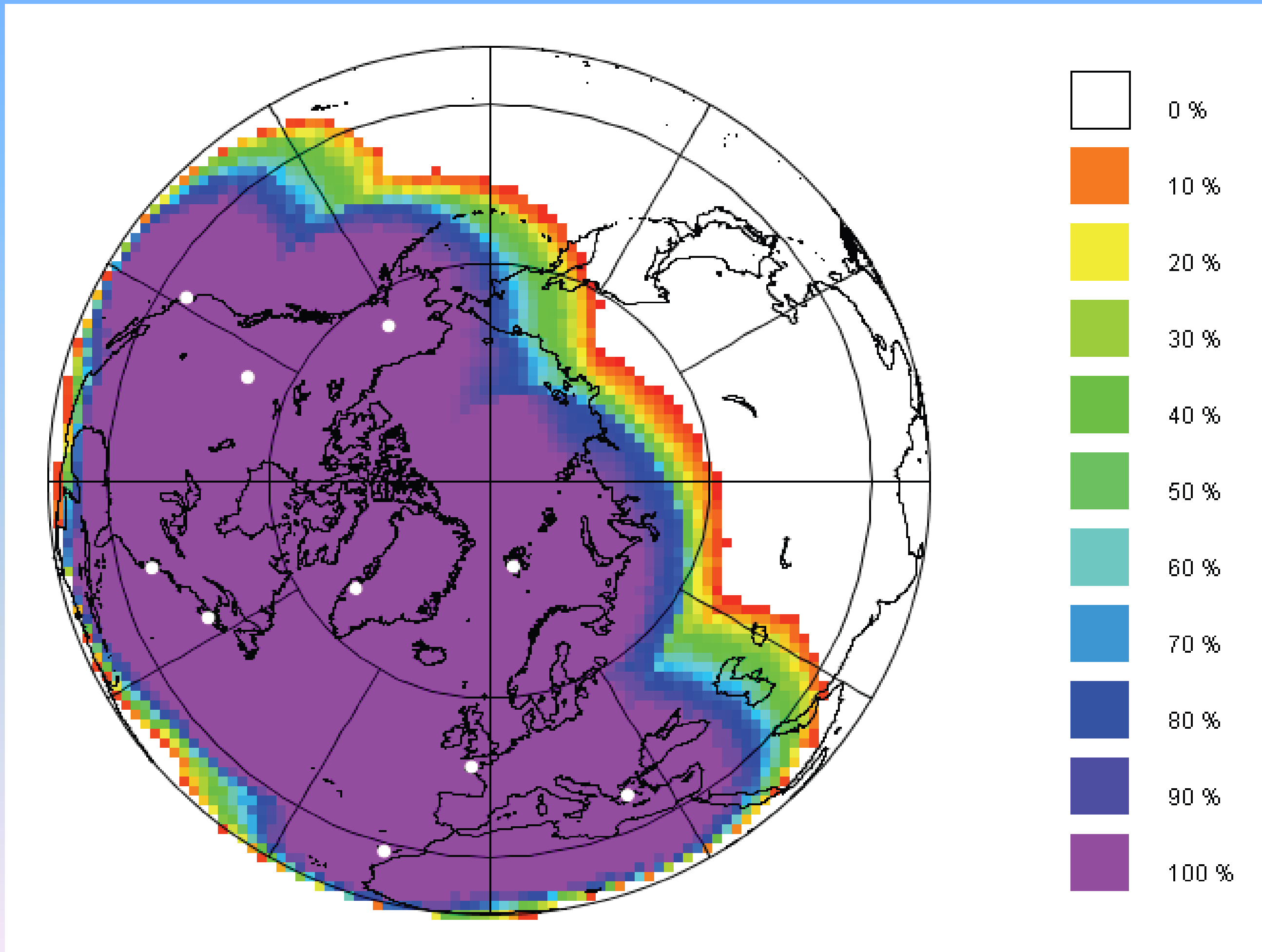
# TOVS and ATOVS

- Data acquired from producer – NESDIS, EUMETSAT, NASA, etc. or intermediate provider (e.g., Met Office)
- Data either:
  - 1b – raw data, earth located, calibrated data and quality controlled.
  - 1c – 1b with calibration applied to raw data and possible antenna correction.
- Inclusion of Antenna pattern correction for microwave.

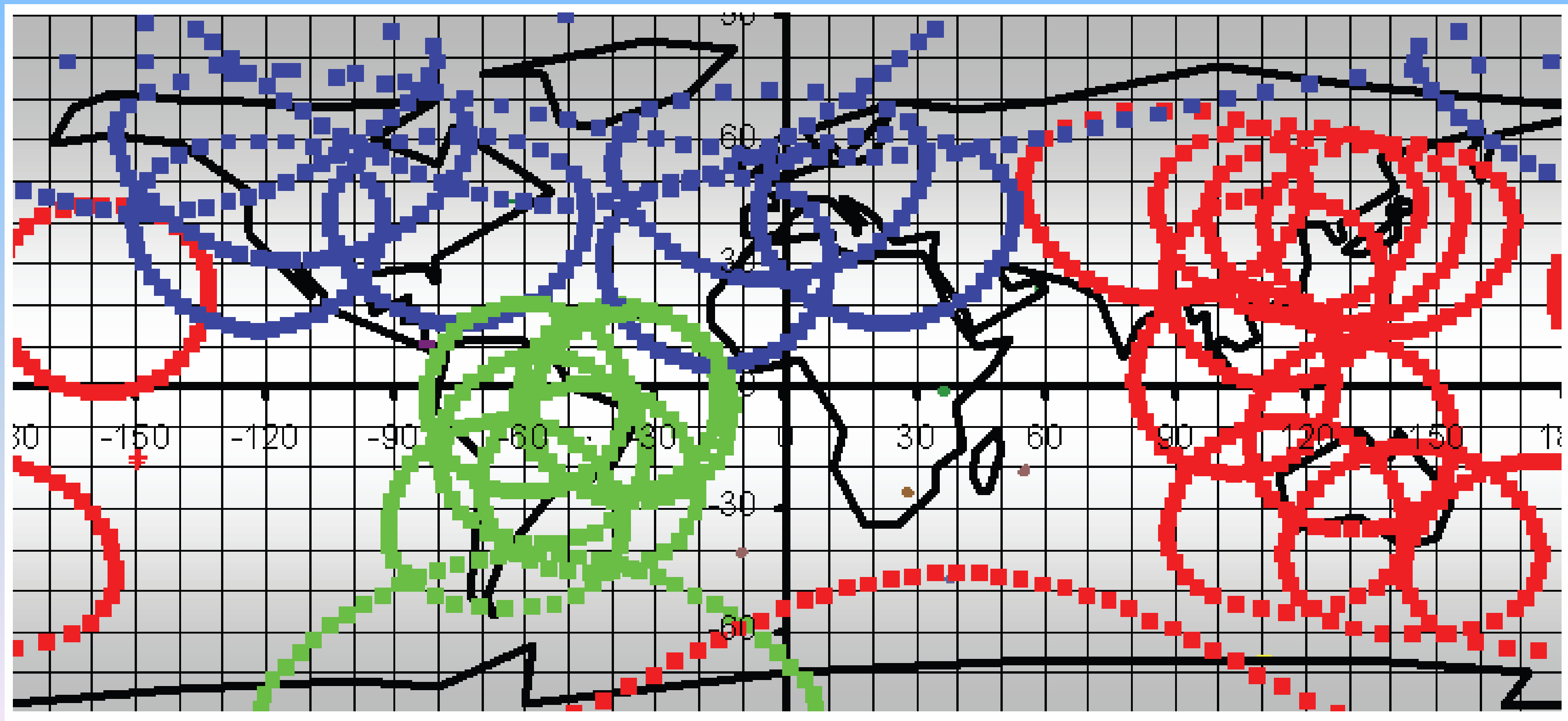
# Regional ATOVS Retransmission Service (RARS)

- EUMETSAT ATOVS Retransmission Service (EARS).
- Asian-Pacific RARS.
- South-American RARS.
- Takes advantage of direct read-out stations.
  - Sharing and combining data from different stations.
  - More timely data.

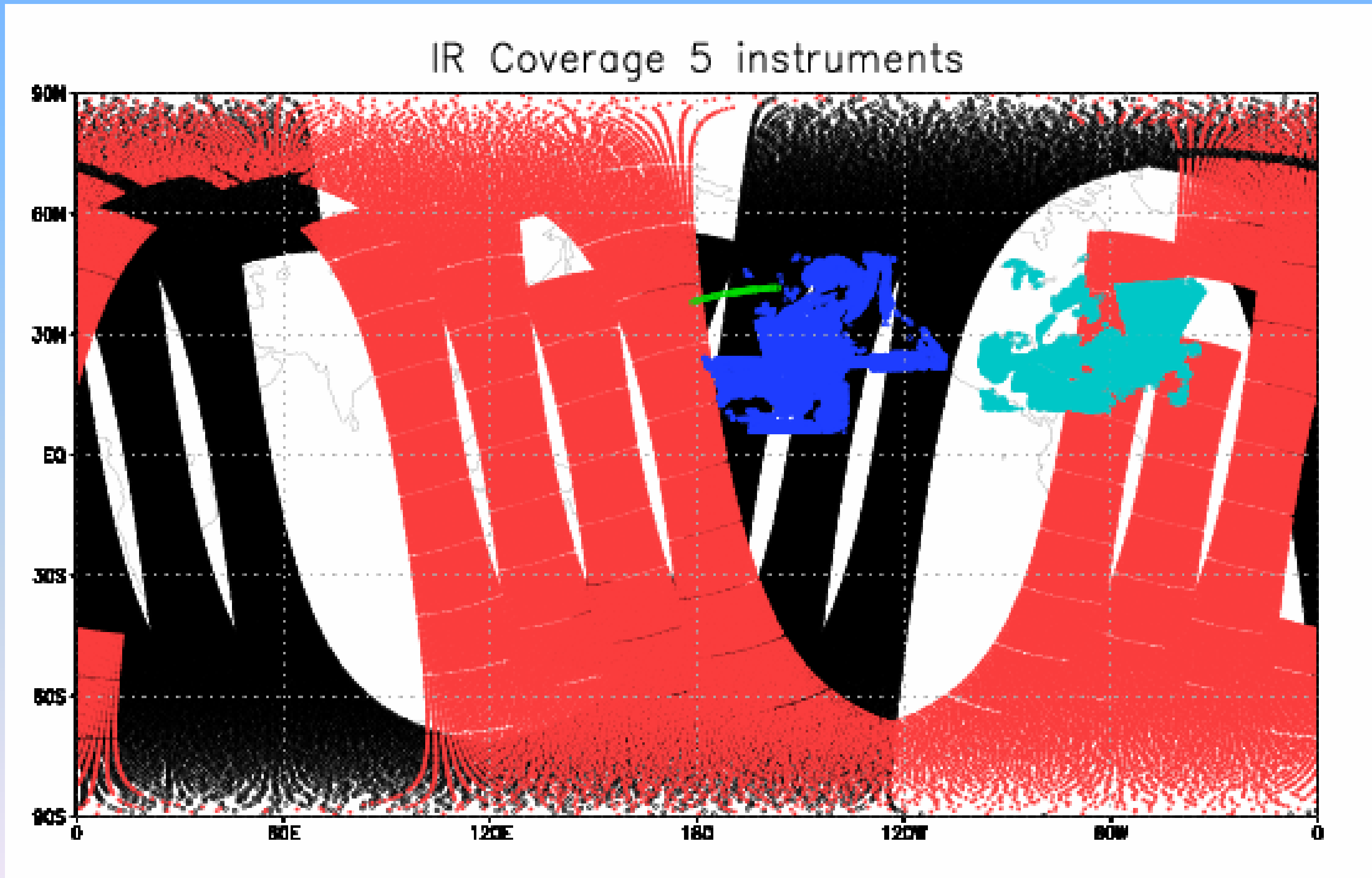
# EARS coverage from Nov. 2006
## From Dumont et al.(2006)



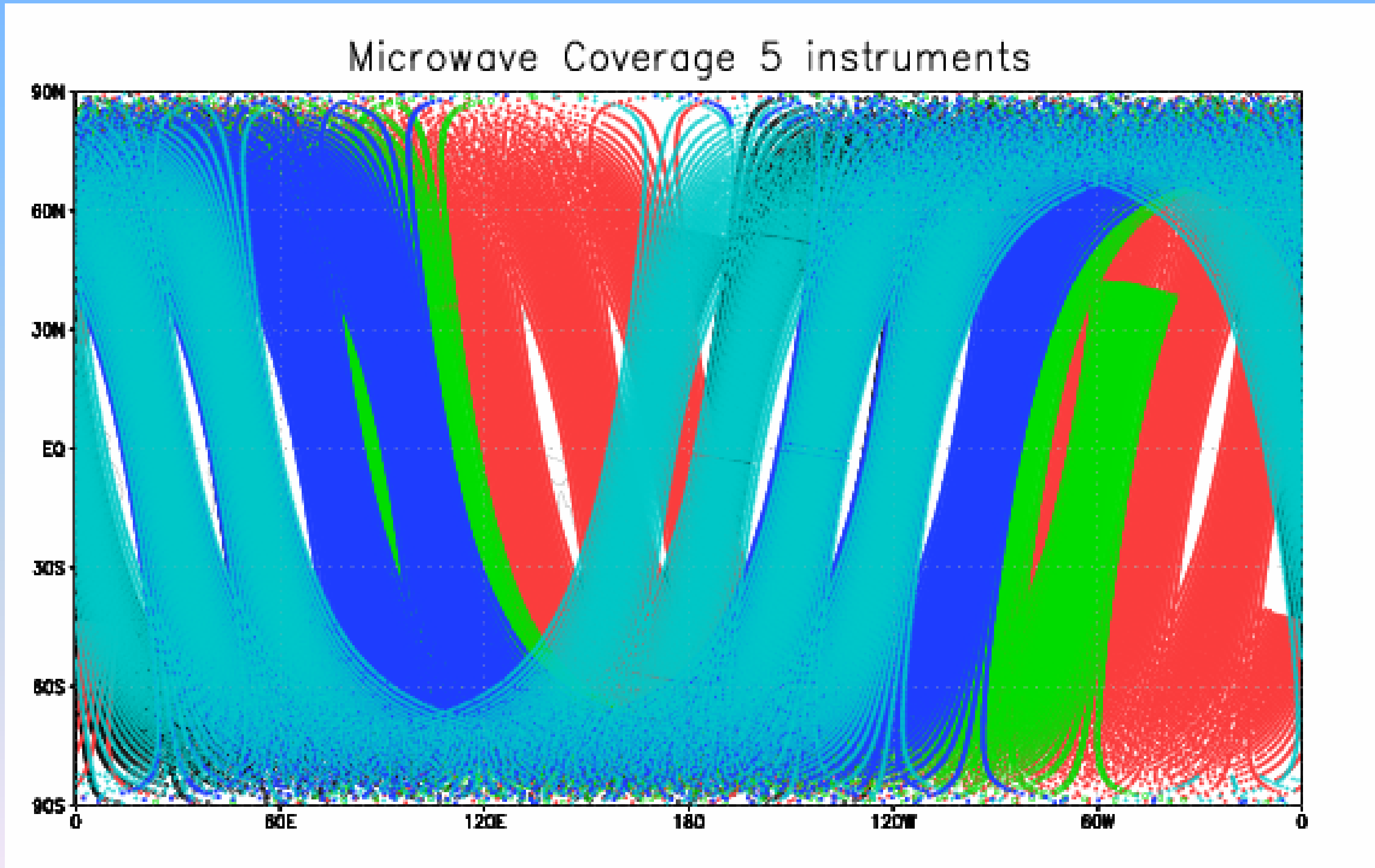
# Expected Global RARS Coverage end of 2007 (DuMont et. al.)



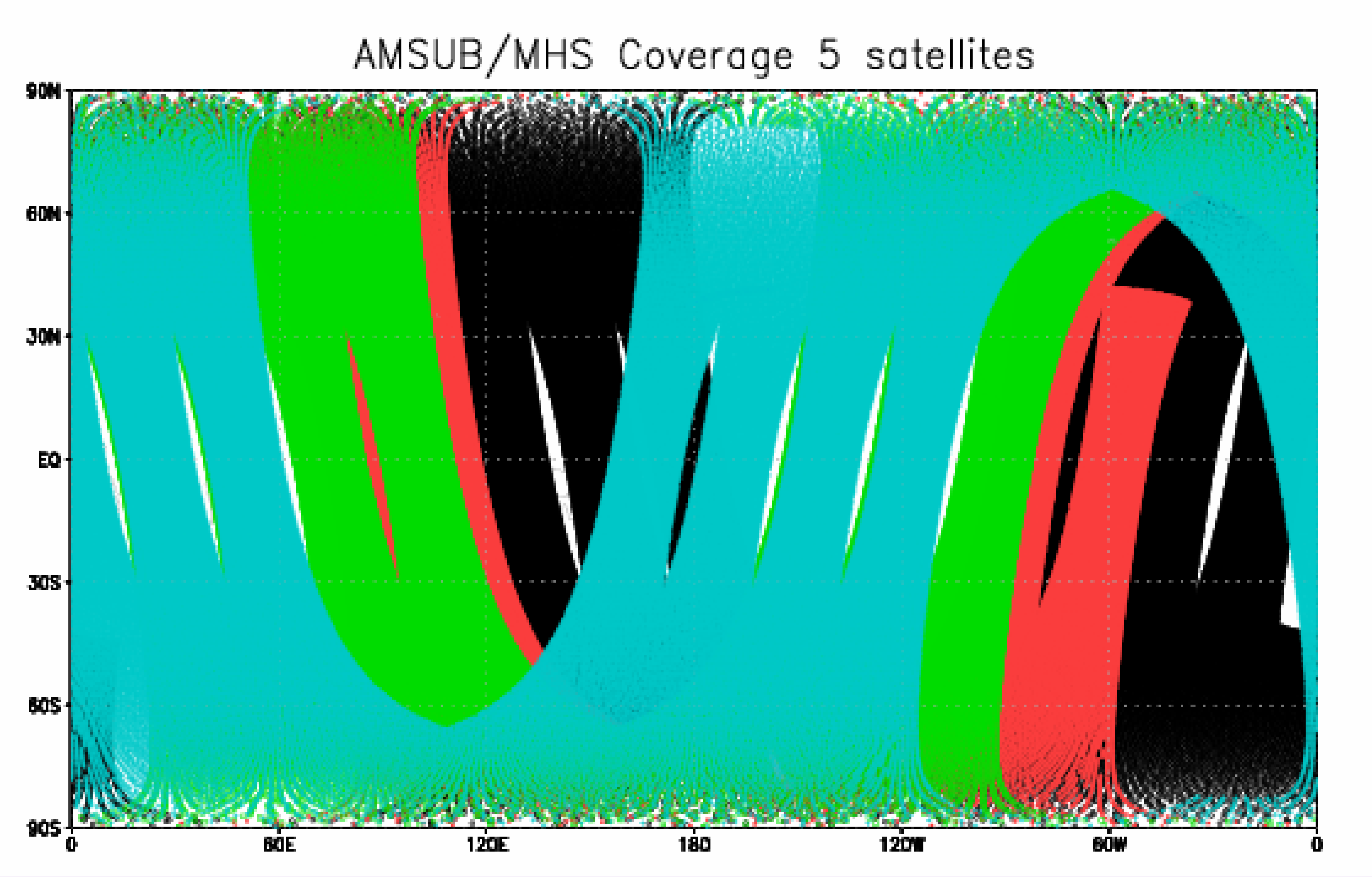
# Coverage IR
# AIRS, METOP, N-17, GOES-11/12



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



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



# Impact from the use of TOVS/ATOVS radiance data

- While not absolutely necessary, the direct use of radiances occurred with the introduction of variational analysis techniques.
- It is impossible to completely separate the effects since changes in the analysis result from and cause changes in the use of the radiance data.
- However, impact of the direct use of radiances has been large.
  - Before -- impact of satellite sounder data, neutral or negative in Northern Hemisphere and small positive in Southern Hemisphere.
  - After -- positive impact in NH, large positive in SH.
  - Most if not all operational centres have noted a large increase in the SH variability
- Presentation by G. Kelly.

# Assimilation of ATOVS Radiances

Variational equations: for 1D-Var, 3D-Var, 4D-Var

Minimize:

$$J[x] = \frac{1}{2} (x-x_b)^T B^{-1} (x-x_b) + \frac{1}{2} (y_o-H[x])^T (E+F)^{-1} (y_o-H[x])$$

where x contains the analysis state,

$x_b$ is background estimate of x (short-range forecast),

B is the error covariance of $x_b$,

$y_o$ is vector of measurements,

H[...] is "observation operator" or "forward model" mapping state x into "measurement space"

E is error covariance of measurements, and

F is error covariance of forward model.

# Assimilation of ATOVS Radiances

- To use radiances need to define:
  - H[…] – the forward model transforming the analysis variables into simulated observations.
  - E+F – the measurement error plus the forward model error .

# Forward Model

- Forward model contains several different components for radiances.
  - Transform analysis variables into forward model variables (e.g., $T^u, \psi, \chi, P_s^u \rightarrow T, u, v, P_s$).
  - Interpolate to observation locations.
  - Fast Radiative transfer model.
  - Bias Correction (if necessary).

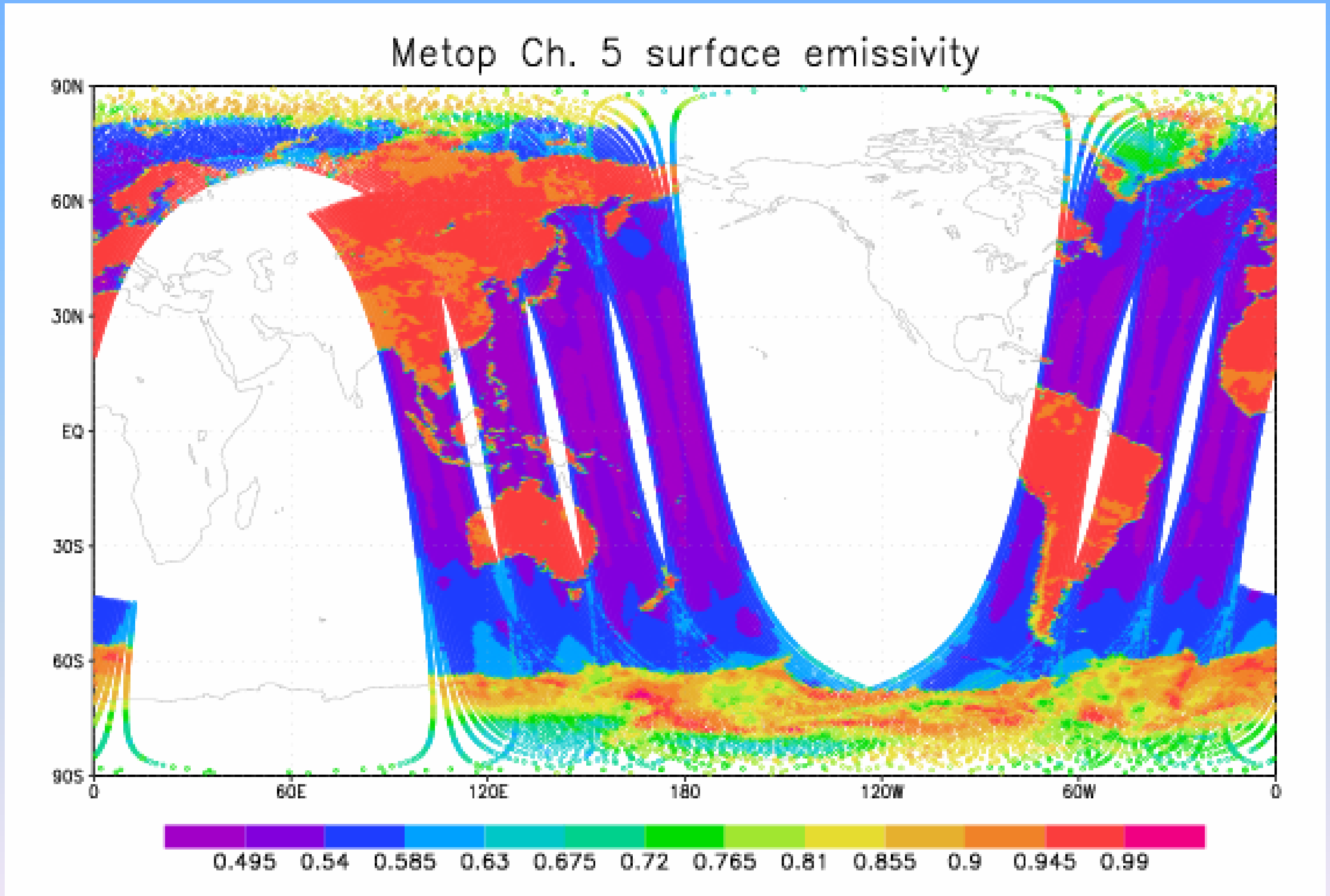
# Fast Radiative Transfer Models

- Several Fast Radiative transfer codes available
  - RTTOV - http://www.metoffice.com/research/interproj/nwpsaf/rtm
  - CRTM - http://www.ssec.wisc.edu/~paulv/Fortran90/CRTM/Developmental/
  - Others at http://cimss.ssec.wisc.edu/itwg/groups/rtwg/fastrt.html

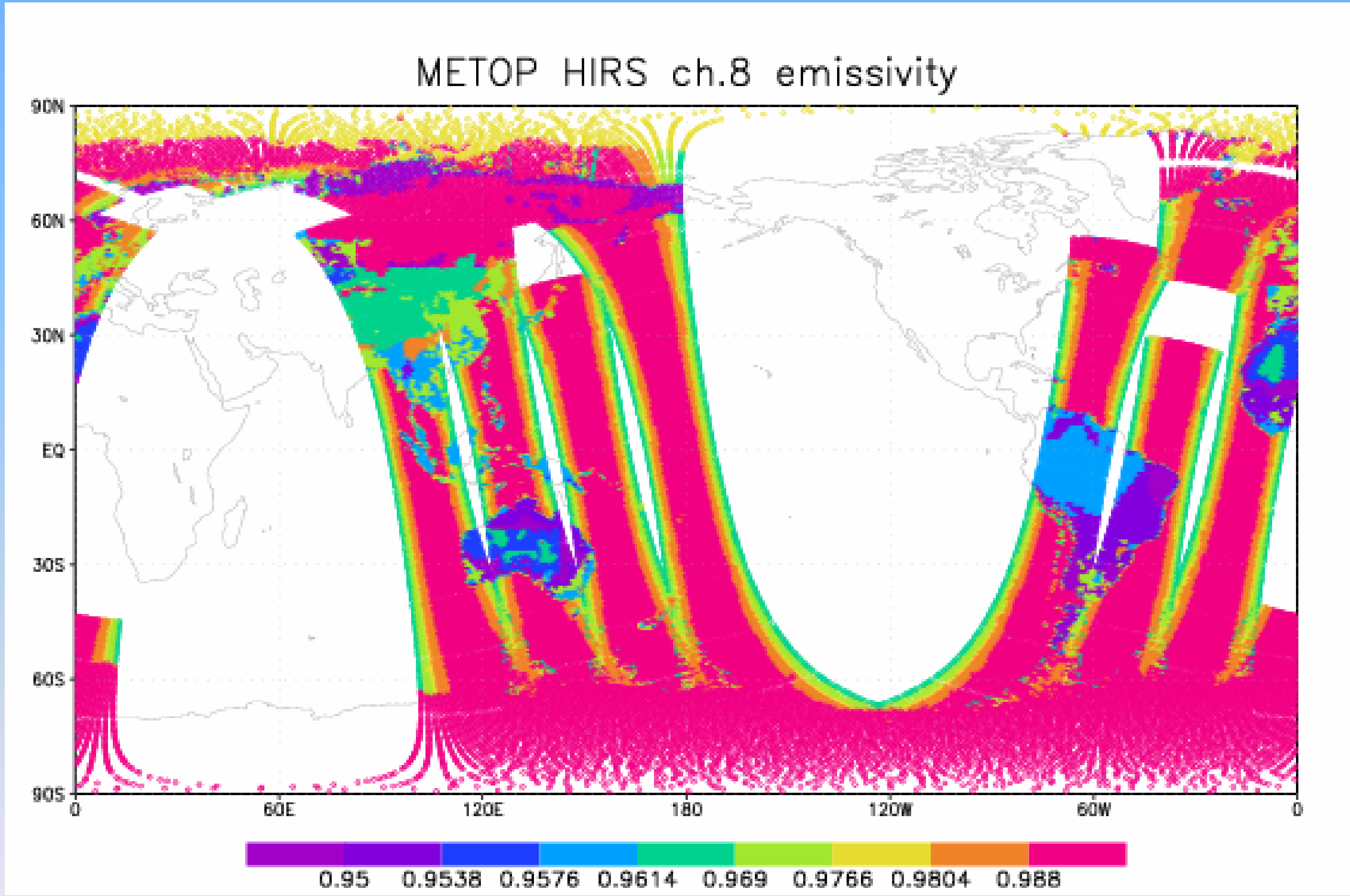
# Fast Radiative Transfer Models

- Fast Radiative transfer models are "tuned" to Line-by-Line models.
- Line-by-Line models computationally expensive.
- Models contain components to accurately model obs:
  – Reflected and emitted radiation from surface (emissivity, temperature, polarization, etc.).
  – Atmospheric transmittances dependent on moisture, temperature, ozone, clouds, aerosols, $CO_2$, methane, ...
  – Cosmic background radiation (important for microwave).
  – View geometry (local zenith angle, view angle (polarization)).
  – Instrument characteristics (spectral response functions, etc.).
  – Scattering from clouds, precipitation and aerosols.

# Surface Emissivity Microwave



# Surface Emissivity Infrared

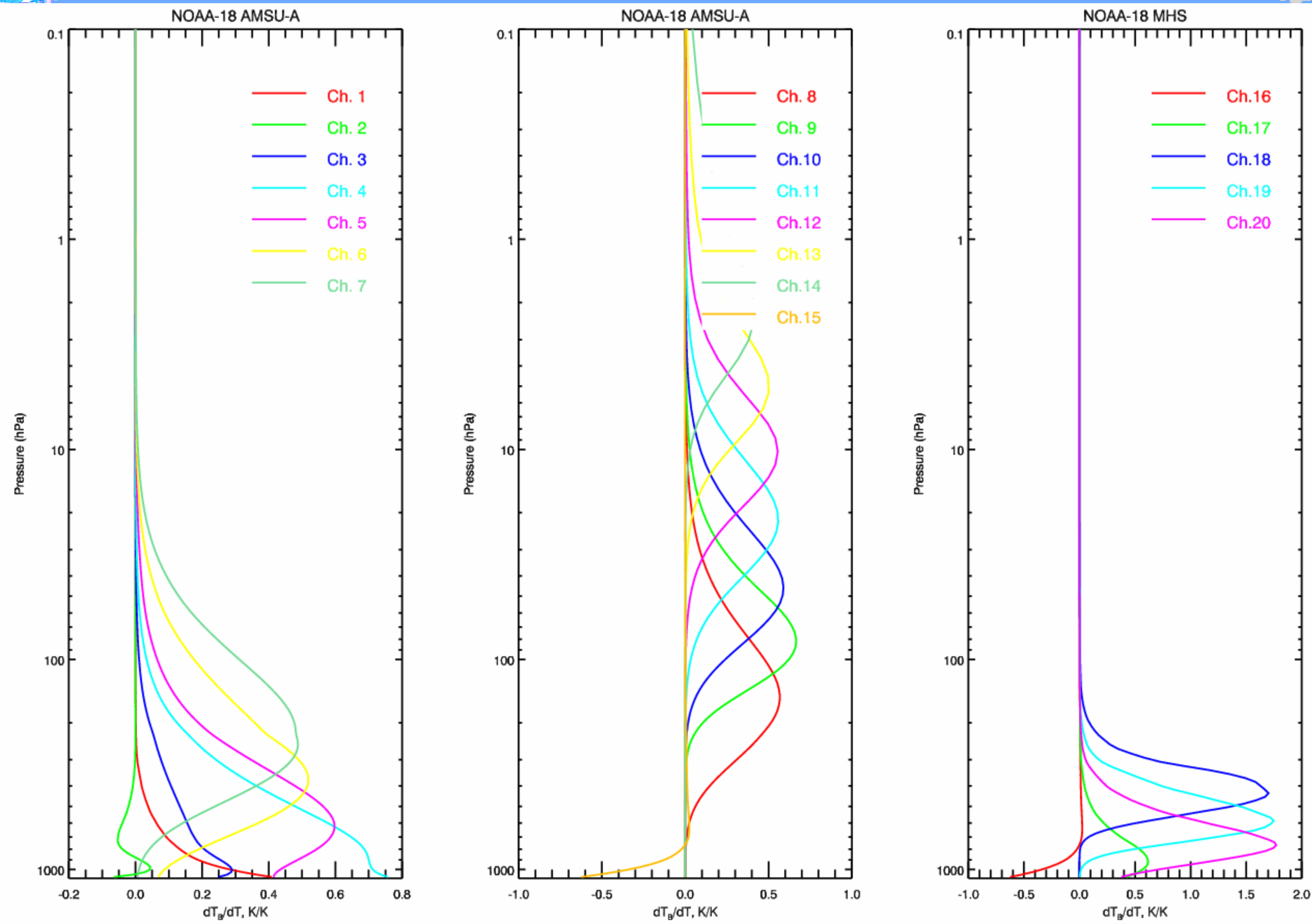


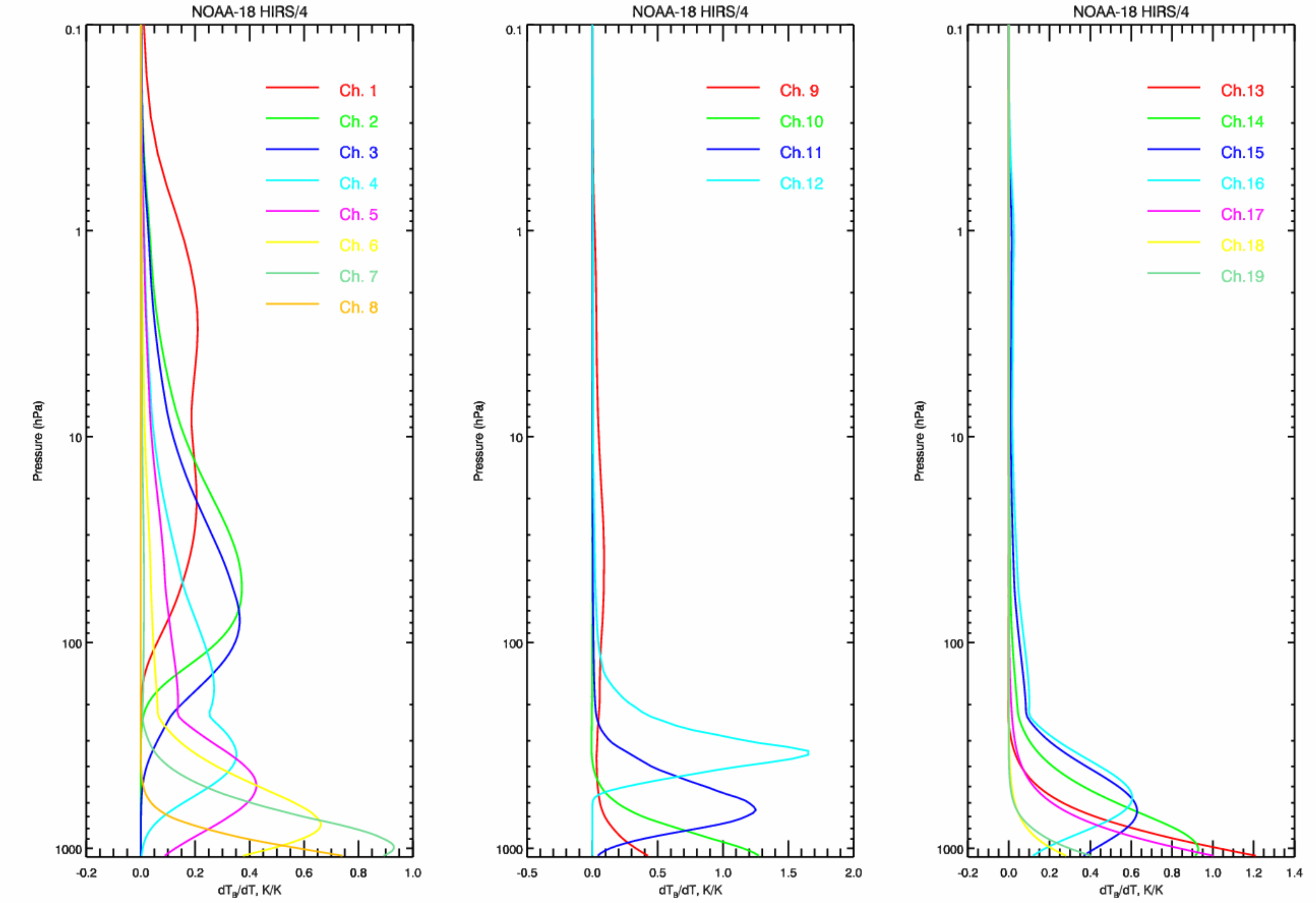
# Fast Radiative Transfer Models

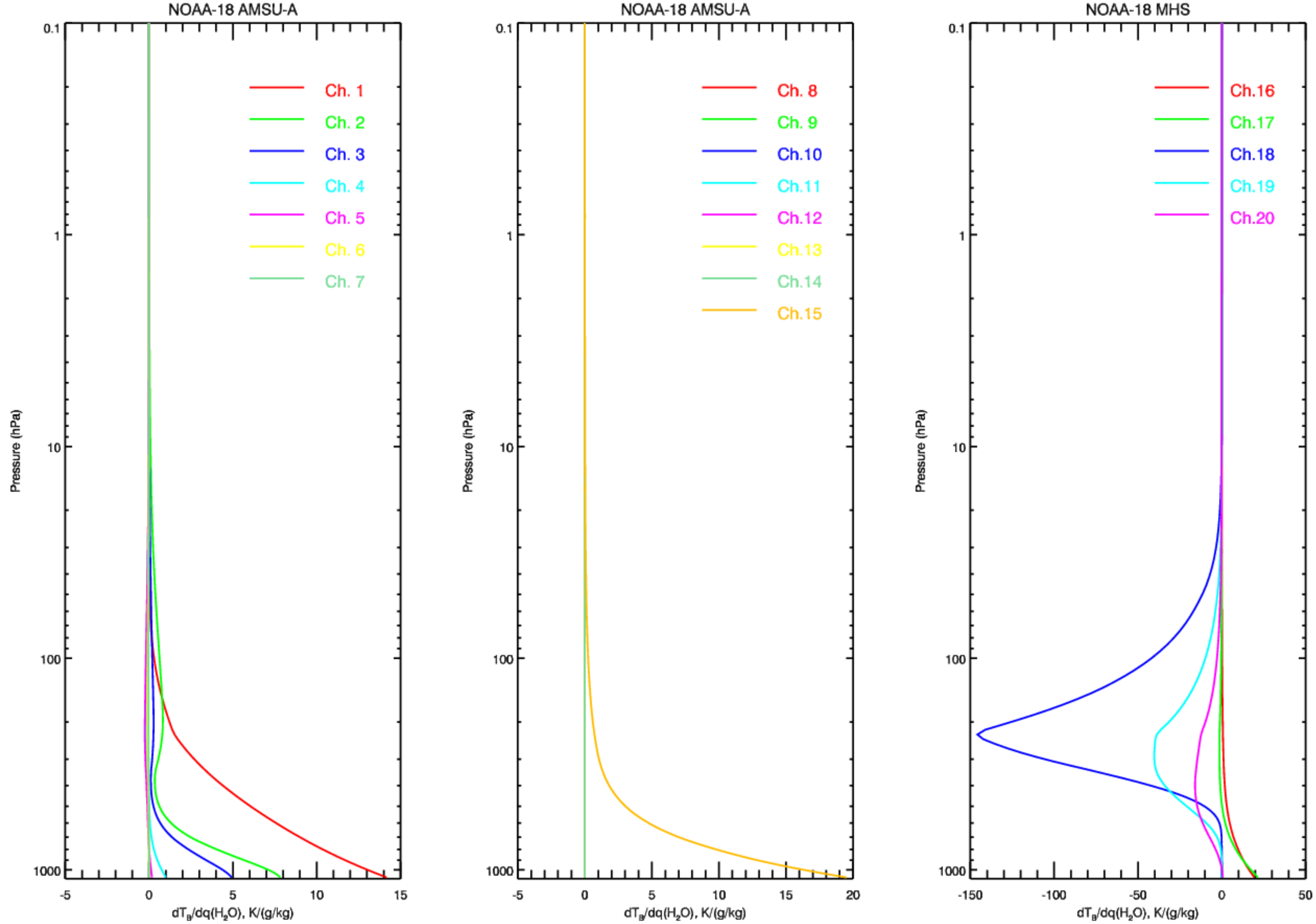
- Need forward model and adjoint to calculate gradient.

$$\nabla_x J[x] = B^{-1}(x-x_b) - \mathbf{H}^T (E+F)^{-1} (y_o - H(x))$$

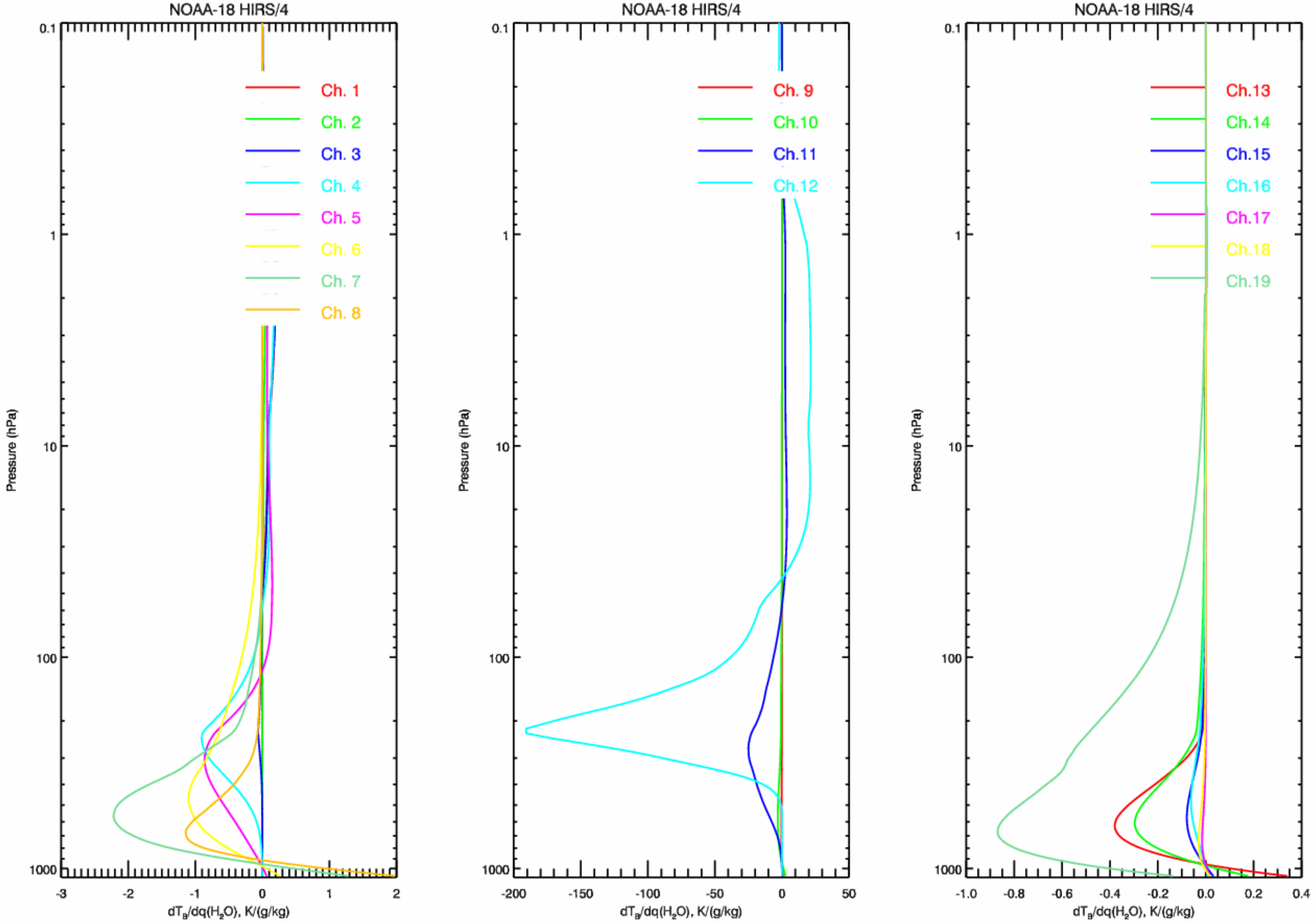
- **Hx** is the linearization of the *H*(x) around the current solution – the tangent linear model.
- $\mathbf{H}^T$y is the adjoint model.
- The **H** matrix is called the Jacobian.
- Adjoint and full nonlinear model only models needed, but tangent linear/Jacobian very useful. e.g., for verifying correctness of adjoint model.

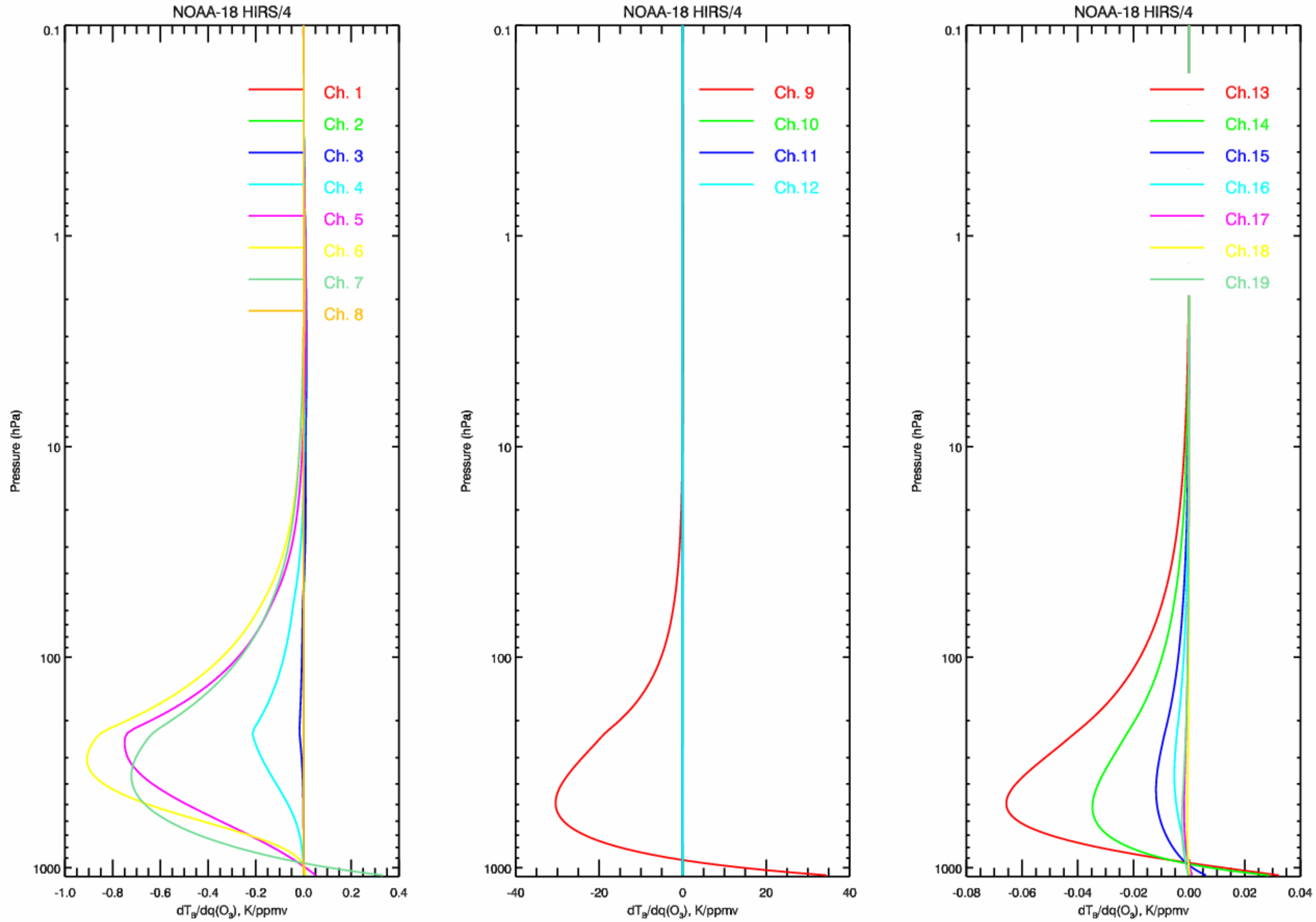

NOAA-18 AMSU-A
Ch. 1
Ch. 2
Ch. 3
Ch. 4
Ch. 5
Ch. 6
Ch. 7
NOAA-18 AMSU-A
Ch. 8
Ch. 9
Ch.10
Ch.11
Ch.12
Ch.13
Ch.14
Ch.15
NOAA-18 MHS
Ch.16
Ch.17
Ch.18
Ch.19
Ch.20
Pressure (hPa)
dT_B/dT, K/K


NOAA-18 HIRS/4
Pressure (hPa)
0.1
1
10
100
1000
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
$dT_B/dT$, K/K
Ch. 1
Ch. 2
Ch. 3
Ch. 4
Ch. 5
Ch. 6
Ch. 7
Ch. 8
NOAA-18 HIRS/4
Pressure (hPa)
-0.5
0.0
0.5
1.0
1.5
2.0
$dT_B/dT$, K/K
Ch. 9
Ch.10
Ch.11
Ch.12
NOAA-18 HIRS/4
Pressure (hPa)
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
$dT_B/dT$, K/K
Ch.13
Ch.14
Ch.15
Ch.16
Ch.17
Ch.18
Ch.19



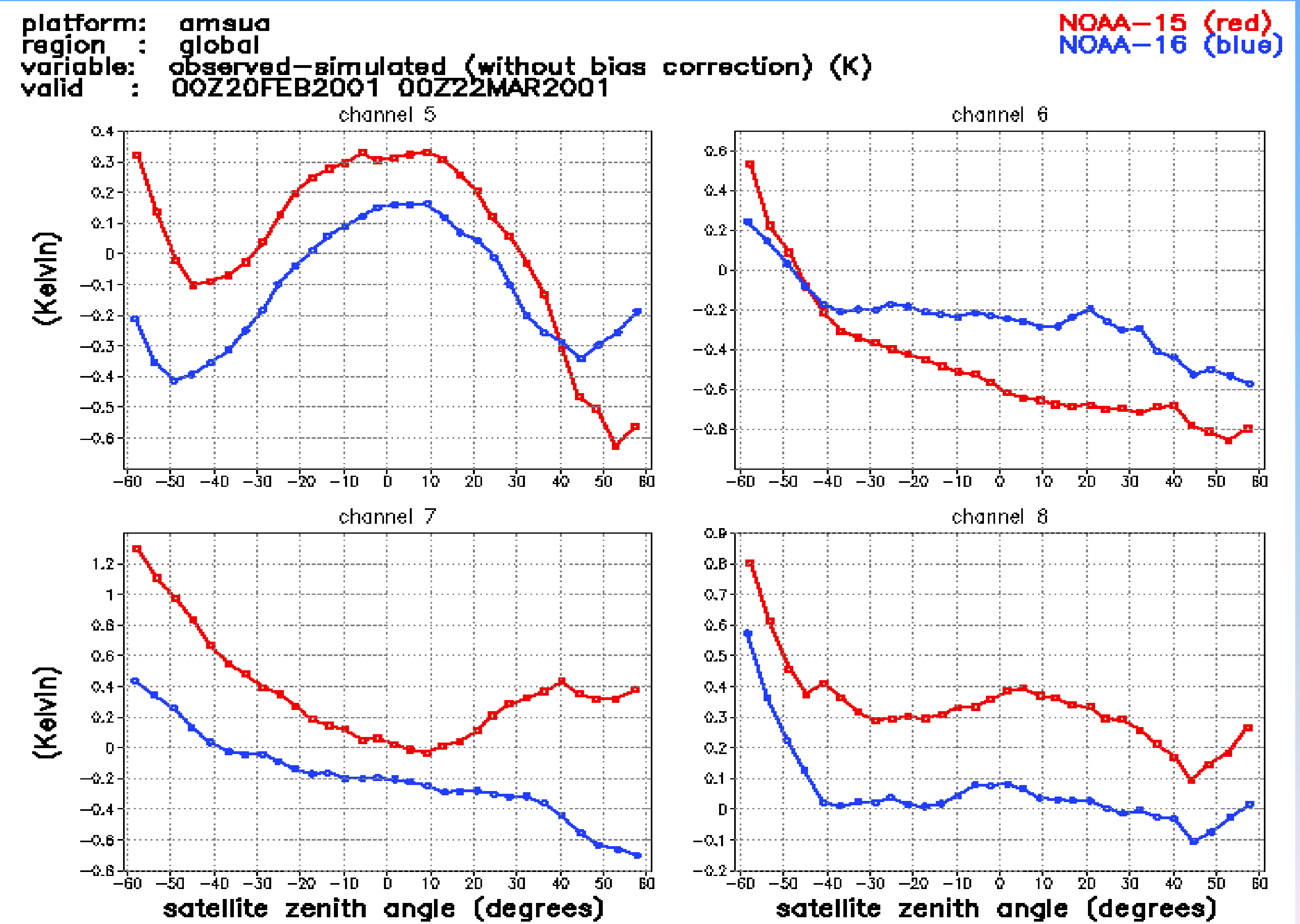
NOAA-18 AMSU-A
Ch. 1
Ch. 2
Ch. 3
Ch. 4
Ch. 5
Ch. 6
Ch. 7
Pressure (hPa)
0.1
1
10
100
1000
-5
0
5
10
15
dT_B/dq(H_2O), K/(g/kg)
NOAA-18 AMSU-A
Ch. 8
Ch. 9
Ch.10
Ch.11
Ch.12
Ch.13
Ch.14
Ch.15
Pressure (hPa)
-5
0
5
10
15
20
dT_B/dq(H_2O), K/(g/kg)
NOAA-18 MHS
Ch.16
Ch.17
Ch.18
Ch.19
Ch.20
Pressure (hPa)
-150
-100
-50
0
50
dT_B/dq(H_2O), K/(g/kg)


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(H_2O), K/(g/kg)
NOAA-18 HIRS/4
Ch. 9
Ch.10
Ch.11
Ch.12
Pressure (hPa)
dT_B/dq(H_2O), K/(g/kg)
NOAA-18 HIRS/4
Ch.13
Ch.14
Ch.15
Ch.16
Ch.17
Ch.18
Ch.19
Pressure (hPa)
dT_B/dq(H_2O), K/(g/kg)


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

# Bias Correction

- Assumption is that the data and background are unbiased.  Is this true?


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)

# Bias Correction

- 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.

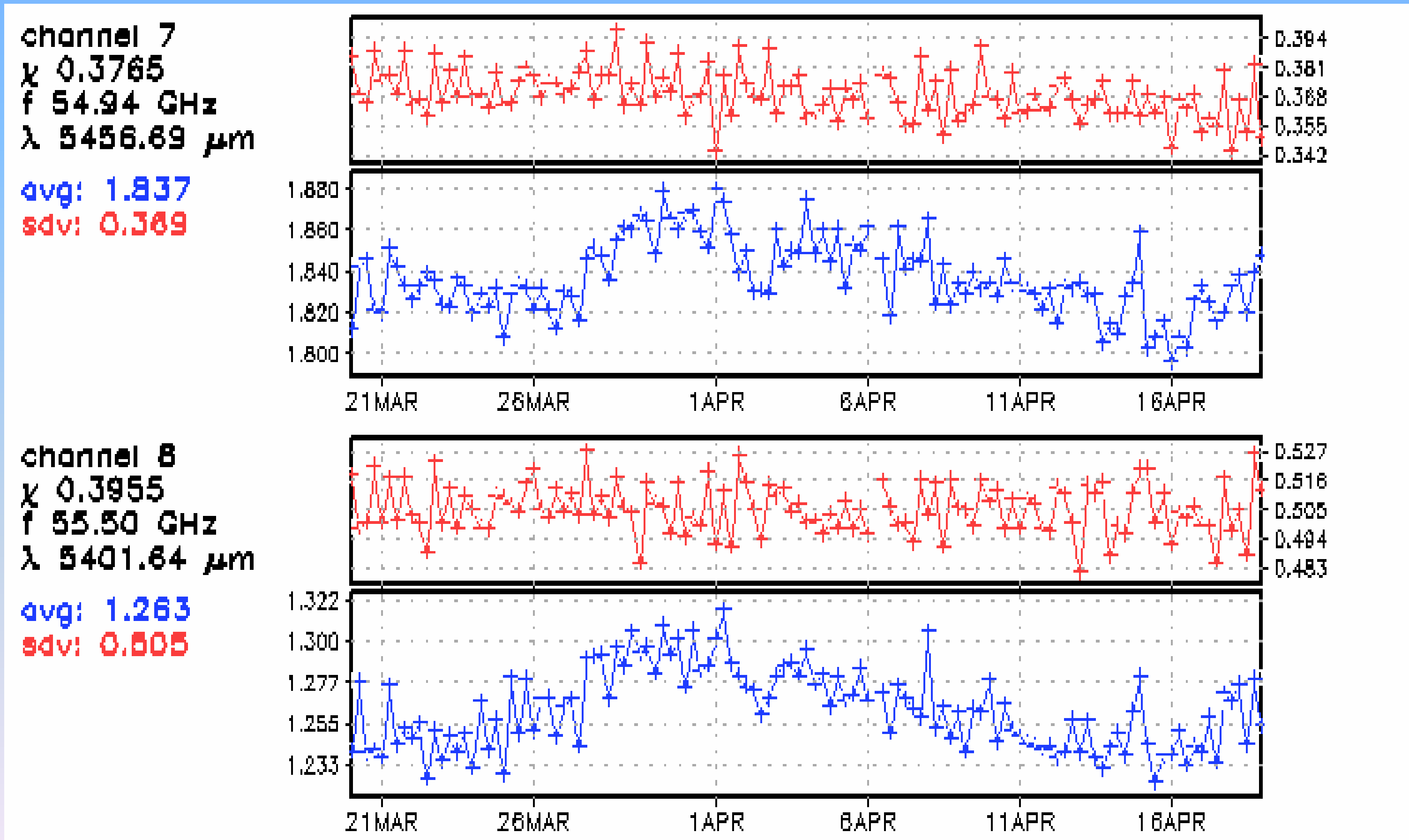
# Bias Correction

- Off-line Bias Correction
  - Bias Correction Coefficient Estimated using Co-located Radiosondes.
  - Eyre (1992), Harris and Kelly (2001)
- Integrated Bias Correction
  - Bias correction coefficients estimated as a part of x, the analysis state.
  - Derber and Wu (1998) – Dee (2004)

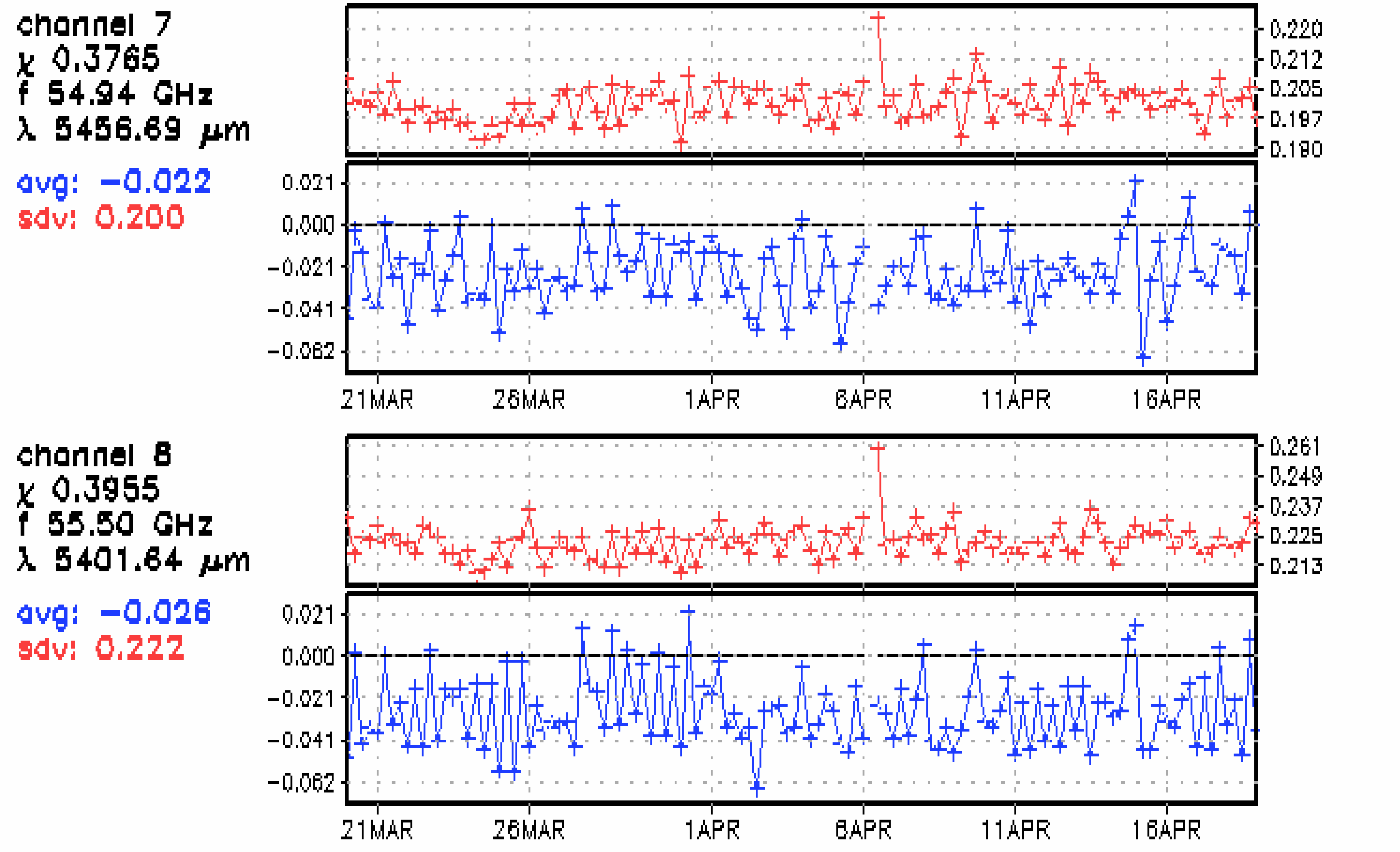
# Bias Correction

- Two components:
  - Scan position Dependent – different correction for each FOV.
  - State Dependent.
    - Linear regression equation with predictors of bias multiplied by coefficients.
    - e.g. $a_0 + a_1$*(mean 1000-500hPa temperature) + …
    - Off line $a_0$, $a_{1,}$… estimated from collocations.
    - Integrated a0, a1, … part of analysis vector.

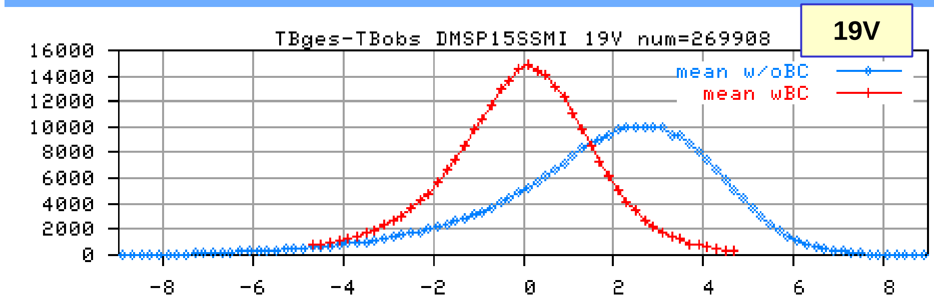
# NOAA 18 AMSU-A
# No Bias Correction

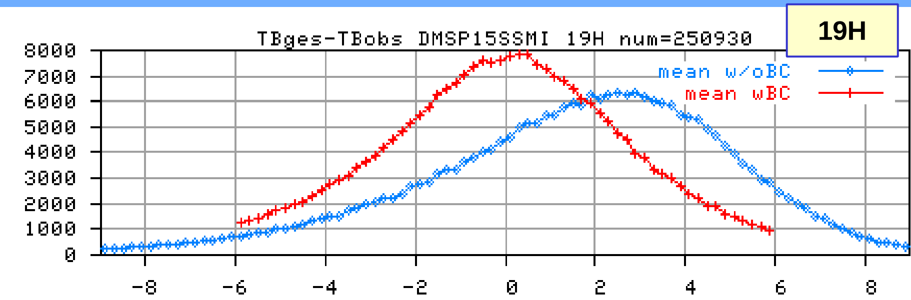


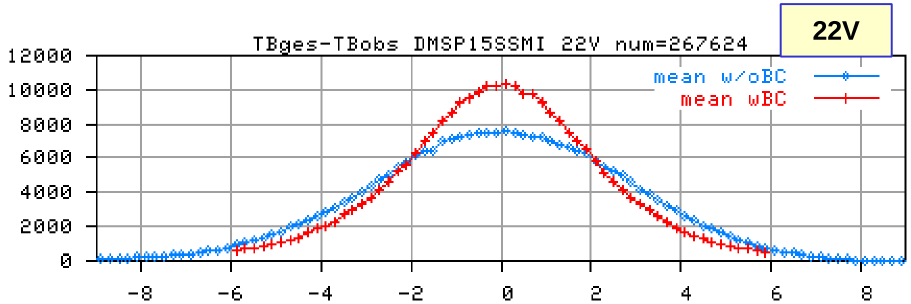
# NOAA 18 AMSU-A
# Bias Corrected

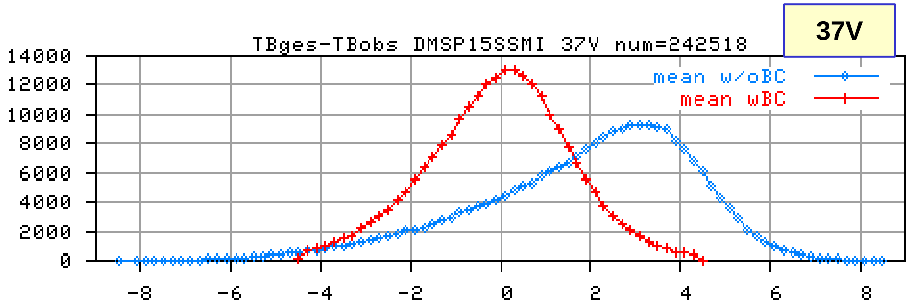


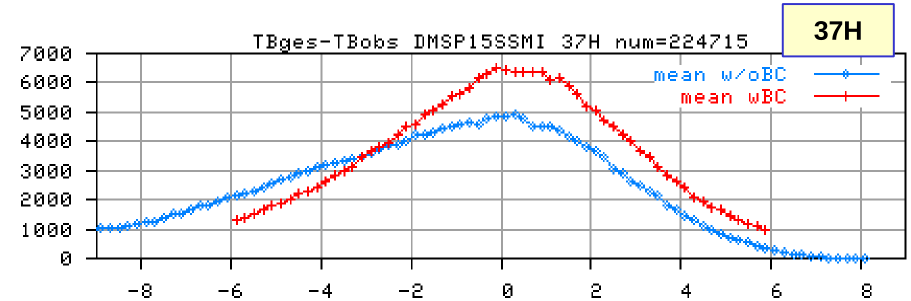
# Background – Ob. histogram

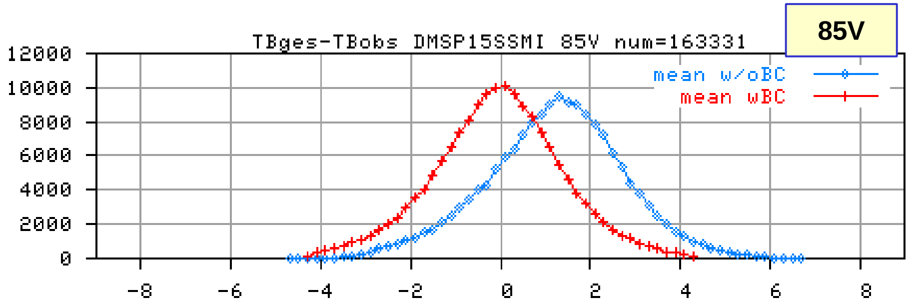


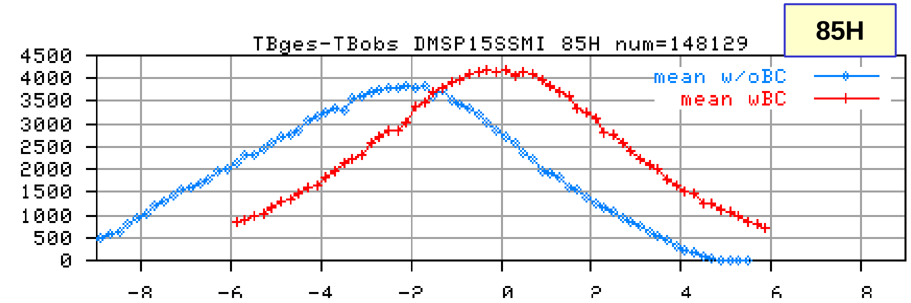




DMSP15 July2004 : 1month

before bias correction

after bias correction

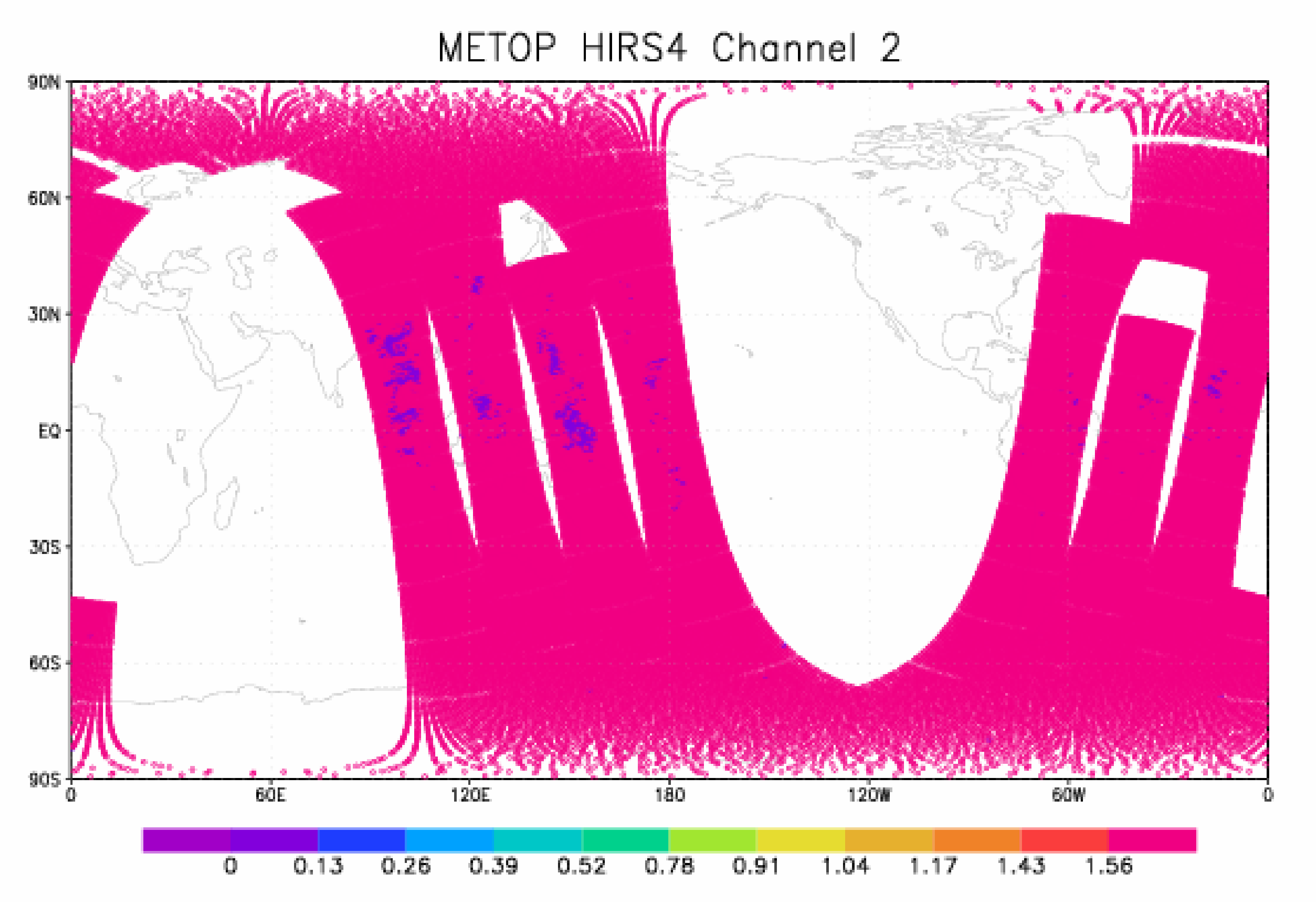
gl use 2004070200-073118(63cases)

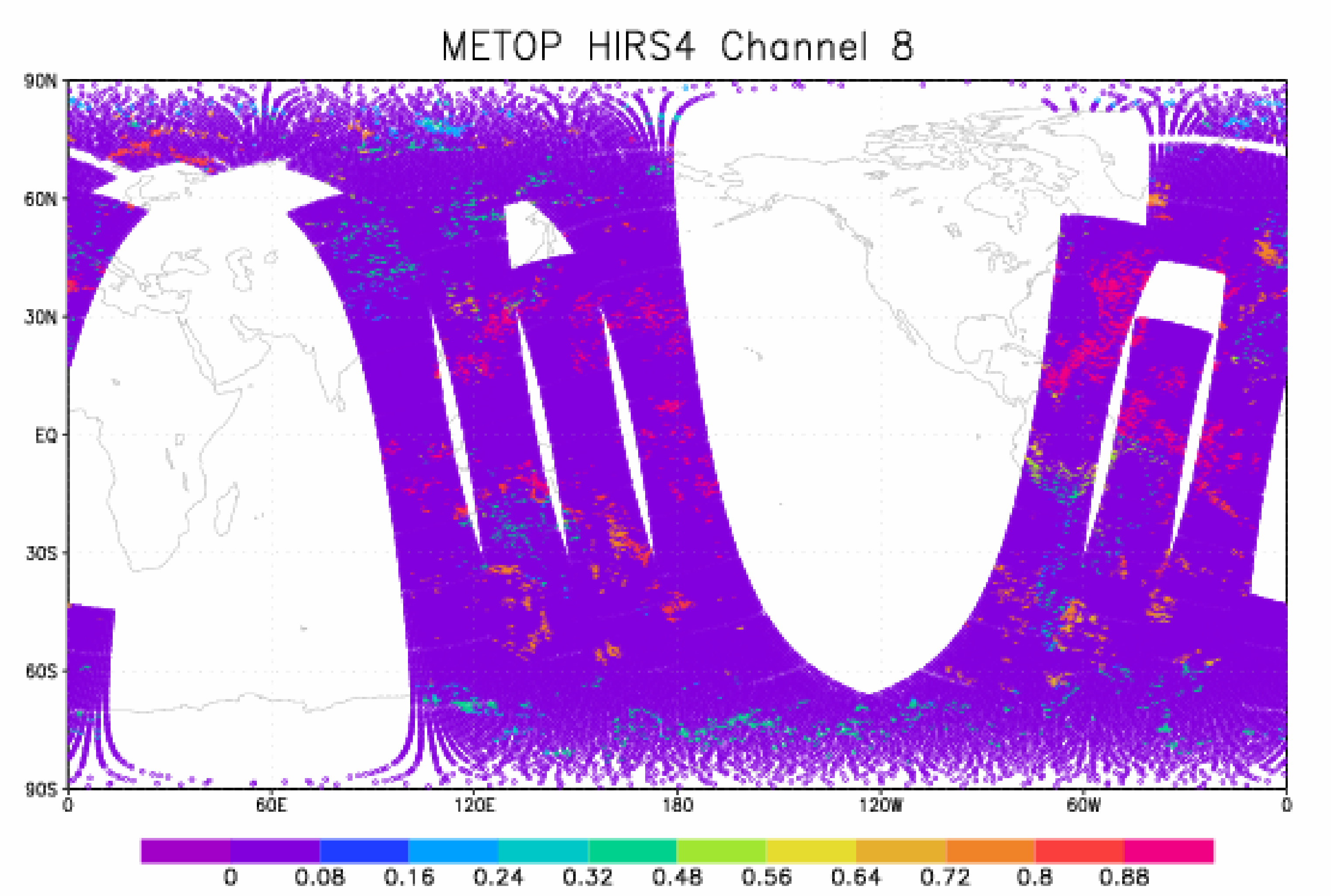
# Quality control procedures

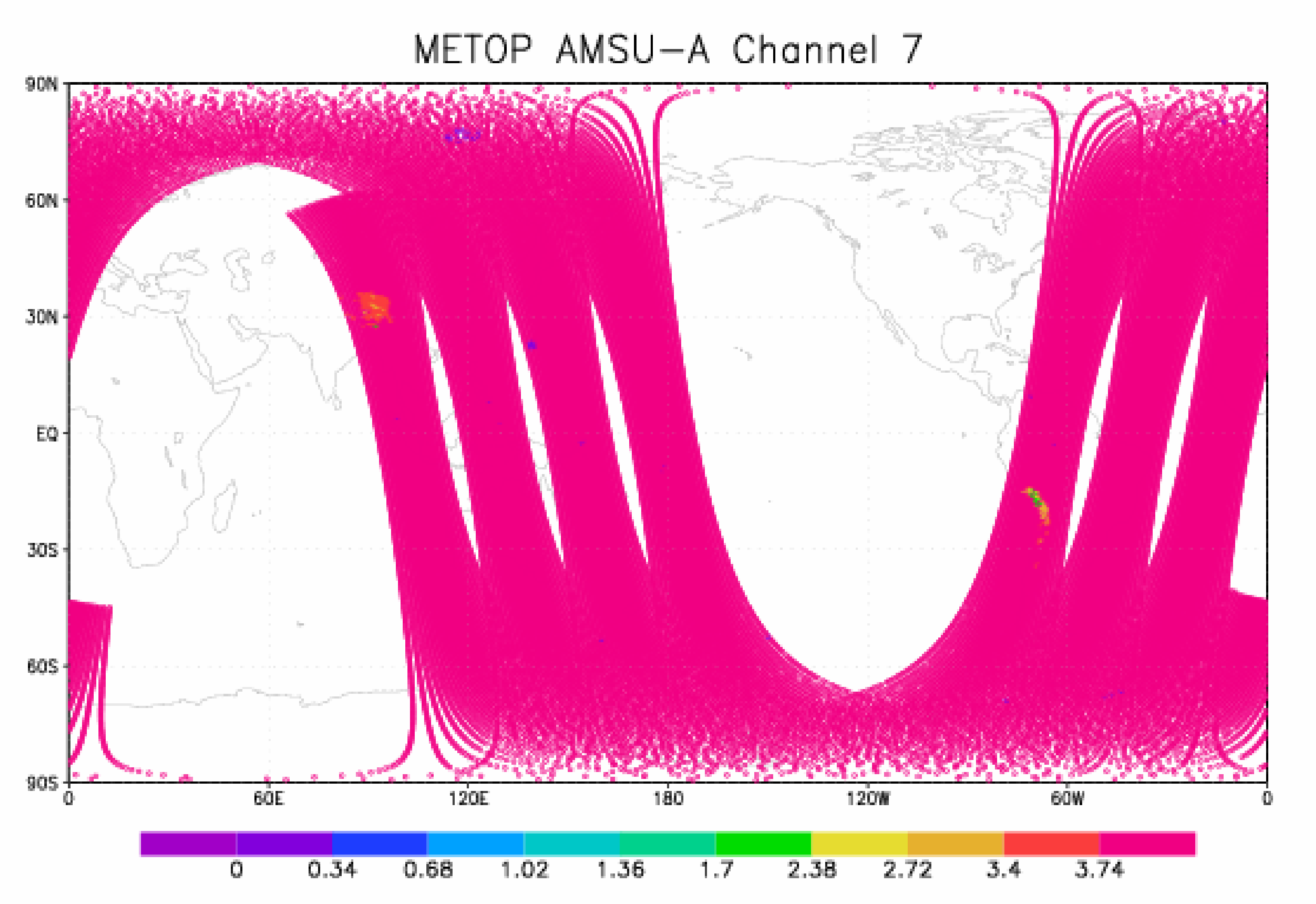
- The quality control step may be the most important aspect of satellite data assimilation.
- Data which has gross errors or which cannot be properly simulated by forward model must be removed.
- Most problems with satellite data come from 3 sources:
  - Instrument errors.
  - Clouds and precipitation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

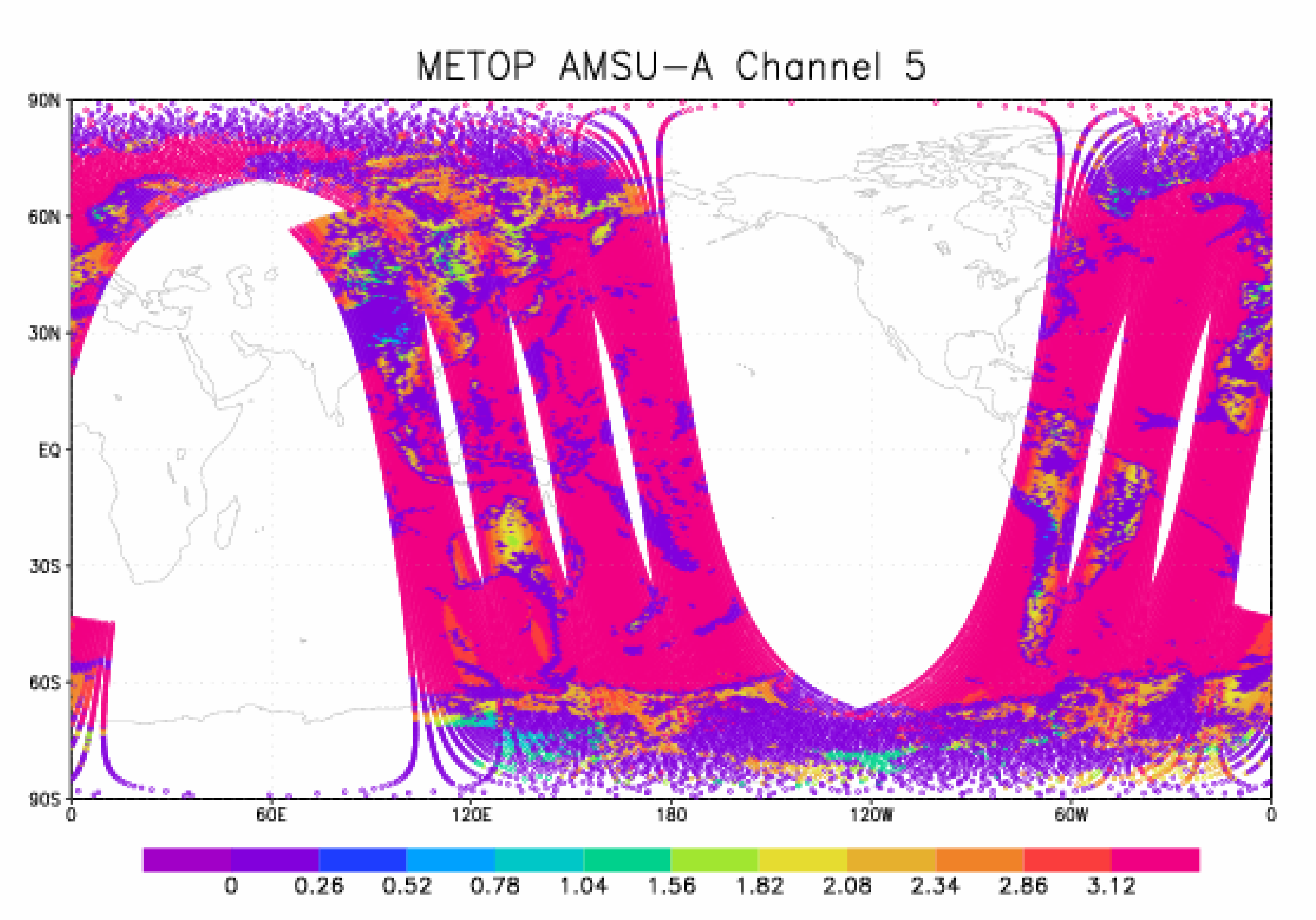
# Quality control procedures

- IR cannot see through clouds.
  - Since deep layers not many channels above clouds – cloud height not always easy to determine.
- Microwave impacted by clouds and precipitation, but signal from thinner clouds can be modeled and mostly accounted for in RT or 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
0.08
0.16
0.24
0.32
0.48
0.56
0.64
0.72
0.8
0.88


METOP AMSU-A Channel 7
90N
60N
30N
EQ
30S
60S
90S
0
60E
120E
180
120W
60W
0
0
0.34
0.68
1.02
1.36
1.7
2.38
2.72
3.4
3.74

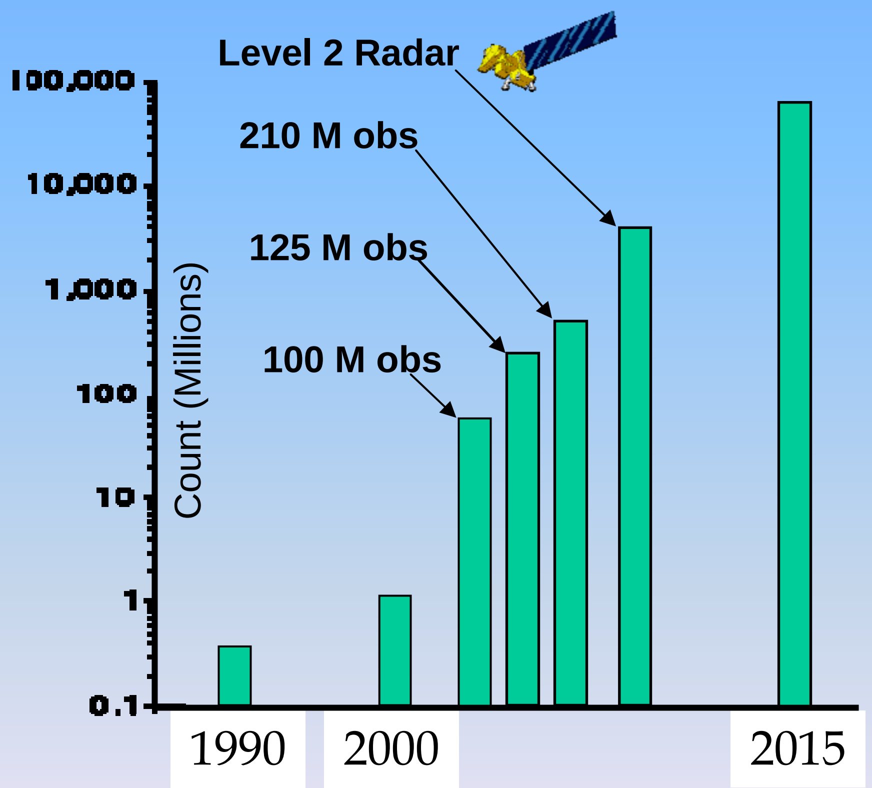

METOP AMSU–A Channel 5
90N
60N
30N
EQ
30S
60S
90S
0
60E
120E
180
120W
60W
0
0
0.26
0.52
0.78
1.04
1.56
1.82
2.08
2.34
2.86
3.12

# Quality control procedures (thinning)

- Some data is thinned prior to using.
  - Redundancy in data.
  - Reduce correlated error.
  - Computational expense
    - ~1500M satellite obs/day go into analysis (before thinning)

# Satellite Data Ingest

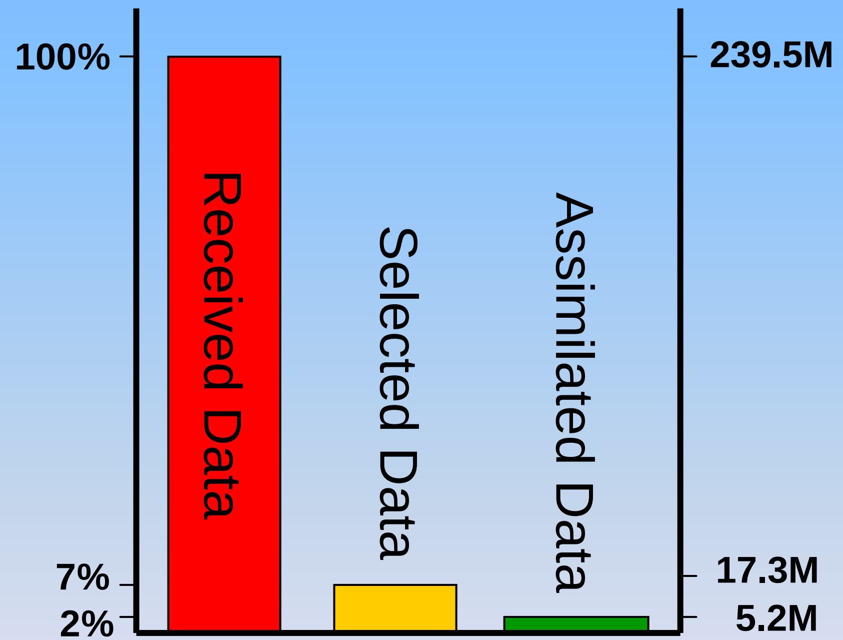
## Daily Satellite & Radar Observation Count




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

## Daily Percentage of Data Ingested into Models

*2005 Data




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

# Measurement and Forward Model errors

- Measurement and forward model errors specified based on instrument developer instrument errors (lower bound) and o-b statistics (upper bound).
  - Desroziers and Ivanov (2001) technique to estimate ob errors.
- Forward model error includes representativeness error – the inability to represent certain features of the atmosphere.
  - Resolution,
  - Missing constituents,
  - Etc.
- Bias must be accounted for since it is often larger than signal.
- Generally for satellite radiances, the error covariance matrix is assumed diagonal – probably not true.

# Correlated observation Error

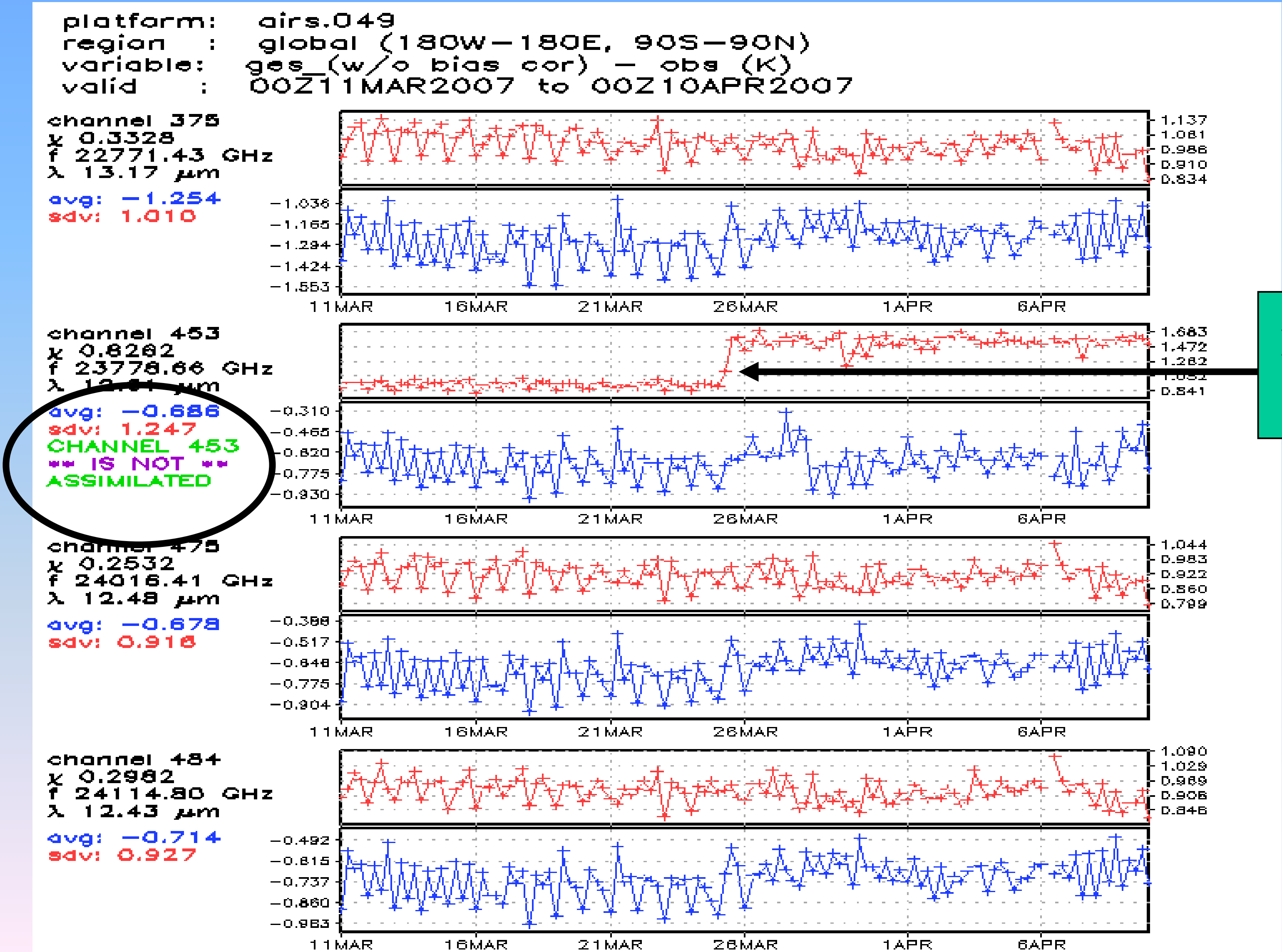
- Correlated error can come from the observations, processing of the observations, or from the forward model.
- Difficult to estimate.
- More important for IASI.
- Generally because we assume no correlated error, diagonal variance is enhanced.

# 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.
- Essential for the introduction of new instruments
- Needs to be ongoing/real time.

# Quality Monitoring of Satellite Data

AIRS Channel 453 25 March 2007




**Increase in SD Fits to Guess**

# Data Monitoring

- ITSC web site listing monitoring from many centres

  http://cimss.ssec.wisc.edu/itwg/nwp/monitoring.shtml

- NCEP web site

  http://www.emc.ncep.noaa.gov/gmb/gdas/radiance/su/opr/index.html

- ECMWF web site

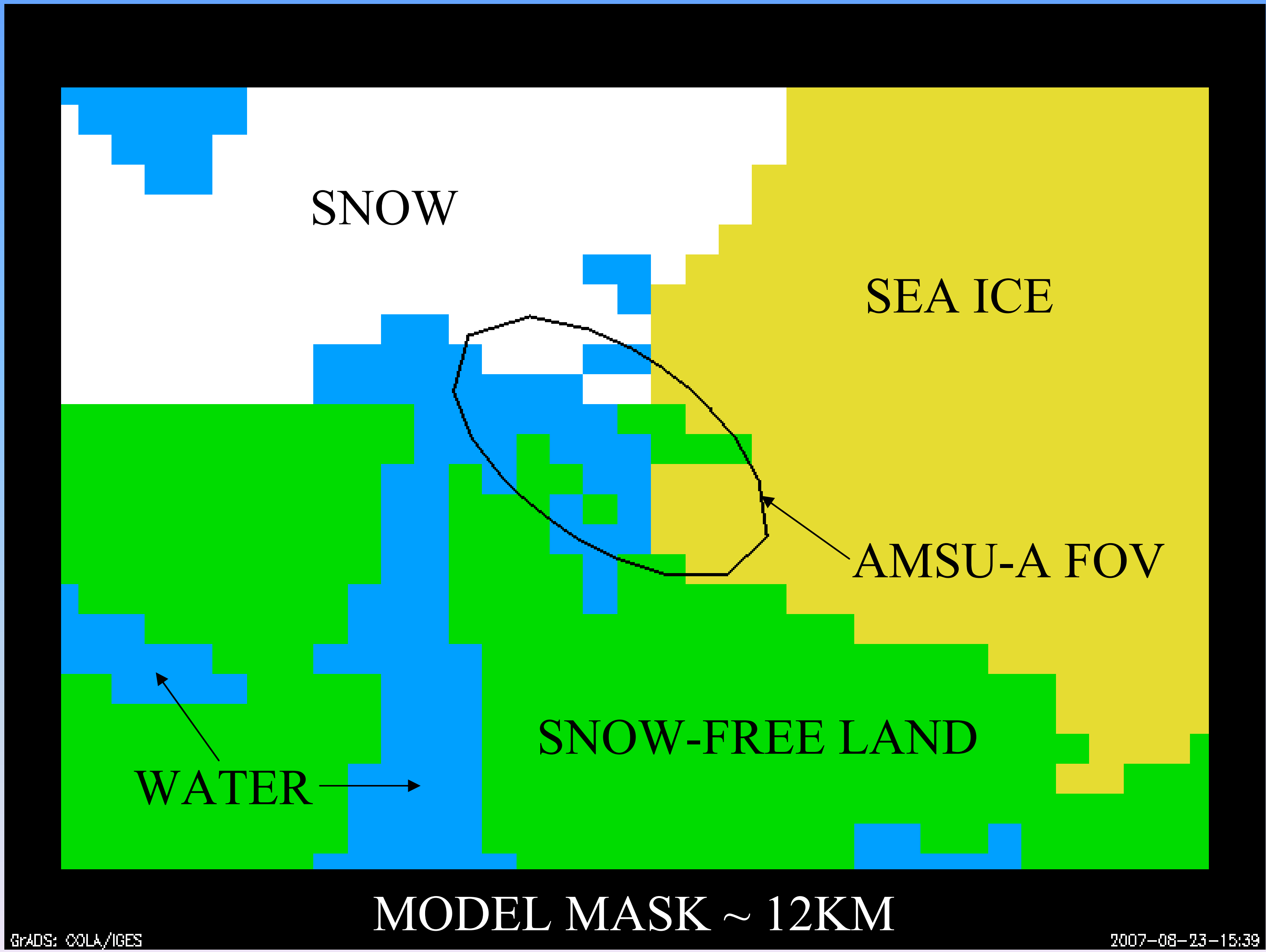
  http://www.ecmwf.int/products/forecasts/d/charts/monitoring/satellite/atovs/

- UKMO web site

  http://www.metoffice.gov.uk/research/nwp/satellite/radiance/atovs/main.html

# ATOVS Assimilation Problem has not been Completed

- FOV
- Antenna Correction
- Slant path
- RT enhancements
  - Surface Emissivity
  - Additional absorbers/scatterers
  - Etc.
- Cloud Assimilation
- Aerosol Assimilation
- Trace Gas Assimilation
- Etc.

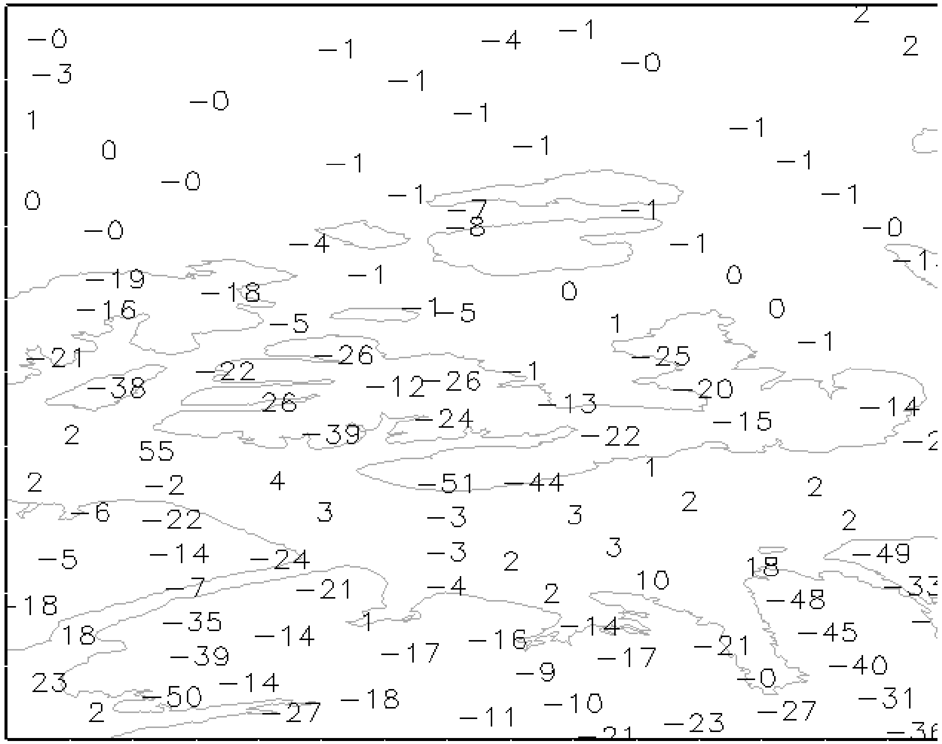

SNOW
SEA ICE
AMSU-A FOV
SNOW-FREE LAND
WATER
MODEL MASK ~ 12KM
GrADS: COLA/IGES
2007-08-23-15:39

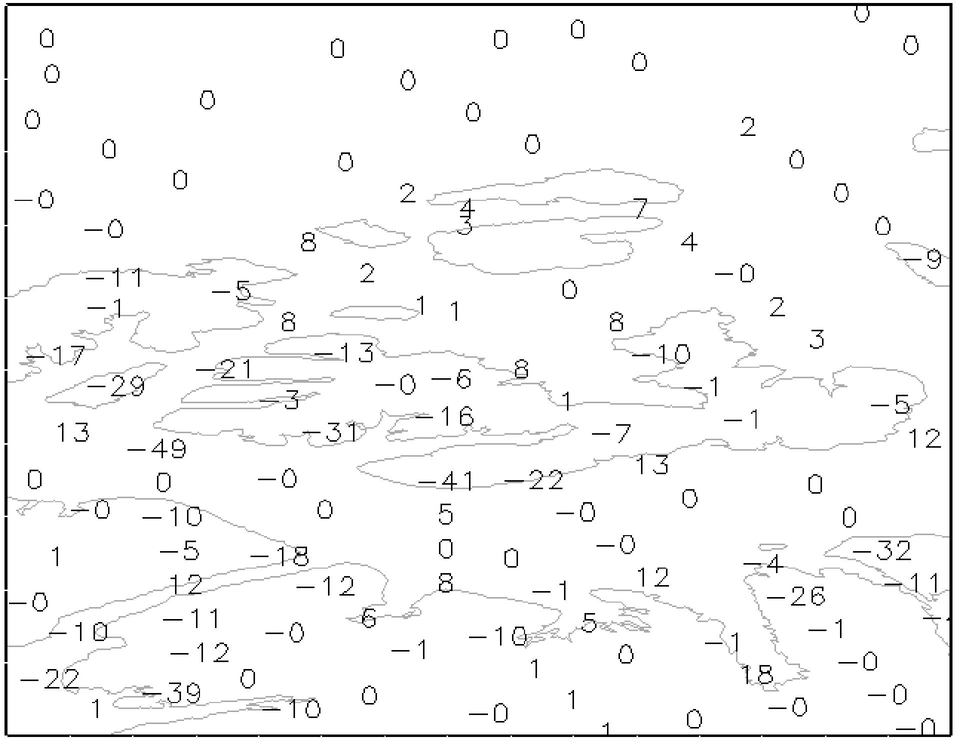
# IMPACT: ACCOUNTING FOR FOV

## EX: NOAA-15 AMSU-A, CHANNEL 2

CONTROL:
OBS. MINUS GUESS $T_b$

IMPACT: CHANGE IN
OBS. MINUS GUESS $T_b$





NORTHERN CANADA

NEGATIVE IS IMPROVEMENT

# Summary

- Radiance assimilation was developed using ATOVS data.
- ATOVS data remains the core of radiance assimilation.
- Details are very important
- Care necessary to get as much information as possible out of the data.
  - Radiative Transfer
  - Bias Correction
  - Quality Control
  - Monitoring
- Additional enhancements still possible, and work is underway.

# Additional information

- International TOVS Working Group (ITWG)

  http://cimss.ssec.wisc.edu/itwg/nwp

- NWP SAF

  http://www.metoffice.gov.uk/research/interproj/nwpsaf/index.html