Radiance Data Assimilation in WRF-Var

NCAR/MMMM

Work supported by AFWA, NASA, NSF, KMA

Outline

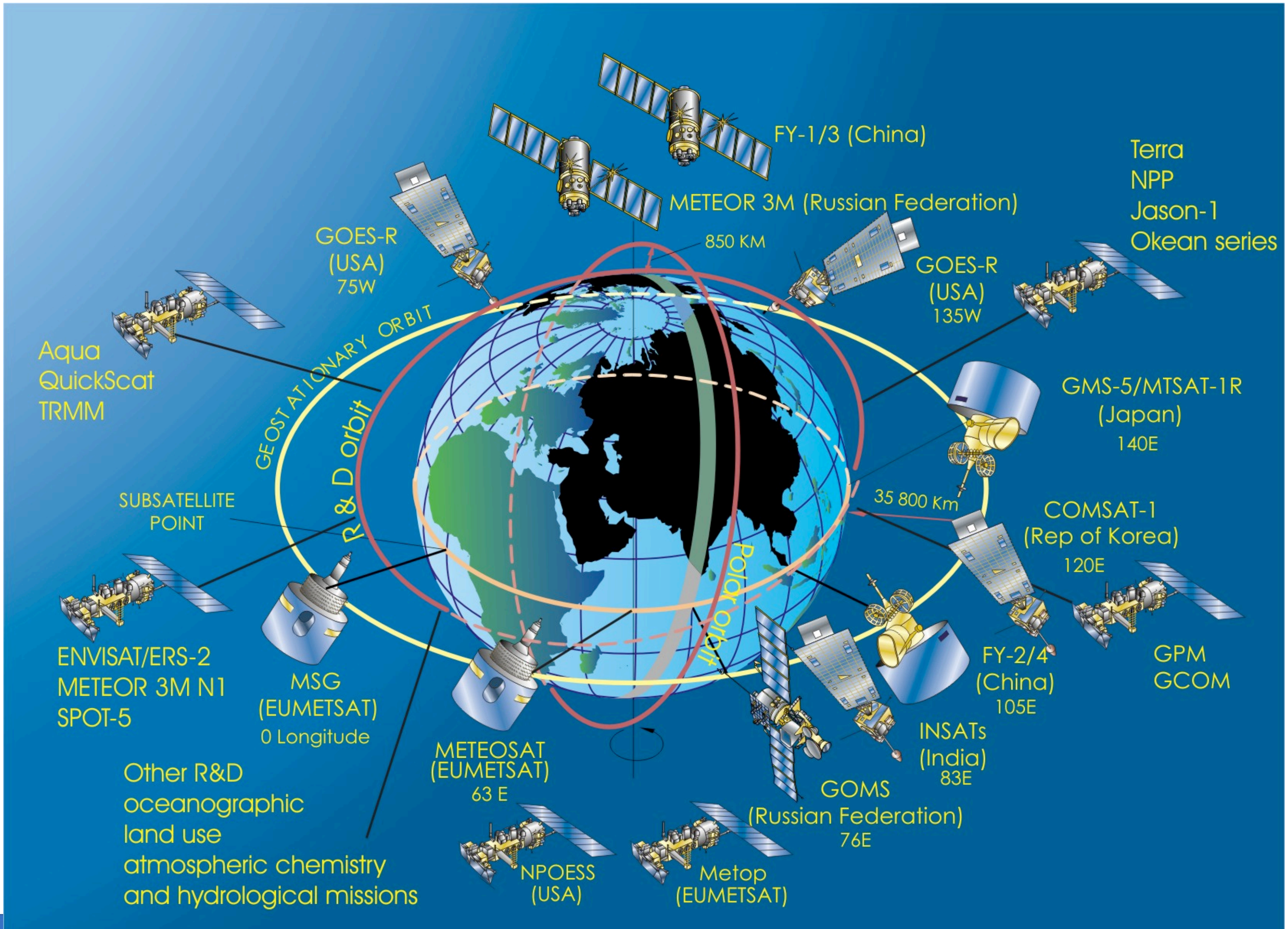
- An introduction of radiance data assimilation (Zhiquan Liu, liuz@ucar.edu)
  - Principal of satellite measurements
  - Introduction to the Radiative Transfer theory
  - Practical implementation

- Practical aspects with WRF-Var

  (Thomas Auligné, auligne@ucar.edu)

Part I: An Introduction of radiance data assimilation

Weather/Environment Satellite Constellation



JCSDA Advisory Panel 01/2009.

Prof. Rick Anthes on satellite data research:

"The national investment in satellite data assimilation is a tiny fraction of the investments in the satellite systems themselves, yet assimilation research and implementation in operational models are essential to realize the enormous potential of the satellite data. Augmented investments in data assimilation research and the supporting computing tools are highly recommended"

Radiance data assimilation for community

- For long time, radiance DA has been the “patent” of operational NWP centers.
  - Usually NWP centers’ DA systems are not accessible to the community or less documented.
  - This prevents the community contributions from advancing radiance DA.
- It is the first time that radiance data assimilation capacity is available to the community with the state-of-the-art techniques, even though we have very limited resource for community support.
  - Question & collaboration are welcome, but do not blame if our response is slow or too brief.
  - Hopefully this talk plus the users’ guide in WRF3.1 can help for your own research.

Satellite Data Used or Tested at JCSDA and NCEP

~33 instruments are used

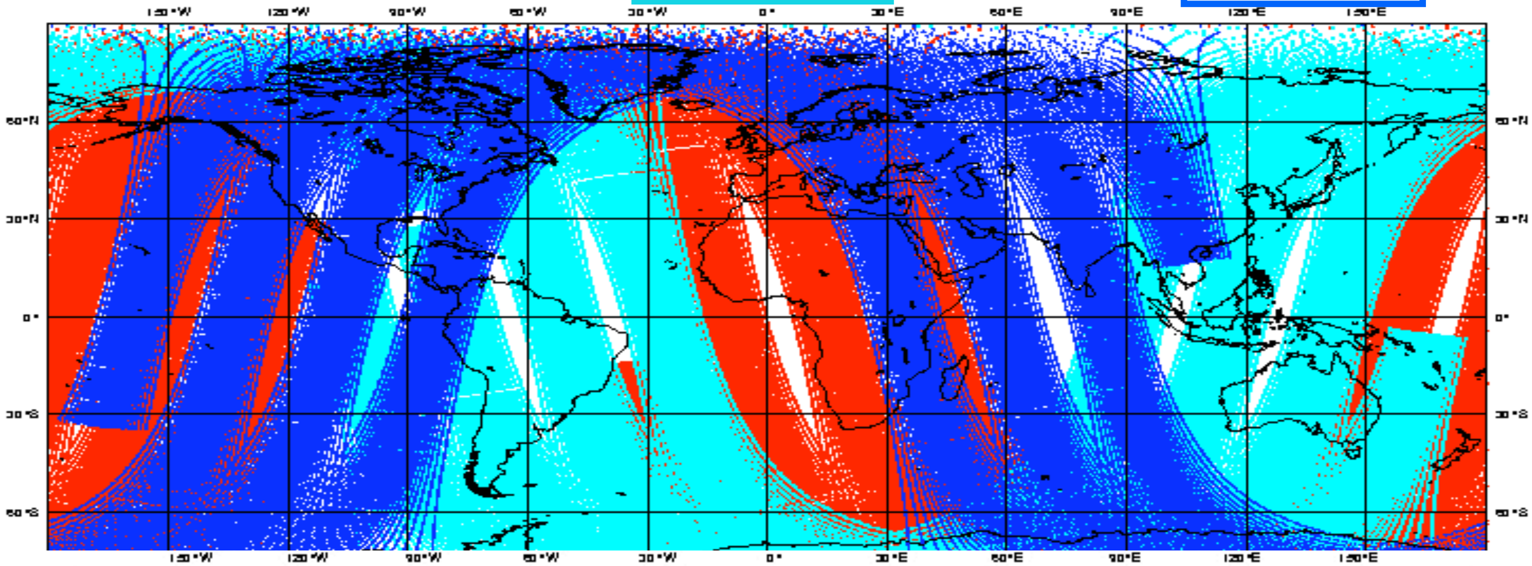
- **HIRS sounder radiances**
- **AMSU-A sounder radiances**
- **AMSU-B/MHS sounder radiances**
- **GOES sounder radiances**
- **GOES, Meteosat, GMS winds**
- **GOES precipitation rate**
- **SSM/I precipitation rate**
- **TRMM precipitation rate**
- **SSM/I ocean surface wind speeds**
- **ERS-2 ocean surface wind vectors**
- **Quikscat ocean surface wind vectors**
- **AVHRR SST**
- **AVHRR vegetation fraction**
- **AVHRR surface type**
- **Multi-satellite snow cover**
- **Multi-satellite sea ice**
- **SBUV/2 ozone profile and total ozone**
- **Altimeter sea level observations (ocean data assimilation)**
- **AIRS**
- **MODIS Winds**
- **COSMIC**

instruments are being tested

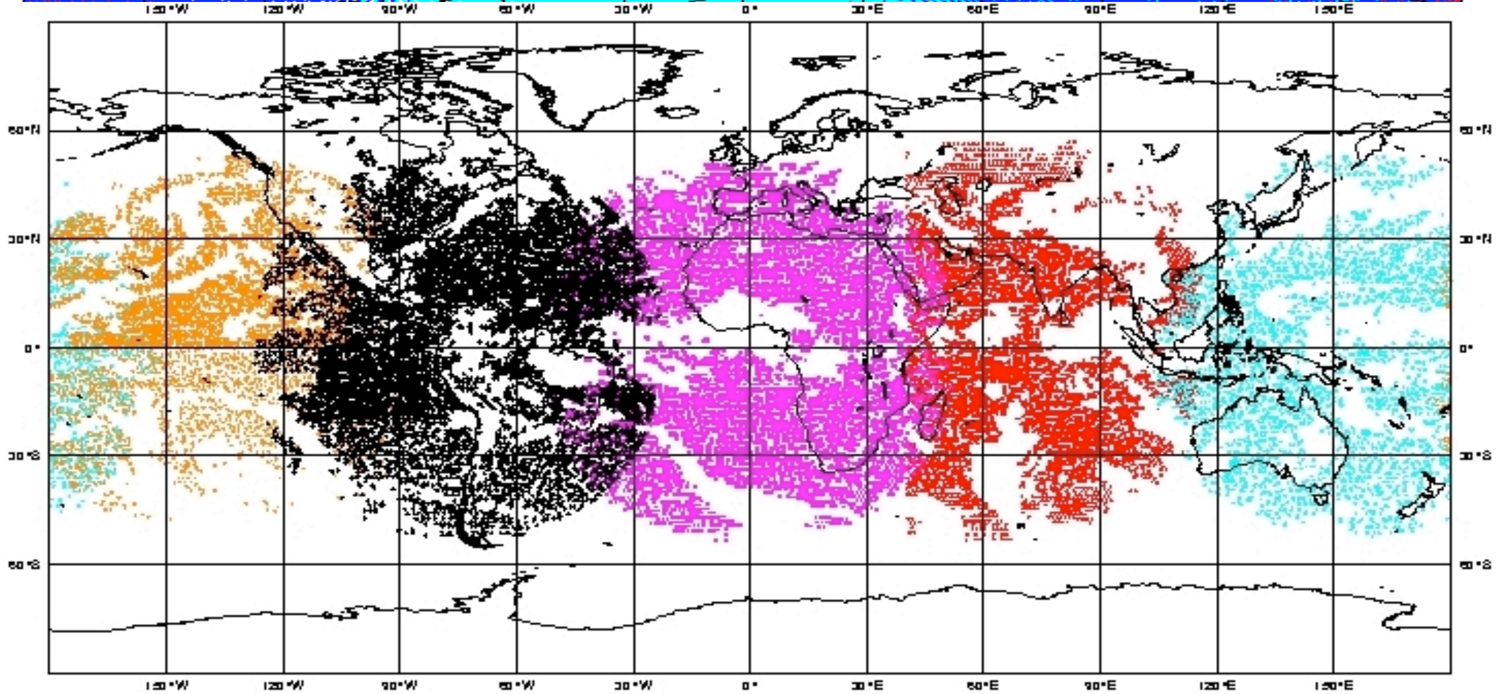
- ***F16 SSMIS***
- ***WindSat EDR, SDR assimilation***
- ***OMI total ozone***
- ***Cloudsat for CRTM validation***
- ***Aura MLS***
- ***IASI***
- ***ASCAT***
- ***GRAS***
- ***GOME2***
- ***FY-2***

Not all assimilated in raw radiances, Some also in retrieved quantities.

NOAA-15 NOAA-16 NOAA-17



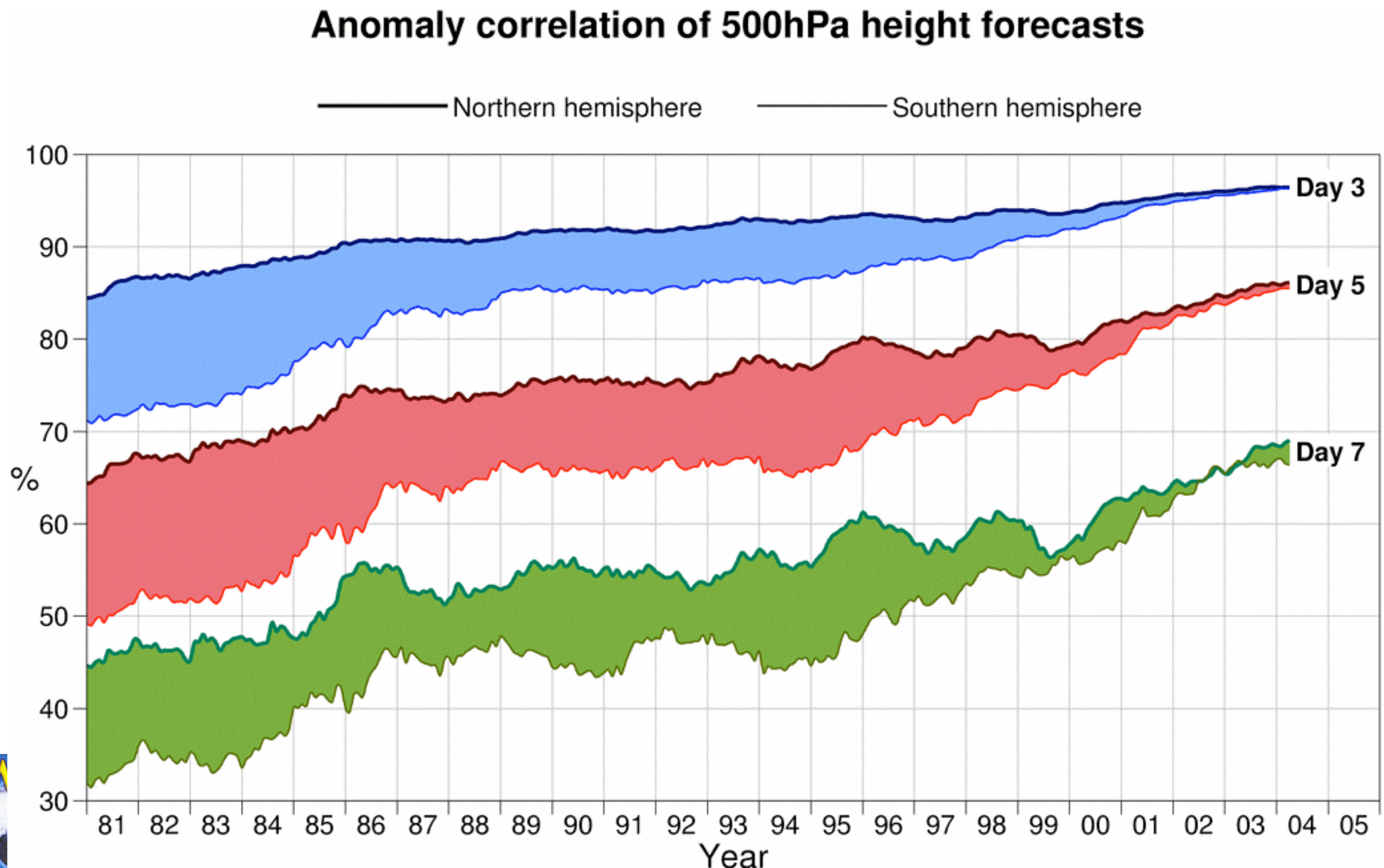
Coverage within
A 6-hour time window



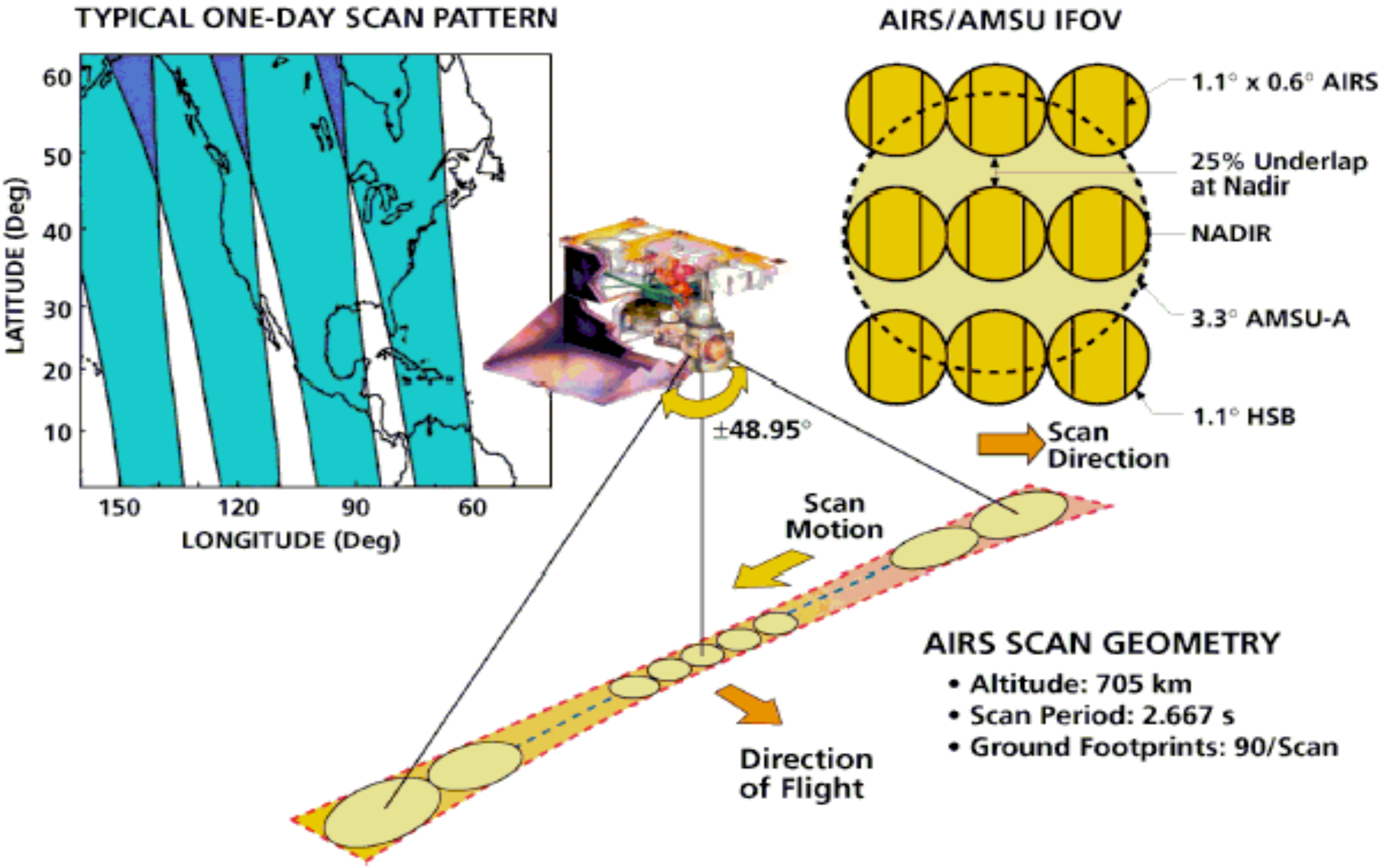
Goes-W Goes-E Met-7 Met-5 GMS(Goes-9)

Evolution of forecast skill for northern and southern hemispheres

Courtesy, Simmons 2004



Cross-track scan geometry of satellite instruments



TMI/SSMI/SSMIS scan geometry

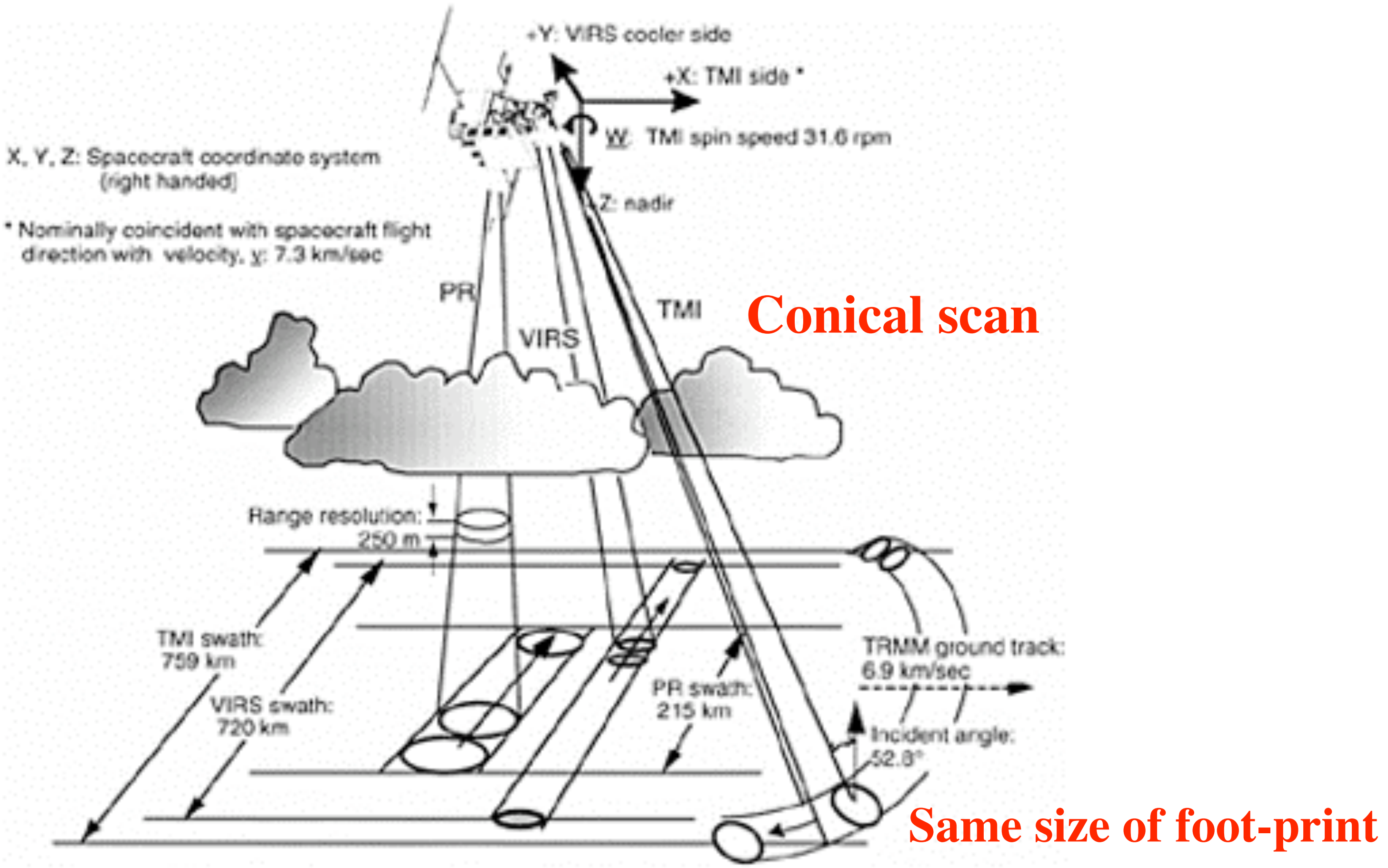


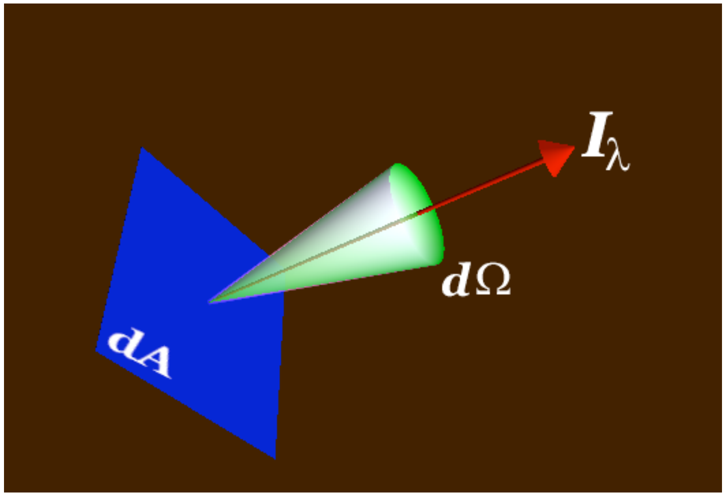
FIG. 1. Schematic view of the scan geometries of the three TRMM primary rainfall sensors: TMI, PR, and VIRS.

What do satellite instruments measure?

They DO NOT measure TEMPERATURE
They DO NOT measure HUMIDITY
They DO NOT measure WIND

Satellite instruments (active and passive) simply measure the radiance *L* that reaches the top of the atmosphere at frequency ν. The measured radiance is related to geophysical atmospheric variables by the radiative transfer equation.

$$L(\nu) = \int_0^\infty B(\nu, T(z)) \left[\frac{d\tau(\nu)}{dz} \right] dz + \text{Surface emission} + \text{Surface reflection/scattering} + \text{Cloud/rain contribution} + \ldots$$



Radiance:
L with [L] = $Wm^{-2}sr^{-1}\mu m^{-1}$

Planck function:

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\left[\exp\left(\frac{h\nu}{kT}\right) - 1\right]^{-1}$$

Radiance: the amount of energy per unit surface per unit time per unit solid angle emitted at the frequency ν or wavelength λ.

Brightness Temperature (in Kelvin) : the temperature that a blackbody would need to have in order to emit radiation of the observed radiance at a given wavelength. Also refer to as "**equivalent blackbody temperature**". Derived by inverting the Planck function.

Usually measurements are given to the users in calibrated **Brightness Temperature.**

For certain microwave sensors, sometimes given in **Antenna Temperature**.

Sensors from Weather/Environment Satellites

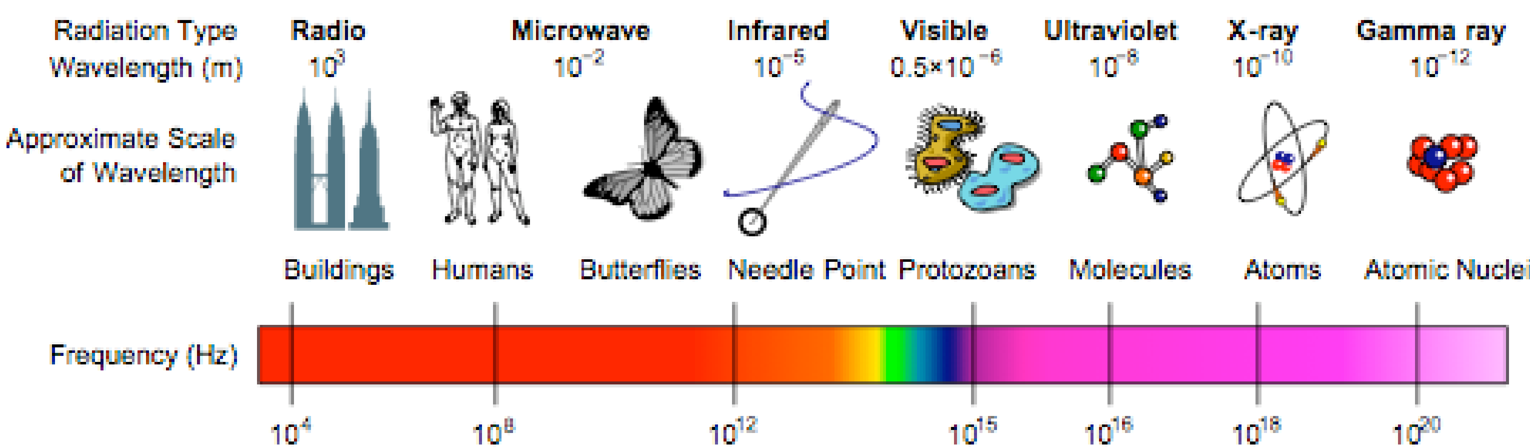
GPSRO

AMSU-A
AMSU-B
MHS
SSMI
SSMIS
TMI
AMSR-E

HIRS
AIRS
IASI

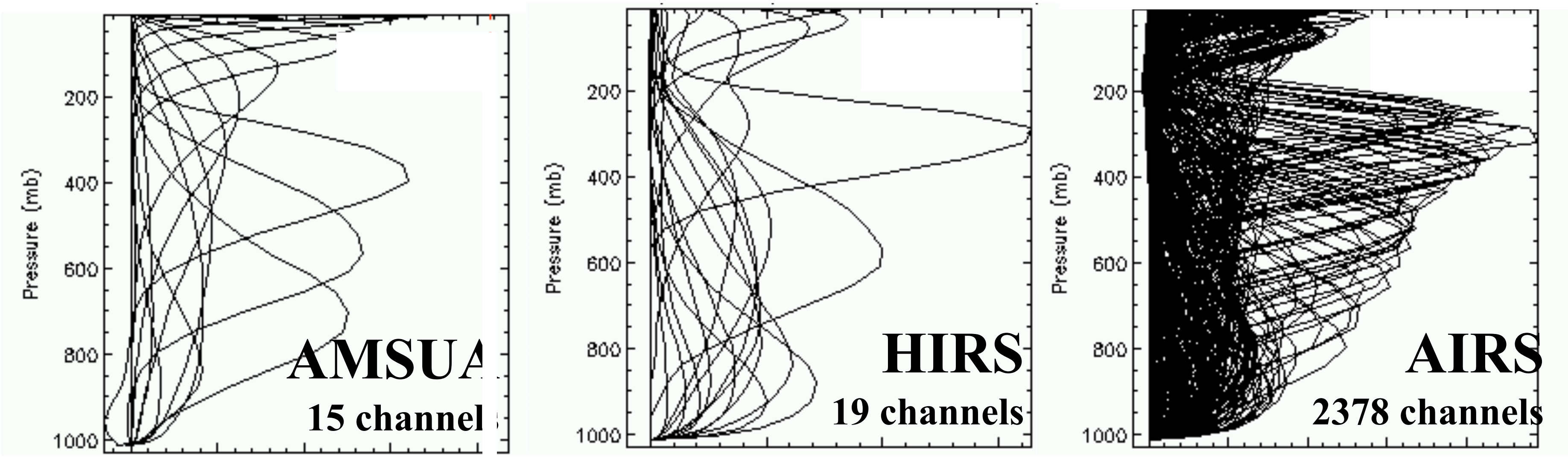
AVHRR
MODIS

SBUV



Electromagnetic Spectrum

From spectral resolution to vertical resolution



$$L(\nu) = \int_0^{\infty} B(\nu, T(z)) \left[\frac{d\tau(\nu)}{dz} \right] dz$$

↓

Weighting function

Why assimilating Radiances?

•Avoid complicated errors (random and systematic) introduced by (unnecessary) pre-processing such as cloud clearing, angle (limb) adjustment and surface corrections.

•Avoid having to change (retune) our assimilation system when the data provider changes the pre-processing

•Faster access to data from new platforms (e.g. AMSU data from NOAA-16 assimilated 6 weeks after launch)

•Allows consistent treatment of historical data for re-analysis projects

History of (A)TOVS data assimilation at ECMWF

- Assimilation of NESDIS retrieval profiles (Andersson et al., 1991)
  – Statistical (no RTM) and physical (RTM) retrievals
  – Climatology as the background
  – Airmass-dependent bias of the retrieval
  – **Issue: OSEs had not shown clear positive impact in the N.H.**

- Assimilation of 1DVAR retrieval profiles (Eyre, 1993)
  – Background from a short-range NWP forecast
  – Radiances bias correction (Eyre, 1992)
  – **Issue: repeated use of the same background**

History of (A)TOVS data assimilation at ECMWF

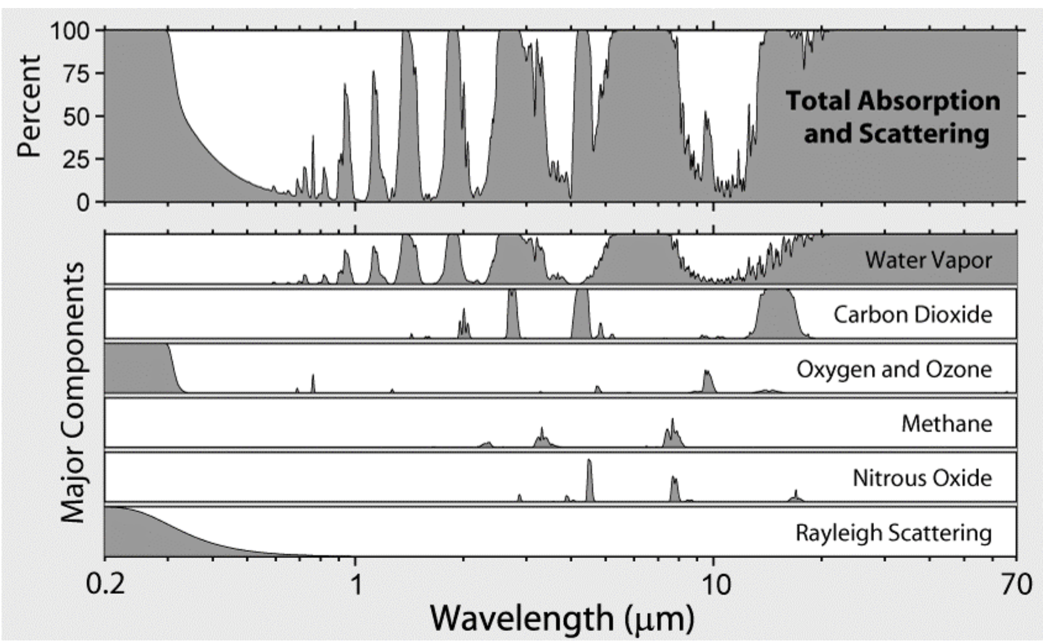
- Assimilation of NESDIS cloud-cleared radiances (Andersson et al., 1994)
  - Combine retrieval and analysis in one step
  - 1DVAR as a pre-processor in the quality control step
  - Provide cloud-cleared data and cloud flags
  - **Issue: NESDIS pre-processing as a black box**

- Assimilation of raw radiances (McNally et al., 2000)
  - Some pre-processing steps are integrated into data assimilation system. The data is more reliable and controllable.
  - Bias correction is easier (Harris and Kelly, 2000).
  - Shorten the delay of the use of data from the new instruments.
  - **Issue: cloud detection is more difficult due to the loss of the Imager information aboard the same satellite.**

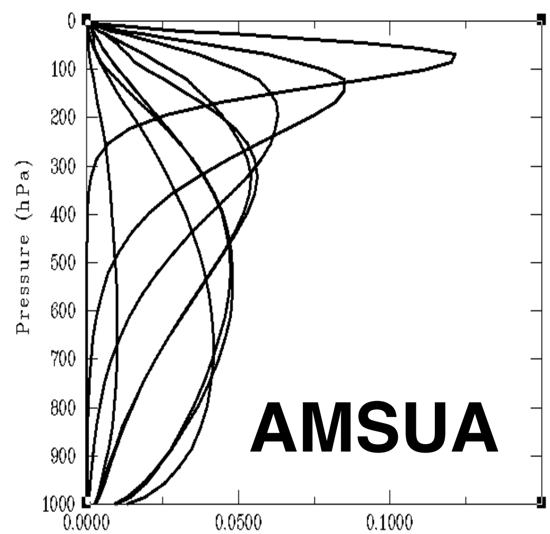
Radiative Transfer: Forward model

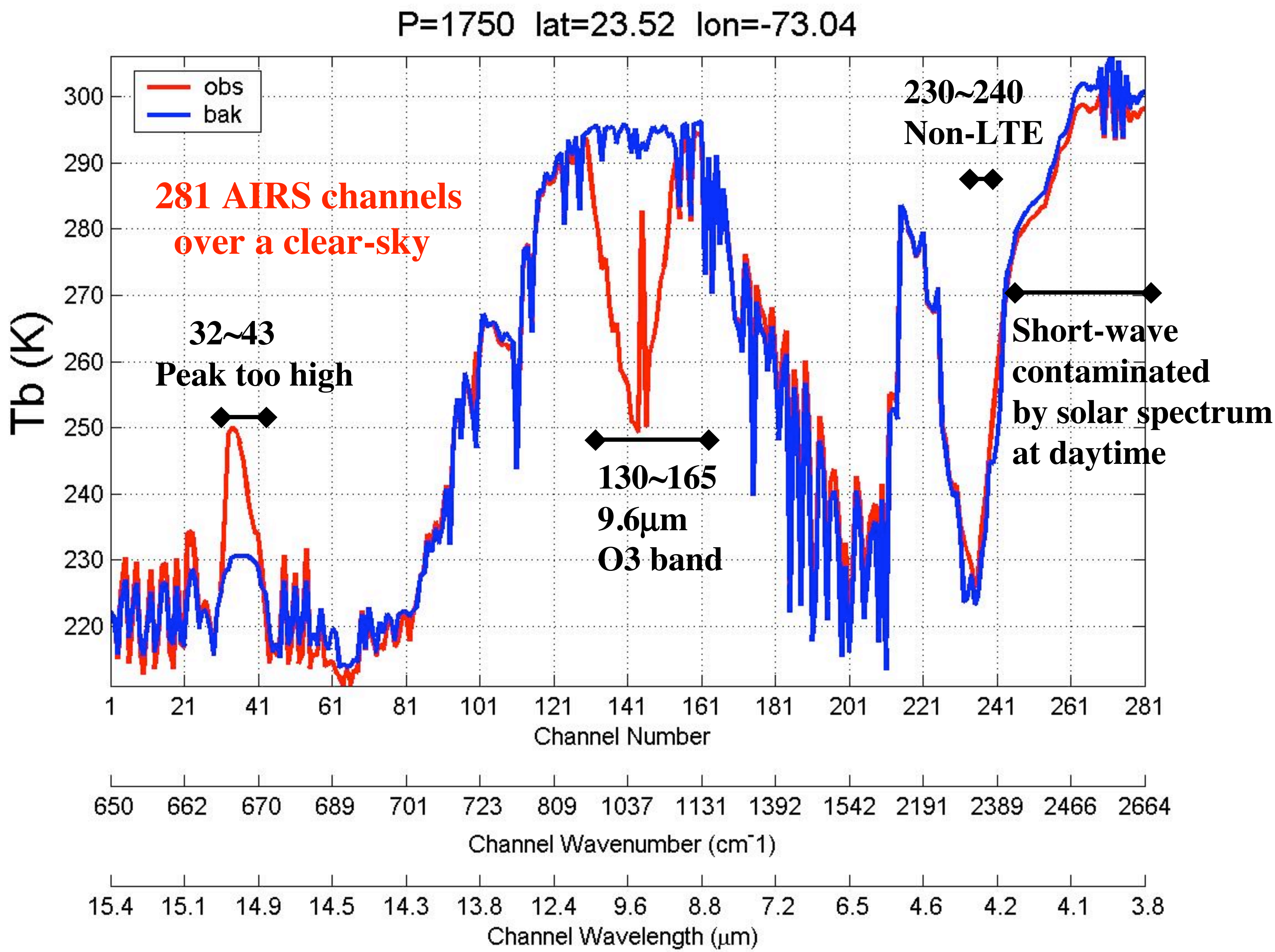
$$L(\nu) = \int_0^\infty B(\nu, T(z)) \left[\frac{d\tau(\nu)}{dz} \right] dz + \text{Surface} + \text{Cloud/rain}$$

- $L(\nu)$: TOA radiance at frequency ν
- $B(\nu, T(z))$: Planck function
- $\frac{d\tau(\nu)}{dz}$: Atmospheric absorption
- Surface: Emission/reflection
- Cloud/rain: Diffusion/scattering



- Temperature information derived from well-mixed absorbents (CO2, …)
- Channels sensitive to Humidity, Ozone, …
- Surface channels: "window" parts of spectrum

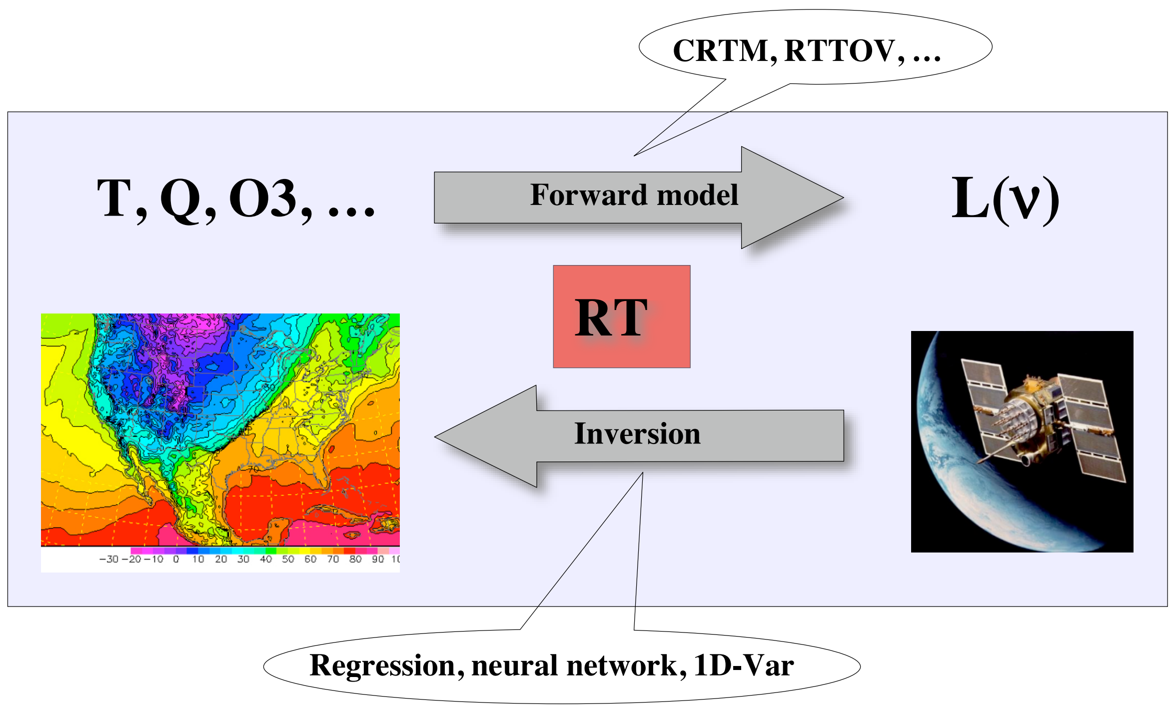



P=1750 lat=23.52 lon=-73.04
obs
bak
281 AIRS channels
over a clear-sky
32~43
Peak too high
130~165
9.6µm
O3 band
230~240
Non-LTE
Short-wave
contaminated
by solar spectrum
at daytime
Tb (K)
300
290
280
270
260
250
240
230
220
1 21 41 61 81 101 121 141 161 181 201 221 241 261 281
Channel Number
650 662 670 689 701 723 809 1037 1131 1392 1542 2191 2389 2466 2664
Channel Wavenumber (cm⁻1)
15.4 15.1 14.9 14.5 14.3 13.8 12.4 9.6 8.8 7.2 6.5 4.6 4.2 4.1 3.8
Channel Wavelength (µm)

Retrieval: Inverse problem of radiative transfer

$$L(\nu) = \int_0^\infty B(\nu, T(z)) \left[\frac{d\tau(\nu)}{dz} \right] dz + \text{Surface} + \text{Cloud/rain}$$

- $L(\nu)$: TOA radiance at frequency ν
- $B(\nu, T(z))$: Planck function
- $\frac{d\tau(\nu)}{dz}$: Atmospheric absorption
- Surface: Emission/reflection
- Cloud/rain: Diffusion/scattering



Radiance Assimilation in 3D/4D-VAR

Solving the inverse problem by minimizing a cost function

$$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x}-\mathbf{x}_b)^T \mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}_b) + \frac{1}{2}[\mathbf{y}-H(\mathbf{x})]^T \mathbf{R}^{-1}[\mathbf{y}-H(\mathbf{x})]$$

Observation operators include Radiative Transfer Model

Differences from the 1D retrieval:

1. **Solving the inverse problem along with other observations in a more consistent way.**
2. **Pixels are no longer independent each other due to the horizontal correction in B.**
3. **Can affect no-measured quantities through multivariate correction in B.**

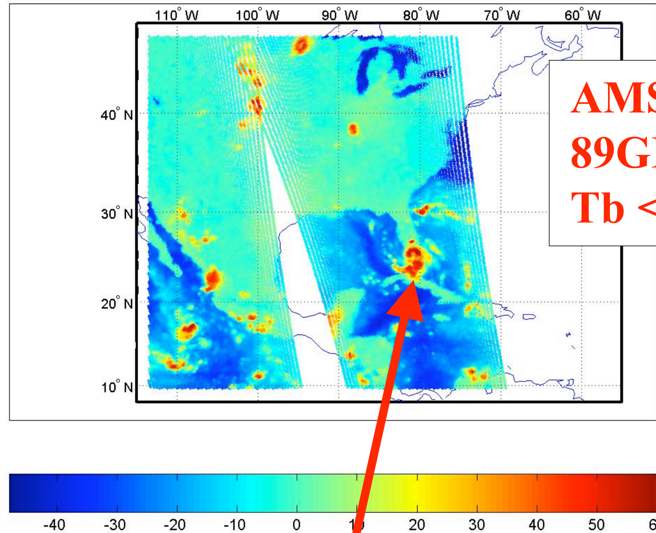
Implementation: Quality Control

- **Specific QC for each sensor**
  AMSU-A, AMSU-B, MHS, SSMIS, AIRS

- **Pixel-level QC**
  – Reject **limb** observations
  – Reject pixels over **land** and **sea-ice**
  – **Cloud/Precipitation** detection
  – **Synergy** with imager (AIRS/VIS-NIR)

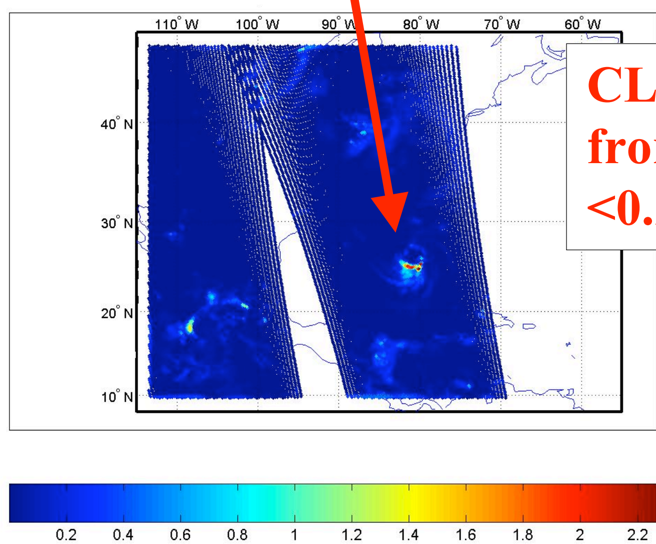
- **Channel-level QC**
  – **Gross check** (innovations <15 K)
  – **First-guess check** (innovations < $3\sigma_o$).

- **No QC scheme is perfect, be careful for your applications**



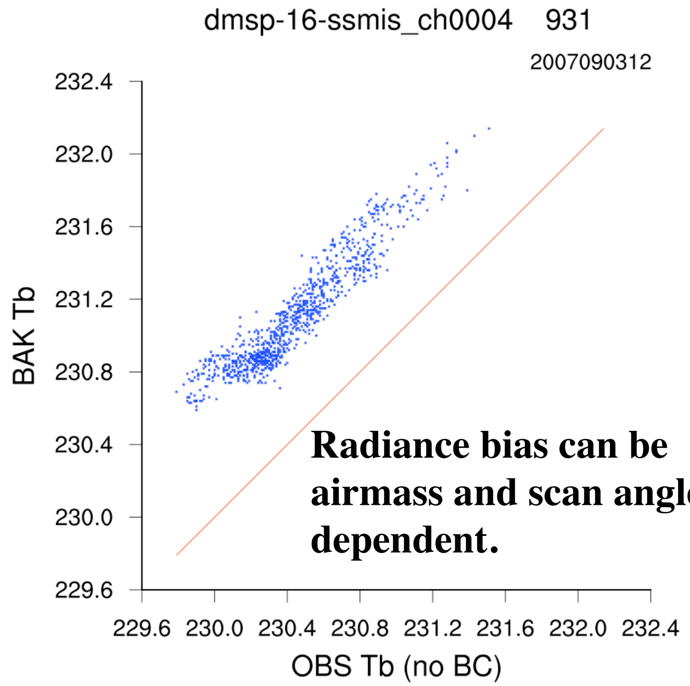
AMSU-B 89GHz-150GHz Tb < 3K

Katrina Location (2005/08/26/06Z)

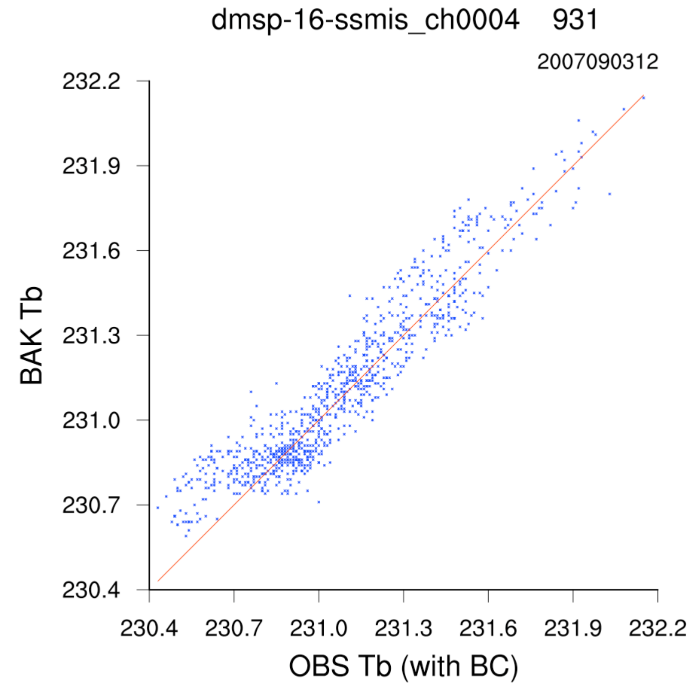


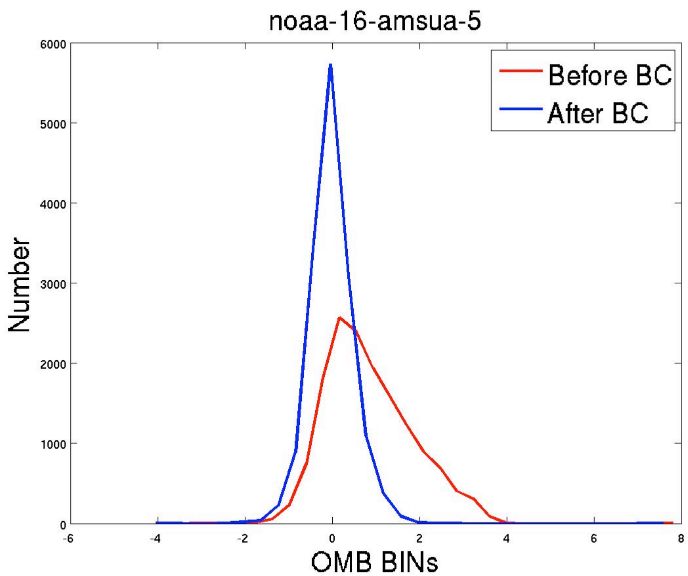
CLWP(mm) from Guess <0.2mm

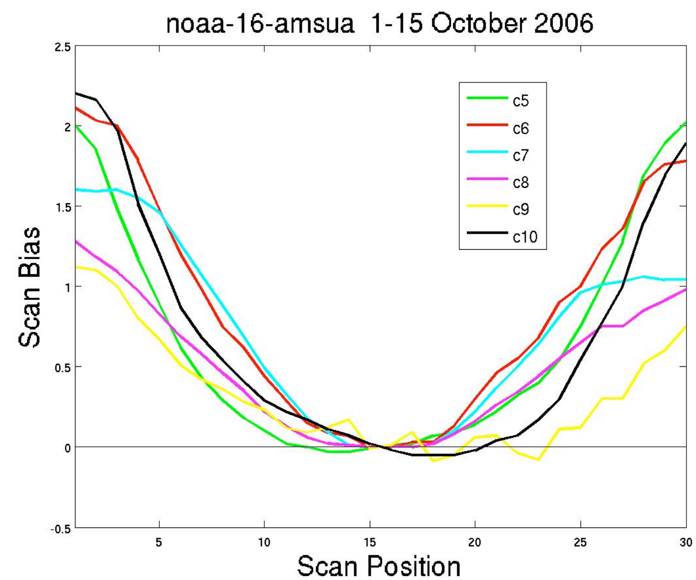
Implementation: Handling Radiance Bias



Radiance bias can be airmass and scan angle dependent.







Implementation: Variational Bias Correction (Thomas Auligne)

Modeling of errors in satellite radiances:

$$y = H(x_t) + B(\beta) + \varepsilon$$

$$\begin{cases} \langle \varepsilon \rangle = 0 \\ B(\beta) = \sum_{i=1}^{N} \beta_i p_i \end{cases}$$

Parameters

Predictors:

- Offset
- 1000-300mb thickness
- 200-50mb thickness
- Surface skin temperature
- Total column water vapor
- Scan

Bias parameters can be estimated within the **variational assimilation**, jointly with the atmospheric model state (Derber and Wu 1998) (Dee 2005) (Aulígné et al. 2007)

Inclusion of the bias parameters in the control vector : $x^T \rightarrow [x, \beta]^T$

J_b: background term for x

J_o: corrected observation term

$$\mathbf{J}(\mathbf{x},\beta) = (\mathbf{x_b} - \mathbf{x})^T \mathbf{B_x}^{-1} (\mathbf{x_b} - \mathbf{x}) + [\mathbf{y} - H(\mathbf{x}) - B(\beta)]^T \mathbf{R}^{-1} [\mathbf{y} - H(\mathbf{x}) - B(\beta)]$$
$$+ (\beta_b - \beta)^T \mathbf{B}_\beta^{-1} (\beta_b - \beta)$$

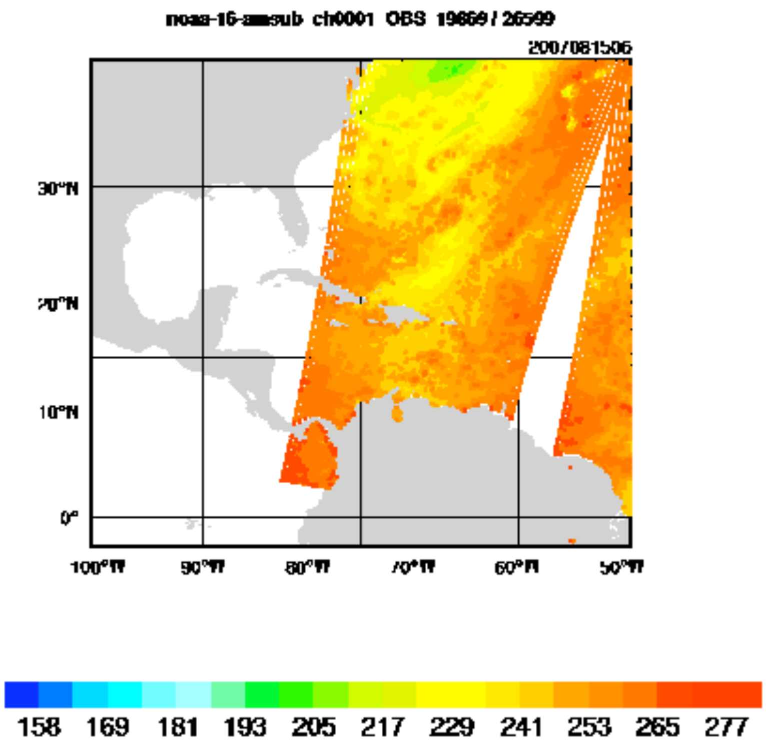
J_β: background term for β

«Optimal » bias correction considering all available information

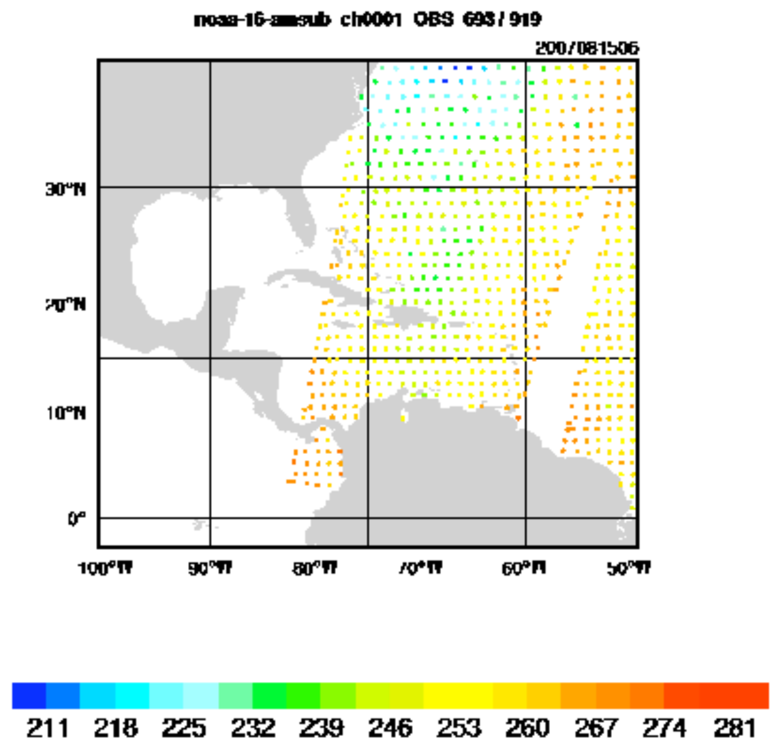
Implementation: Thinning

Dense data are very likely correlated, which is not taken into account in the observation covariance matrix R.

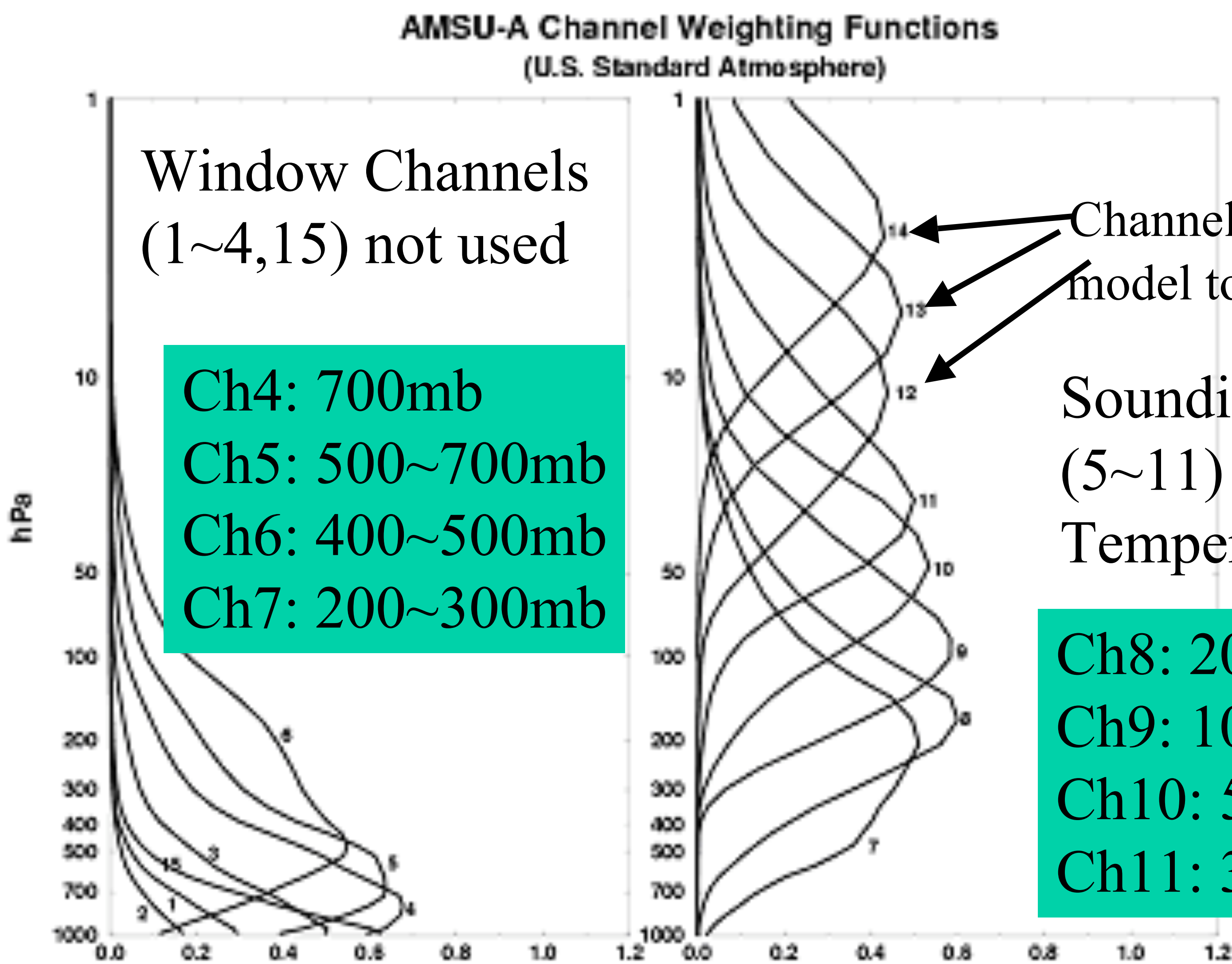
No Thinning



120km Thinning Mesh



Implementation: Channel selection



Window Channels (1~4,15) not used

Ch4: 700mb
Ch5: 500~700mb
Ch6: 400~500mb
Ch7: 200~300mb

Channels 12~14 above model top removed

Sounding Channels (5~11) sensitive to Temperature.

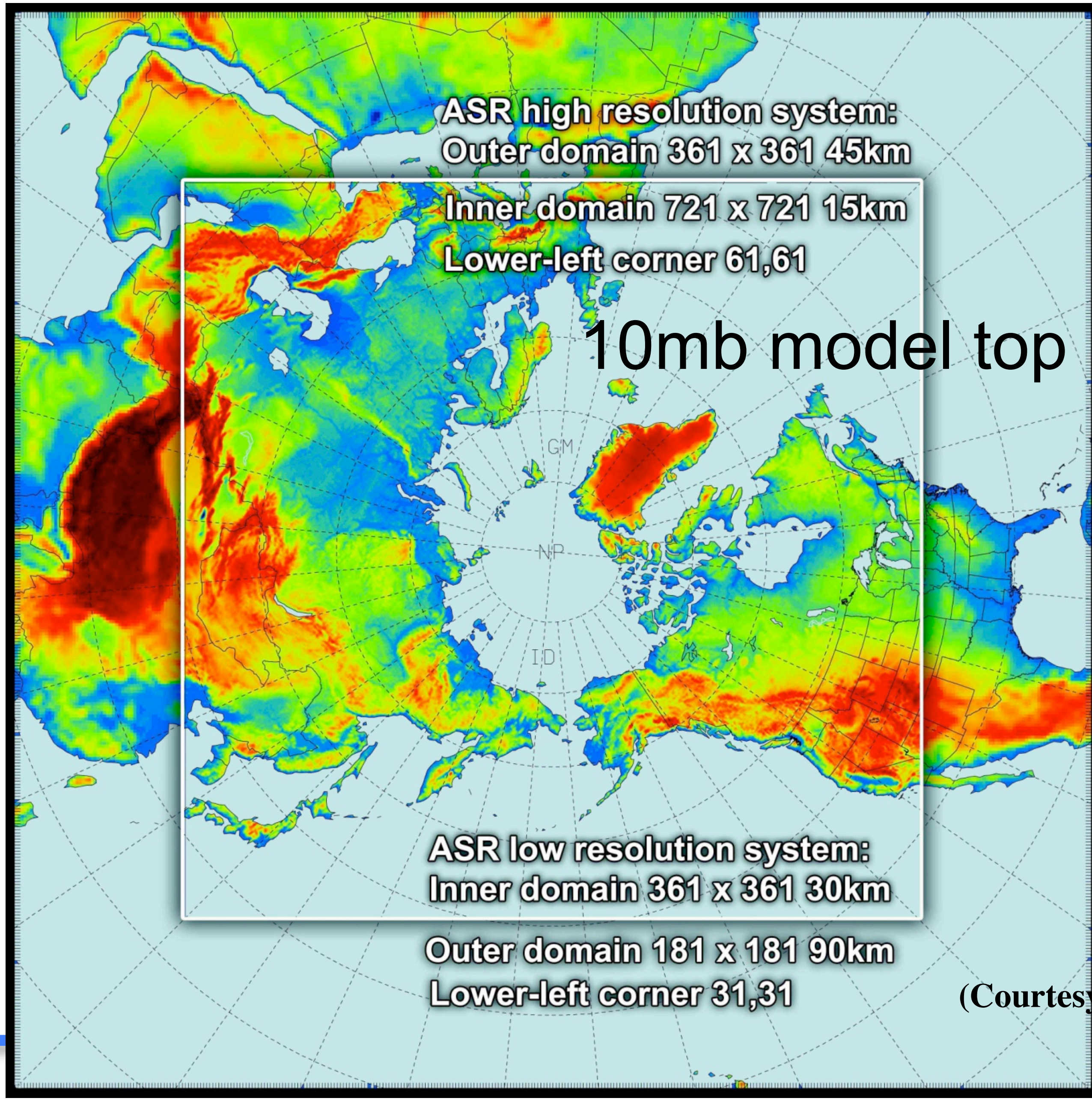
Ch8: 200mb
Ch9: 100mb
Ch10: 50mb
Ch11: 30mb

Implementation: Observation error specification and tuning

- Observation errors are specified through a table file for each instrument

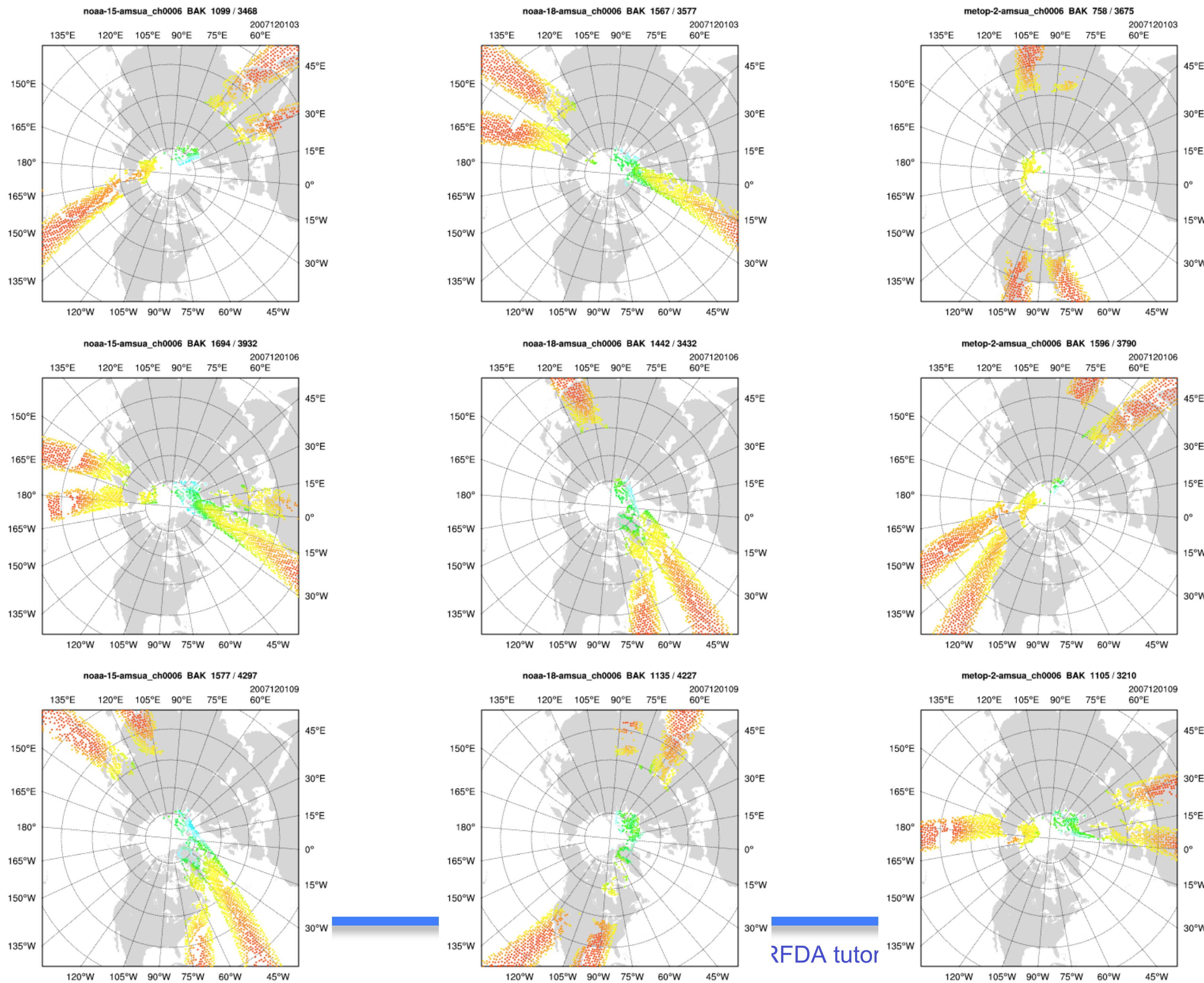
- Error tuning code is available, but not works well for radiance error tuning.

Application: Arctic System Reanalysis



(Courtesy, David Bromwich)

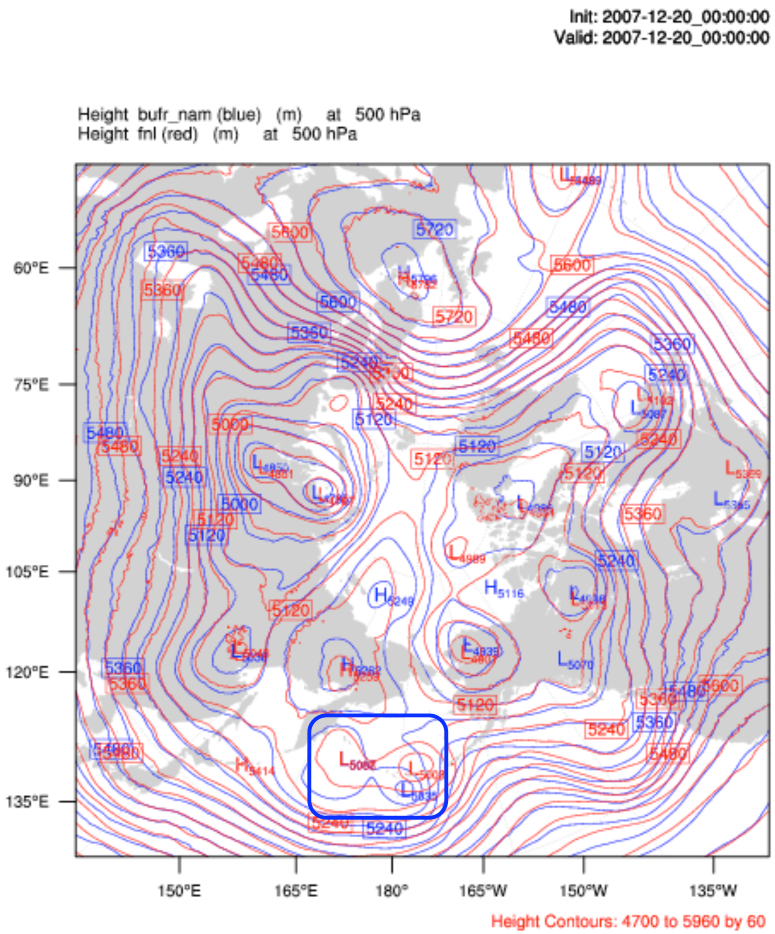
noaa-15-amsua   noaa-18-amsua   metop-2-amsua



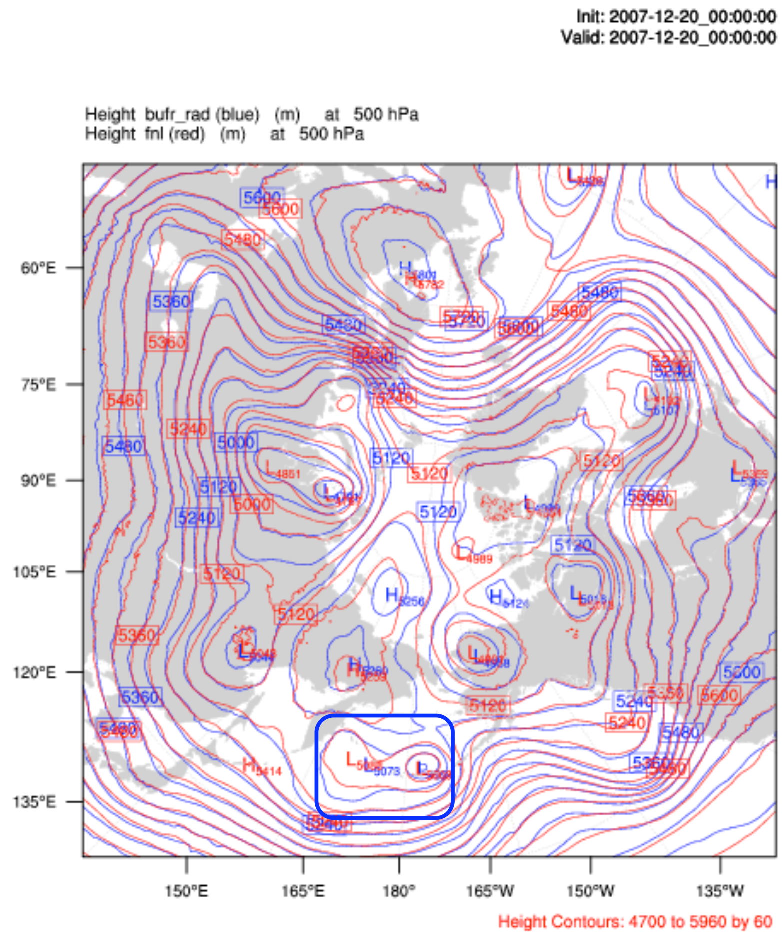
500 hPa geo-potential height valid at 2007122000 (after a 20-day cycling)

Blue: full cycling WRF-Var analysis

Red: interpolated from FNL



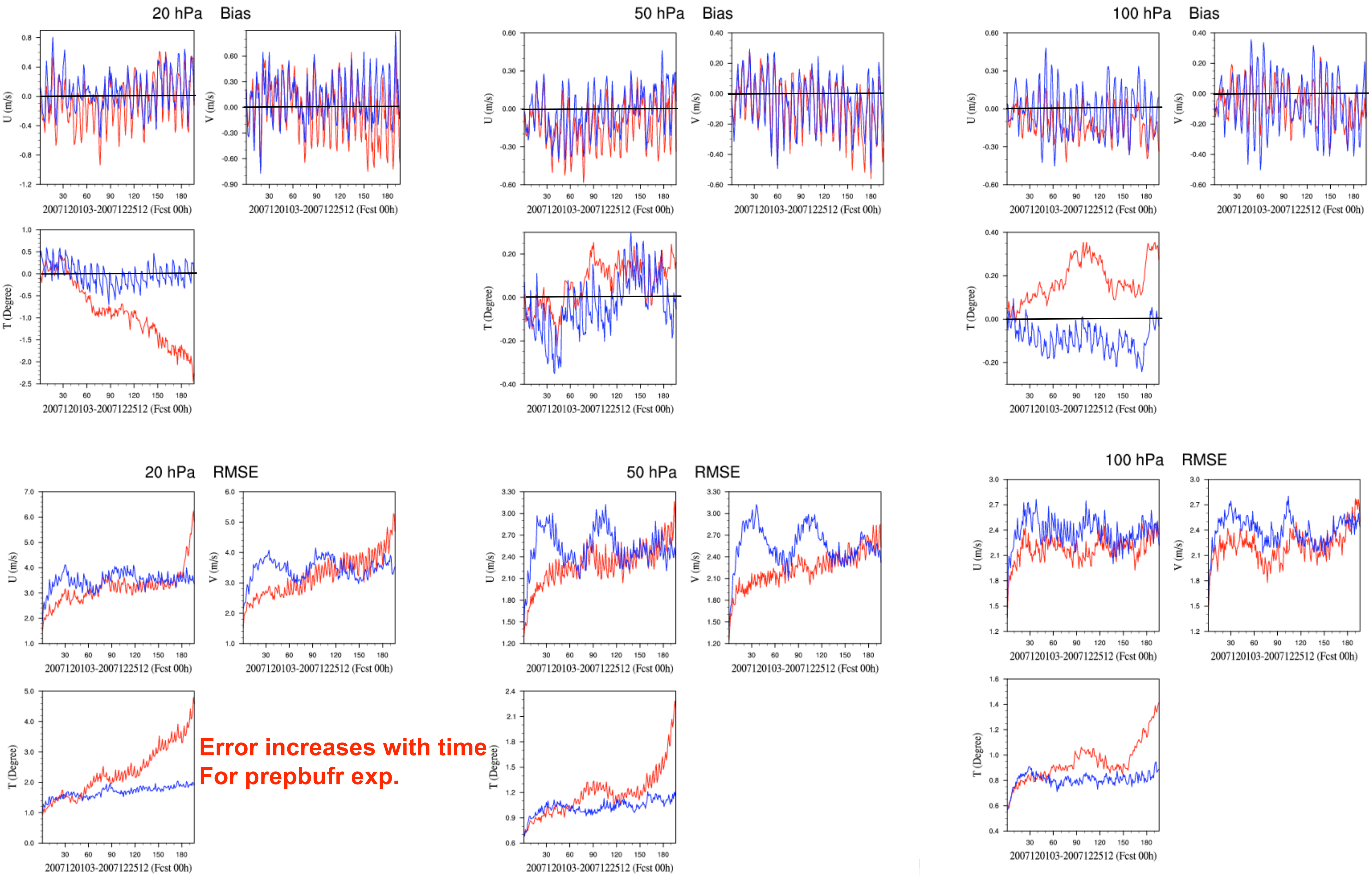
PREPBUFR



PREPBUFR+AMSUA

Verification against FNL

Red: prepbufr
Blue: prepbufr + amsu-a



Part II: Practice with WRF-Var

- **Data Ingest (sources, instruments)**
- **Radiative transfer model**
- **Channel selection**
- **Variational Bias correction**
- **Diagnostics and monitoring**

Data Ingest

- NCEP global BUFR format radiance data within a 6h time window (Total: 15 sensors from 6 satellites)
  - **4 HIRS** from NOAA16, 17, 18, METOP-2
  - **5 AMSU-A** from NOAA15, 16, 18, EOS-Aqua, METOP-2
  - **3 AMSU-B** from NOAA15, 16, 17
  - **2 MHS** from NOAA18, METOP-2
  - **1 AIRS** from EOS-Aqua

- NRL/AFWA/NESDIS produced DMSP-16 SSMI/S BUFR radiance data.

NCEP near real-time ftp server with radiance BUFR data

ftp://ftp.ncep.noaa.gov/pub/data/nccf/com/gfs/prod/gdas.${yyyymmddhh}

NOAA Historical archive: http://nomads.ncdc.noaa.gov/

NCAR archive: http://dss.ucar.edu/datasets/ds735.0/

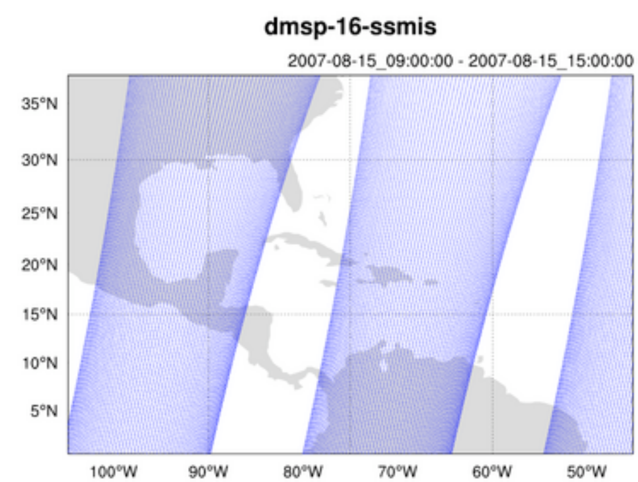
NCEP naming convention	WRF-Var naming convention
`gdas1.t00z.1bamua.tm00.bufr_d`	`amsua.bufr`
`gdas1.t00z.1bamub.tm00.bufr_d`	`amsub.bufr`
`gdas1.t00z.1bhrs3.tm00.bufr_d`	`hirs3.bufr`
`gdas1.t00z.1bhrs4.tm00.bufr_d`	`hirs4.bufr`
`gdas1.t00z.1bmhs.tm00.bufr_d`	`mhs.bufr`
`gdas1.t00z.airsev.tm00.bufr_d`	`airs.bufr`

Direct input to WRF-Var, no pre-processing required.

Quality control, thinning, time and domain check, bias correction are done inside WRF-Var

Namelist switches to decide if reading the data or not

- Use_amsuaobs
- Use_amsubobs
- Use_hirs3obs
- Use_hirs4obs
- Use_mhsobs
- Use_airsobs
- Use_eos_amsuaobs
- Use_ssmisobs



Choose Radiative Transfer Model

Controlled by the namelist variable: "rtm_option"

2=CRTM (Community Radiative Transfer Model)

JCSDA (Joint Center for Satellite Data Assimilation)

ftp://ftp.emc.ncep.noaa.gov/jcsda/CRTM/

Latest released version: CRTM REL-1.2.1,

ftp://ftp.emc.ncep.noaa.gov/jcsda/CRTM/CRTM_User_Guide.pdf

1=RTTOV (Radiative Transfer for TOVS)

EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites)

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

Latest released version: RTTOV_9_3,

Version used in WRF-Var: RTTOV_8_7 (no plan/resource to update to RTTOV_9)

Channel selection and error specification

```
WRFDA/var/run/radiance_info>ls -l
total 160
-rw-r--r--   1 hclin  users   1588 Aug 22 17:01 dmsp-16-ssmis.info
-rw-r--r--   1 hclin  users  17790 Aug 22 17:01 eos-2-airs.info
-rw-r--r--   1 hclin  users   1033 Aug 22 17:01 eos-2-amsua.info
-rw-r--r--   1 hclin  users   1036 Aug 22 17:01 metop-2-amsua.info
-rw-r--r--   1 hclin  users    391 Aug 22 17:01 metop-2-mhs.info
-rw-r--r--   1 hclin  users   1021 Aug 22 17:01 noaa-15-amsua.info
-rw-r--r--   1 hclin  users    391 Aug 22 17:01 noaa-15-amsub.info
-rw-r--r--   1 hclin  users   1277 Aug 22 17:01 noaa-15-hirs.info
-rw-r--r--   1 hclin  users   1021 Aug 22 17:01 noaa-16-amsua.info
-rw-r--r--   1 hclin  users    391 Aug 22 17:01 noaa-16-amsub.info
-rw-r--r--   1 hclin  users   1275 Aug 22 17:01 noaa-16-hirs.info
-rw-r--r--   1 hclin  users    391 Aug 22 17:01 noaa-17-amsub.info
-rw-r--r--   1 hclin  users   1277 Aug 22 17:01 noaa-17-hirs.info
-rw-r--r--   1 hclin  users   1036 Aug 22 17:01 noaa-18-amsua.info
-rw-r--r--   1 hclin  users   1286 Aug 22 17:01 noaa-18-hirs.info
-rw-r--r--   1 hclin  users    391 Aug 22 17:01 noaa-18-mhs.info
```

metop-2-mhs.info **-1: not used; 1: used** **error for each channel**

```
sensor channel IR/MW use idum   varch   polarisation(0:vertical;1:horizontal)
   203     1      1   -1    0  0.2500000000E+01  0.0000000000E+00
   203     2      1   -1    0  0.2500000000E+01  0.0000000000E+00
   203     3      1    1    0  0.2500000000E+01  0.1000000000E+01
   203     4      1    1    0  0.2000000000E+01  0.1000000000E+01
   203     5      1    1    0  0.2000000000E+01  0.0000000000E+00
```

Setup and run WRF-Var with radiances

To run **WRF-Var**, first create a working directory,
for example, WRFDA/var/test, then follow the steps below:

cd WRFDA/var/test (go to the working directory)

ln -sf WRFDA/run/LANDUSE.TBL ./LANDUSE.TBL
ln -sf $DAT_DIR/rc/2007010200/wrfinput_d01 ./**fg** (link first guess file as fg)
ln -sf WRFDA/var/obsproc/obs_gts_2007-01-02_00:00:00.3DVAR ./**ob.ascii** (link OBSPROC processed observation file as ob.ascii)
ln -sf $DAT_DIR/be/be.dat ./**be.dat** (link background error statistics as be.dat)
ln -sf WRFDA/var/da/da_wrfvar.exe ./da_wrfvar.exe (link executable)

ln -sf $DAT_DIR/2007010200/gdas1.t00z.1bamua.tm00.bufr_d ./**amsua.bufr**
ln -sf ~WRFDA/var/run/radiance_info ./**radiance_info**

(**CRTM** only) ln -sf $CRTM_COEFFS_DIR ./**crtm_coeffs**
(**RTTOV** only) ln -sf $RTTOV_COEFFS_DIR/rtcoef*.dat ./**rtcoef*.dat**

ln -sf ~WRFDA/var/run/**VARBC.in .**

vi namelist.input (&wrfvar4, &wrfvar14, &wrfvar21, &wrfvar22)

da_wrfvar.exe >&! wrfda.log

Control which instruments to be assimilated and Which CRTM/RTTOV coeffs files to be loaded

Namelist variables for tested instruments:

```
RTMINIT_NSENSOR  = 12
RTMINIT_PLATFORM =  1, 1, 1, 9,10, 1, 1, 1, 1,10, 9, 2
RTMINIT_SATID    = 15,16,18, 2, 2,15,16,17,18, 2, 2,16
RTMINIT_SENSOR   =  3, 3, 3, 3, 3, 4, 4, 4,15,15,11,10
```

NOAA-15-AMSUA
NOAA-16-AMSUA
NOAA-18-AMSUA
EOS-2-AMSUA
METOP-2-AMSUA
NOAA-15-AMSUB
NOAA-16-AMSUB
NOAA-17-AMSUB
NOAA-18-MHS
METOP-2-MHS
EOS-2-AIRS
DMSP-16-SSMIS

CRTM and RTTOV share the same "instrument triplet" convention for user's config.

Internal convert b.w. CRTM&RTTOV Convention is invisible to users.

This facilitates the user's config. When switch b.w. two RTMs.

more sensors supported, from RTTOV_8_7 Users Guide
http://www.metoffice.gov.uk/research/interproj/nwpsaf/rtm/rttov8_ug.pdf

Instrument triplets platform_id
satellite_id
sensor_id

platform_id satellite_id

Platform	RTTOV id	Sat id range
NOAA¶	1	1 to 18
DMSP	2	8 to 16
Meteosat	3	5 to 7
GOES	4	8 to 12
GMS	5	5
FY-2	6	2 to 3
TRMM	7	1
ERS	8	1 to 2
EOS	9	1 to 2
METOP	*10*	*1 to 3*
ENVISAT	11	1
MSG	12	1 to 2
FY-1	13	3
ADEOS	14	1 to 2
MTSAT	15	1
CORIOLIS	16	1

¶ Includes TIROS-N

Table 2. Platforms supported by RTTOV_8_7 as at 17 Nov 2005 in normal text. Platforms in italics are not yet supported by RTTOV_8_7 but soon will be.

sensor_id

Sensor	RTTOV id	Sensor Channel #	RTTOV-7 Channel #	RTTOV-8 Channel #
HIRS	0	1 to 19	1 to 19	1 to 19
MSU	1	1 to 4	1 to 4	1 to 4
SSU	2	1 to 3	1 to 3	1 to 3
AMSU-A	3	1 to 15	1 to 15	1 to 15
AMSU-B	4	1 to 5	1 to 5	1 to 5
AVHRR	5	3b to 5	1 to 3	1 to 3
SSMI	6	1 to 7	1 to 7	1 to 4
VTPR1	7	1 to 8	1 to 8	1 to 8
VTPR2	8	1 to 8	1 to 8	1 to 8
TMI	9	1 to 9	1 to 5	1 to 9
SSMIS	10	1 to 24*	1 to 24*	1 to 21
AIRS	11	1 to 2378	1 to 2378	1 to 2378
HSB	12	1 to 4	1 to 4	1 to 4
MODIS	13	1 to 17	1 to 17	1 to 17
ATSR	14	1 to 3	1 to 3	1 to 3
MHS	15	1 to 5	1 to 5	1 to 5
IASI	16	1 to 8461	N/A	1 to 8461
AMSR	17	1 to 14	1 to 14	1 to 7
MVIRI	20	1 to 2	1 to 2	1 to 2
SEVIRI	21	4 to 11	1 to 8	1 to 8
GOES-Imager	22	1 to 4	1 to 4	1 to 4
GOES-Sounder	23	1 to 18	1 to 18	1 to 18
GMS/MTSAT imager	24	1 to 4	1 to 4	1 to 4
FY2-VISSR	25	1 to 2	1 to 2	1 to 2
FY1-MVISR	26	1 to 3	1 to 3	1 to 3
CriS	27	TBD	N/A	TBD
CMISS	28	TBD	N/A	TBD
VIIRS	29	TBD	N/A	TBD
WINDSAT	30	1 to 10	N/A	1 to 5

**channels 19-21 are not simulated accurately*

Table 3. Instruments supported by RTTOV_8_7 as at 17 Nov 2005. Sensors in italics are not yet supported by RTTOV_8_7 but soon will be.

CRTM coefficients

After untarring
ftp://ftp.emc.ncep.noaa.gov/jcsda/CRTM/REL-1.2/REL-1.2.Coeffs.JCSDA_CRTM.tar.gz

```
CRTM_Coefficients>ls -l
drwxr-xr-x    5 hclin    ncar  8192 Feb 06 15:48 AerosolCoeff
drwxr-xr-x    5 hclin    ncar  8192 Feb 06 15:48 CloudCoeff
drwxr-xr-x    5 hclin    ncar  8192 Feb 06 15:48 EmisCoeff
drwxr-xr-x    5 hclin    ncar  8192 Feb 06 15:48 SpcCoeff
drwxr-xr-x    5 hclin    ncar  8192 Feb 06 15:48 TauCoeff
```

Each *Coeff has 3 subdirectories containing coefficient files in different format.
Big_Endian (binary) files are used in WRF-Var.

```
CRTM_Coefficients/SpcCoeff>ls -l
drwxr-xr-x    2 hclin    ncar  16384 Feb 06 15:48 Big_Endian
drwxr-xr-x    2 hclin    ncar  16384 Feb 06 15:48 Little_Endian
drwxr-xr-x    2 hclin    ncar  16384 Feb 06 15:48 netCDF
```

Link selected files from *Coeff/Big_Endian directories into a single directory, then link the directory as **crtm_coeffs** in the WRF-Var working directory

More namelist variables

RAD_MONITORING (30): Integer array with dimension RTMINIT_NSENSER, where 0 for assimilating mode, 1 for monitoring mode (only calculate innovation).

THINNING: Logical, TRUE will perform thinning

THINNING_MESH (30): Real array with dimension RTMINIT_NSENSOR, values indicate thinning mesh (in KM) for different sensors.

QC_RAD=true: Logical, control if perform quality control, always set to TRUE.

WRITE_IV_RAD_ASCII: Logical, control if output Observation minus Background files, which are ASCII format and separated by sensors and processors.

WRITE_OA_RAD_ASCII: Logical, control if output Observation minus Analysis files (including also O minus B), which are ASCII format and separated by sensors and processors.

ONLY_SEA_RAD: Logical, control if only assimilating radiance over water.

TIME_WINDOW_MIN: String, e.g., "2007-08-15_03:00:00.0000", start time of assimilation time window

TIME_WINDOW_MAX: String, e.g., "2007-08-15_09:00:00.0000", end time of assimilation time window
USE_ANTCORR: CRTM and Microwave only, control if perform "antenna pattern correction" for Antenna Temperature data
USE_VARBC=true
freeze_varbc=false
varbc_factor=10. (for scaling the VarBC preconditioning**)**
varbc_nobsmin=100. **(**defines the minimum number of observations required for the computation of the predictor statistics during the first assimilation cycle. If there are not enough data (according to "VARBC_NOBSMIN") on the first cycle, the next cycle will perform a coldstart again**)**

crtm_atmosphere=1~6 (specify climate profile above model top. 1: Tropical2: Midlatitude summer3: Midlatitude winter4: Subarctic summer5: Subarctic winter6: U.S. Standard Atmosphere)

Variational Bias Correction (VarBC)

VARBC.in file is an ASCII file that controls all of what is going into the VarBC.

Sample VARBC.in

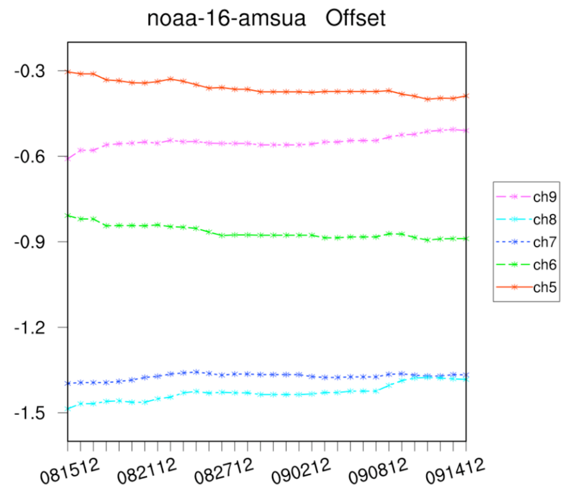
Cold start from an empty coeffs file
For the first cycle

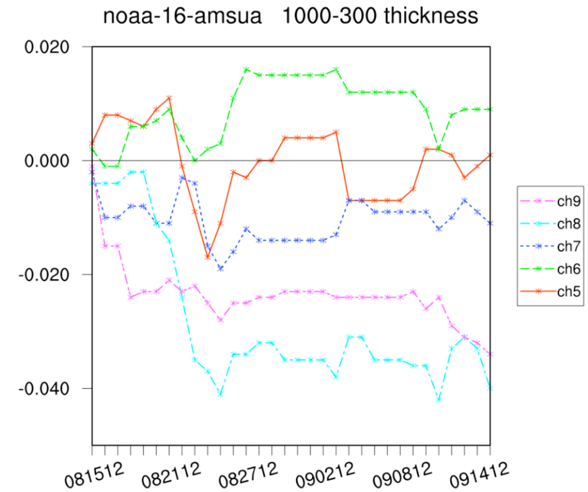
```
VARBC version 1.0 - Number of instruments:
   2
  ------------------------------------------------
  Platform_id  Sat_id  Sensor_id  Nchanl  Npredmax
  ------------------------------------------------
  1 15 3 5 8
   -----> Bias predictor statistics:  Mean & Std & Nbgerr
        1.0         0.0        0.0        0.0        0.0        0.0        0.0        0.0
        0.0         1.0        1.0        1.0        1.0        1.0        1.0        1.0
        10000       10000      10000      10000      10000      10000      10000      10000
   -----> Chanl_id Chanl_nb  Pred_use(-1/0/1)  Param
    5      5  0  0  0  0  0  0  0  0
    6      6  0  0  0  0  0  0  0  0
    7      7  0  0  0  0  0  0  0  0
    8      8  0  0  0  0  0  0  0  0
    9      9  0  0  0  0  0  0  0  0
  ------------------------------------------------
  Platform_id  Sat_id  Sensor_id  Nchanl  Npredmax
  ------------------------------------------------
  1 16 4 3 8
   -----> Bias predictor statistics:  Mean & Std & Nbgerr
        1.0         0.0        0.0        0.0        0.0        0.0        0.0        0.0
        0.0         1.0        1.0        1.0        1.0        1.0        1.0        1.0
      10000       10000      10000      10000      10000      10000      10000      10000
   -----> Chanl_id Chanl_nb  Pred_use(-1/0/1)  Param
    3      3  0  0  0  0  0  0  0  0
    4      4  0  0  0  0  0  0  0  0
    5      5  0  0  0  0  0  0  0  0
```

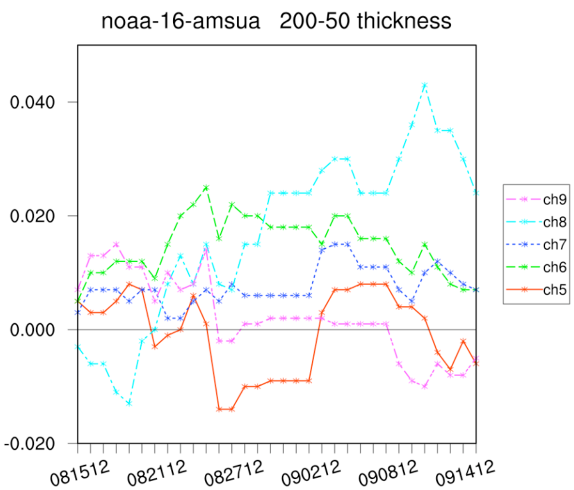
Sample VARBC.out (output from WRF-Var, used as VARBC.in for the next cycle)

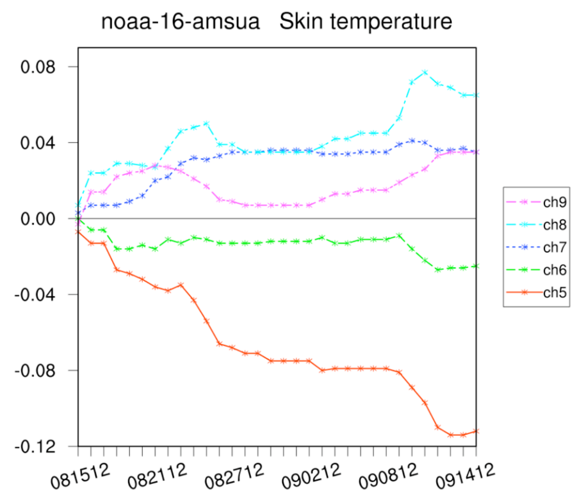
```
VARBC version 1.0 - Number of instruments:
4
------------------------------------------------
Platform_id  Sat_id  Sensor_id  Nchanl  Npredmax
------------------------------------------------
1 15 4 5 8
 -----> Bias predictor statistics:  Mean & Std & Nbgerr
      1.0     9273.1    8677.8     290.4      24.0       51.7     3502.8   260484.8
      0.0      273.5     293.3       8.0      12.3       28.9     2827.2   252657.9
    10000      10000     10000     10000     10000      10000      10000      10000
 -----> Chanl_id Chanl_nb  Pred_use(-1/0/1)  Param
  1      1  0  0  0  0  0  0  0  0  -3.400   0.000   0.000   0.000   0.000   0.000   0.000   0.000
  2      2  0  0  0  0  0  0  0  0  -0.200   0.000   0.000   0.000   0.000   0.000   0.000   0.000
  3      3  1  1  1  1  1  1  1  1   1.213  -0.062   0.003  -0.070   0.008  -0.230  -0.111  -0.024
  4      4  1  1  1  1  1  1  1  1   3.056   0.050   0.053   0.015  -0.059   0.304   0.241   0.203
  5      5  1  1  1  1  1  1  1  1   0.869   0.034  -0.089   0.074   0.019  -0.118  -0.031   0.022
------------------------------------------------
Platform_id  Sat_id  Sensor_id  Nchanl  Npredmax
------------------------------------------------
1 16 4 5 8
 -----> Bias predictor statistics:  Mean & Std & Nbgerr
      1.0     9280.2    8641.2     290.0      24.1       52.6     3568.9   264767.4
      0.0      209.5     245.9       7.9      11.3       28.3     2792.1   249977.0
    10000      10000     10000     10000     10000      10000      10000      10000
 -----> Chanl_id Chanl_nb  Pred_use(-1/0/1)  Param
  1      1  0  0  0  0  0  0  0  0   0.700   0.000   0.000   0.000   0.000   0.000   0.000   0.000
  2      2  0  0  0  0  0  0  0  0  -0.800   0.000   0.000   0.000   0.000   0.000   0.000   0.000
  3      3  1  1  1  1  1  1  1  1   0.372  -0.028   0.010   0.060   0.025   0.117   0.023  -0.042
  4      4  1  1  1  1  1  1  1  1   0.968   0.016  -0.003  -0.041   0.045  -0.018  -0.030  -0.028
  5      5  1  1  1  1  1  1  1  1  -3.290   0.073  -0.093   0.096   0.018   0.011   0.010   0.004
```

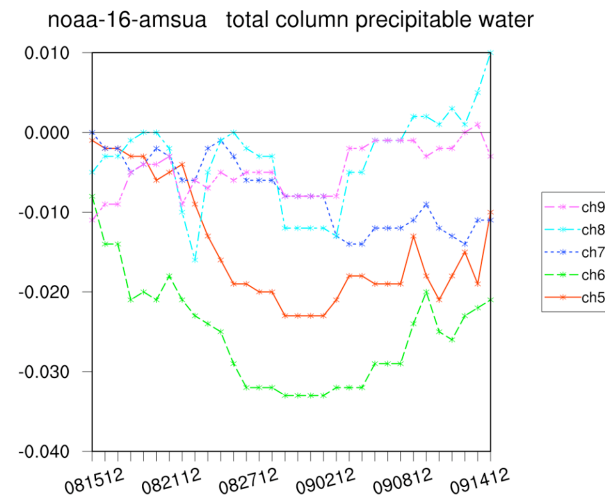
WRFDA/var/graphics/ncl/
plot_rad_varbc_param.ncl
is used for plotting time series
of parameters in VARBC.out files.

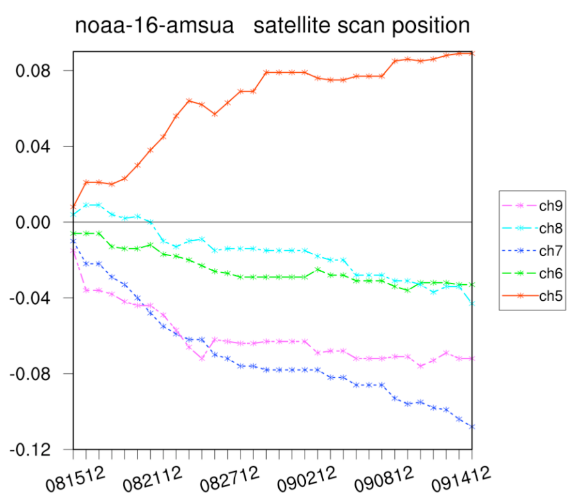


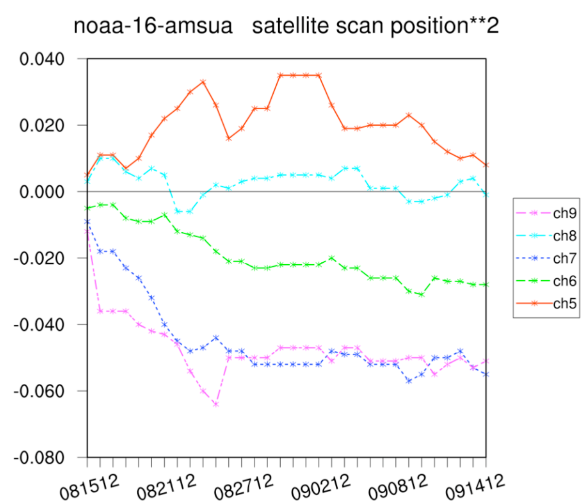


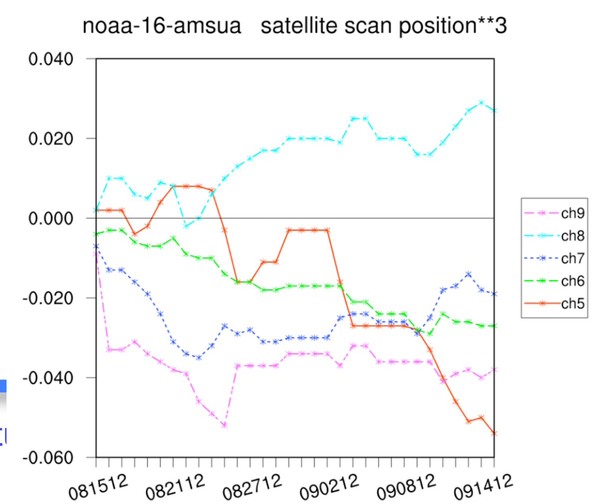










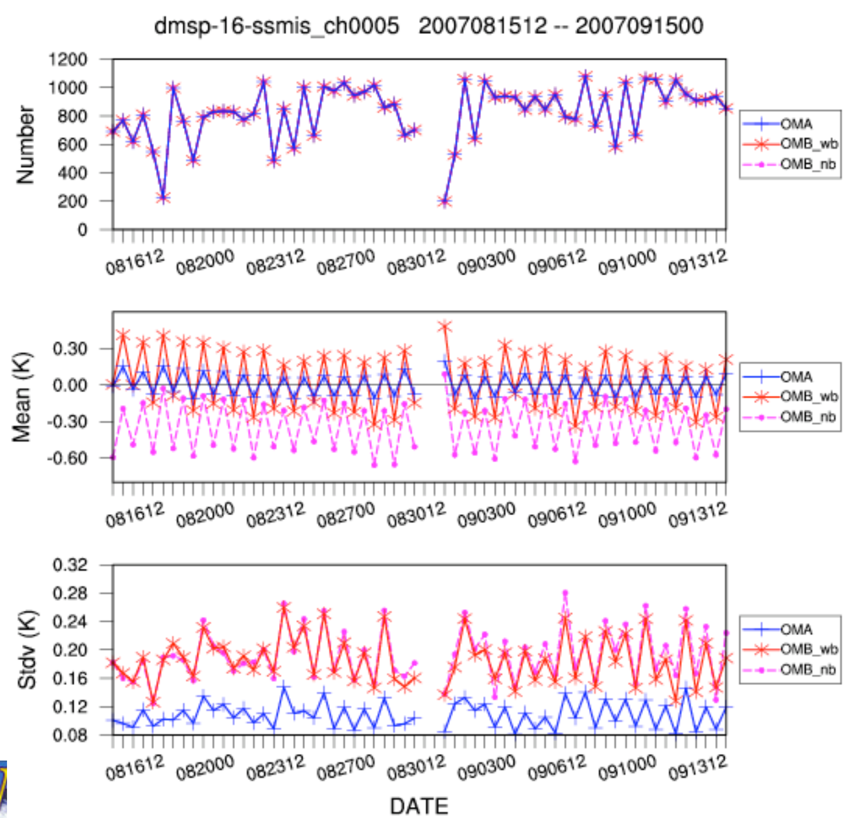


Consider diurnal cycle or descending/ascending orbit issue with VarBC for regional applications

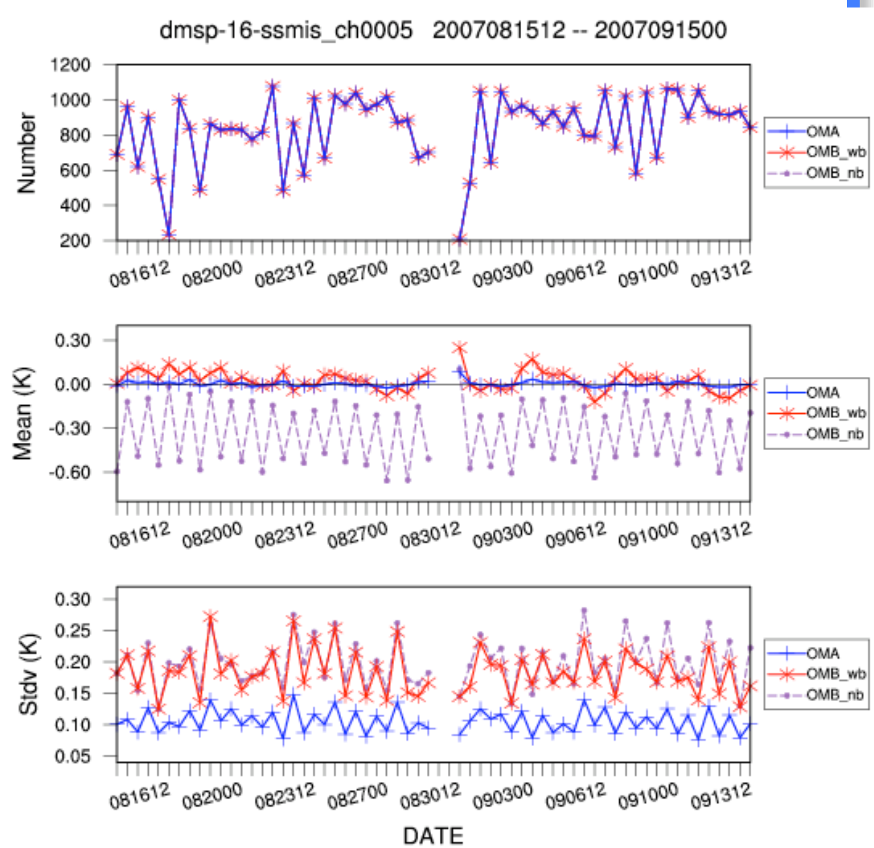
Bias with diurnal cycle.
Morning (12Z): -0.60K
Evening (00Z): -0.15K

(Related to Descending/Ascending nodes)

Use one set of BC coefs for 00Z/12Z
(oscillation still exists after BC)

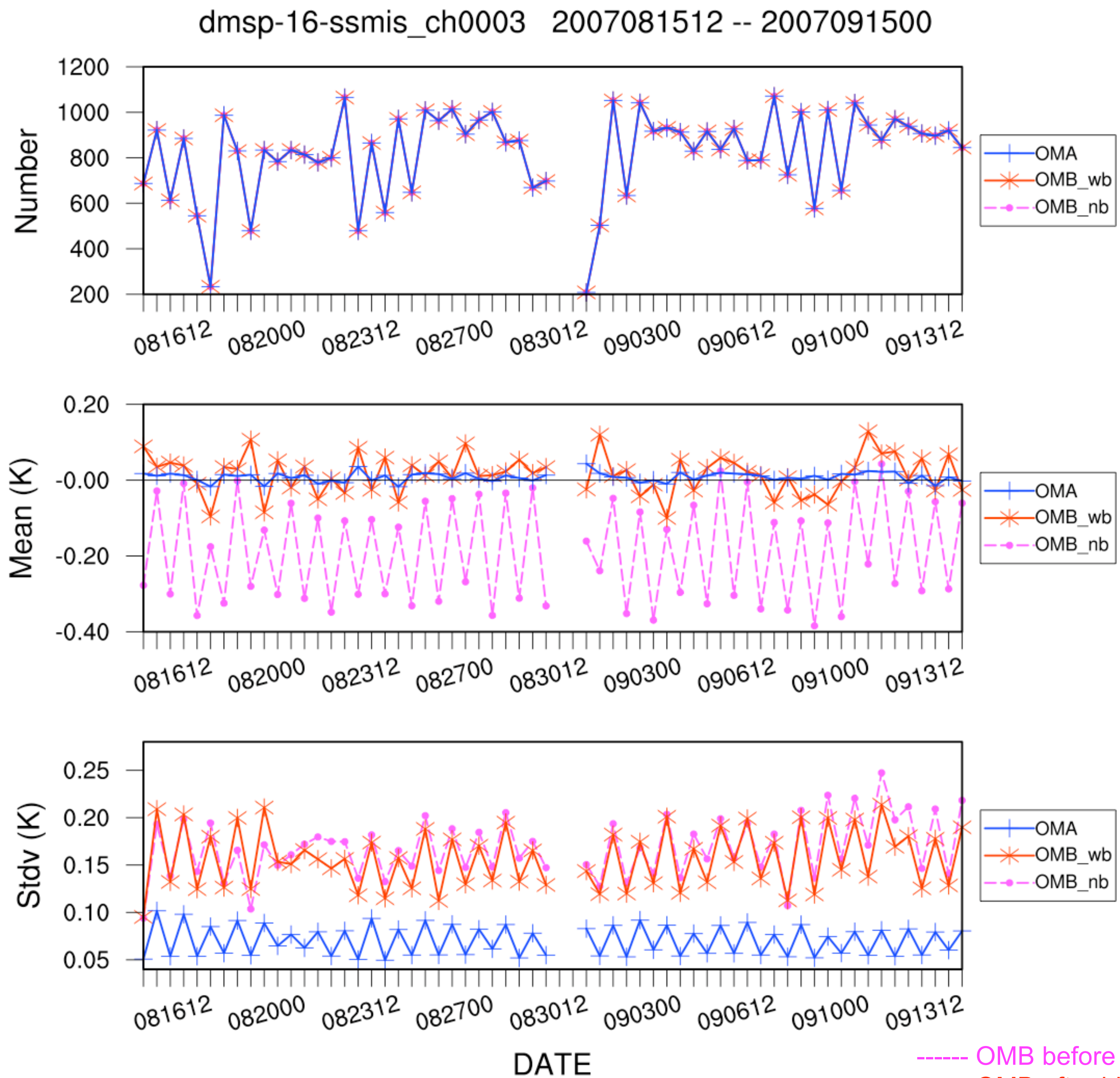


Use separated BC coefs for 00Z/12Z
(Oscillation is removed after BC)



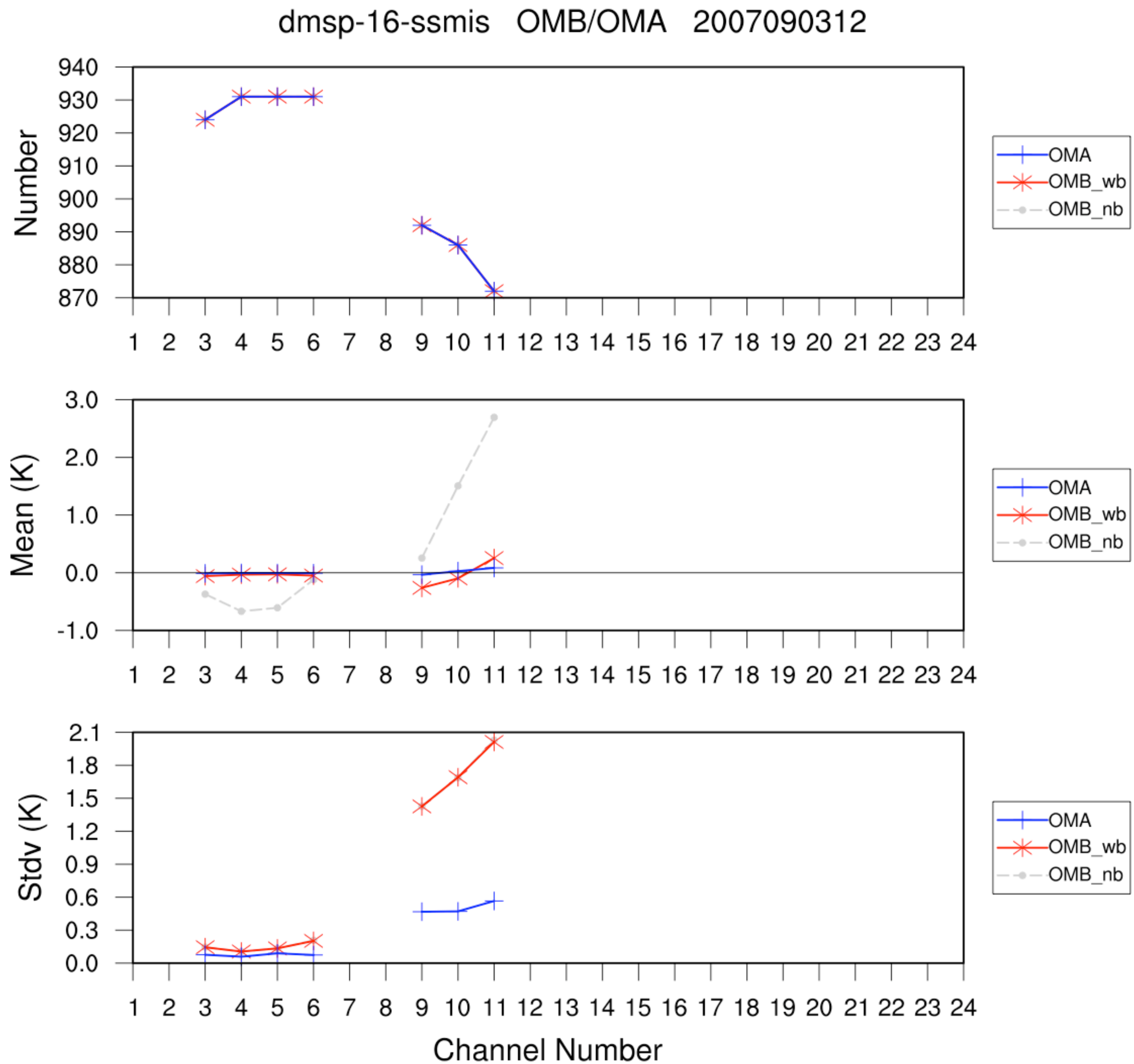
Radiance output Post-Processing/Visualization (Hui-Chuan Lin)

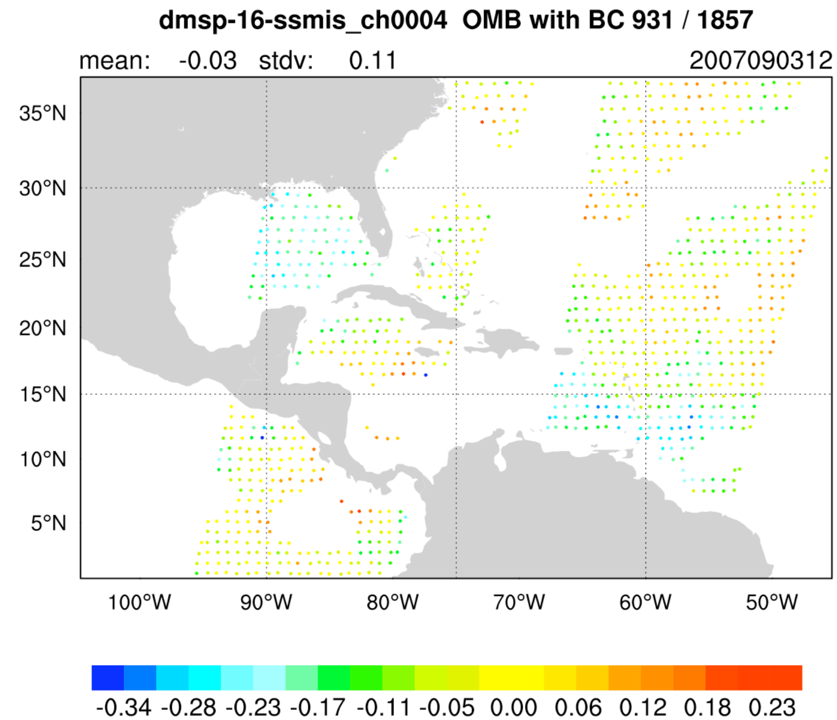
- ~WRFDA/var/scripts/da_rad_diags.ksh
  - WRF-Var will output radiance inv* or oma* ASCII files separated for different sensors and CPUs.
  - Script vonverts ASCII files to one NETCDF file for each sensor (a Fortran90 program), then plot *.nc files with a NCL script
  - NCL script can plot various graphics
    - Channel TB, Histogram, scatter plot, time series etc.
    - Can be included in the script to routinely produce graphics after WRF-Var runs
    - Users can control (by simple script parameter setup) to plot over smaller domain, only over land or sea, QCed or no-QCed observations.

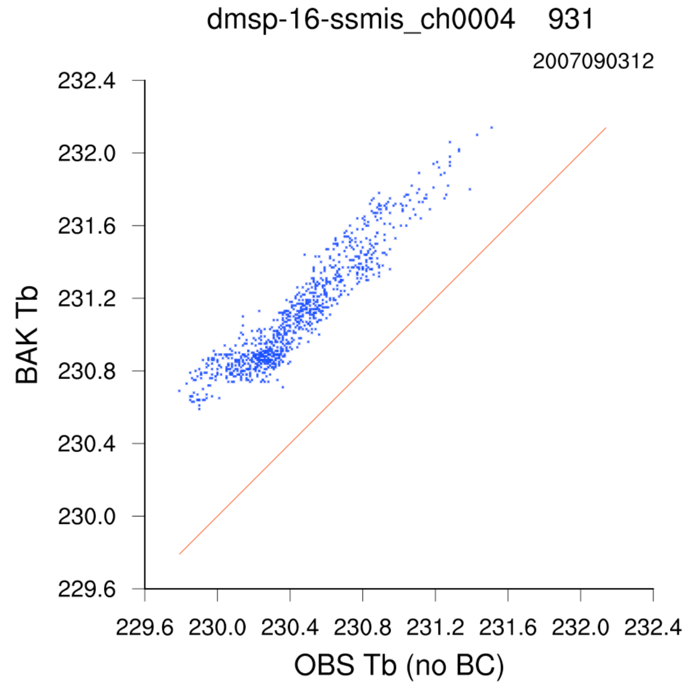


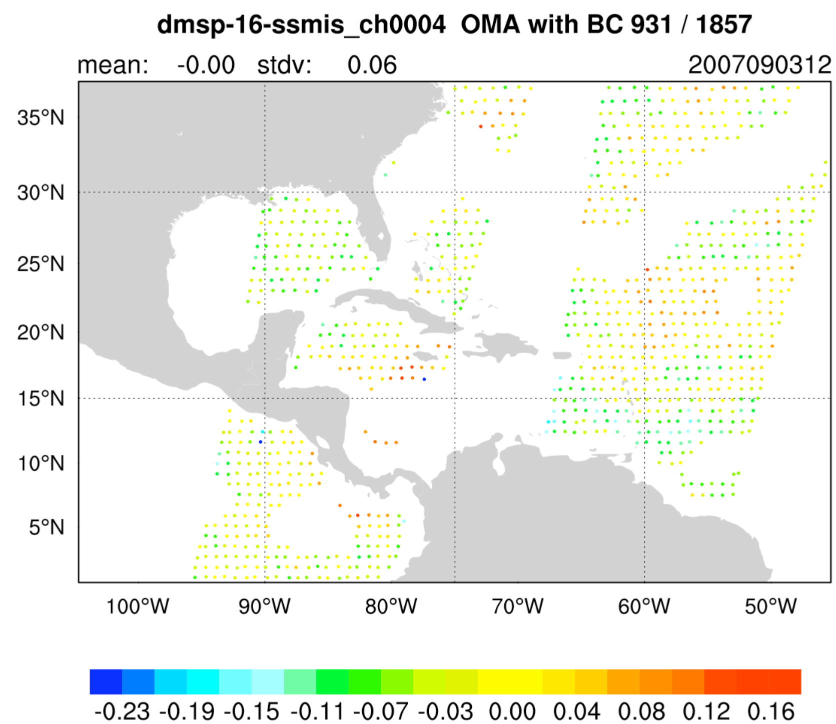
------ OMB before bias correction

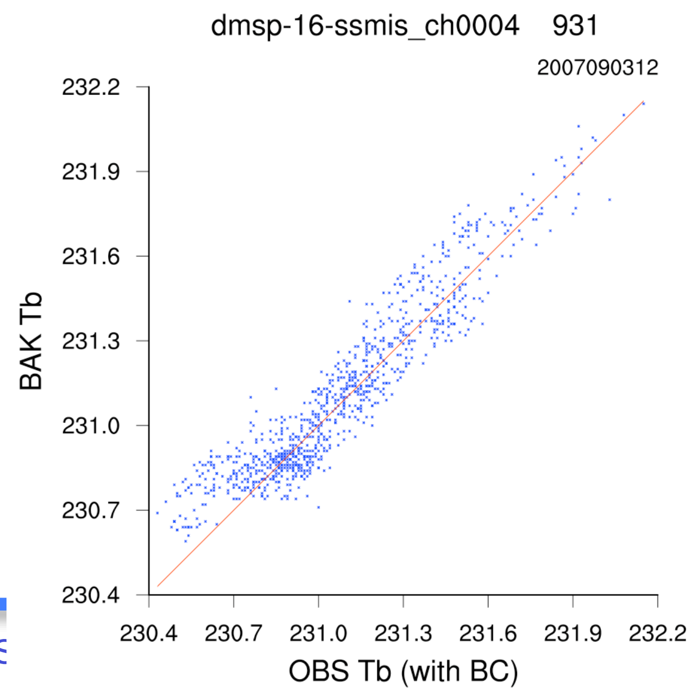
------ OMB after bias correction

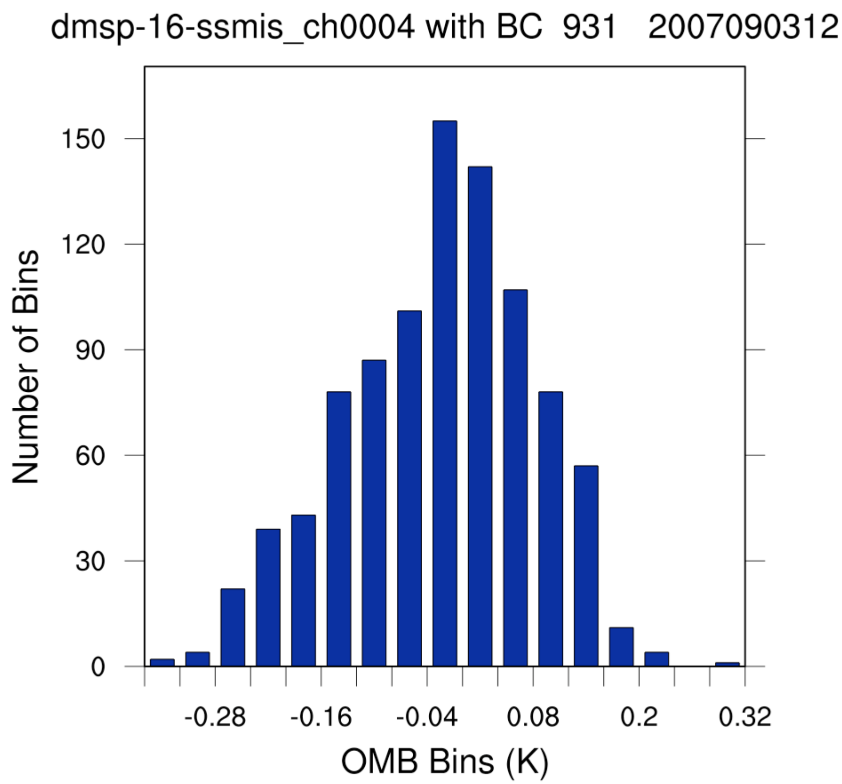

dmsp-16-ssmis OMB/OMA 2007090312
Number
Mean (K)
Stdv (K)
Channel Number
OMA
OMB_wb
OMB_nb

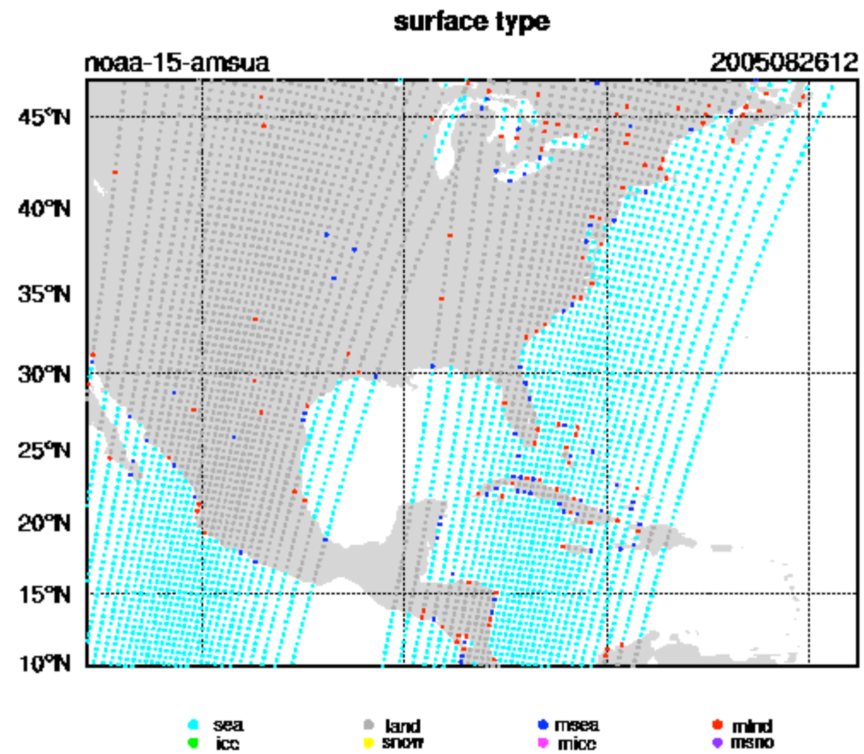

dmsp-16-ssmis_ch0004 OMB with BC 931 / 1857
mean: -0.03 stdv: 0.11
2007090312
35°N
30°N
25°N
20°N
15°N
10°N
5°N
100°W
90°W
80°W
70°W
60°W
50°W
-0.34 -0.28 -0.23 -0.17 -0.11 -0.05 0.00 0.06 0.12 0.18 0.23


dmsp-16-ssmis_ch0004 931
2007090312
BAK Tb
232.4
232.0
231.6
231.2
230.8
230.4
230.0
229.6
229.6 230.0 230.4 230.8 231.2 231.6 232.0 232.4
OBS Tb (no BC)


dmsp-16-ssmis_ch0004 OMA with BC 931 / 1857
mean: -0.00 stdv: 0.06
2007090312
35°N
30°N
25°N
20°N
15°N
10°N
5°N
100°W
90°W
80°W
70°W
60°W
50°W
-0.23 -0.19 -0.15 -0.11 -0.07 -0.03 0.00 0.04 0.08 0.12 0.16

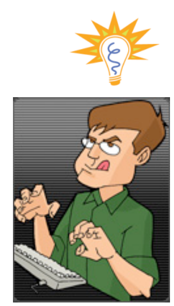

dmsp-16-ssmis_ch0004 931
2007090312
BAK Tb
232.2
231.9
231.6
231.3
231.0
230.7
230.4
230.4 230.7 231.0 231.3 231.6 231.9 232.2
OBS Tb (with BC)


dmsp-16-ssmis_ch0004 with BC 931 2007090312
Number of Bins
150
120
90
60
30
0
-0.28
-0.16
-0.04
0.08
0.2
0.32
OMB Bins (K)


surface type
noaa-15-amsua
2005082612
45°N
40°N
35°N
30°N
25°N
20°N
15°N
10°N
sea
ice
land
snow
msea
mice
mlnd
msno

Conclusions

- **Radiance data assimilation are important**
  - Major source of information within observations for global NWP
  - Positive impact on Limited Area Models
- **Radiance DA is not trivial**
  - Very easy to degrade the analysis!
  - Each sensor requires a lot of attention (observation operator, bias correction, QC, observation error, cloud/rain detection, …)
- **It's only the beginning…**
  - New generation of satellite instruments
  - Future developments will increase satellite impact
    - Better representation of surface emissivity over land
    - Use of cloudy/rainy radiances
    - ………………………………………………………
- **Get familiar with radiance DA with more practice**
  - There are radiance DA test cases for your play.



Questions