Radiance Data Assimilation in WRFDA

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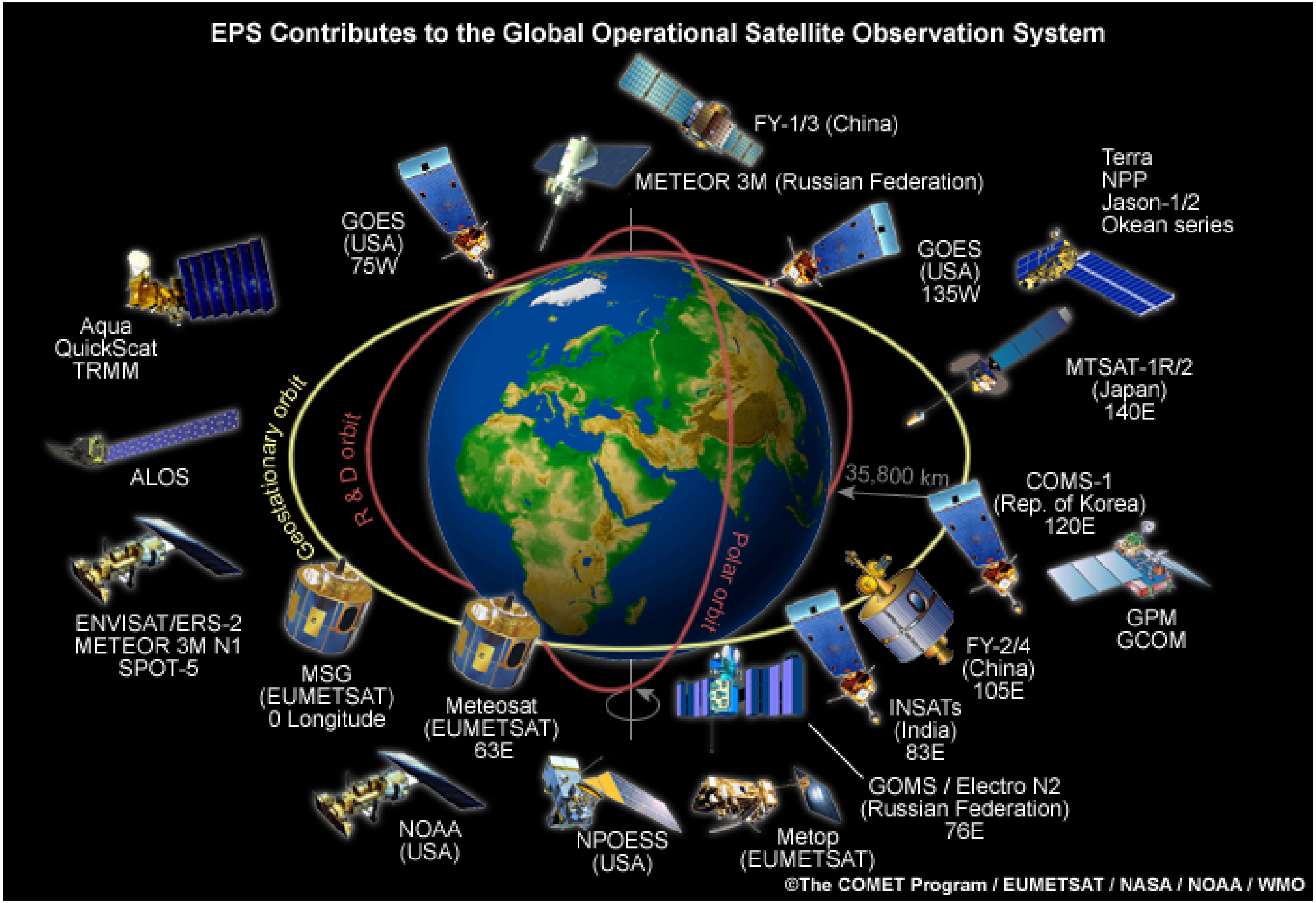
Outline

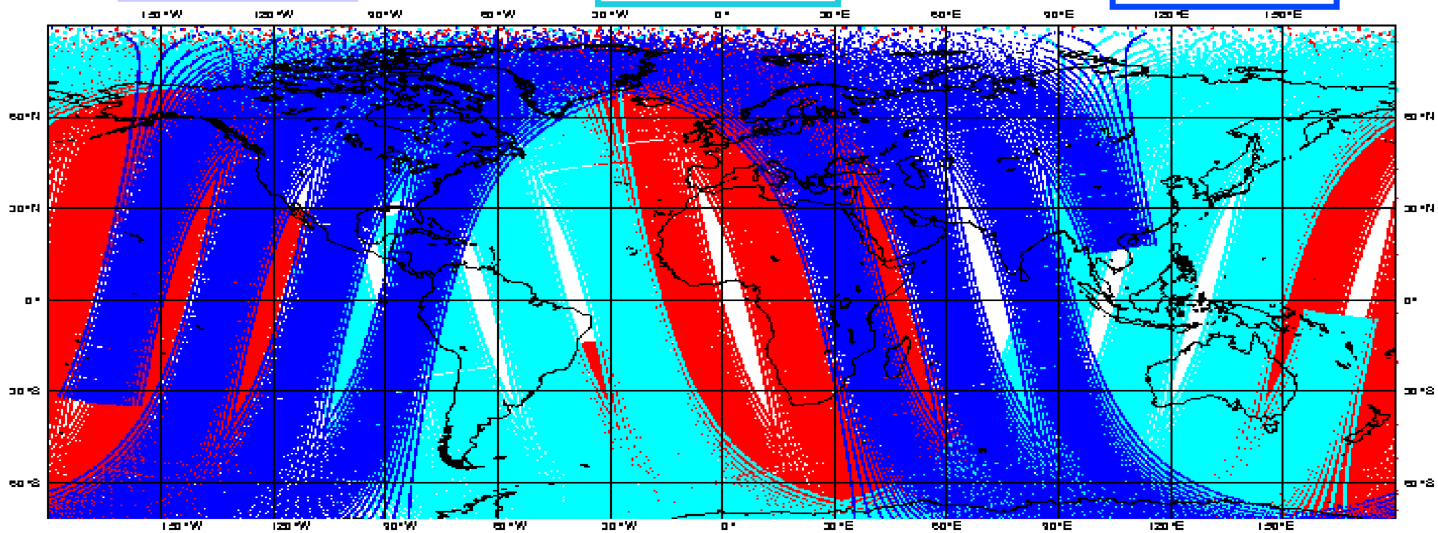
- An introduction of radiance data assimilation
  - Principal of satellite measurements
  - Introduction to the Radiative Transfer theory
  - Elements of Radiance DA

- Practical aspects with WRFDA

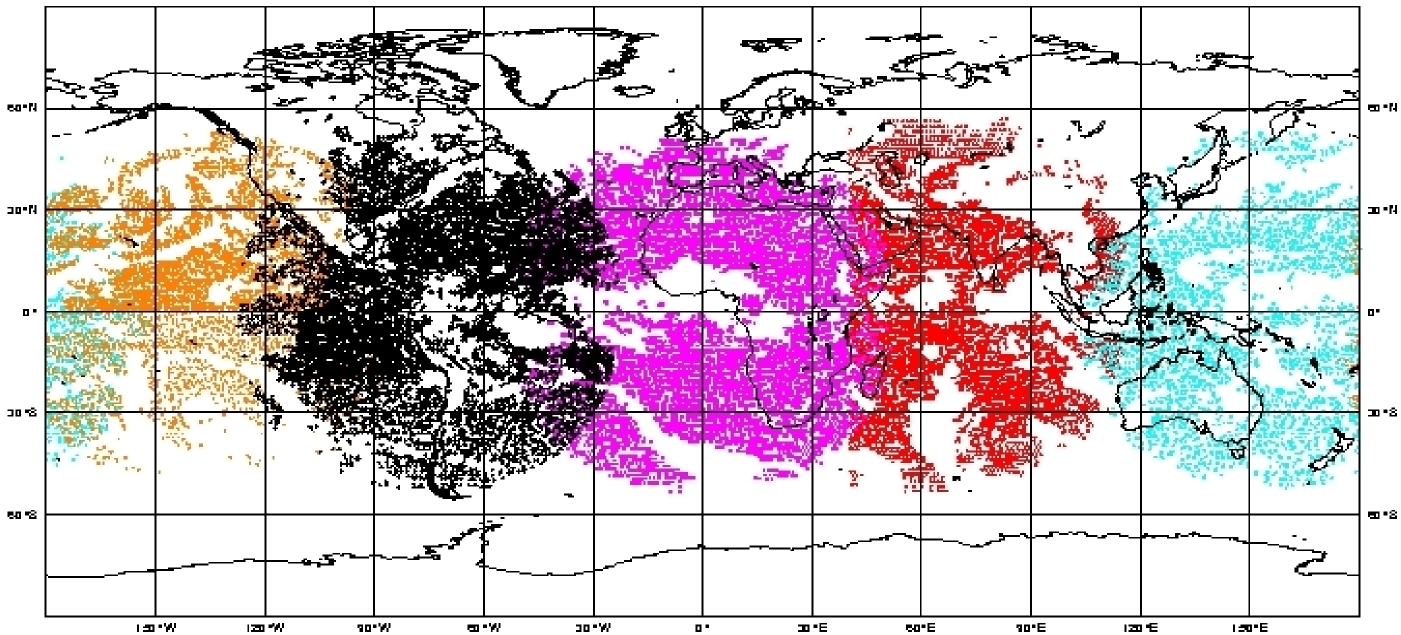
Part I: An Introduction of radiance data assimilation

Environment monitoring satellites



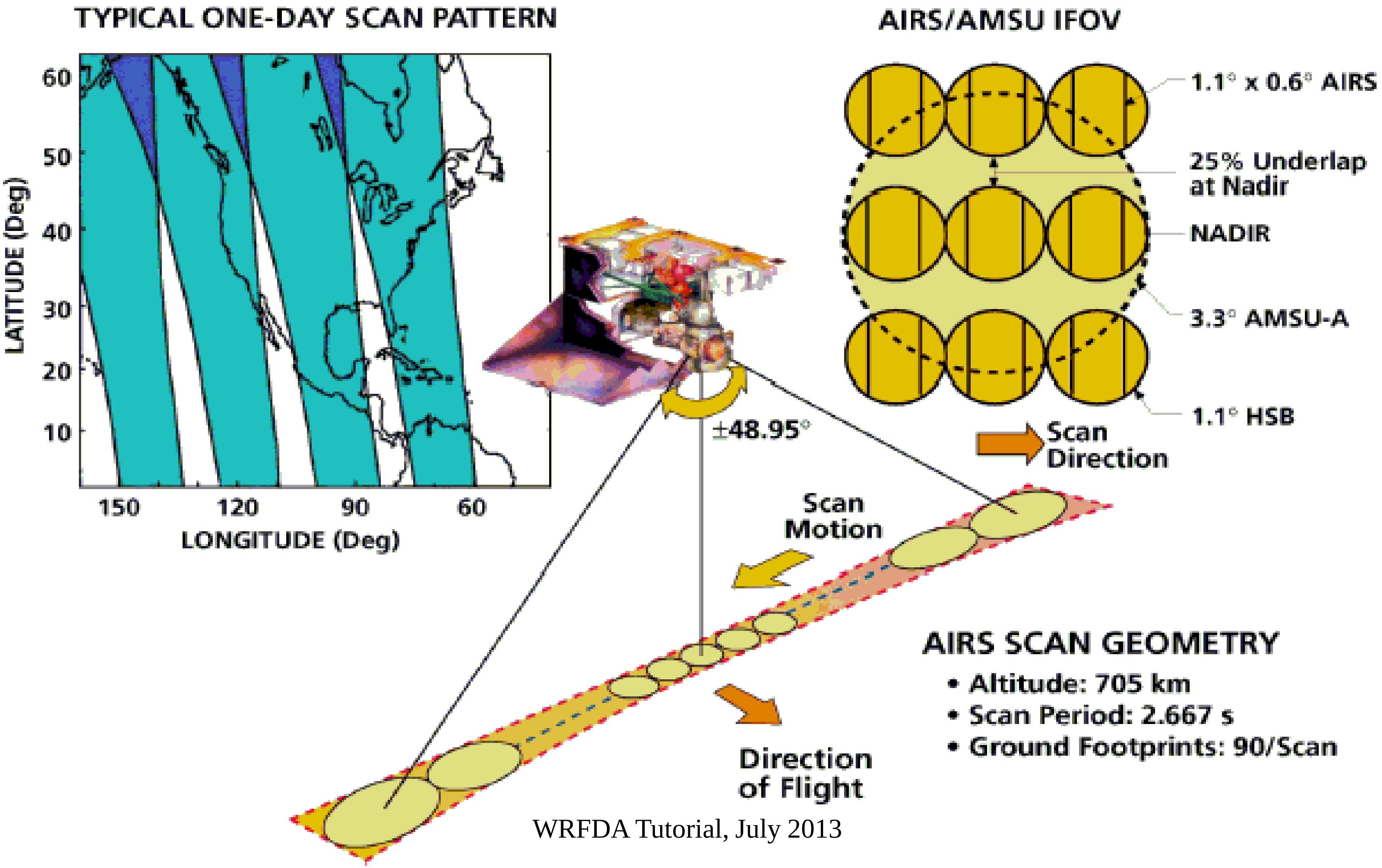


Polar-orbiting satellites



Geostationary satellites

Cross-track scan geometry of satellite instruments



TMI/SSMI/SSMIS scan geometry

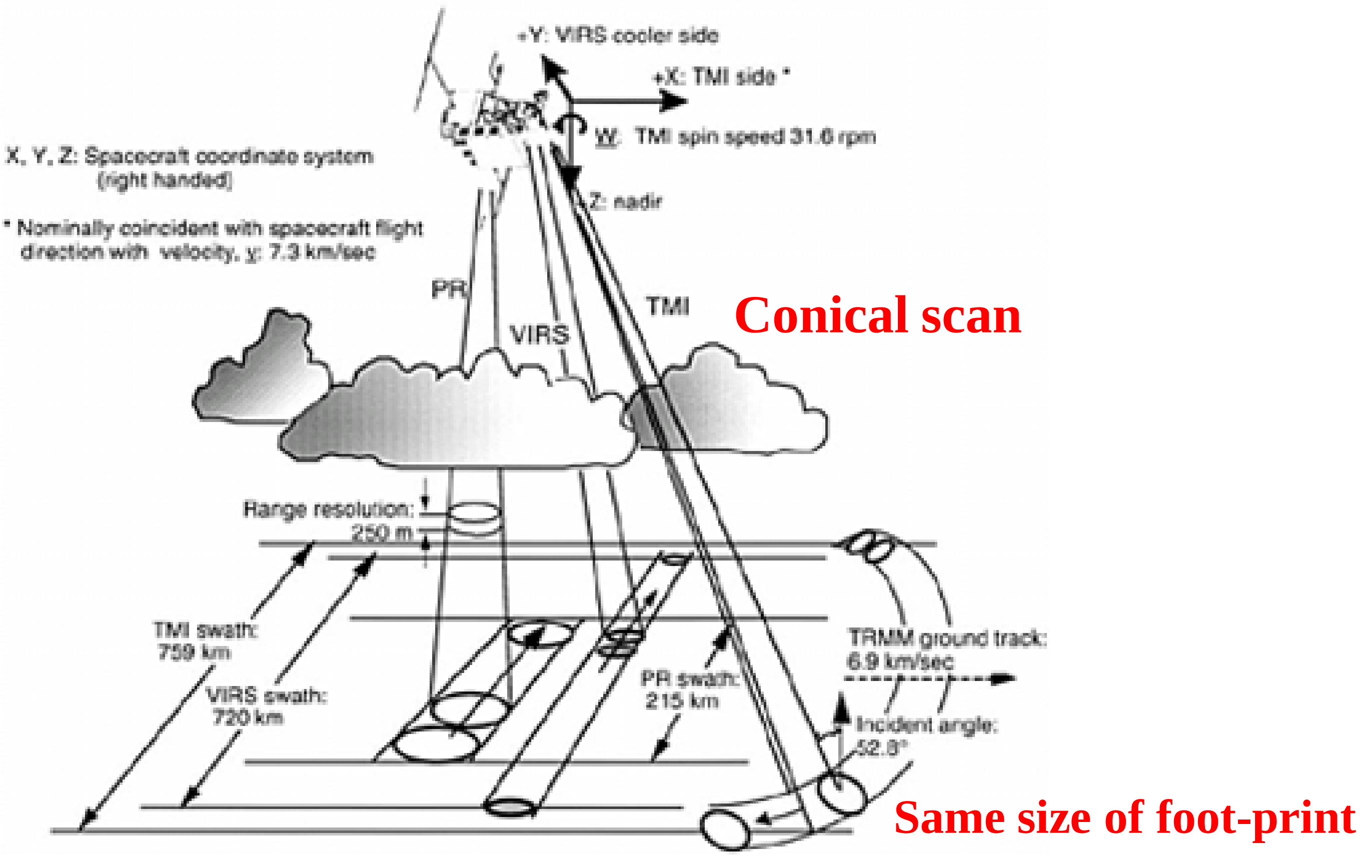


FIG. 1. Schematic view of the scan geometries of the three TRMM primary rainfall sensors: TMI, PR, and VIRS.

What do satellite instruments measure?

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

Satellite (**passive**) instruments simply measure the **radiance** *(energy in specific unit)* that reaches the top of the atmosphere (TOA) at frequency range $\nu_1 \sim \nu_2$. The measured radiance is related to geophysical atmospheric variables by the **radiative transfer** equation. Radiances are often converted to "**brightness temperature**" (equivalent blackbody temperature, by inverting Planck function).

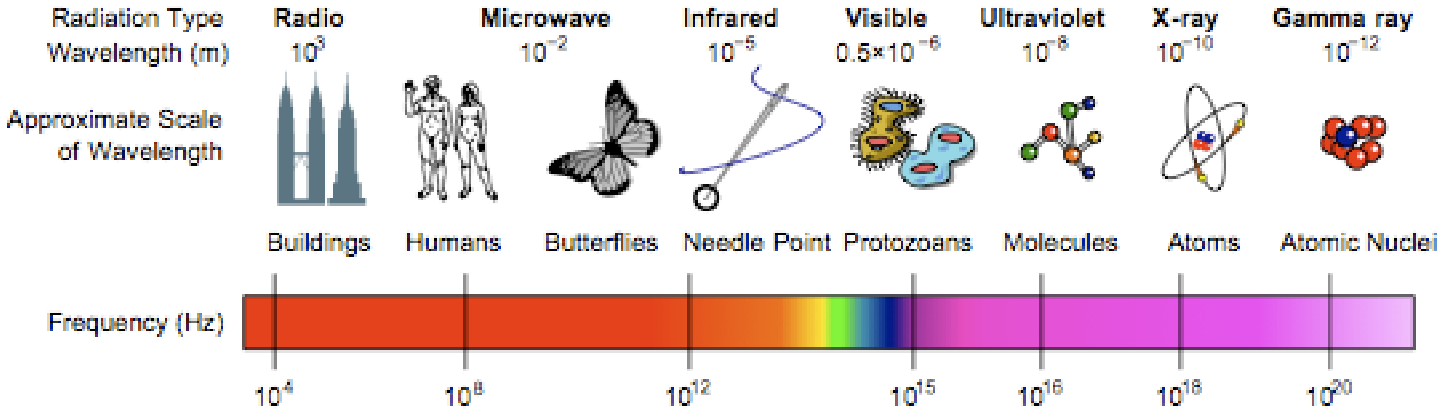
Passive Sensors from Weather/Environment Satellites

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

HIRS
AIRS
IASI
CrIS

AVHRR
MODIS
VIIRS

SBUV



Electromagnetic Spectrum

Why assimilating Radiances?

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

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

•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 appplications

Radiative Transfer: Forward model

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

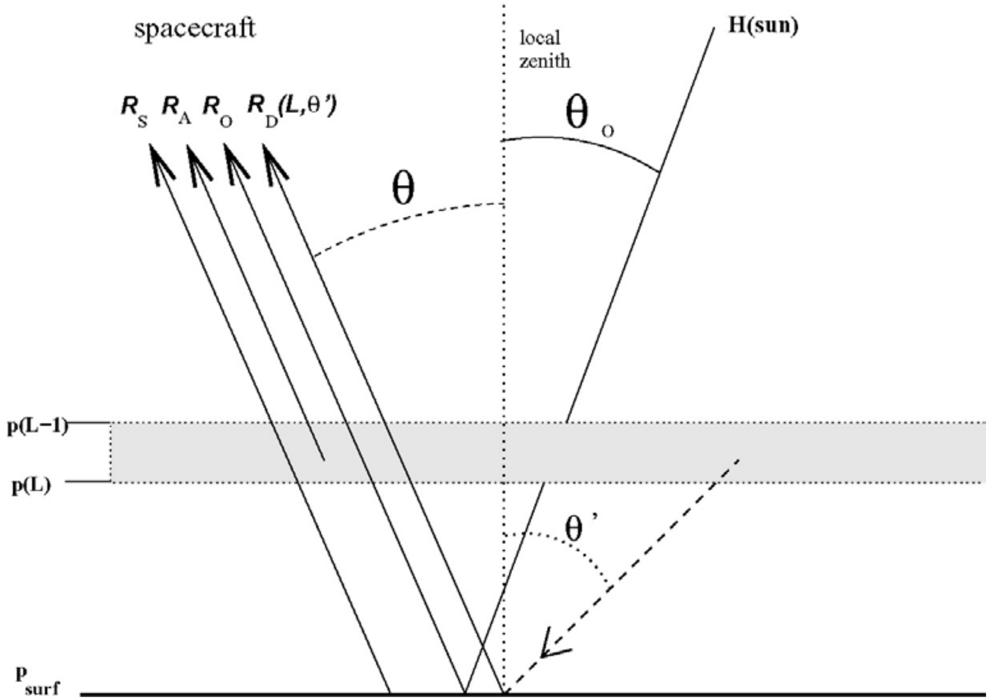
- $L(\nu)$: TOA radiance at frequency ν
- $B(\nu, T(z))$: Planck function
- $\frac{d\tau(\nu)}{dz}$: Atmospheric Absorption (weighting function)
- Surface: Emission/reflection
- Cloud/Rain Aerosol: Diffusion/scattering

Surface emission R_s

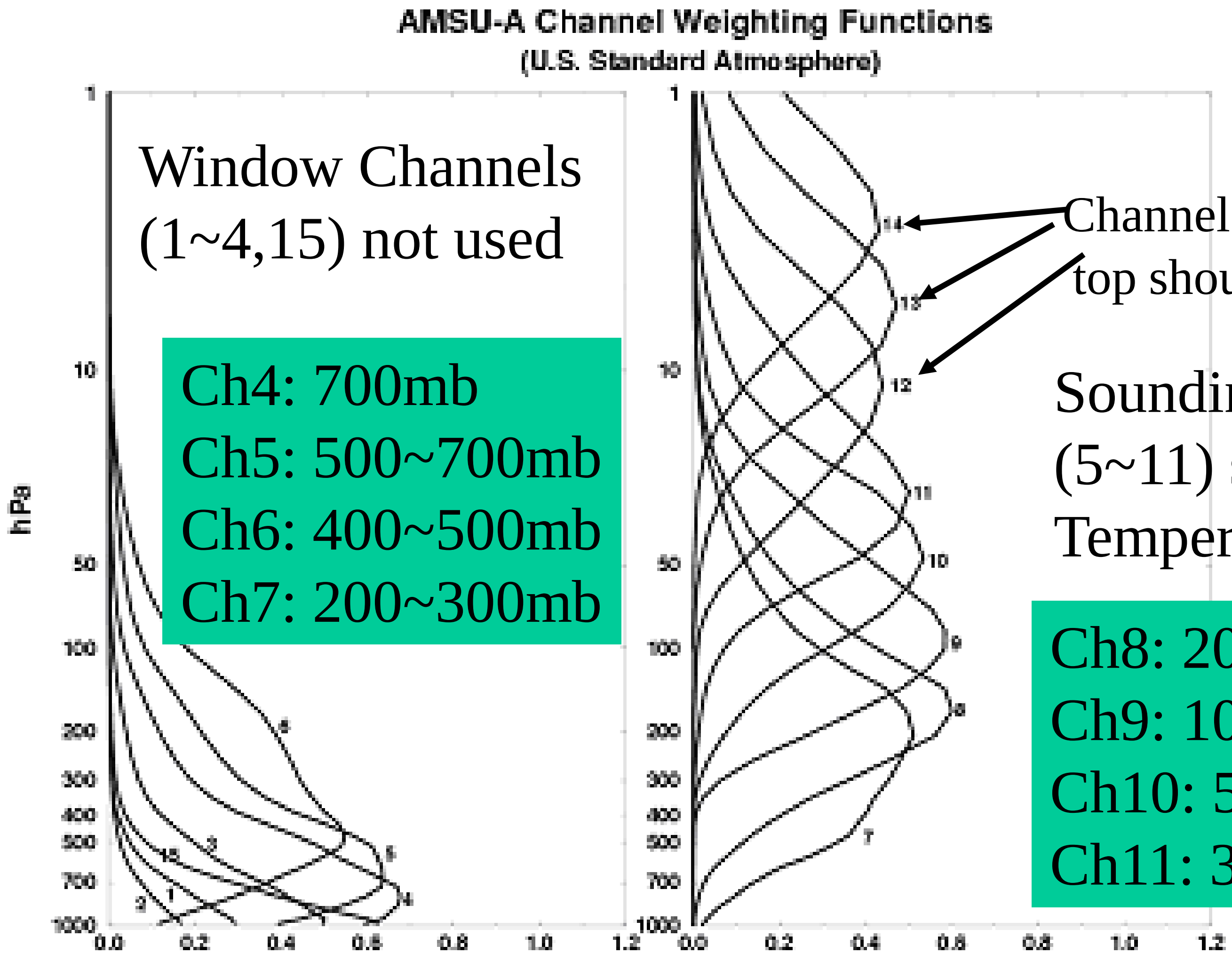
Up-welling atmosphere emission R_A

Reflected solar radiation R_O

Down-welling & reflected atmos. Emission (R_D)



Weighting functions of different channels



Window Channels (1~4,15) not used

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

Channels above model top should not be used

Sounding Channels (5~11) sensitive to Temperature.

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

Radiance Assimilation in 3D/4D-VAR

Solving the inverse problem by minimizing a cost function

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

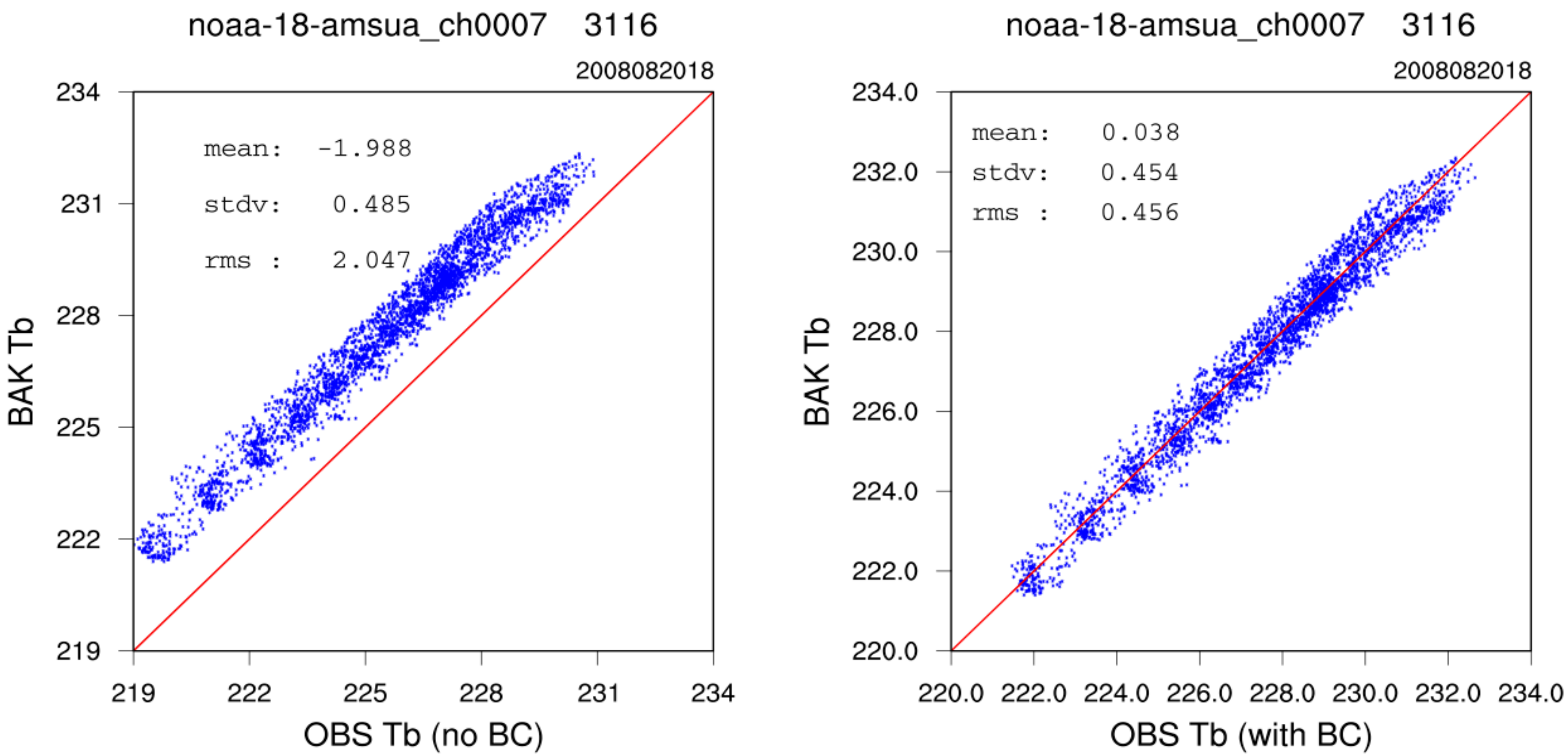
Observation operators include Radiative Transfer Model

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 correlation in B.

3. Can affect no-measured quantities through multivariate correlation in B.

Radiance obs is biased



Variational Bias Correction (VarBC) in WRFDA (T. Auligné)

Modeling of errors in satellite radiances:

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

Bias-correction coefficients

Predictors:

- **Offset (i.e., 1)**
- **1000-300mb thickness**
- **200-50mb thickness**
- **Surface skin temperature**
- **Total column water vapor**
- **Scan, Scan^2, Scan^3**

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

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

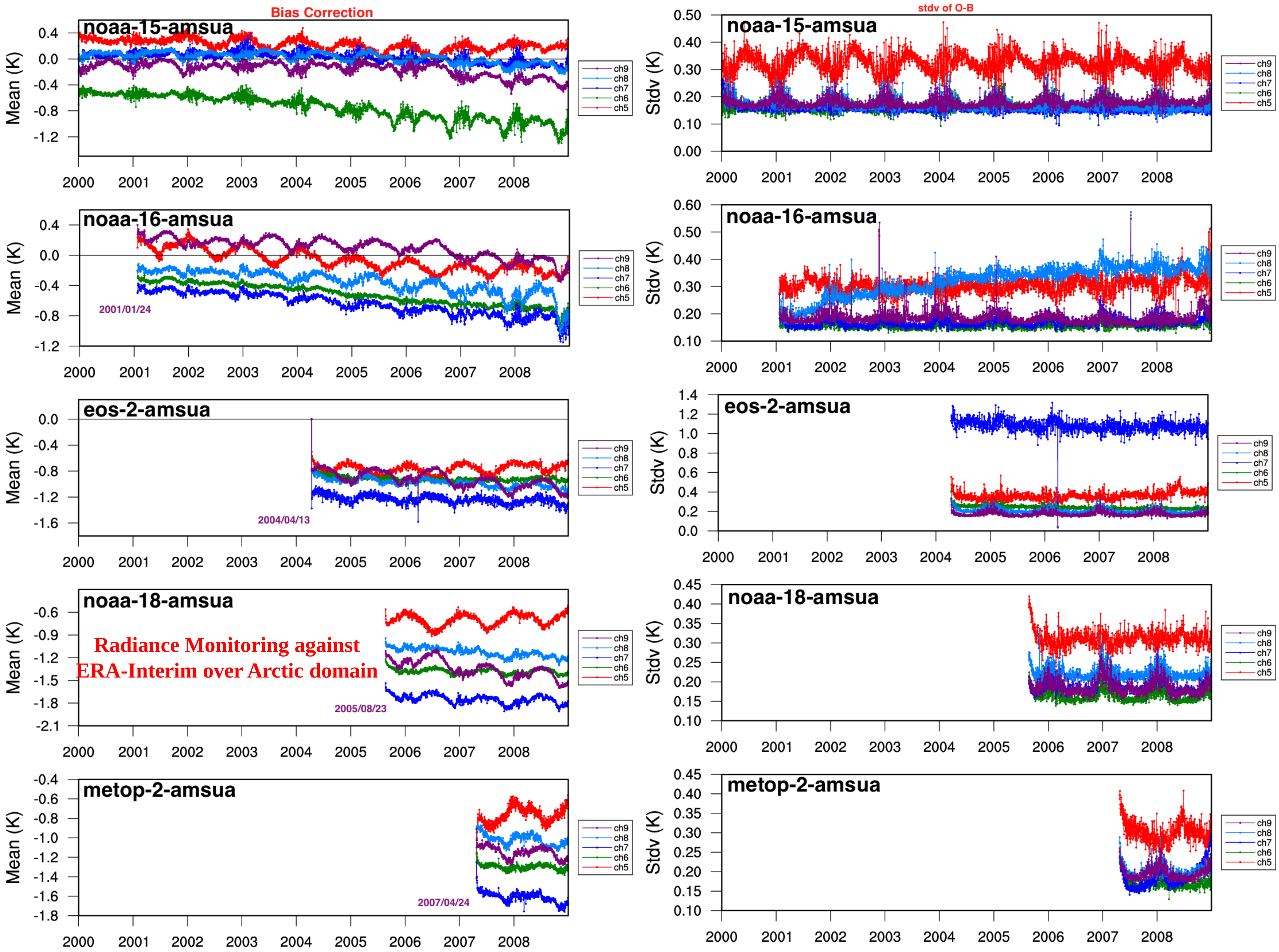
J_b: background term for x

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_p: background term for β

Can be used for radiance offline monitoring by removing J_b term and other obs., and using some analysis fields as reference.

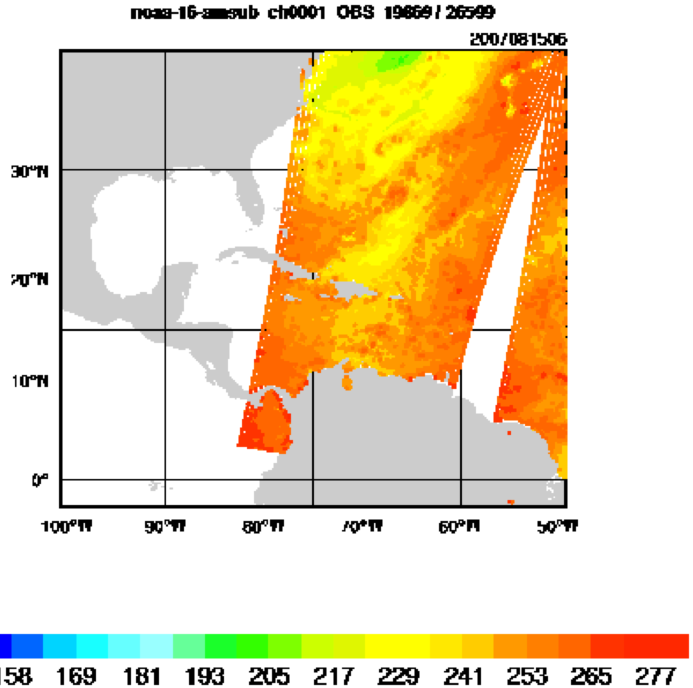


Bias Correction
stdv of O-B
noaa-15-amsua
noaa-16-amsua
eos-2-amsua
noaa-18-amsua
metop-2-amsua
Mean (K)
Stdv (K)
ch9
ch8
ch7
ch6
ch5
2001/01/24
2004/04/13
2005/08/23
2007/04/24
Radiance Monitoring against
ERA-Interim over Arctic domain
2000 2001 2002 2003 2004 2005 2006 2007 2008

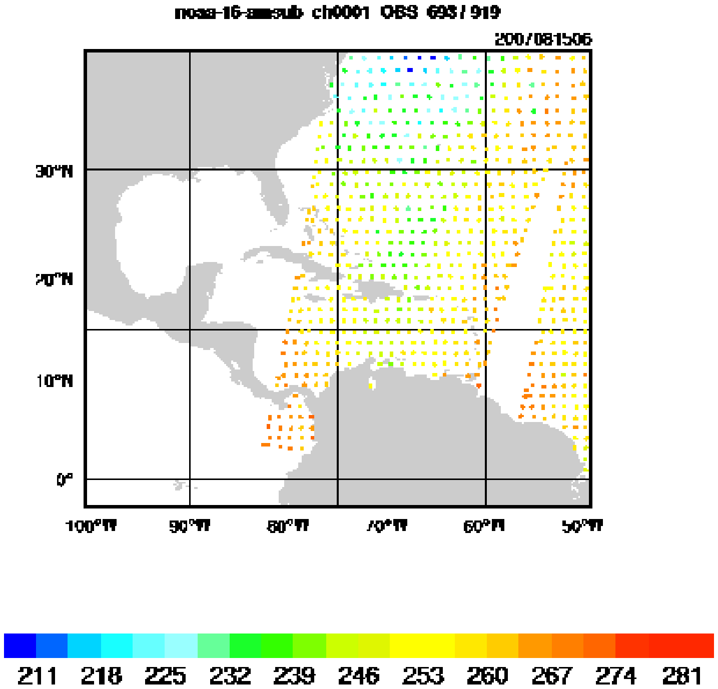
Observation Thinning

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

No Thinning



120km Thinning Mesh



Part II: Practice with WRFDA

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

Data Ingest (V3.5)

- NCEP global BUFR format radiance data within a 6h time window (20 sensors from 9 satellites)
  - **5 HIRS** from NOAA16, 17, 18, 19, METOP-2
  - **6 AMSU-A** from NOAA15,16,18,19, EOS-Aqua, METOP-2
  - **3 AMSU-B** from NOAA15, 16, 17
  - **3 MHS** from NOAA18, 19, METOP-2
  - **1 AIRS** from EOS-Aqua
  - 1 IASI from METOP-2
  - 1 ATMS from NPP
- NRL/AFWA/NESDIS produced DMSP-16 SSMI/S BUFR radiance data.
- FY-3 MWTS and MWHS, CMA binary format.

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/data/gdas/

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

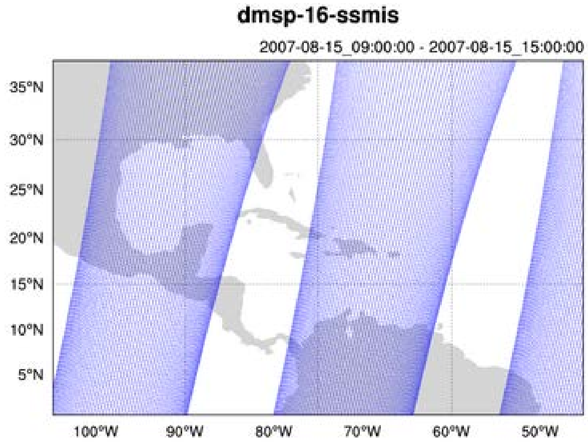
NCEP naming convention	WRF-Var naming convention
gdas1.t00z.1bamua.tm00.bufr_d	amsua.bufr
gdas1.t00z.1bamub.tm00.bufr_d	amsub.bufr
gdas1.t00z.1bhrs3.tm00.bufr_d	hirs3.bufr
gdas1.t00z.1bhrs4.tm00.bufr_d	hirs4.bufr
gdas1.t00z.1bmhs.tm00.bufr_d	mhs.bufr
gdas1.t00z.airsev.tm00.bufr_d	airs.bufr

Direct input to WRFDA, 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 (**C**ommunity **R**adiative **T**ransfer **M**odel)

JCSDA (Joint Center for Satellite Data Assimilation)

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

Latest released version: CRTM REL-2.1.3,

Version included in WRFDA: CRTM REL-2.0.2

CRTM code and (limited) coeffs included in WRFDA release (since V3.2.1)

1=RTTOV (**R**adiative **T**ransfer for **TOVS**)

EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites)

Latest released version: RTTOV11.1,

Version used in WRFDA: RTTOV10

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 WRFDA with radiances

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

(CRTM only) > ln -sf WRFDA/var/run/crtm_coeffs ./crtm_coeffs #(crtm_coeffs is a directory)
(RTTOV only) > ln -sf your_path/rtcoef_rttov10/rttov7pred51L ./rttov_coeffs #(rttov_coeffs is a directory)

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

da_wrfvar.exe >&! wrfda.log

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

Namelist variables for tested instruments:

```
RTMINIT_NSENSOR  = 14
RTMINIT_PLATFORM =  1, 1, 1, 1, 9,10, 1, 1, 1, 1, 1, 10, 9, 2
RTMINIT_SATID    = 15,16,18,19, 2, 2,15,16,17,18, 19, 2, 2,16
RTMINIT_SENSOR   =  3, 3, 3, 3, 3, 3, 4, 4, 4,15, 15,15,11,10
```

NOAA-15-AMSUA (1, 15 ,3)
NOAA-16-AMSUA
NOAA-18-AMSUA
NOAA-19-AMSUA
EOS-2-AMSUA (9, 2, 3)
METOP-2-AMSUA (10, 2, 3)
NOAA-15-AMSUB (1, 15, 4)
NOAA-16-AMSUB
NOAA-17-AMSUB
NOAA-18-MHS (1, 18, 15)
NOAA-19-MHS
METOP-2-MHS (10, 2, 15)
EOS-2-AIRS (9, 2, 11)
DMSP-16-SSMIS (2, 16, 10)

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

This facilitates the user's config. When switching 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 → RTTOV id; satellite_id → Sat id range

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 → RTTOV 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.

Radiance namelist variables

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.

USE_CRTM_KMATRIX: new from Version 3.1.1, much faster. Set to TRUE.
USE_RTTOV_KMATRIX: new from version 3.3, much faster. Set to TRUE

Radiance namelist (VarBC related)

USE_VARBC=true

freeze_varbc=false (VarBC coeffs not change during minimization)

varbc_factor=1. (for scaling the VarBC preconditioning**)**

varbc_nbgerr=5000, (default value prior to V3.3.1 is 1 which is improper)

varbc_nobsmin=500. (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**)**

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
```

Not used any more. Now controlled by namelist "varbc_nbgerr"

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
```

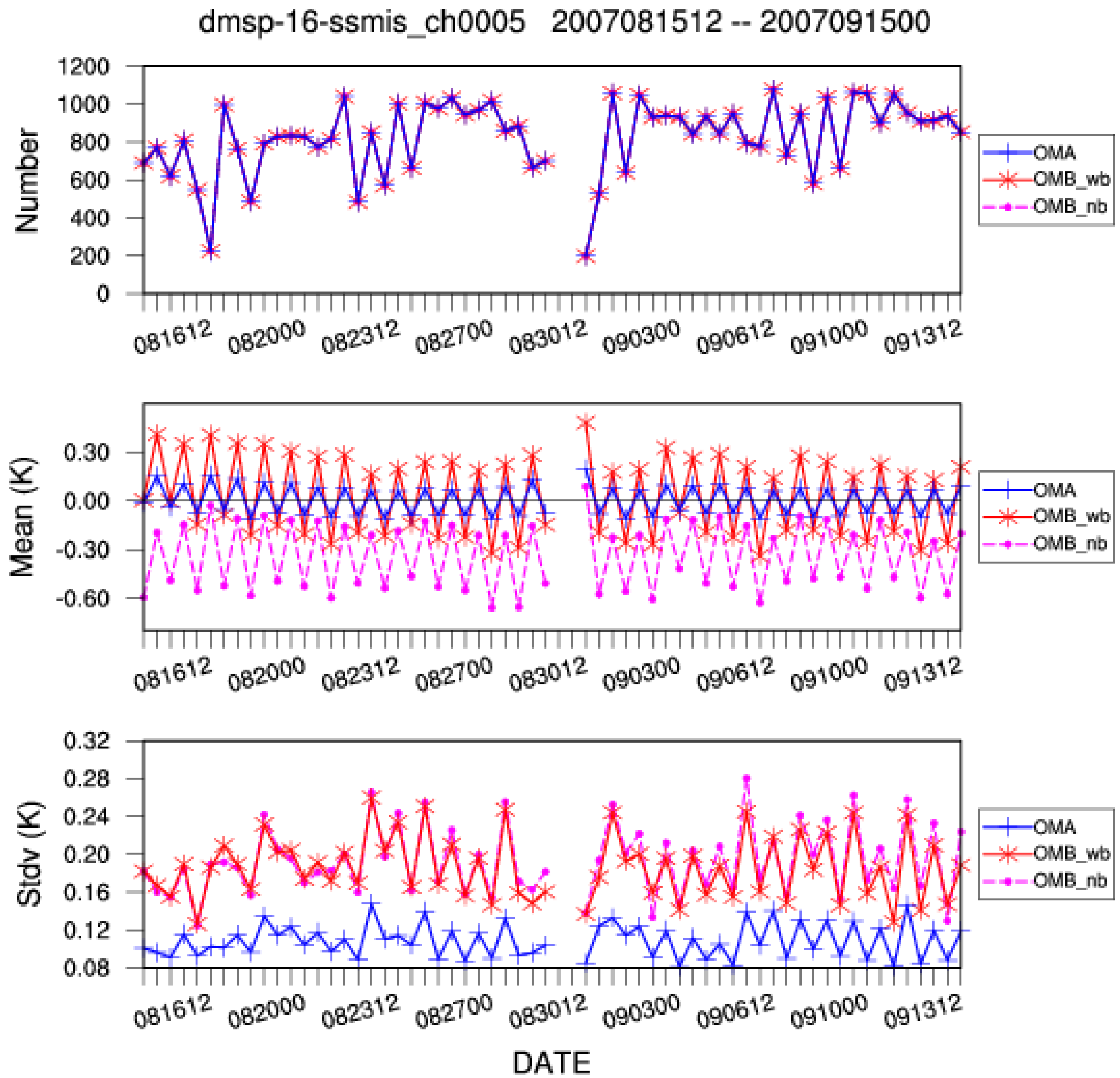
Control whether a cold-start (if 0)
Or warm-start (if 1) VarBC

Bias correction coefficients for 8 predictors
(used only for warm-start case)

Radiance output Post-Processing/Visualization

- ~WRFDA/var/scripts/da_rad_diags.ksh (included in the TOOLS bundle that can be downloaded from http://www.mmm.ucar.edu/wrf/users/wrfda/download/tools.html
  - WRFDA will output radiance inv* or oma* ASCII files separated for different sensors and CPUs.
  - Script converts 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.

Time series of radiance OMB/OMA for DMSP-16 SSMI/S



Conclusions

- **Radiance data assimilation are important**
  - Major source of information over ocean and Southern Hemisphere
- **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, …)
  - Challenge for regional DA: lower model top, bias correction
- **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**
  - wrfhelp@ucar.edu