Radiance Data Assimilation in WRFDA

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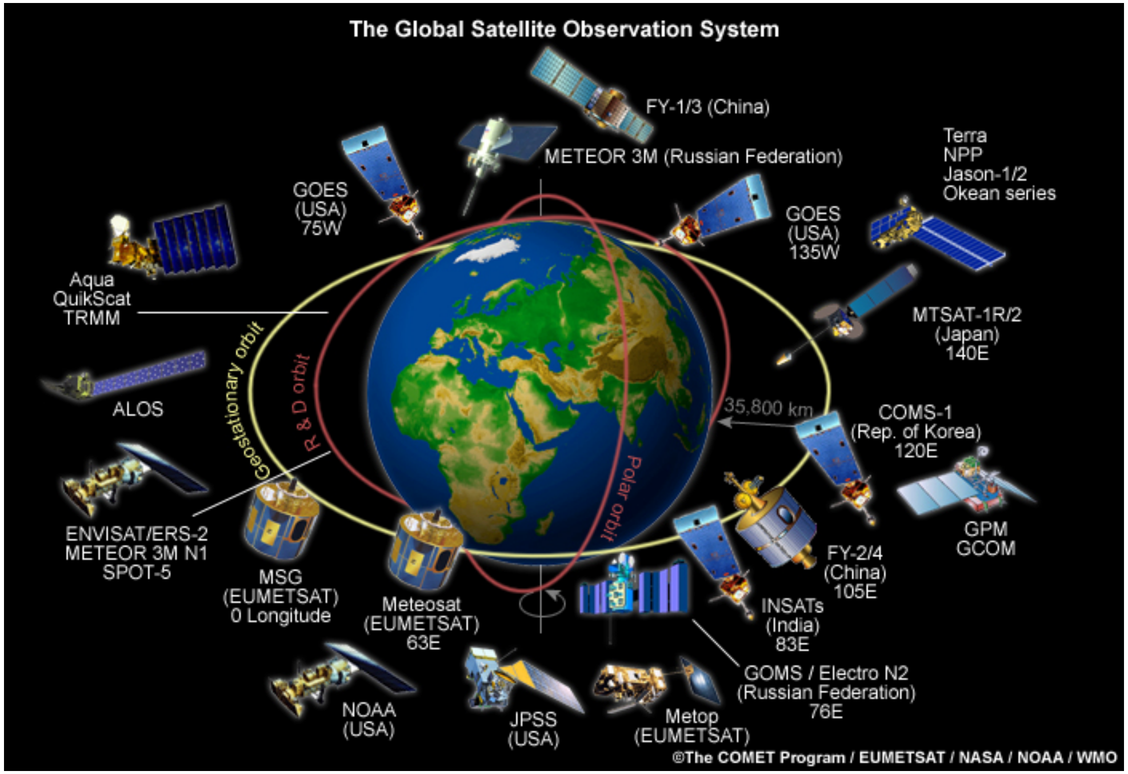
WRFDA tutorial
Aug 2015

- Introduction to radiance data assimilation
  - Principals of satellite measurements
  - Introduction to the Radiative Transfer theory
  - Elements of Radiance DA
- Practical aspects with WRFDA

Part I: Introduction to radiance data assimilation

Environment monitoring satellites

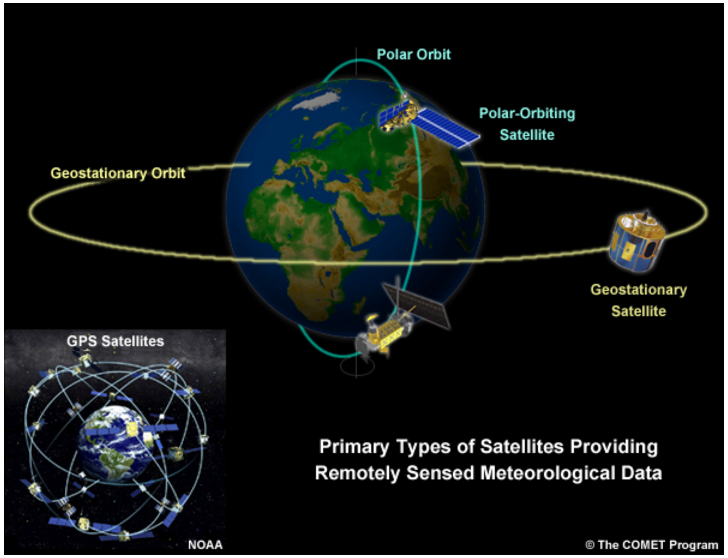


Various types of **instruments/sensors** onboard the **satellites**

Valuable information from the satellite measurements

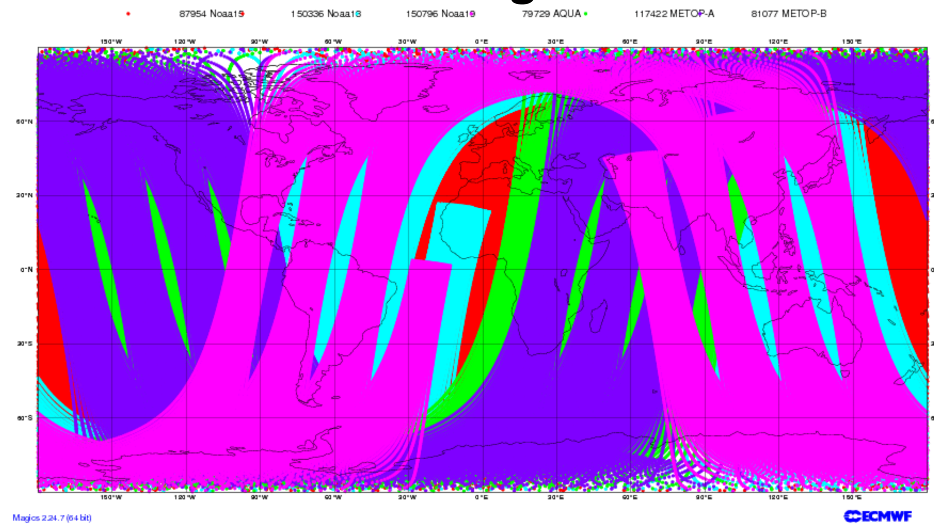
- images
- retrieved/derived products
- radiances

Types of satellites



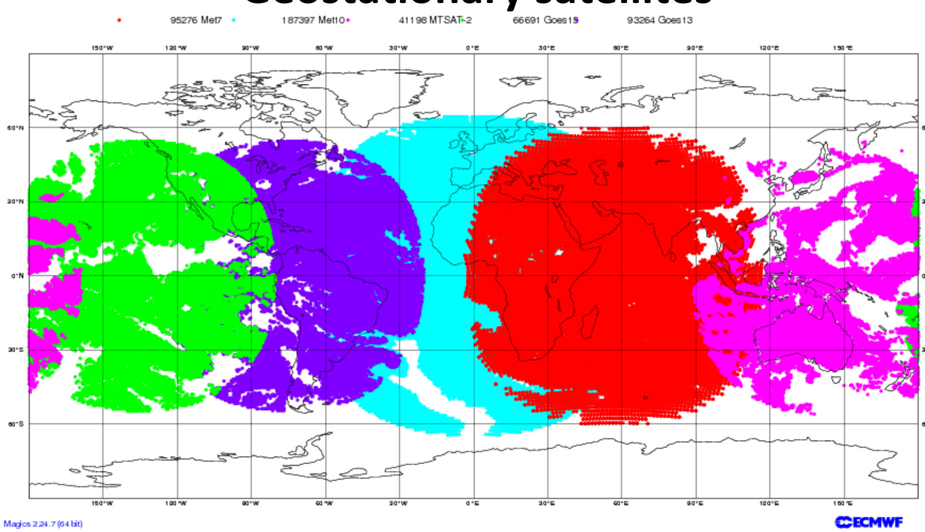
ECMWF Data Coverage (All obs DA) - AMSU-A
05/Jul/2015; 06 UTC
Total number of obs = 667314

Polar-orbiting satellites



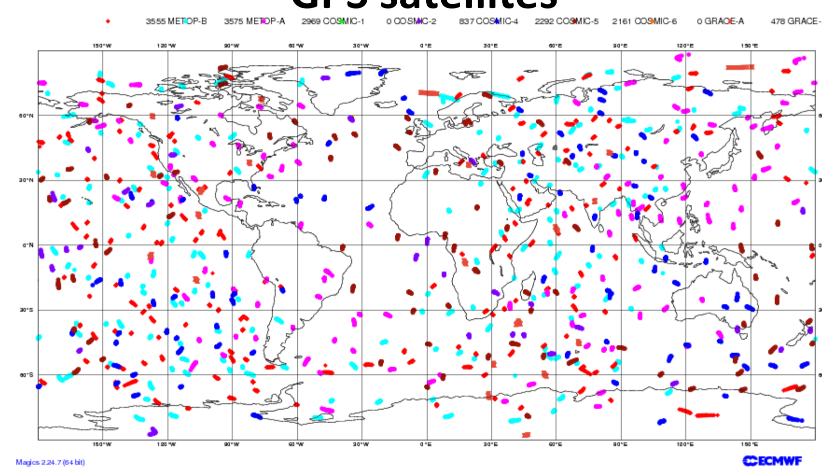
ECMWF Data Coverage (All obs DA) - GRAD
05/Jul/2015; 06 UTC
Total number of obs = 483826

Geostationary satellites



ECMWF Data Coverage (All obs DA) - GPSRO
05/Jul/2015; 06 UTC
Total number of obs = 15867

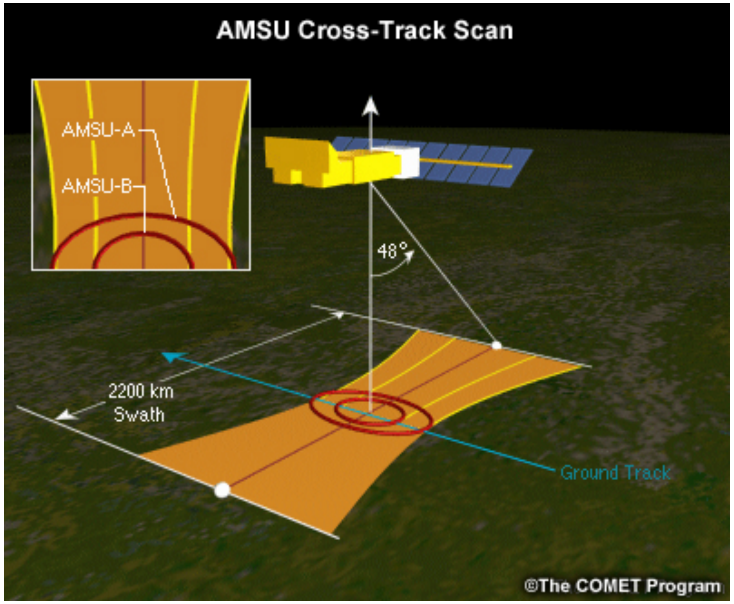
GPS satellites



Satellite instruments / sensors

Types of sensors

- •Passive
  - Visible
  - IR
  - Microwave
- •Active
- •Occultation



Scan strategies and viewing geometry

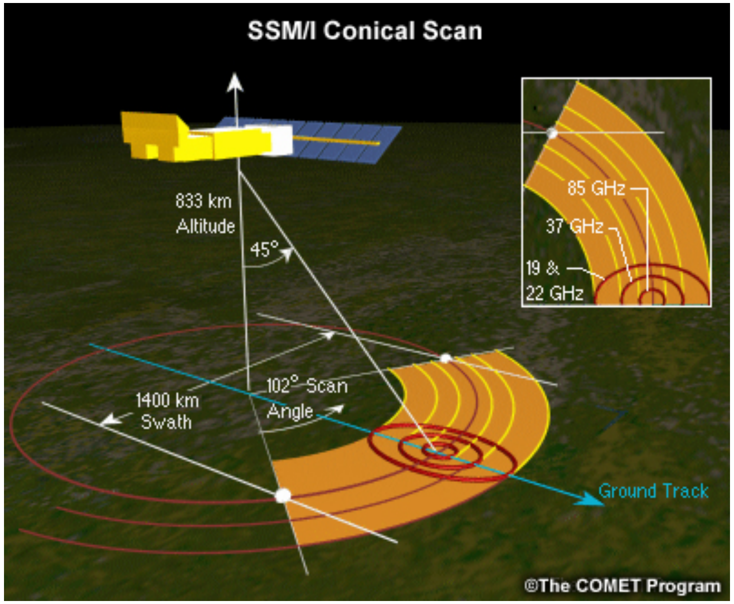
affecting **coverage** and
ground or field-of-view **resolution**

<u>cross-track scan</u>

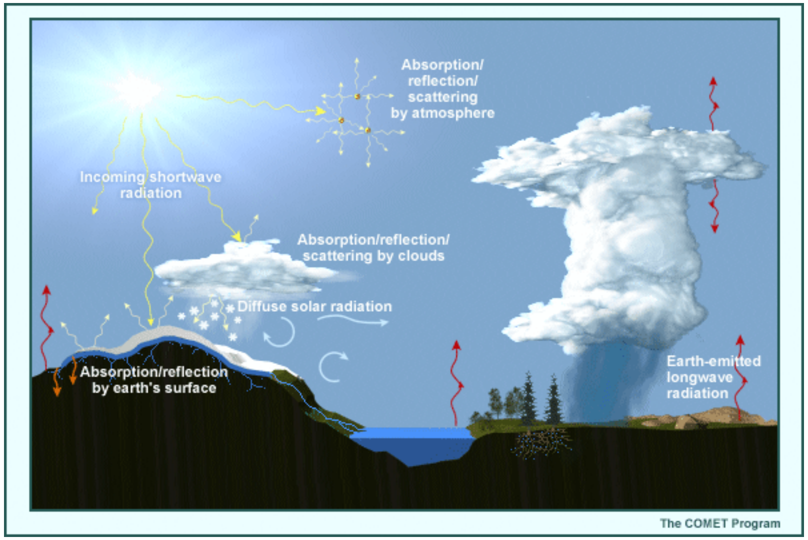
- resolution degrades toward the edge of the swath because the viewing angle changes across the swath

<u>conical scan</u>

- constant ground resolution
- generally narrower swaths than cross-track scan swaths



What do satellite instruments measure?



Satellite **passive** sensors

- observe **radiation** emitted and scattered from the earth's surface and atmosphere at discrete **wavelength intervals**

- measured radiation is calibrated and commonly processed into a unit of power known as a spectral radiance
- radiance is related to geophysical atmospheric variables by the **radiative transfer equation**
- radiances are often converted to "**brightness temperature**" (equivalent blackbody temperature, by inverting Plank function)

Radiative Transfer

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

TOA radiance at frequency ν

Planck function

Atmospheric Absorption (weighting function)

Emission/reflection

Diffusion/scattering

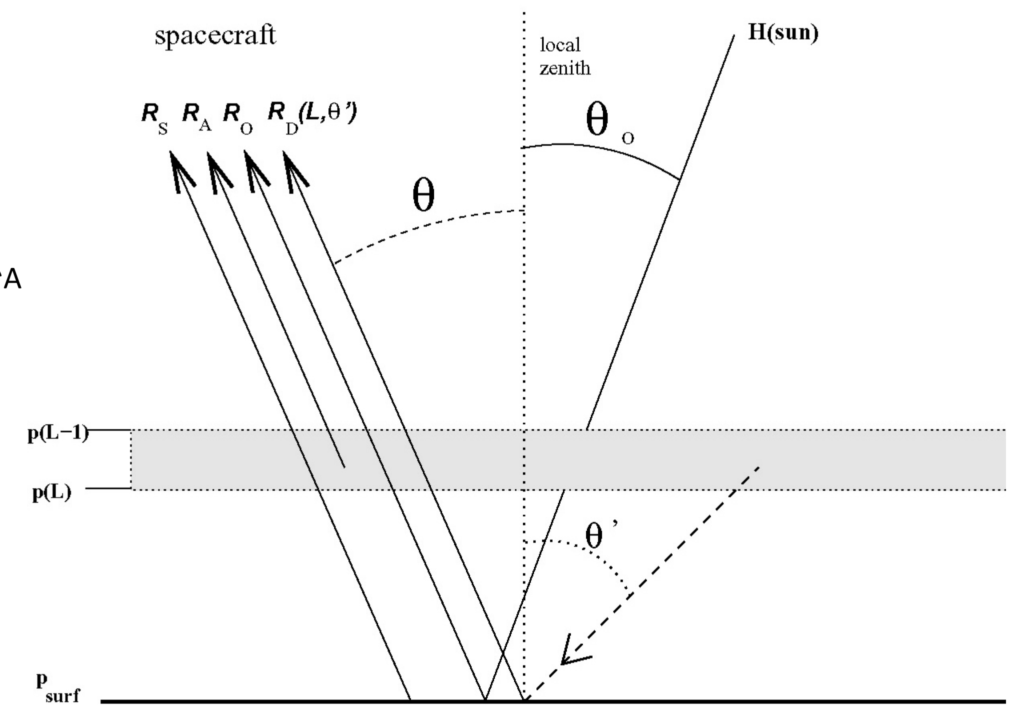
Surface emission R_s

Up-welling atmosphere emission R_A

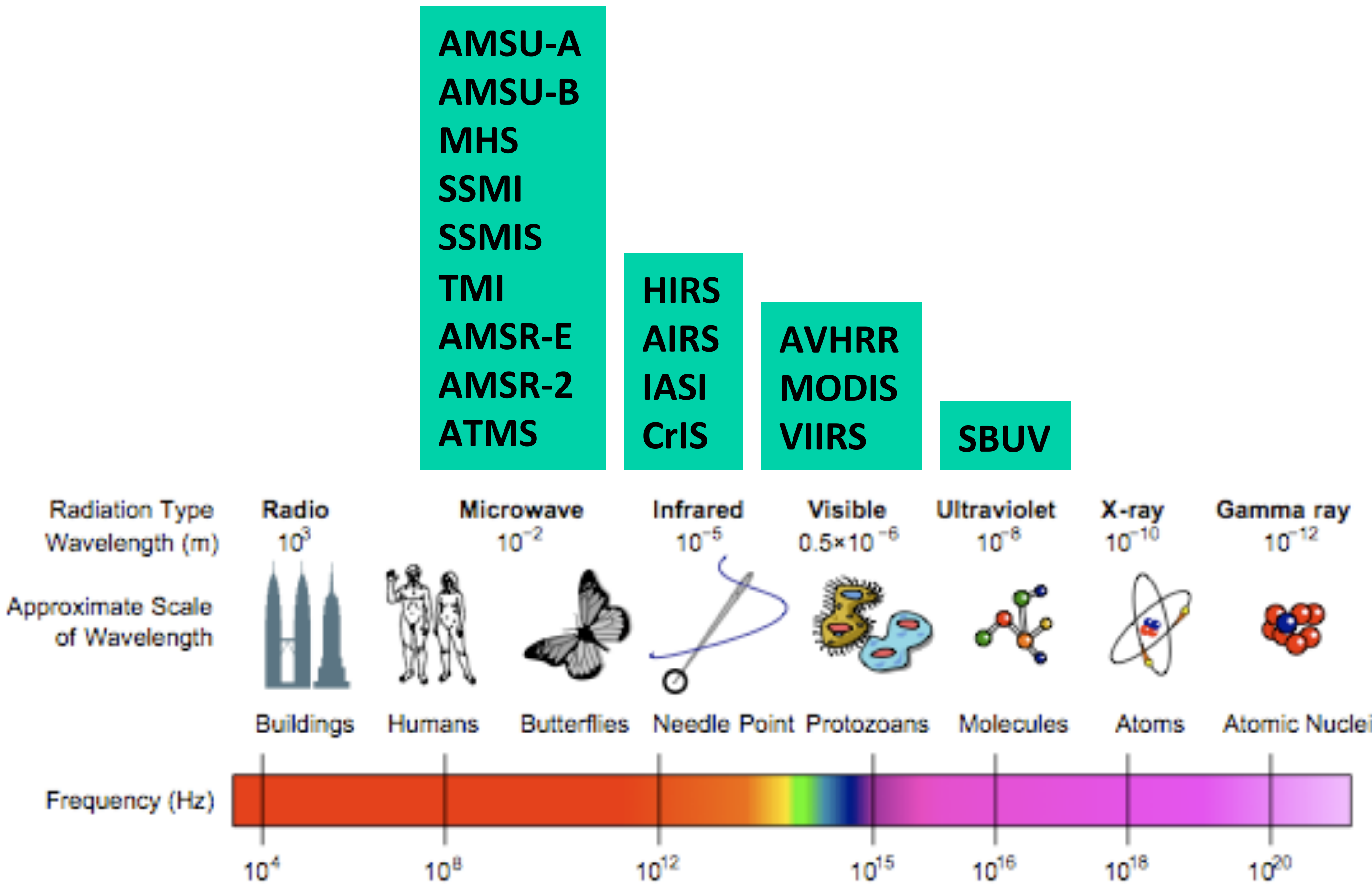
Reflected solar radiation R_O

Down-welling & reflected atmos.

Emission (R_D)

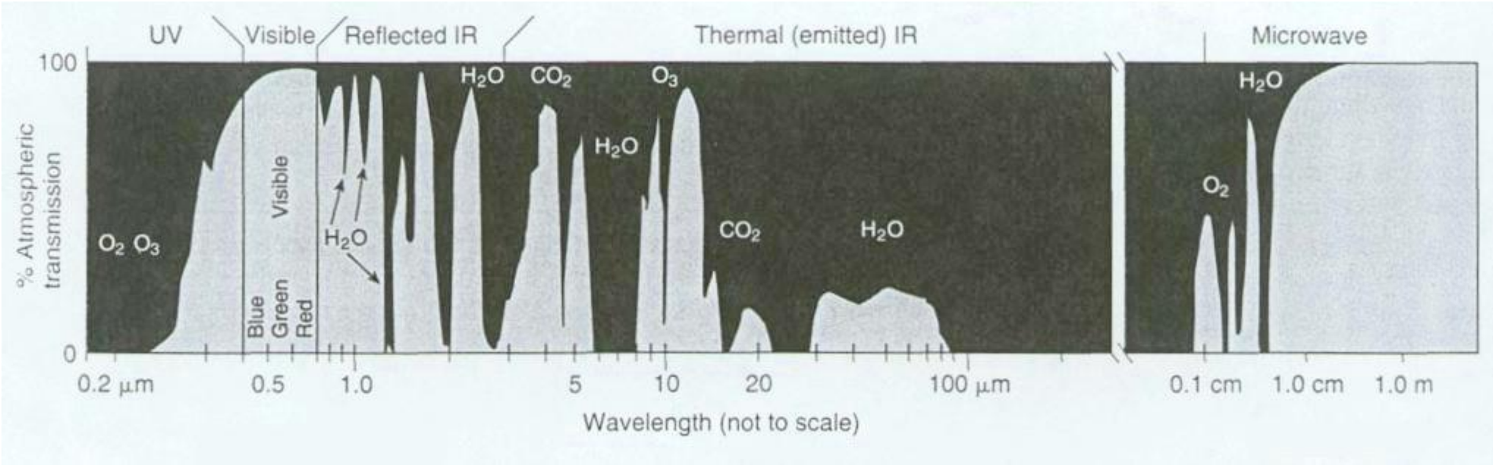


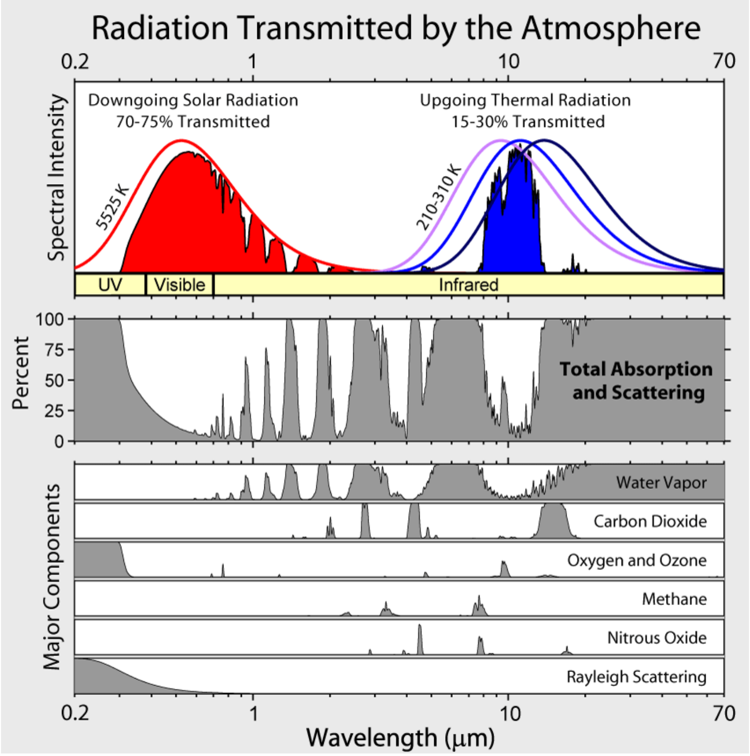
Passive Sensors from Weather/Environment Satellites

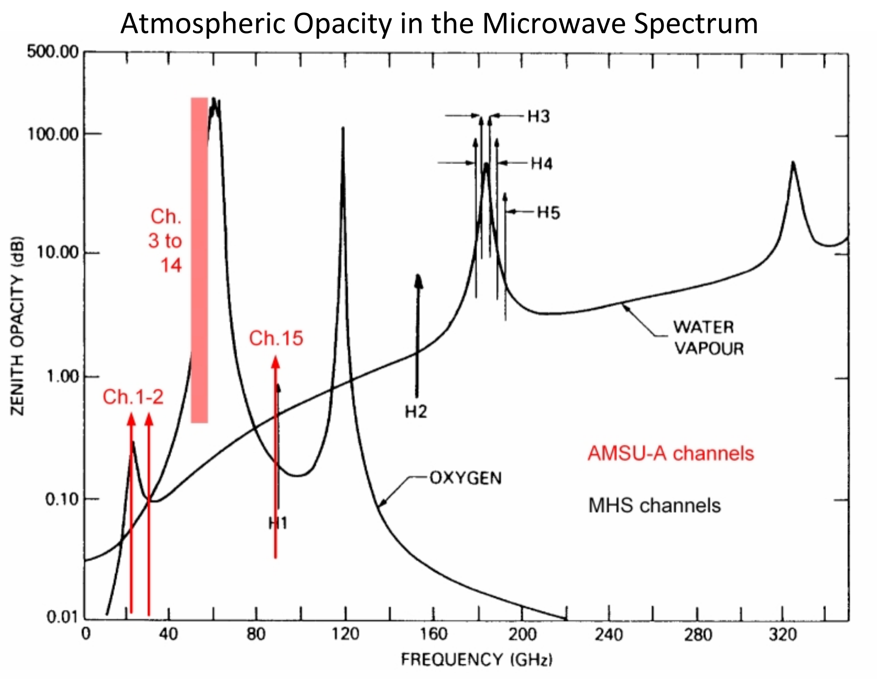


Electromagnetic Spectrum

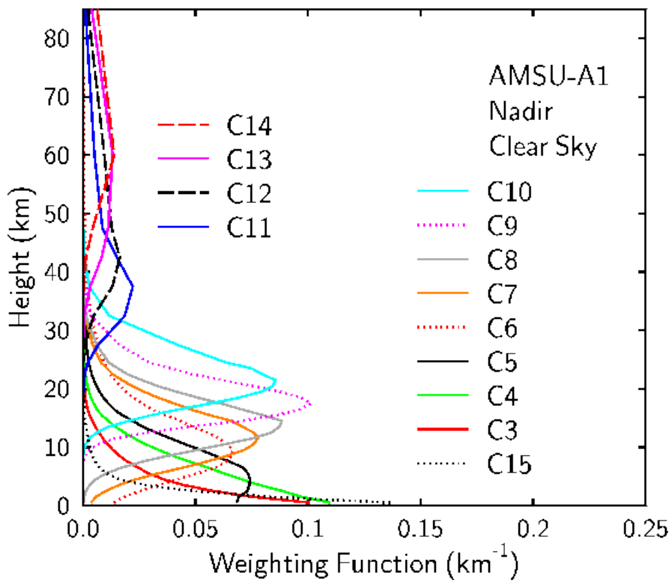
Atmospheric gas absorption-transmission







Weighting functions



Weighting functions indicate the contribution to the outgoing radiance from various layers of the atmosphere

Weight functions are frequency (channel) dependent

Channel selection for NWP data assimilation

- Atmospheric sounding channels (measured radiance has no contribution from the surface)
- By selecting a number of channels with varying absorption strengths (i.e. varying peaking weight functions) we sample the atmospheric temperature at different altitudes
- Channels whose peaks of the weighting functions occur above the model top should not be used in data assimilation
- Window channels are sensitive to properties associated with earth and ocean surfaces as well as clouds

Radiance Assimilation in 3D/4D-VAR

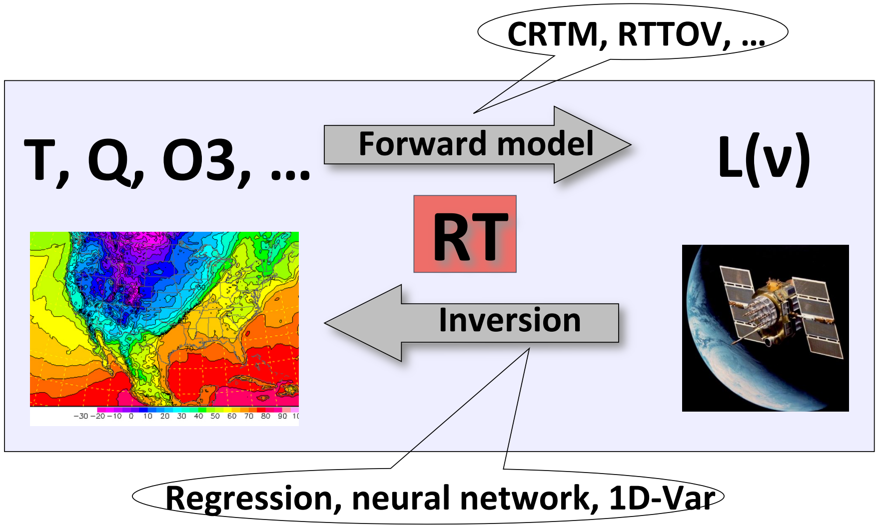
Solving the inverse problem by minimizing a cost function

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

Observation operators include (Fast) Radiative Transfer Model

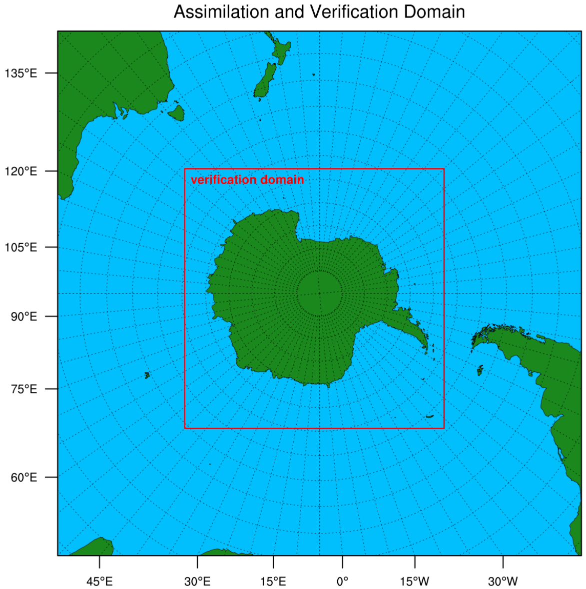
- Solving the inverse problem (extracting atmospheric information from the radiance) along with other observations in a more consistent way.
- Pixels are no longer independent of each other due to the horizontal correlation in B.
- Can affect non-measured quantities through multivariate correlation in B.

✓ Radiative transfer model
✓ Channel selection
✓ Observation errors
✓ Bias correction
✓ Quality control
✓ Thinning
✓ Monitoring

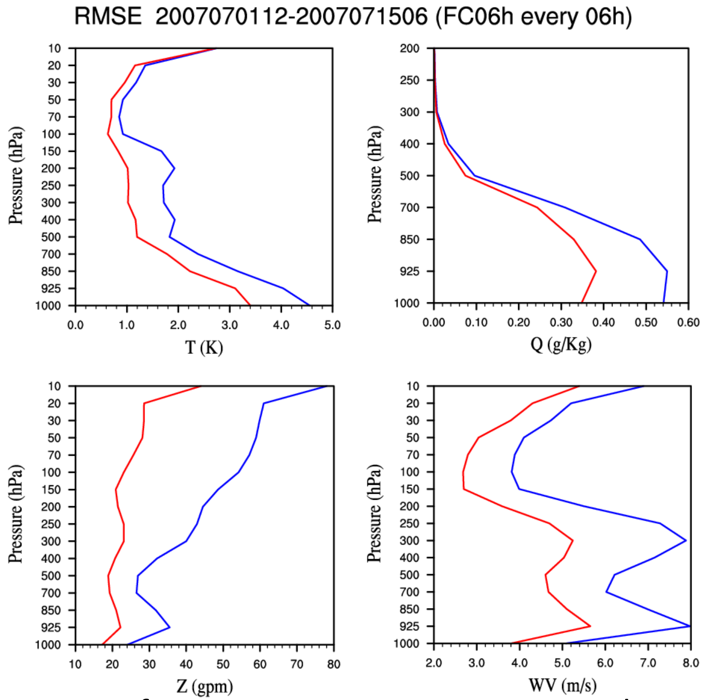


Part II: Practical implementation with WRFDA

- WRFDA applications
- Practical aspects
  - Quality Control
  - Variational bias correction
  - Data ingest (sources, instruments)
  - Radiative transfer model
  - Channel selection
  - Diagnostics and monitoring



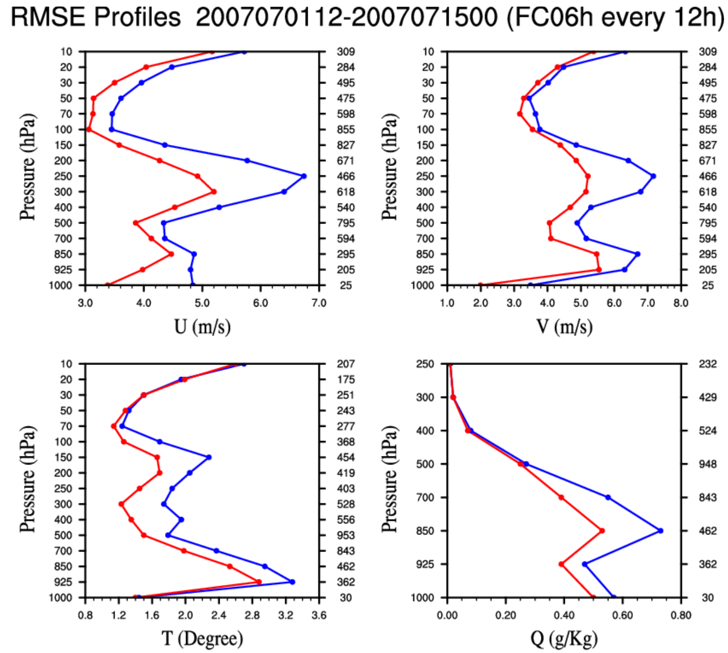
- WRF/WRFDA V3.6+ (V3.6 with modifications and fixes)
- 1-hPa model top, 71 levels, 60-km resolution
- low/lateral boundary conditions from ERA-interim
- Snow from NCEP FNL
- 6-hour cycling starting from 2007070100
- 240-second time step, 180-sec for a couple dates that exceeded CFL criteria
- WSM 5-class microphysics
- RRTMG SW/LW radiation
- Ozone and aerosol climatology
- MYNN surface layer
- MYNN 2.5 TKE PBL
- Grell 3D cumulus parameterization
- conv: conventional data only
- conv_amsua: conventional data and AMSU-A radiances from NOAA-15, NOAA-16, NOAA-18, EOS-AQUA, METOP-2



verification against ERA-interim analysis

conv amsua

conv



verification against SOUNDs

conv amsua

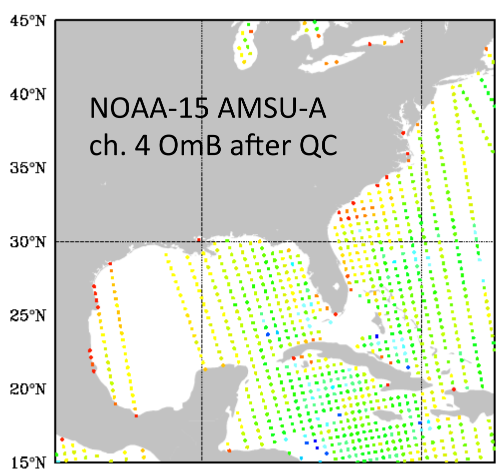
conv

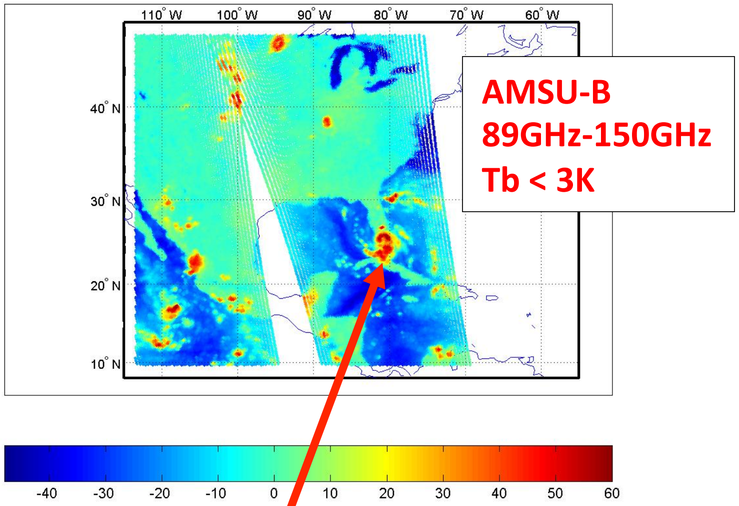
Quality control

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

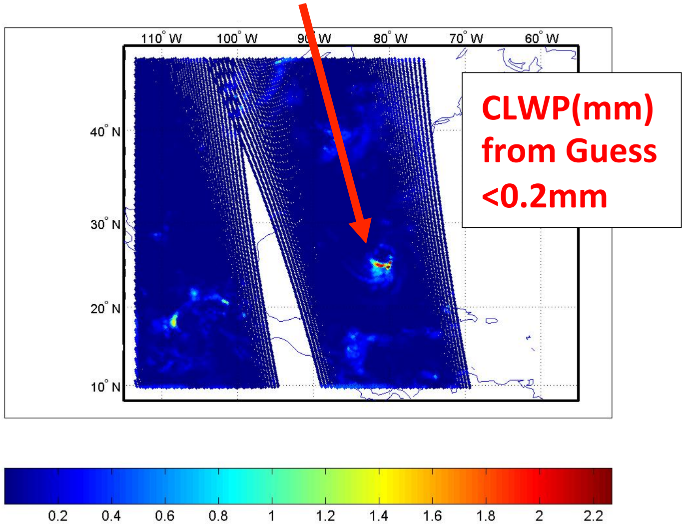
- **Pixel-level QC**
  - Reject **limb** observations
  - Reject pixels over **land** and **sea-ice**
  - **Cloud/Precipitation** detection
  - **Synergy** with imager (AIRS/VIS-NIR)

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



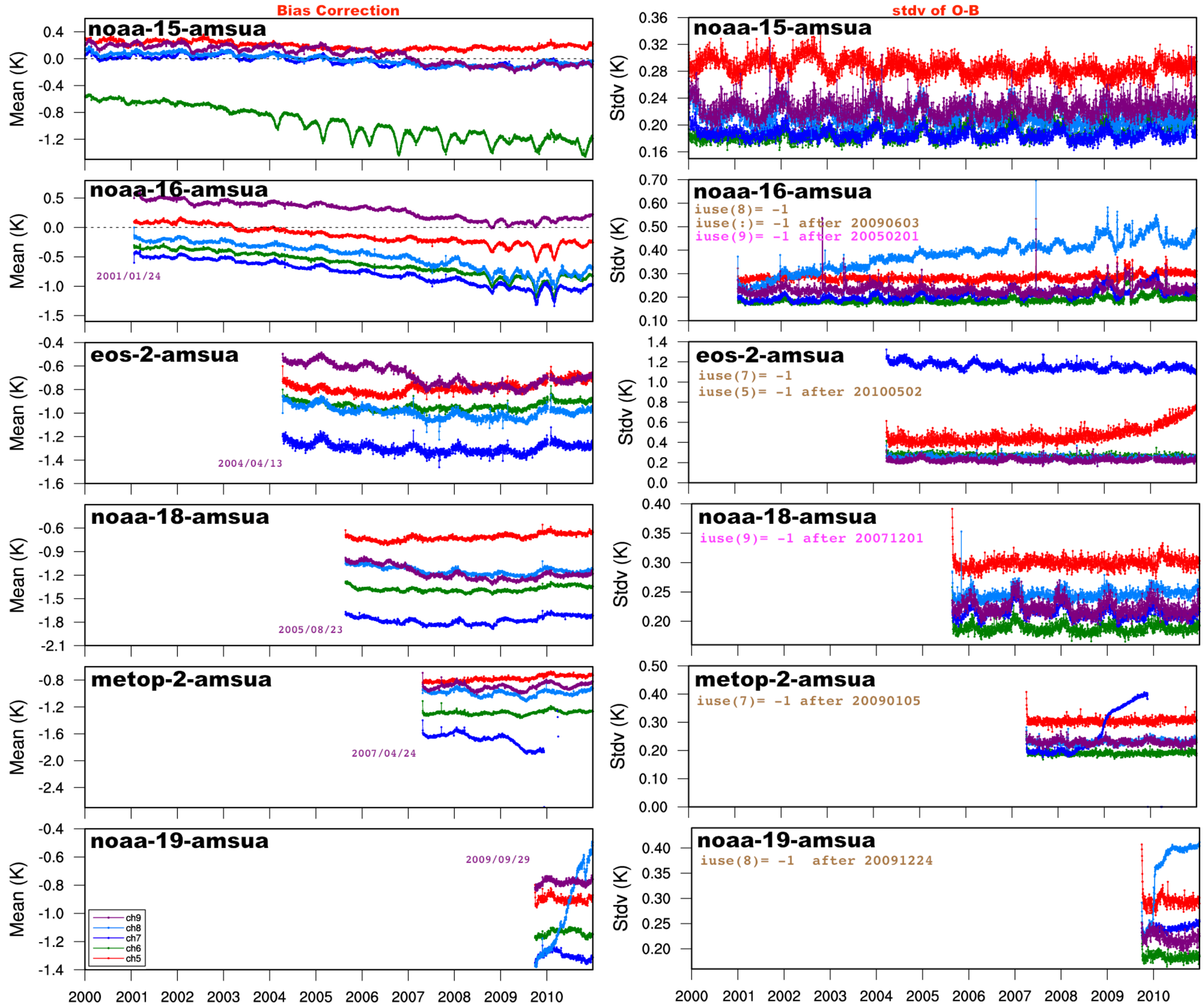


Katrina Location (2005/08/26/06Z)



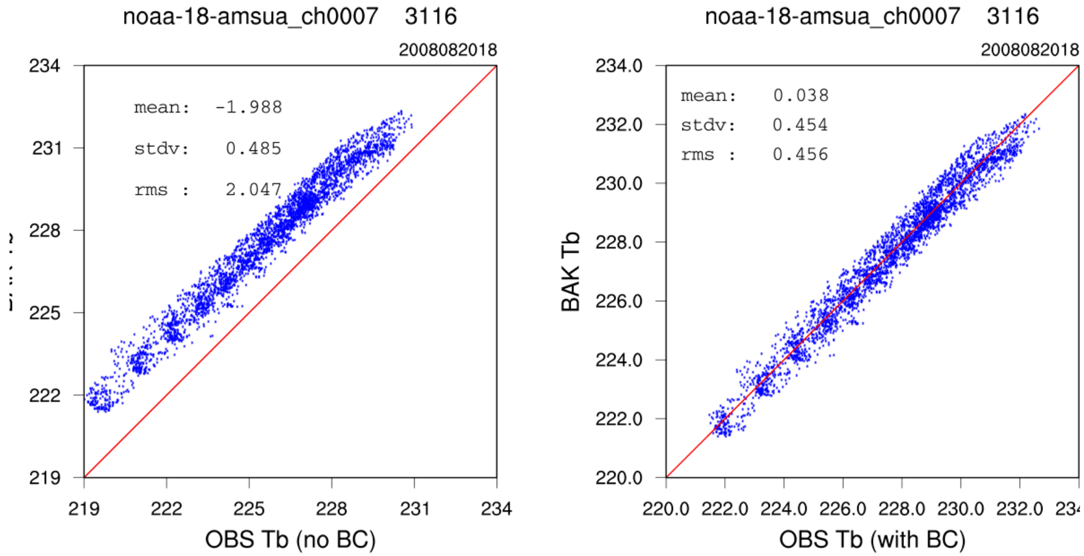
Quality control

monitoring and blacklisting



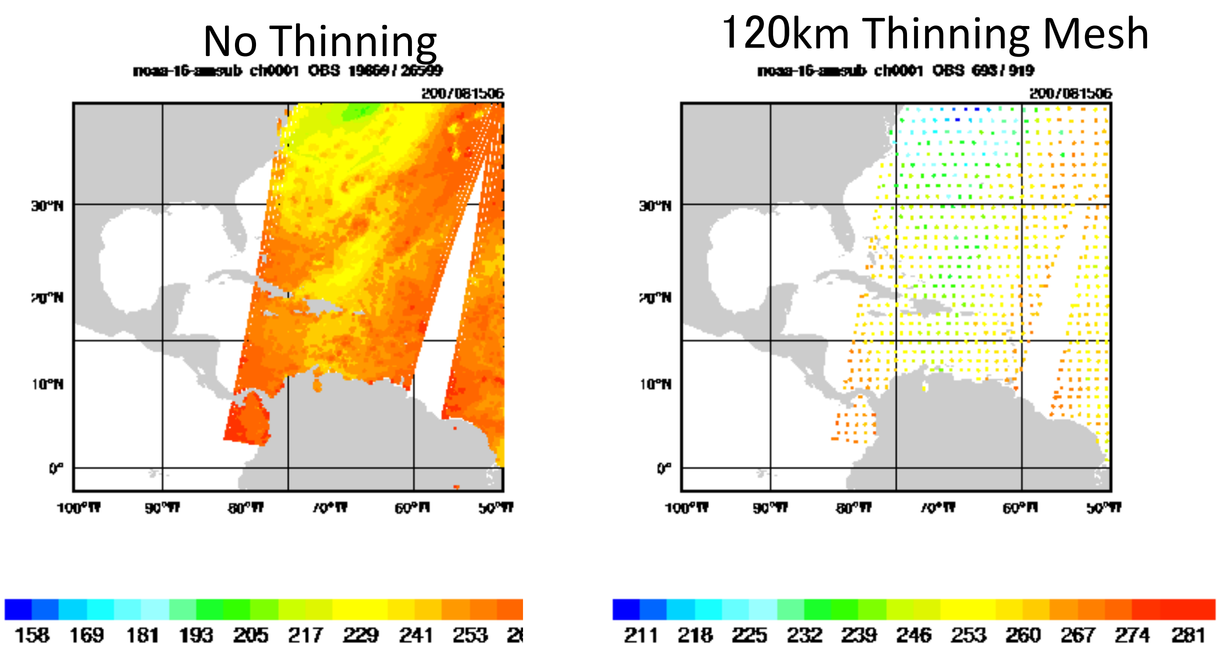
Global radiance monitoring against ERA-Interim

Bias Correction



Thinning

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



Variational Bias Correction (VarBC) in WRFDA

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 (β_i)

Predictors (p_i):

- **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 : $x^T \rightarrow [x, \beta]^T$

$$\mathbf{J}(\mathbf{x},\beta) = \underbrace{(\mathbf{x_b} - \mathbf{x})^{\mathbf{T}} \mathbf{B_x^{-1}} (\mathbf{x_b} - \mathbf{x})}_{J_b\text{: background term for x}} + \underbrace{[\mathbf{y} - H(\mathbf{x}) - B(\beta)]^{\mathbf{T}} \mathbf{R}^{-1} [\mathbf{y} - H(\mathbf{x}) - B(\beta)]}_{J_o\text{: corrected observation term}}$$
$$+ \underbrace{(\beta_\mathbf{b} - \beta)^{\mathbf{T}} \mathbf{B}_\beta^{-1} (\beta_\mathbf{b} - \beta)}_{J_p\text{: background term for } \beta}$$

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

Sensors that can be assimilated in WRFDA

- NCEP global BUFR format radiance data within a 6-h time window (27 sensors from 12 satellites)
  - 6 HIRS from NOAA-16/17/18/19, METOP-2/1
  - 7 AMSU-A from NOAA-15/16/18/19, EOS-2, METOP-2/1
  - 3 AMSU-B from NOAA-15/16/17
  - 4 MHS from NOAA-18/19, METOP-2/1
  - 1 AIRS from EOS-2
  - 2 IASI from METOP-2/1
  - 1 ATMS from NPP
  - 3 SEVIRI from Meteosat-8/9/10
- NRL/AFWA/NESDIS produced DMSP-16/17/18/19 SSMI/S BUFR radiance data
- FY-3 MWTS and MWHS, CMA binary format.

Data sources and ingest

NCEP near real-time ftp server with radiance BUFR data

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

NOAA archive: *http://nomads.ncdc.noaa.gov/data/gdas*

NCAR archive: *http://rda.ucar.edu/datasets/ds735.0*

NCEP naming convention	WRFDA naming convention
gdas1.thhz.1bamua.tm00.bufr_d	amsua.bufr
gdas1.thhz.1bamub.tm00.bufr_d	amsub.bufr
gdas1.thhz.1bhrs3.tm00.bufr_d	hirs3.bufr
gdas1.thhz.1bhrs4.tm00.bufr_d	hirs4.bufr
gdas1.thhz.1bmhs.tm00.bufr_d	mhs.bufr
gdas1.thhz.airsev.tm00.bufr_d	airs.bufr
gdas1.thhz.atms.tm00.bufr_d	atms.bufr
gdas1.thhz.mtiasi.tm00.bufr_d	iasi.bufr
gdas1.thhz.sevcsr.tm00.bufr_d	seviri.bufr

hh is the analysis time: 00/06/12/18

- ✓ Direct input to WRFDA, no pre-processing required.
- ✓ Quality control, thinning, time and domain check, bias correction are done inside WRFDA

Namelist switches (in wrfvar4 section) to decide if **reading** the data or not

Use_amsuaobs	Use_hirs3obs	Use_airsobs	Use_seviriobs
Use_eos_amsuaobs	Use_hirs4obs	Use_iasiobs	Use_ssmisobs
Use_amsubobs			
Use_mhsobs			
Use_atmsobs			

✧ NOTE: there are a couple typos in WRFDA/var/README.namelist

Choose Radiative Transfer Model

Controlled by the namelist variable: "**rtm_option**" (under wrfvar14)

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/

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

Latest available released version: CRTM REL-2.1.3,

Version included in WRFDA: CRTM REL-2.1.3

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)

http://research.metoffice.gov.uk/research/interproj/nwpsaf/rtm

Latest released version: RTTOV 11.2,

Version used in WRFDA: RTTOV 11, 11.1, 11.2

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  0.250000000E+01  0.000000000E+00
   203     2      1   -1    0  0.250000000E+01  0.000000000E+00
   203     3      1    1    0  0.250000000E+01  0.100000000E+01
   203     4      1    1    0  0.200000000E+01  0.100000000E+01
   203     5      1    1    0  0.200000000E+01  0.000000000E+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 (link radiance bufr files)
ln –sf WRFDA/var/run/radiance_info ./radiance_info (radiance_info is a directory)
ln –sf WRFDA/var/run/VARBC.in ./VARBC.in

(CRTM only) > ln -sf WRFDA/var/run/crtm_coeffs ./crtm_coeffs #(crtm_coeffs is a directory)
this step is not needed if setting **crtm_coef_path='/your_full_path_where_crtm_coeffs_reside'**
(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 to assimilate and which CRTM/RTTOV coefficient files to load

Sample namelist settings for instruments onboard various satellites:

```
&wrfvar14
  RTMINIT_NSENSOR   = 14
  RTMINIT_PLATFORM = 12, 1, 1, 1, 9,10, 1, 1,17, 1, 1, 10, 9, 2
  RTMINIT_SATID     =  3,16,18,19, 2, 2,15,16, 0,18, 19, 2, 2,16
  RTMINIT_SENSOR    = 21, 3, 3, 3, 3, 3, 4, 4,19,15, 15,15,11,10
```

- MSG-3-SEVIRI (12, 3, 21)
- 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
- JPSS-0-ATMS (17, 0, 19)
- 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 have different naming convention for referring sensors

CRTM	RTTOV
seviri_m10.SpcCoeff.bin	rtcoef_msg_3_seviri.dat
amsua_n19.SpcCoeff.bin	rtcoef_noaa_19_amsua.dat

WRFDA is designed to use specified "instrument triplets" to retrieve proper names internally for the rtm_option selected

RTTOV Users Guide
http://nwpsaf.eu/deliverables/rtm/docs_rttov11/users_guide_11_v1.3.pdf
Table 2 and Table 3

Instrument triplets **platform_id**
satellite_id
sensor_id

platform	platform_id	satellite_id
NOAA	1	15, 16, 17, 18 ,19
METOP	10	1, 2
EOS	9	2
JPSS	17	0
MSG	12	1, 2, 3
DMSP	2	16, 17, 18, 19
FY3	23	1, 2

```
metop-2 = metop-a
metop-1 = metop-b
jpss-0  = npp
msg-2   = meteosat-9
msg-3   = meteosat-10
```

sensor	sensor_id
HIRS	0
AMSU-A	3
AMSU-B	4
SSMIS	10
AIRS	11
MHS	15
IASI	16
ATMS	19
SEVIRI	21
FY3 MWTS	40
FY3 MWHS	41

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, controls if performing quality control, always set to TRUE.

WRITE_IV_RAD_ASCII: Logical, controls writing of Observation minus Background files, which are ASCII format and separated by sensors and processors.

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

ONLY_SEA_RAD: Logical, controls 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 changed 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

```
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
```

Cold starting from an empty parameter file for the first cycle

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

Sample VARBC.out (output from WRFDA, 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
```

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

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

Diagnostics

rsl.out.0000

```
Reading radiance 1b data from amsua.bufr
 Bufr file date is         2015           7           9          12
 amsua
num_tovs_file num_tovs_global num_tovs_local num_tovs_used num_tovs_thinned
    269588      3528       152         58        94
Allocating space for radiance innov structure  3  noaa-19-amsua  58
Observation summary
   ob time  1
      sound                102 global,       0 local
      synop                939 global,       0 local
      pilot                 90 global,       0 local
      satem                 36 global,       4 local
      geoamv             30171 global,     708 local
      airep              20533 global,       0 local
      gpspw                446 global,       0 local
      gpsrf               1673 global,       0 local
      metar               2809 global,       0 local
      ships                156 global,       0 local
      profiler              21 global,       0 local
      buoy                 529 global,       0 local
      radiance            3528 global,      58 local
      sonde_sfc            102 global,       0 local

VARBC: Applying bias correction for noaa-15-amsua
VARBC: Applying bias correction for noaa-18-amsua
VARBC: Applying bias correction for noaa-19-amsua
VARBC: Applying bias correction for metop-2-amsua
VARBC: Estimate Hessian for preconditioning
VARBC:     0 active observations for noaa-15-amsua channel    6
VARBC:     0 active observations for noaa-15-amsua channel    7
VARBC:     0 active observations for noaa-15-amsua channel    8
VARBC:     0 active observations for noaa-18-amsua channel    6
VARBC:     0 active observations for noaa-18-amsua channel    7
VARBC:     0 active observations for noaa-18-amsua channel    8
VARBC:  1074 active observations for noaa-19-amsua channel    6
VARBC:  1019 active observations for noaa-19-amsua channel    7
VARBC:     0 active observations for metop-2-amsua channel    6
VARBC:     0 active observations for metop-2-amsua channel    8
```

```
Diagnostics
   Final cost function J        =     40665.61

   Total number of obs.         =   162763
   Final value of J             =     40665.60731
   Final value of Jo            =     33961.58347
   Final value of Jb            =      2805.68023
   Final value of Jc            =         0.00000
   Final value of Je            =      3897.27532
   Final value of Jp            =         1.06829
   Final value of Jl            =         0.00000
   Final J / total num_obs      =         0.24985
   Jb factor used(1)            =         1.00000
   Jb factor used(2)            =         1.00000
   Jb factor used(3)            =         1.00000
   Jb factor used(4)            =         1.00000
   Jb factor used(5)            =         1.00000
   Jb factor used               =         2.00000
   Je factor used               =         2.00000
   VarBC factor used            =         1.00000

   Total number of radiances    =     2093
   Cost function for radiances  =       782.70972

Writing radiance OMA ascii file

VARBC: Updating bias parameters
VARBC: Writing information in VARBC.out file
*** WRF-Var completed successfully ***
```

Diagnostics

01_qcstat_noaa-19-amsua

```
Quality Control Statistics for noaa-19-amsua

 num_proc_domain  =    1528
 nrej_mixsurface  =      41
 nrej_windowchanl =     695
 nrej_si          =      22
 nrej_clw         =      40
 nrej_topo        =     184
 nrej_limb        =     376
 nrej_omb_abs(:)  =
    245    386     37      0      0      0      0      0      0      0
      0      0     11      0    135
 nrej_omb_std(:)  =
    148    301     37    607    542      3    129    476    535    653
    614    403     12      0     17
 nrej(:)          =
   1528   1528   1528   1528   1528    454    509   1528   1528   1528
   1528   1528   1528   1528   1528
 ngood(:)         =
      0      0      0      0      0   1074   1019      0      0      0
      0      0      0      0      0
```

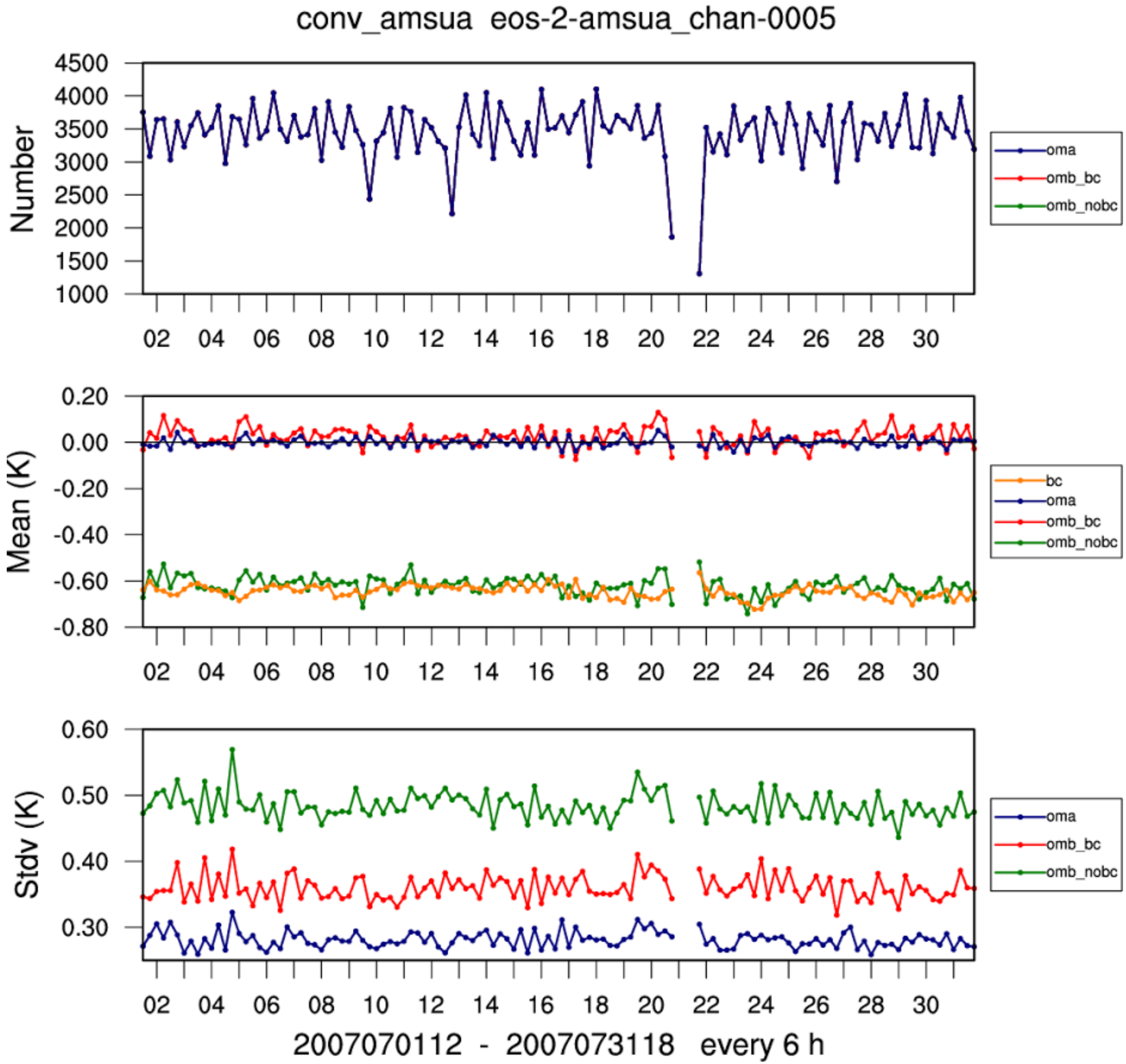
Diagnostics

statistics

```
Diagnostics of OI for radiance         noaa-19-amsua

 used_nchan:     2
 Channel  num   ave   rms   min   max
  6   1074    0.13    0.26   -0.72    0.72
  7   1019    0.08    0.37   -0.81    0.81

 Diagnostics of AO for radiance         noaa-19-amsua

 used_nchan:     2
 Channel  num   ave   rms   min   max
  6   1074    0.02    0.15   -0.49    0.42
  7   1019    0.00    0.29   -0.77    0.79
```

Radiance output Post-Processing/Visualization

- `WRFDA/var/scripts/da_rad_diags.ksh` (included in the TOOLS bundle that can be downloaded from *http://www2.mmm.ucar.edu/wrf/users/wrfda/download/tools.html*
  - WRFDA outputs radiance 01_inv* or 01_oma* ASCII files separated for different sensors and CPUs.
  - the script converts ASCII files to one NETCDF file for each sensor (by executing a Fortran90 program), then generates graphics from *.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 WRFDA runs
    - Users can control (by simple script parameter setup) to plot over smaller domain, only over land or sea, QCed or no-QCed observations.



conv_amsua eos-2-amsua_chan-0005
Number
4500
4000
3500
3000
2500
2000
1500
1000
oma
omb_bc
omb_nobc
Mean (K)
0.20
0.00
-0.20
-0.40
-0.60
-0.80
bc
oma
omb_bc
omb_nobc
Stdv (K)
0.60
0.50
0.40
0.30
oma
omb_bc
omb_nobc
02 04 06 08 10 12 14 16 18 20 22 24 26 28 30
2007070112 - 2007073118 every 6 h

Conclusions

- **Radiance data assimilation is 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