Radiance Data Assimilation in WRFDA

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WRFDA tutorial
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- Introduction to radiance data assimilation
  - Principles of satellite measurements
  - Introduction to Radiative Transfer theory
  - Elements of Radiance DA

- Practical aspects with WRFDA

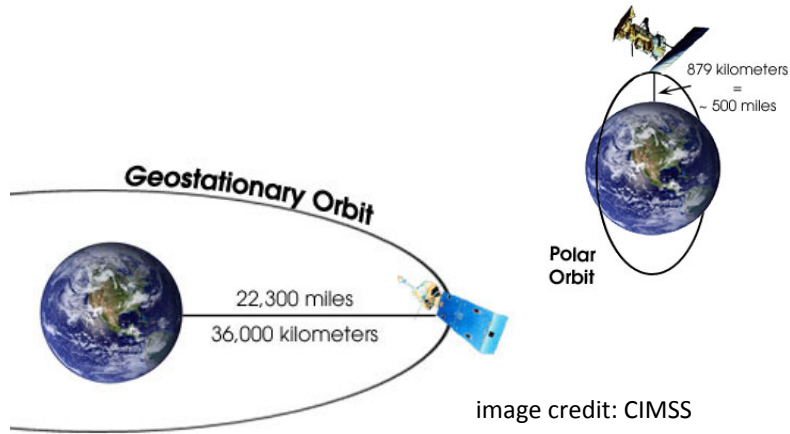# Part I: Introduction to radiance data assimilation

Environment monitoring satellites

Image credit: WMO Space Programme
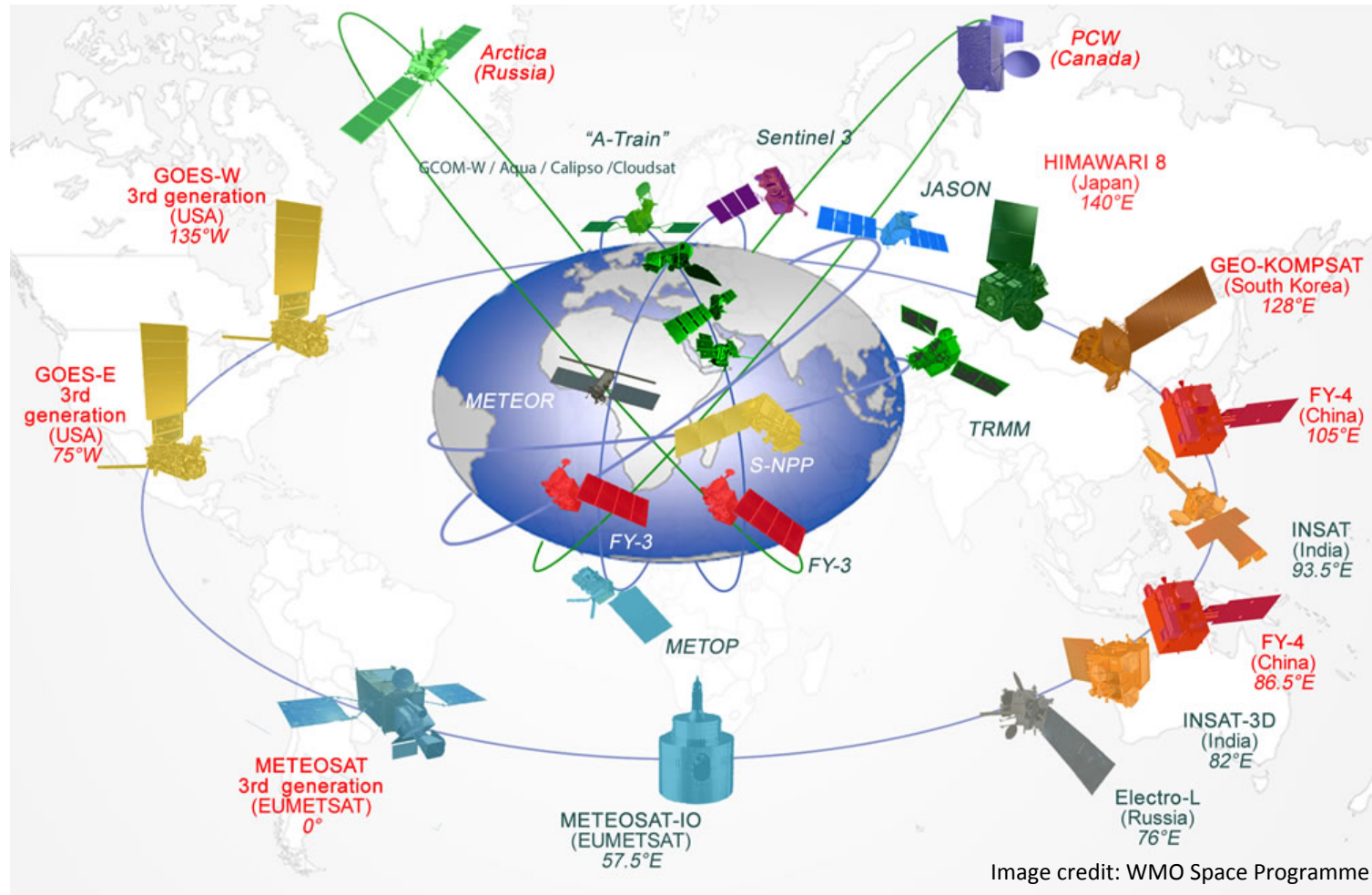
Valuable information from satellite measurements
- images
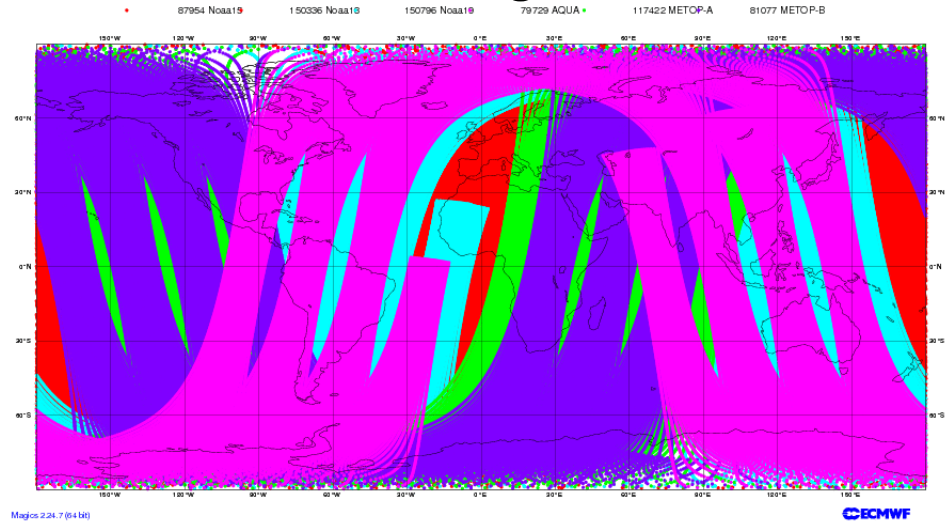- retrieved/derived products
- radiances

Types of satellites

image credit: CIMSS

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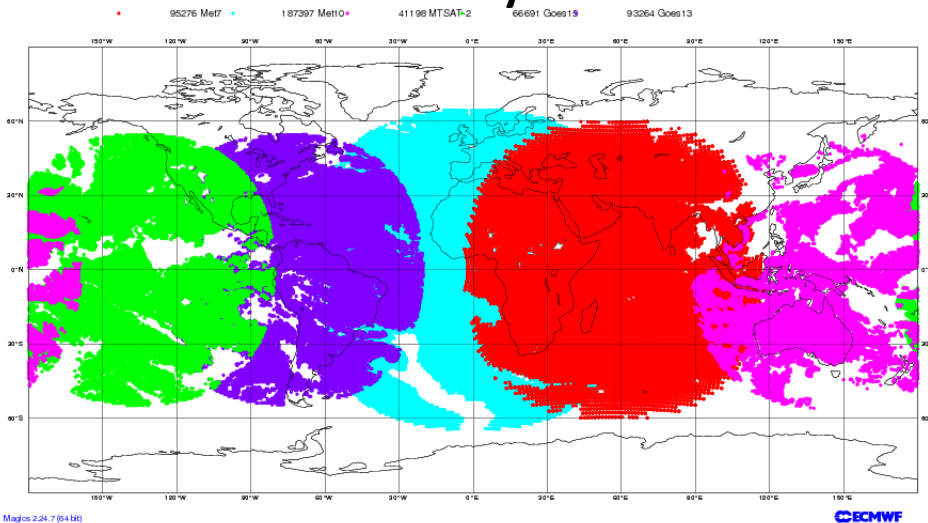05/Jul/2015; 06 UTC
Total number of obs = 667314
Polar-orbiting satellites

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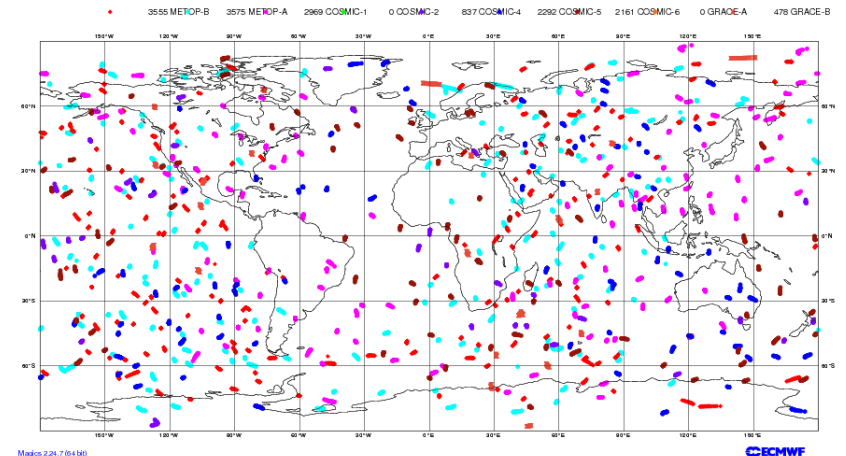05/Jul/2015; 06 UTC
Total number of obs = 483826
Geostationary satellites

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

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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

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

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

AMSU Scanning Geometry and Resolution

150km   Resolution ~ 50km   150km

FOV 1   FOV 30

CIMSS

Flight direction

GMI

407 km altitude,
65 deg inclination

DPR

Range resolution
= 250m and 500m

KuPR
Swath: 245 km

KaPR
Swath: 120 km

GMI
Swath: 800km

5km
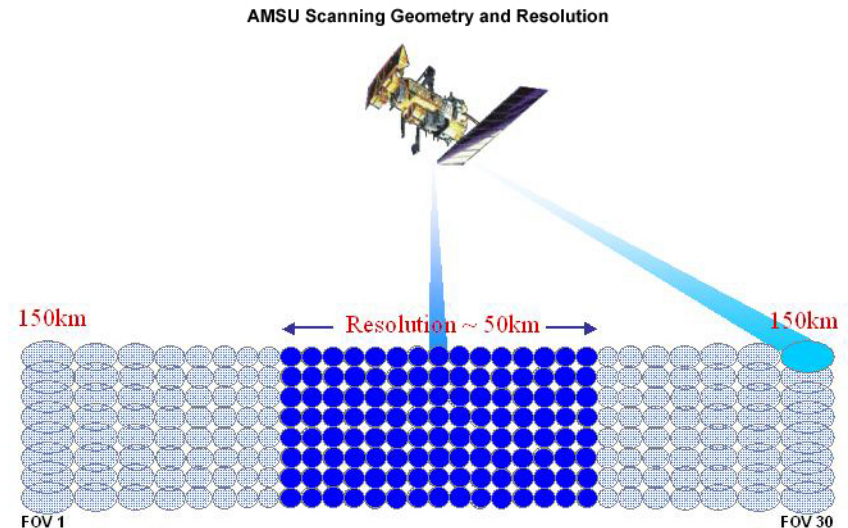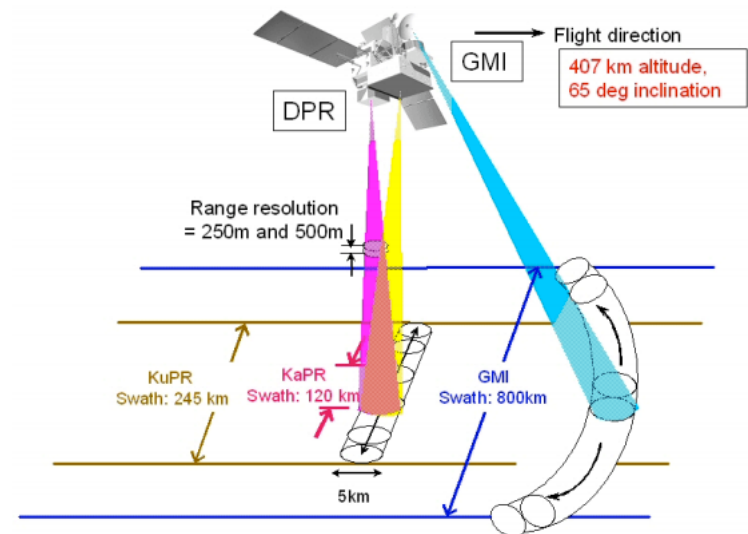
Figure 2. GPM swath measurements
image credit: NASA

What do satellite instruments measure?
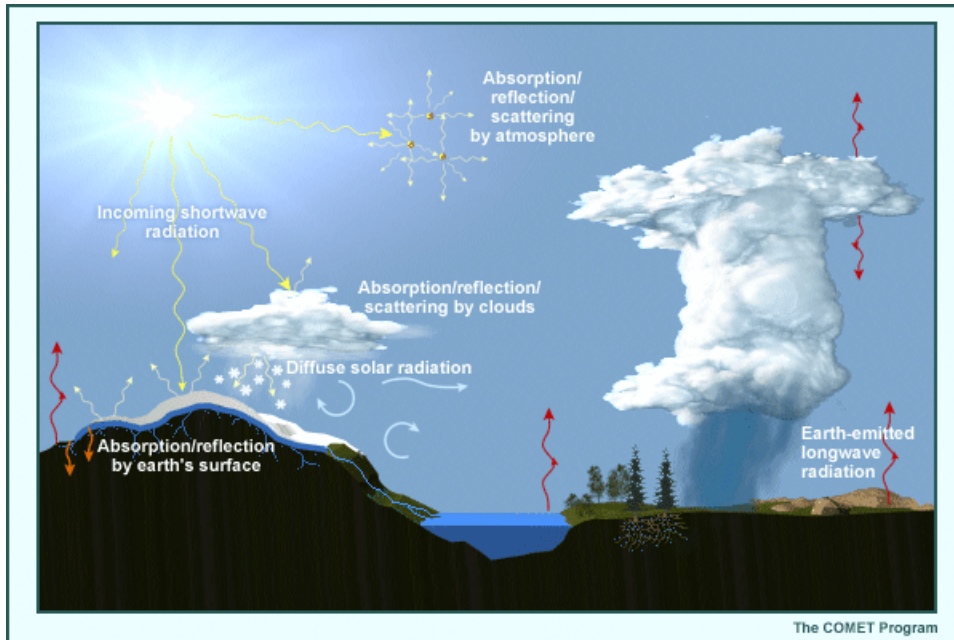
Satellite passive sensors

- 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 "**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

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

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)
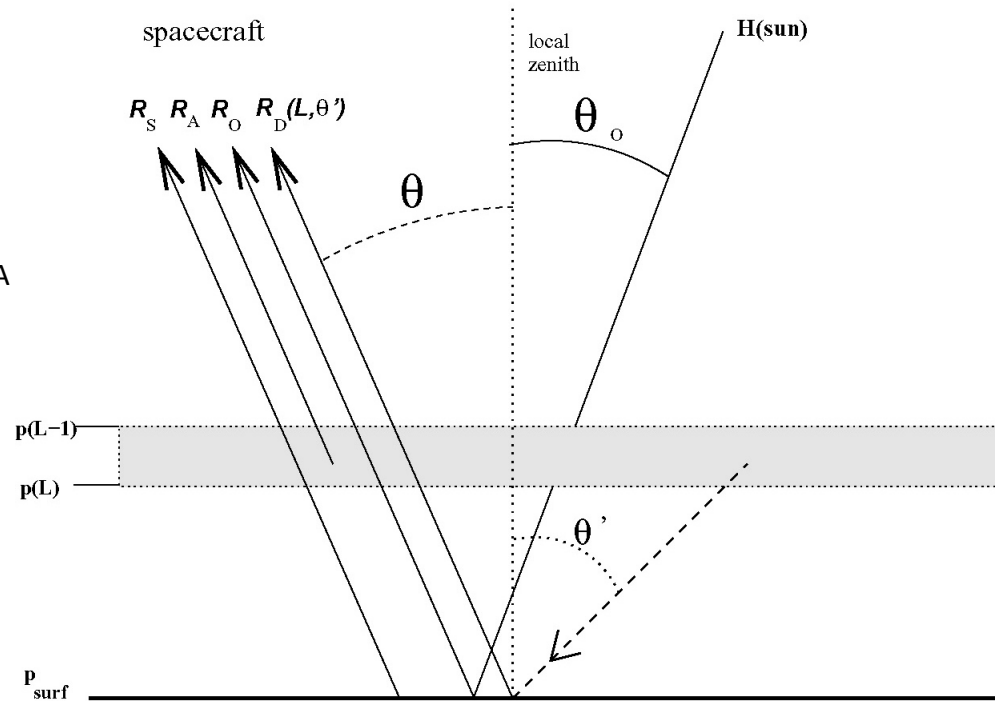
Passive Sensors from Weather/Environment Satellites

AMSU-A
AMSU-B
MHS
SSMI
SSMIS
ATMS
TMI
AMSR-E
AMSR-2
GMI

GOES Imager
AHI
ABI

HIRS
AIRS
IASI
CrIS

AVHRR
MODIS
VIIRS

SBUV

Radiation Type	Radio	Microwave	Infrared	Visible	Ultraviolet	X-ray	Gamma ray
Wavelength (m)	10^3	10^{-2}	10^{-5}	0.5×10^{-6}	10^{-8}	10^{-10}	10^{-12}

Approximate Scale of Wavelength

Buildings   Humans   Butterflies   Needle Point   Protozoans   Molecules   Atoms   Atomic Nuclei

Frequency (Hz)	10^4	10^8	10^{12}	10^{15}	10^{16}	10^{18}	10^{20}

Electromagnetic Spectrum

Atmospheric gas absorption-transmission

Radiation Transmitted by the Atmosphere

Atmospheric Opacity in the Microwave Spectrum
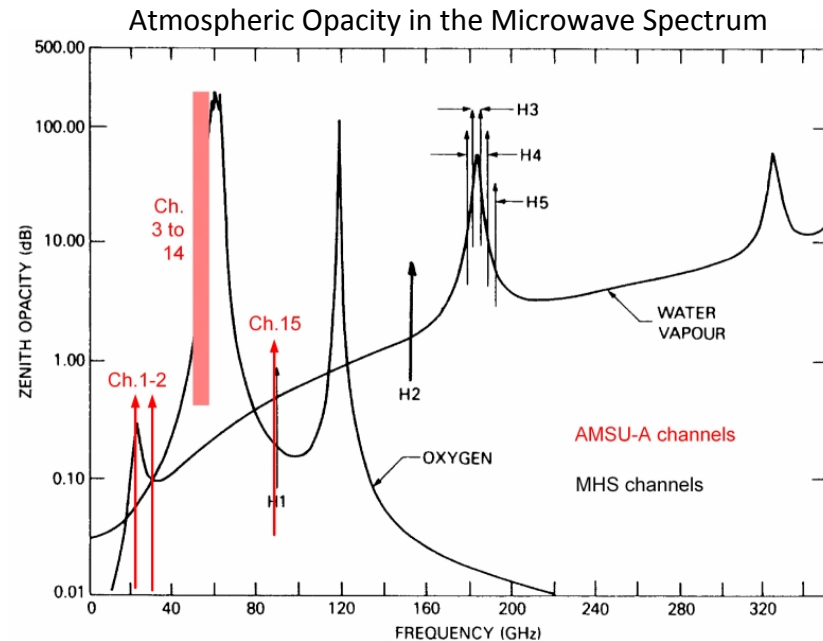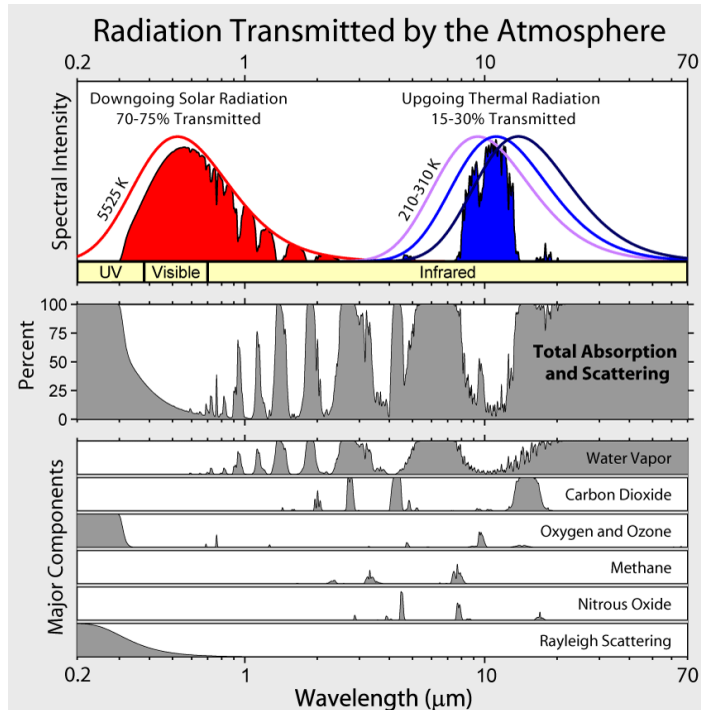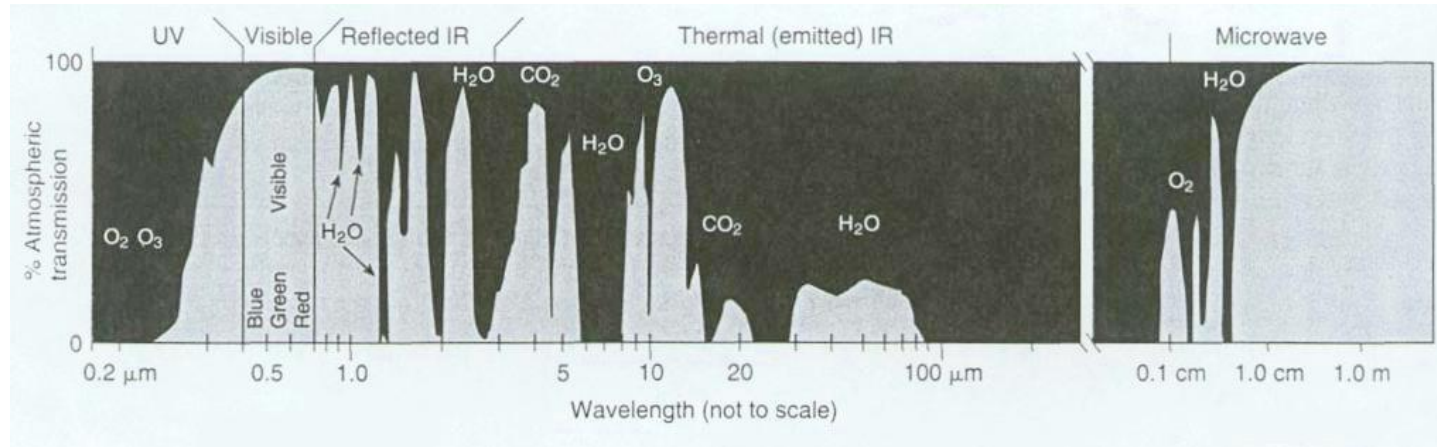
Satellite sensors are designed to make use of the frequency-dependent atmospheric absorption

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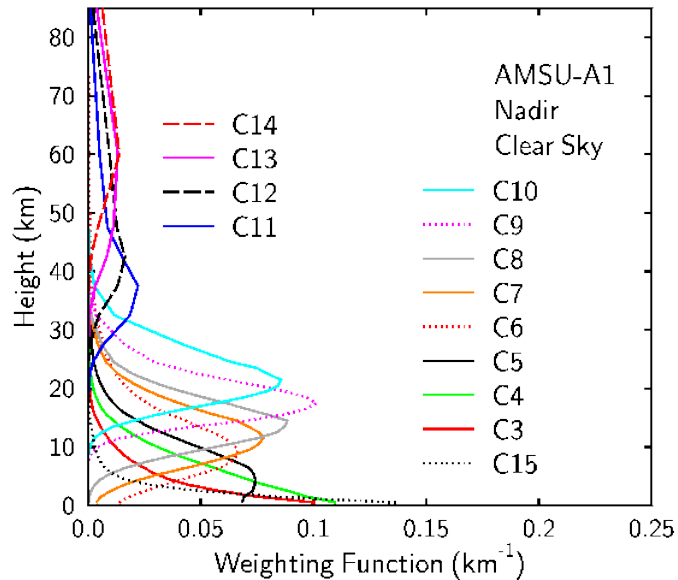
Weighting functions indicate the contribution to the outgoing radiance from various layers of the atmosphere

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

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

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

CRTM, RTTOV, …

T, Q, O3, …   Forward model   L(v)

RT

Inversion

Regression, neural network, 1D-Var

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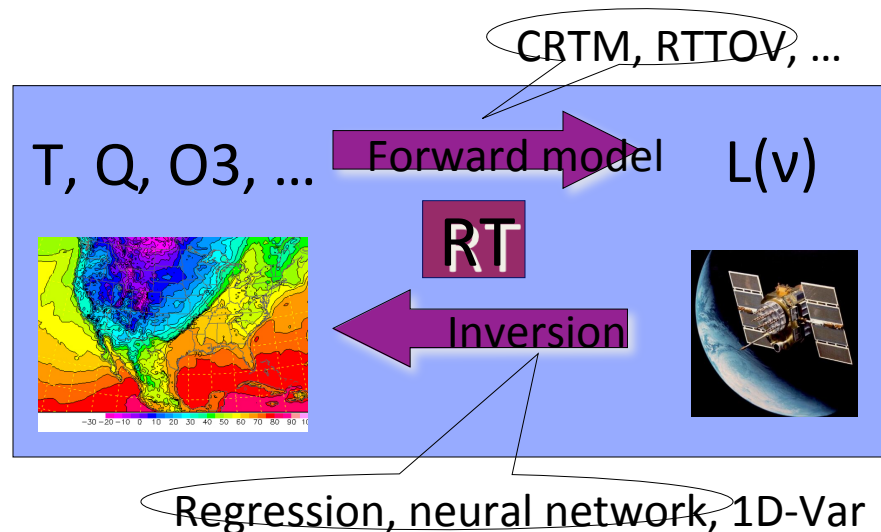
Part II: Practical implementation with WRFDA

- WRFDA applications

- Practical aspects

  o Data ingest (sources, instruments)

  o Radiative transfer model

  o Channel selection and observation errors

  o Variational bias correction

  o Diagnostics and monitoring

Assimilation and Verification Domain
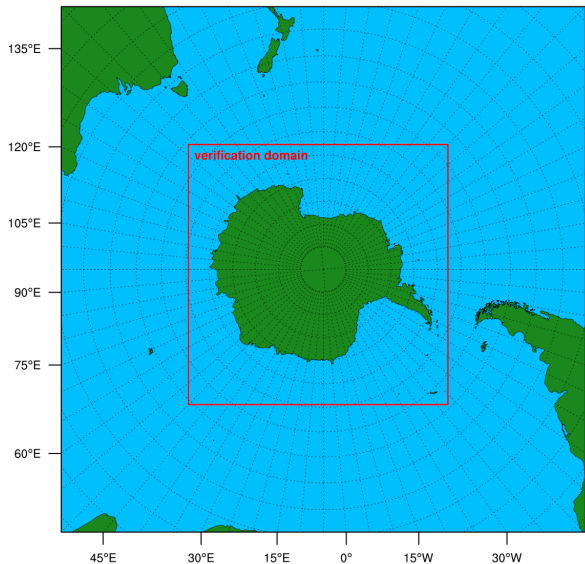
- WRF/WRFDA V3.6+ (V3.6 with modifications and fixes)
- 1-hPa model top, 71 levels, 60-km resolution
- low/lateral boundary conditions from ERA-interim
- Snow from NCEP FNL
- 6-hour cycling starting from 2007070100
- 240-second time step, 180-sec for a couple dates that exceeded CFL criteria
- WSM 5-class 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

RMSE 2007070112-2007071506 (FC06h every 06h)

RMSE Profiles 2007070112-2007071500 (FC06h every 12h)
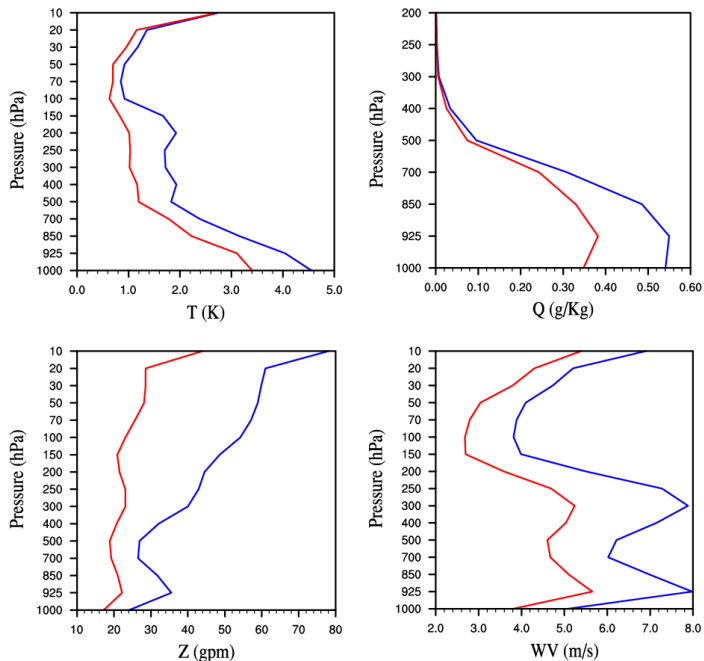
verification against ERA-interim analysis
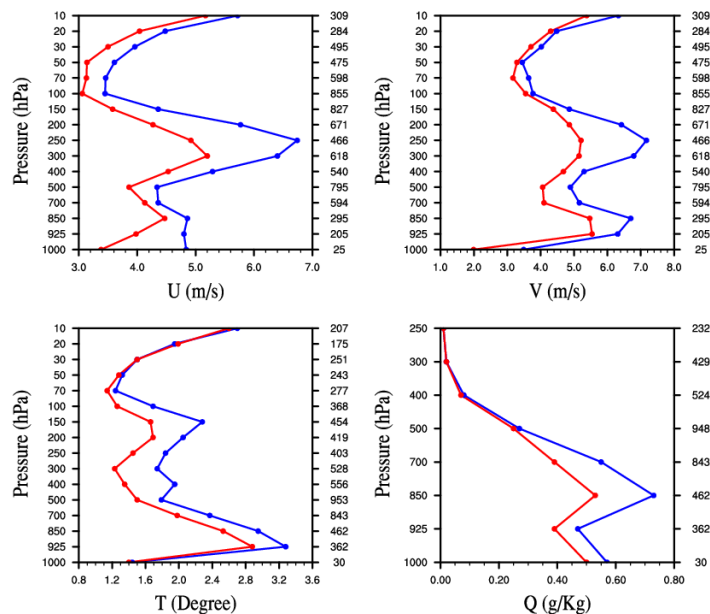
verification against SOUNDs

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Quality control

- **Specific QC for each sensor**
  AMSU-A, AMSU-B, MHS, SSMIS, AIRS, AMSR2…

- **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 < $3\sigma_o$).

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

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

NOAA-15 AMSU-A
ch. 4 OmB after QC

CLWP(mm)
from Guess
<0.2mm
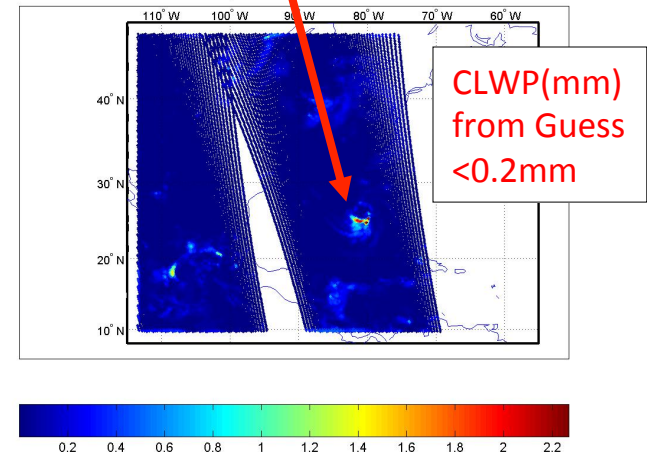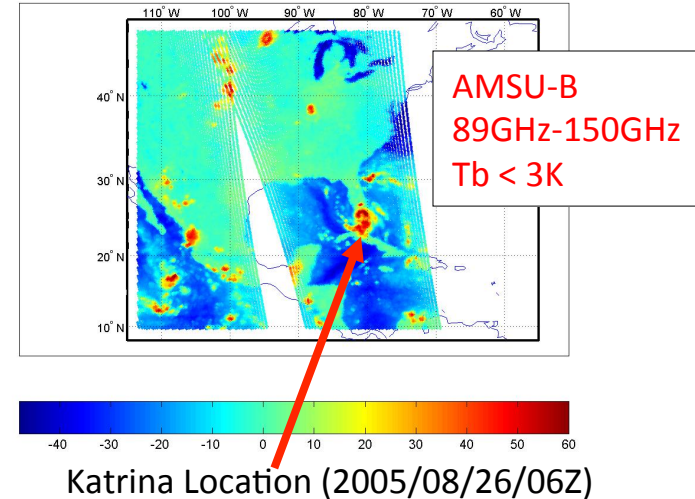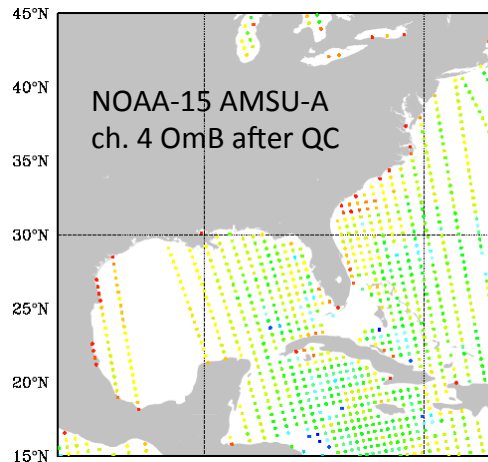
Quality control monitoring and blacklisting

Global radiance monitoring against ERA-Interim

Bias Correction

noaa-18-amsua_ch0007   3116   2008082018

mean: -1.988
stdv: 0.485
rms :   2.047

OBS Tb (no BC)

noaa-18-amsua_ch0007   3116   2008082018

mean: 0.038
stdv: 0.454
rms :   0.456

BAK Tb

OBS Tb (with BC)
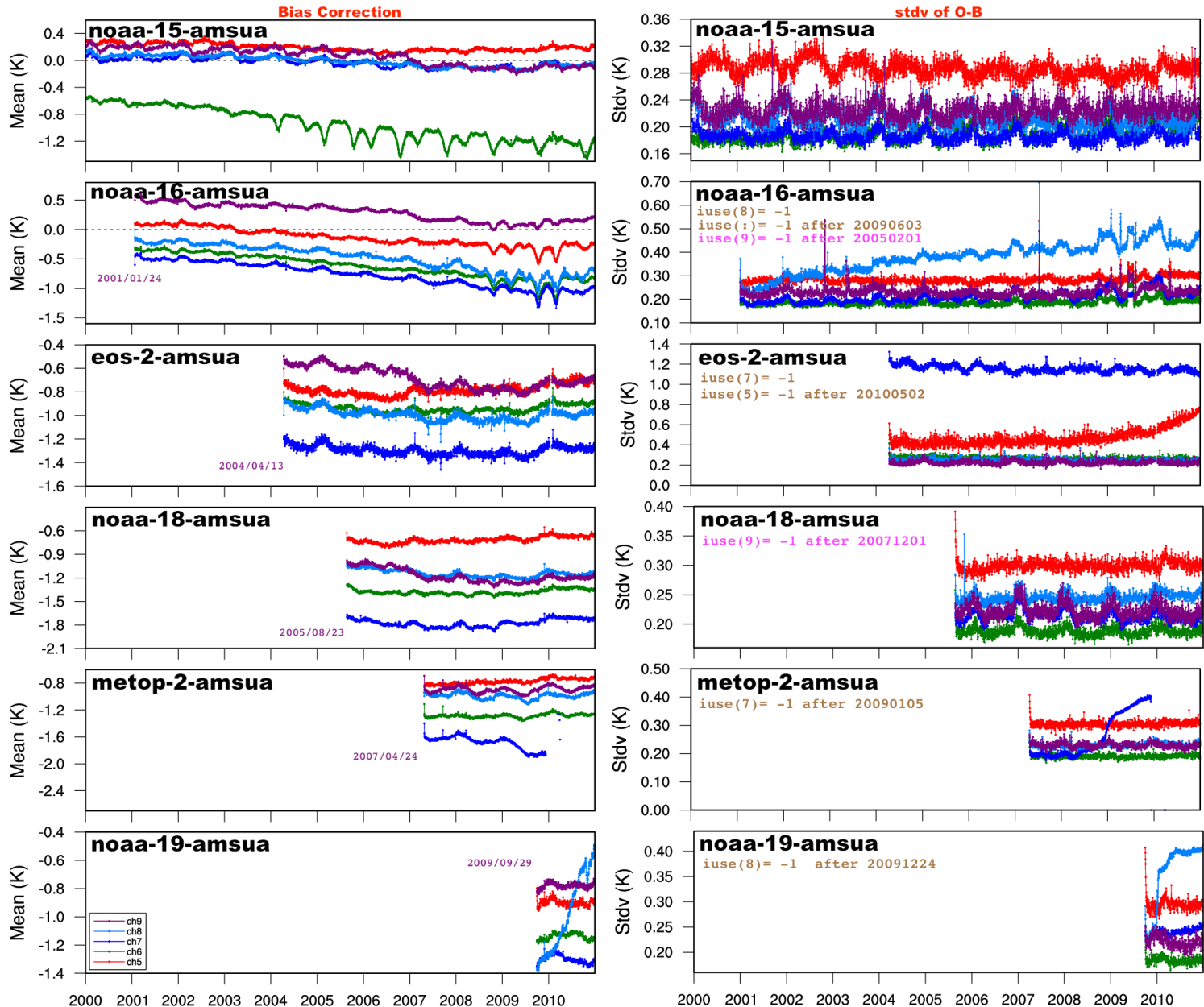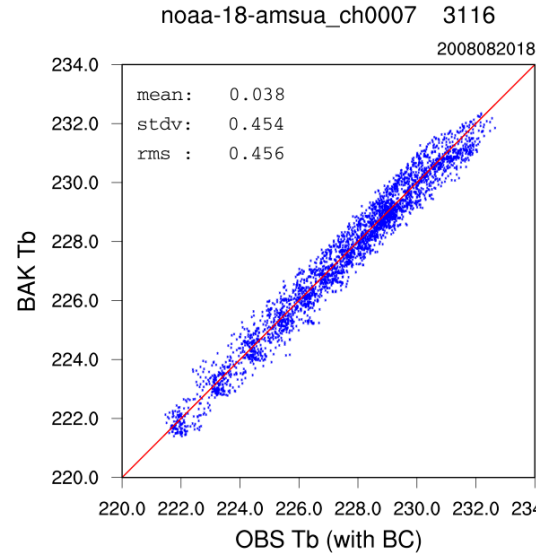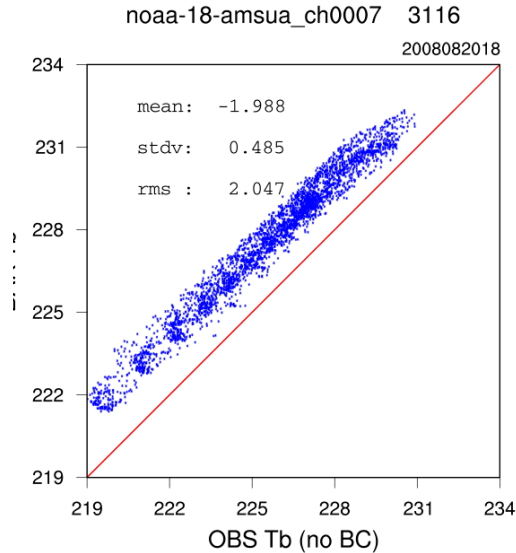
Thinning

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

No Thinning

noaa-16-amsub ch0001 OBS 19669/26599   200/081506

120km Thinning Mesh

noaa-16-amsub ch0001 OBS 693/919   200/081506

158 169 181 193 205 217 229 241 253

211 218 225 232 239 246 253 260 267 274 281
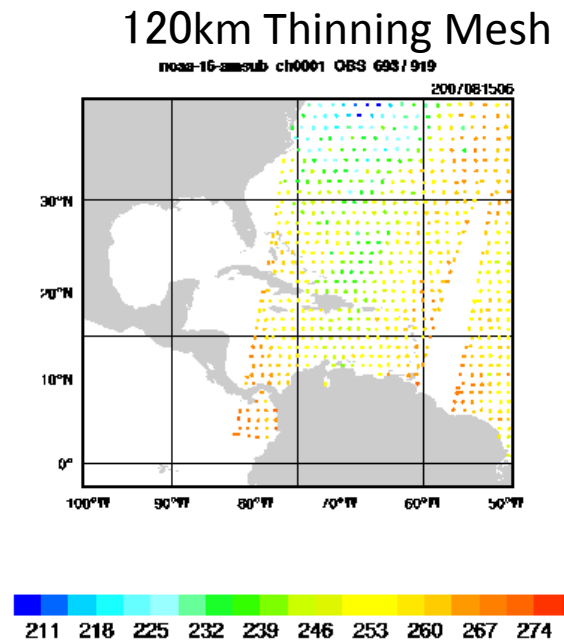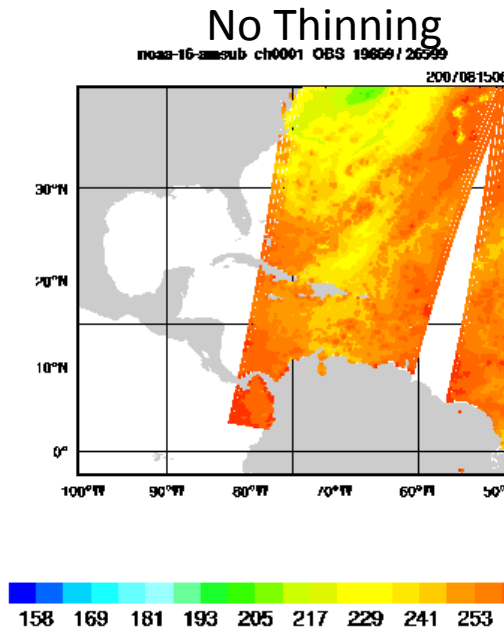
Variational Bias Correction (VarBC) in WRFDA

Modeling of errors in satellite radiances:

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

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

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 : x^T ➡ $[x, \beta]^T$

J_b: background term for x J_o: corrected observation term

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

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.

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`
- JAXA `GCOM-W1 AMSR-2` radiance data in HDF5 format
- 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 CISL archive: *http://rda.ucar.edu/datasets/ds735.0*

NCAR CISL archive: *http://rda.ucar.edu/datasets/ds099.0*

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

JAXA AMSR2 radiance HDF5 data

http://suzaku.eorc.jaxa.jp/GCOM_W/data/data_w_index.html

JAXA naming convention	WRFDA naming convention
GW1AM2_201210271433_082A_L1SGRTBR_1110110.h5	L1SGRTBR-01.h5

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

Data sources and ingest

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_amsubobs
use_mhsobs
use_atmsobs
use_amsr2obs

Choose Radiative Transfer Model

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

2 = CRTM (Community Radiative Transfer Model)

    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 (CRTM REL-2.2.3 is available)

    Version included in WRFDA: CRTM REL-2.1.3

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

1 = RTTOV (Radiative Transfer for TOVS)

    EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites)

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

    Latest released version: RTTOV 11.3,

    Version used in WRFDA: RTTOV 11, 11.1, 11.2, 11.3

Channel selection and error specification

```
WRFDA/var/run/radiance_info>ls -l
total 160
-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      391 Aug 22 17:01 noaa-16-amsub.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
```

gcom-w-1-amsr2.info

clear-sky obs error

```
478    5   1    1    0   0.8660000000E+00   0.0000000000E+00   21.93555
478    6   1    1    0   1.1290000000E+00   1.0000000000E+00   40.92418
478    7   1    1    0   1.2270000000E+00   0.0000000000E+00   28.30175
478    8   1    1    0   1.7470000000E+00   1.0000000000E+00   57.58830
478    9   1    1    0   1.6000000000E+00   0.0000000000E+00   12.69287
478   10   1    1    0   2.6790000000E+00   1.0000000000E+00   27.33099
478   11   1    1    0   1.1790000000E+00   0.0000000000E+00   23.24269
478   12   1    1    0   2.2680000000E+00   1.0000000000E+00   53.35099
478   13   1   -1    0   2.1310000000E+00   0.0000000000E+00   36.07700
478   14   1   -1    0   4.0750000000E+00   1.0000000000E+00   33.61592
```

-1: not used; 1: used

cloudy obs error (AMSR2 only)

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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)
GCOM-W1-AMSR2   (29, 1, 63)

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_v1.4.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
GCOM-W	29	1

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
AMSR2	63

```
metop-2 = metop-a
metop-1 = metop-b
jpss-0  = npp
msg-1   = meteosat-8
msg-2   = meteosat-9
msg-3   = meteosat-10
```

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, 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

Cold starting from an empty parameter 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
```

**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)**

Radiance namelist (cloudy radiance related)

`&wrfvar14`
    `crtm_cloud=true`
        to include the cloud effect in the CRTM calculation

`&wrfvar7`
    `cloud_cv_options=1`
        to get **cloud water** and **rainwater** analysis increments through
        the total water control variable modeling via a warm-rain scheme

Other cloud_cv_options (with additional cloud variables included) requires WRFDA to be compiled differently. The implementation is still preliminary and ad hoc.

For now, proper quality control procedures and observation error assignments for cloudy radiance are only implemented for AMSR2 instrument. The capability is available in a WRFDA beta release.
http://www2.mmm.ucar.edu/wrf/users/wrfda/beta.html

✓ http://www2.mmm.ucar.edu/wrf/users/wrfda/Docs/
WRFDA_hydrometeors_and_cloudy_radiance.pdf

Diagnostics

```
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
```

rsl.out.0000

```
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
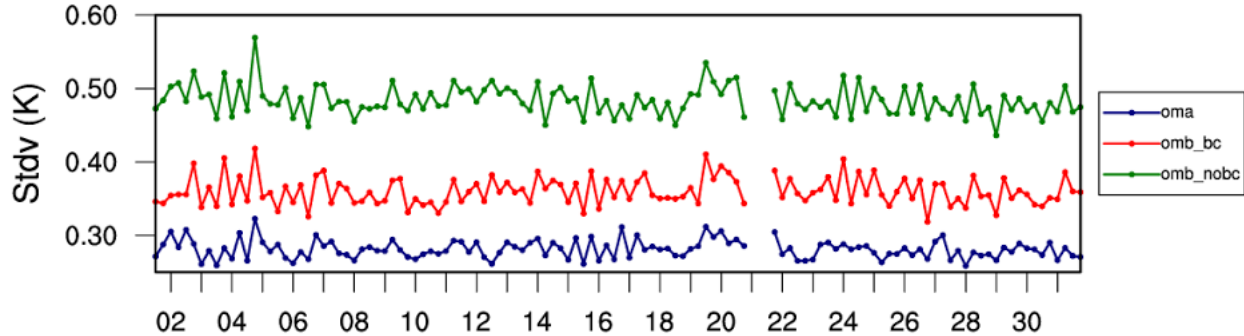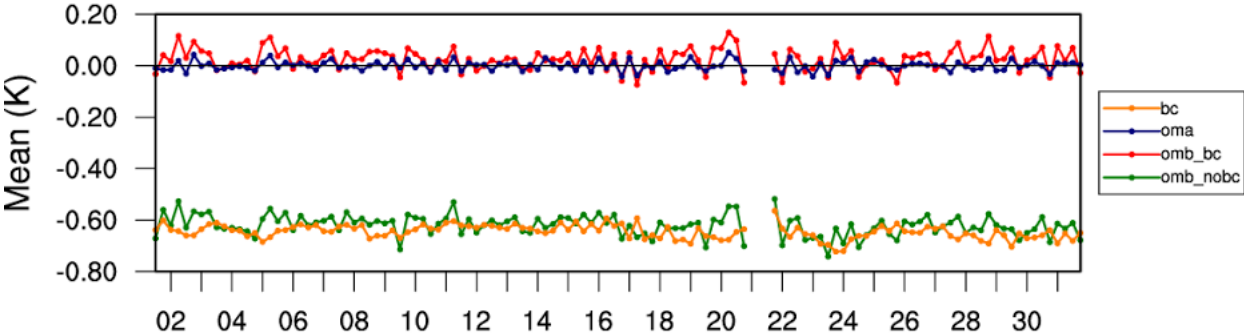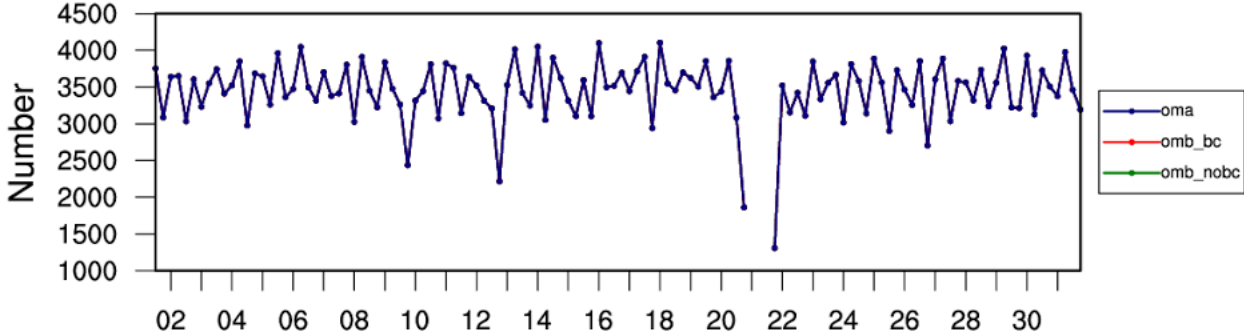
2007070112 - 2007073118 every 6 h

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