Radiance Data Assimilation in WRFDA

Craig Schwartz, Jamie Bresch
Zhiquan Liu, Tom Auligné

WRFDA tutorial
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WRFDA can assimilate …

- **<u>In-Situ conventional observations</u>**:
  - Surface (SYNOP, METAR, SHIP, BUOY)
  - Upper air (TEMP, PIBAL, AIREP, ACARS, AMDAR, TAMDAR)

- **<u>Remotely sensed observations</u>**:
  - Atmospheric Motion Vectors (geo/polar) (SATOB)
  - SATEM thickness
  - Ground-based GPS Total Precipitable Water/Zenith Total Delay (GPSPW/GPSZTD)
  - SSM/I oceanic surface wind speed and TPW
  - Scatterometer oceanic surface winds (QSCAT)
  - Wind profiler (PROFL)
  - Radar radial velocities and reflectivity
  - Satellite temperature/humidity/thickness profiles (AIRSR)
  - GPS refractivity (GPSRF/GPSEP)
  - Stage IV precipitation data/rain rate (only in 4DVAR mode)

QuikSCAT/SeaWinds – **ended in Nov 2009**
ASCAT (METOP-A)
ASCAT (METOP-B)
ASCAT (EARS)
OSCAT (Oceansat-2) –**ceased in April 2014**
WindSAT

- **<u>Radiances</u>** (using RTTOV or CRTM):

HIRS	NOAA-16, NOAA-17, NOAA-18, NOAA-19, METOP-A, METOP-B
AMSU-A	NOAA-15, NOAA-16, NOAA-18, NOAA-19, EOS-Aqua, METOP-A, METOP-B
AMSU-B	NOAA-15, NOAA-16, NOAA-17
MHS	NOAA-18, NOAA-19, METOP-A, METOP-B
AIRS	EOS-Aqua
SSMIS	DMSP-16, DMSP-17, DMSP-18
IASI	METOP-A, METOP-B
ATMS	Suomi-NPP
MWTS	FY-3
MWHS	FY-3
SEVIRI	METEOSAT-8, METEOSAT-9, METEOSAT-10
AMSR-2	GCOM-W1

- 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

Global Analysis Systems

- Assimilation of satellite observations is a key component of analysis systems at nearly every operational center
    - Satellites provide observational data in regions where few conventional observations are available
        - Marine areas
        - Deserts
        - Other unpopulated regions
- Greatest forecast benefit from radiance data assimilation is seen in the 3-7 day range in <u>global</u> computer models
    - Benefits from radiance data assimilation in regional models also possible, but as we'll see, trickier.

Environment monitoring satellites

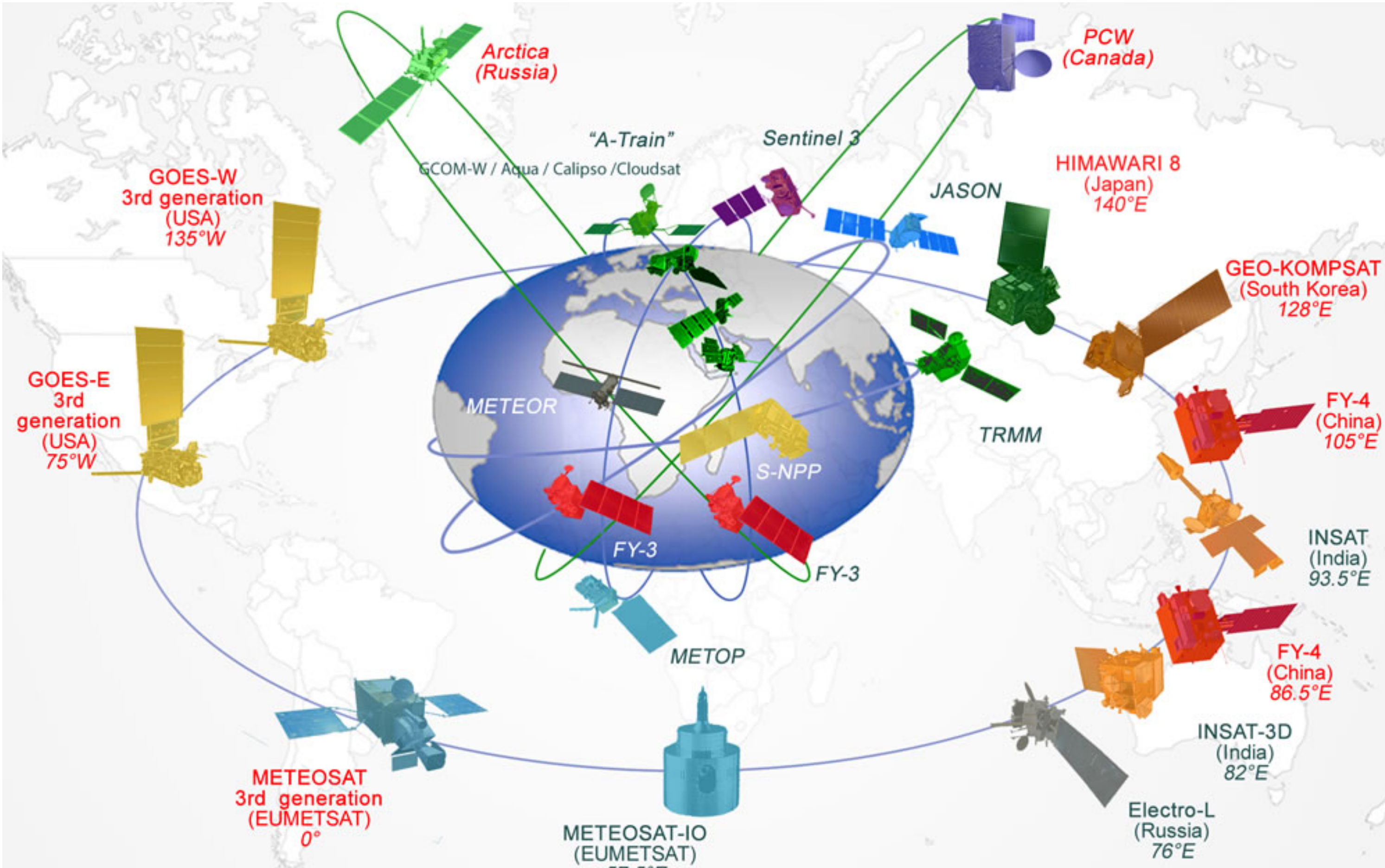


Image credit: WMO Space Programme

Valuable information from satellite measurements:

- images
- retrieved/derived products
- radiances

Types of satellites

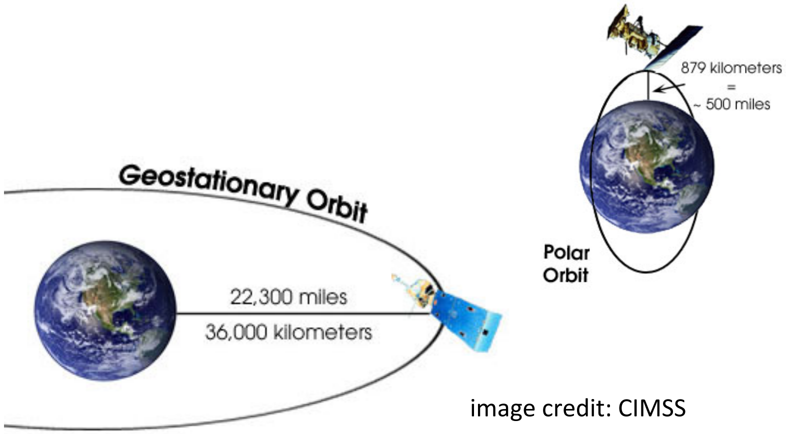
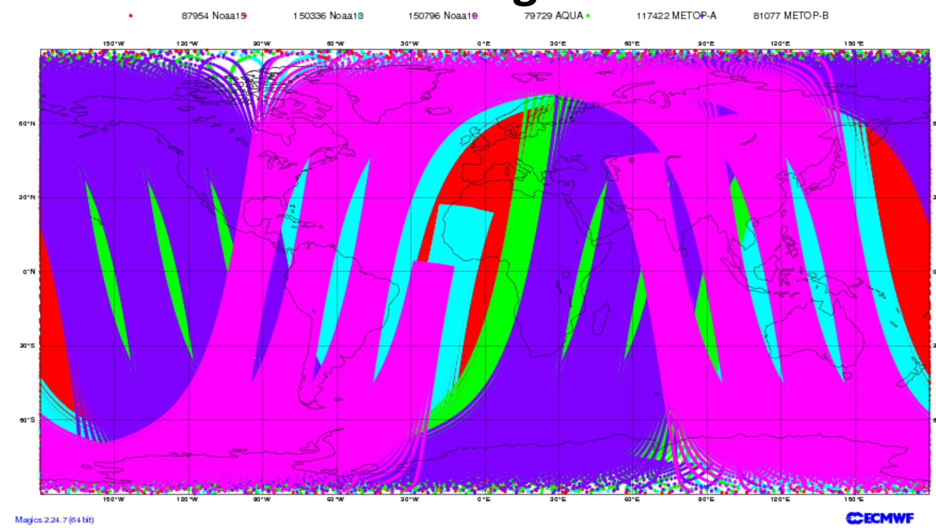
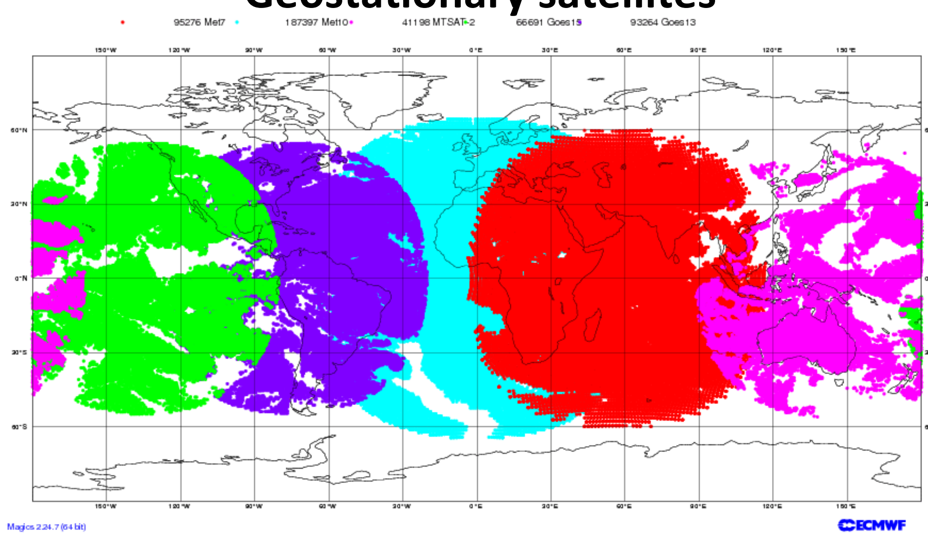


image credit: CIMSS

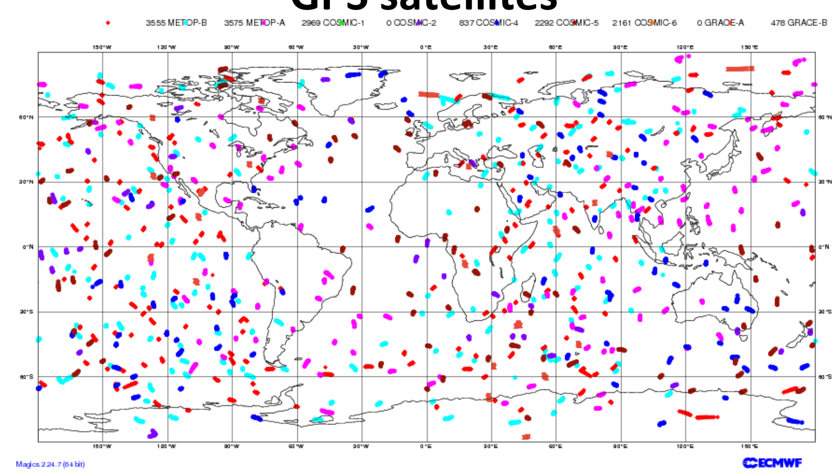
Polar-orbiting satellites



Geostationary satellites



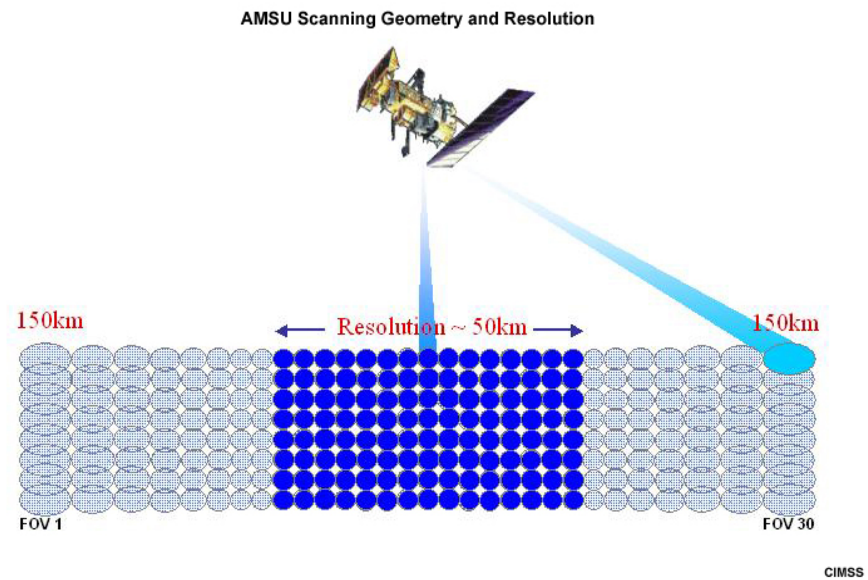
GPS satellites



Satellite instruments / sensors

Types of sensors

- Passive
- Active
- Occultation



Scan strategies and viewing geometry affect coverage and field-of-view (FOV) 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

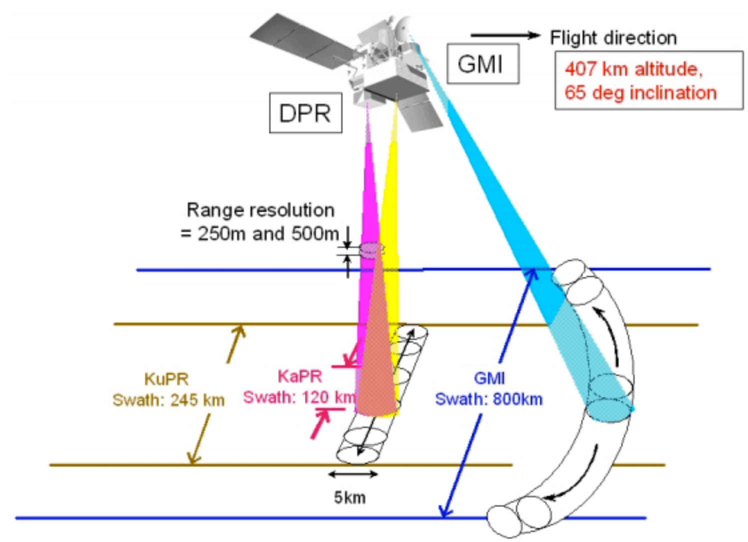
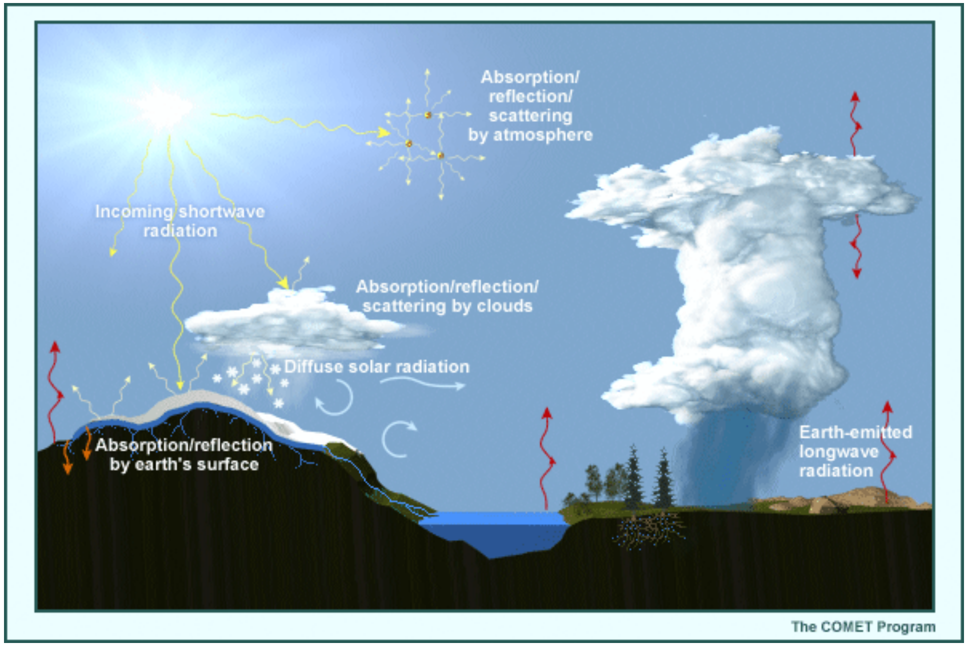


Figure 2. GPM swath measurements
image credit: NASA

What do satellite instruments measure?



Satellite passive sensors

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

Passive Sensors from Weather/Environment Satellites

Different sensors measure radiation at different wavelengths (e.g., microwave, IR, visible)

As long as an entity's temperature is above absolute zero (0 K), the entity emits radiation

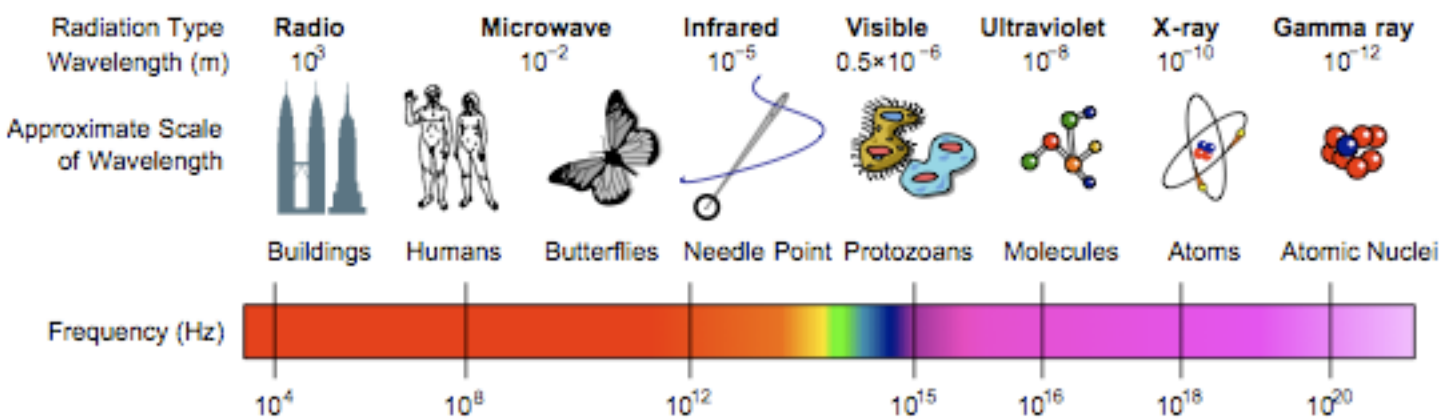
Microwave:
AMSU-A
AMSU-B
MHS
SSMI
SSMIS
ATMS
TMI
AMSR-E
AMSR-2
GMI

Infrared:
GOES Imager
AHI
ABI

HIRS
AIRS
IASI
CrIS

Visible:
AVHRR
MODIS
VIIRS

Ultraviolet:
SBUV



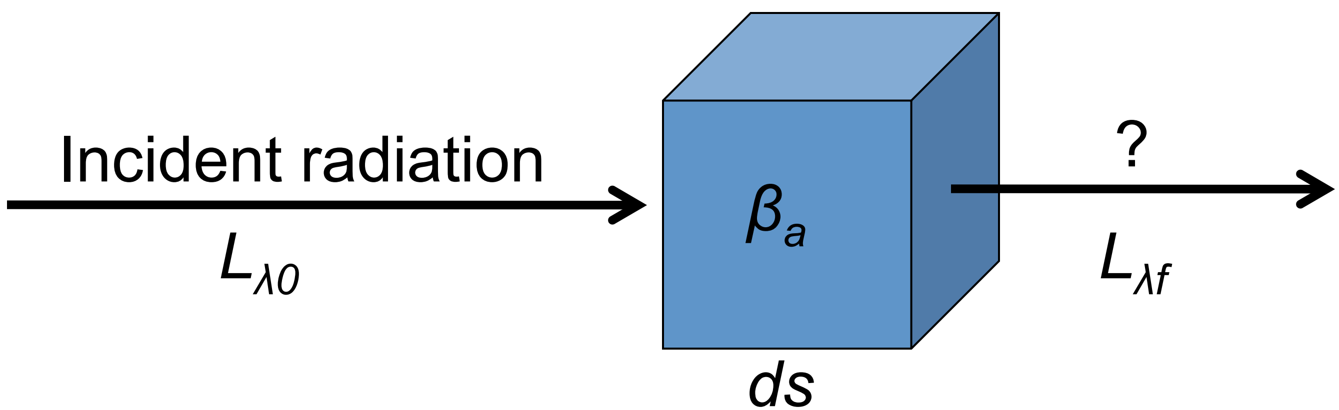
Electromagnetic Spectrum

What is radiance?

- By definition, radiance (*L*) is the amount of energy per unit area per unit time per unit solid angle emitted at a wavelength λ (or frequency v)
    - Recall, $c = \lambda v$, where c is the speed of light.
- Physically, can think of radiance as the "brightness" of an object
- 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)

Atmospheric Transmittance

- Consider radiation at wavelength λ with radiance $L_{\lambda 0}$ incident upon an absorbing medium of thickness *ds*
    - Use an absorption coefficient (β_a; units m^{-1}) to quantify degree of absorption
- Ignore emission from the medium and scattering
- What is the radiance at the other side of the surface?



Atmospheric Transmittance

•Beer's Law gives the amount of radiation that emerges from the material:

$$L_{\lambda f} = L_{\lambda 0} \exp\left[-\int_{s_1}^{s_2} \beta_a(s) ds \right]$$

•The ratio of the amount of radiation that emerges from the cube to the amount that entered is the transmittance:

$$\tau_\lambda = \frac{L_{\lambda f}}{L_{\lambda 0}} = \exp\left[-\int_{s_1}^{s_2} \beta_a(s) ds \right]$$

•Transmittance in the real atmosphere varies in space (especially in the vertical) and time

•Letting a_λ denote the absorption of the medium at wavelength λ, then in the absence of scattering

$$\boxed{a_\lambda + \tau_\lambda = 1}$$

Radiative Transfer

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

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

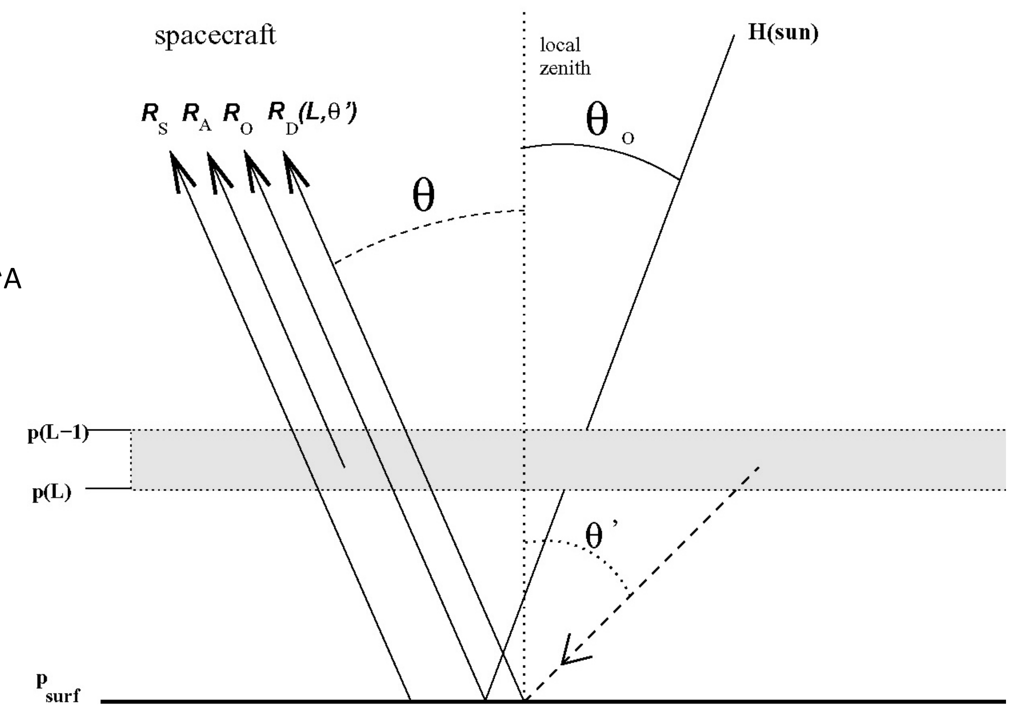
Surface emission R_s

Up-welling atmosphere emission R_A

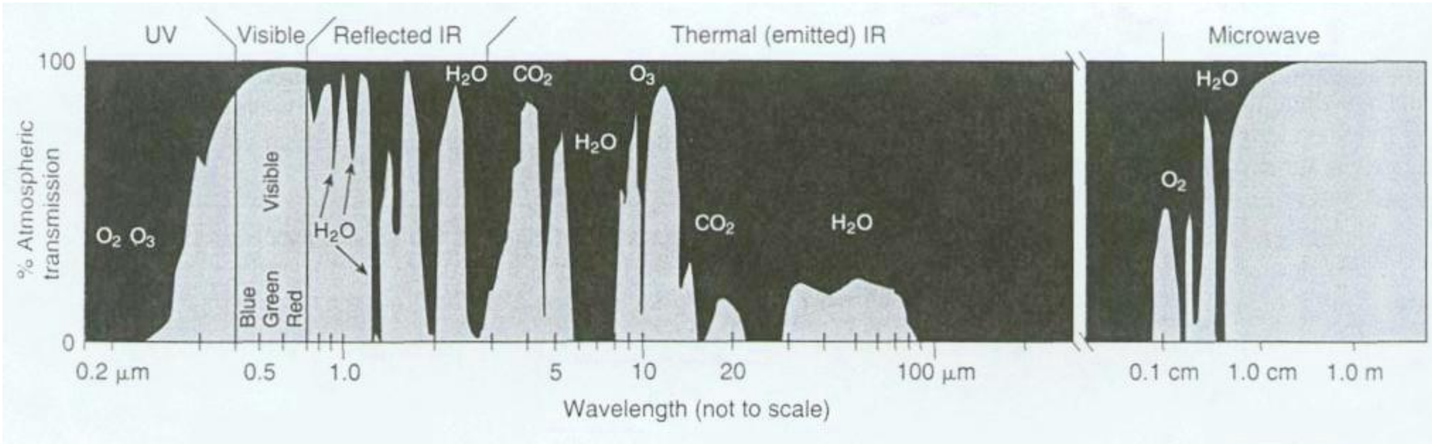
Reflected solar radiation R_O

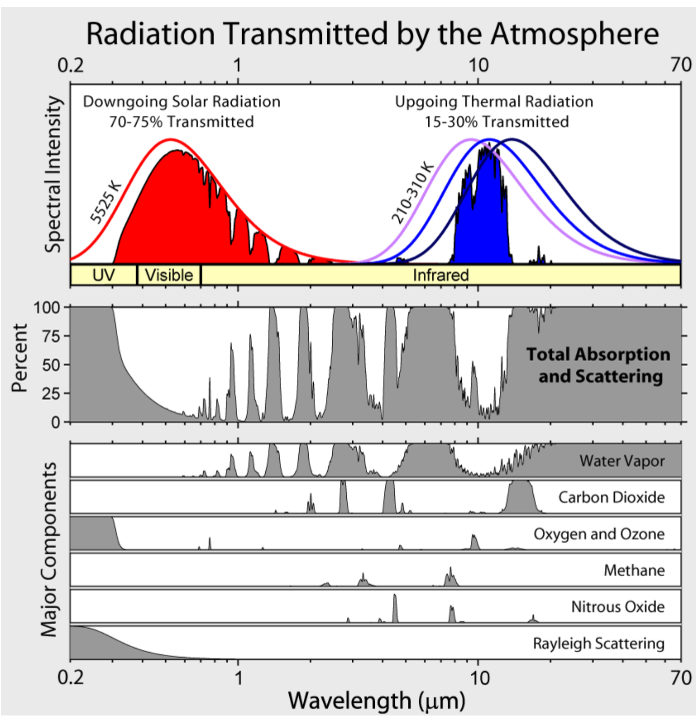
Down-welling & reflected atmos.

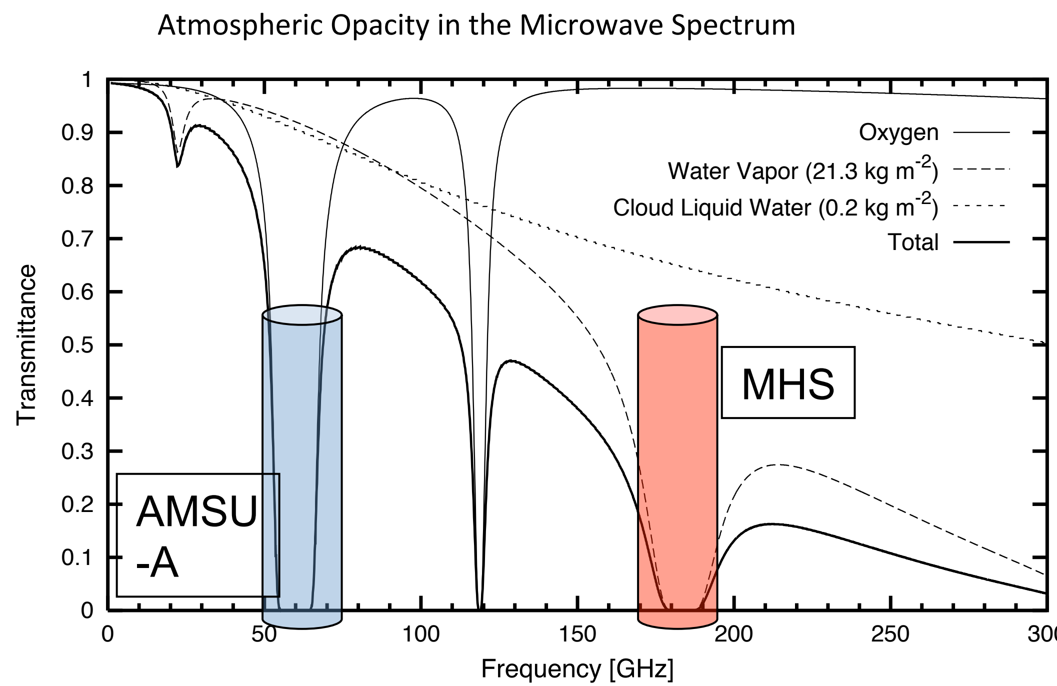
Emission (R_D)



Atmospheric gas absorption-transmission

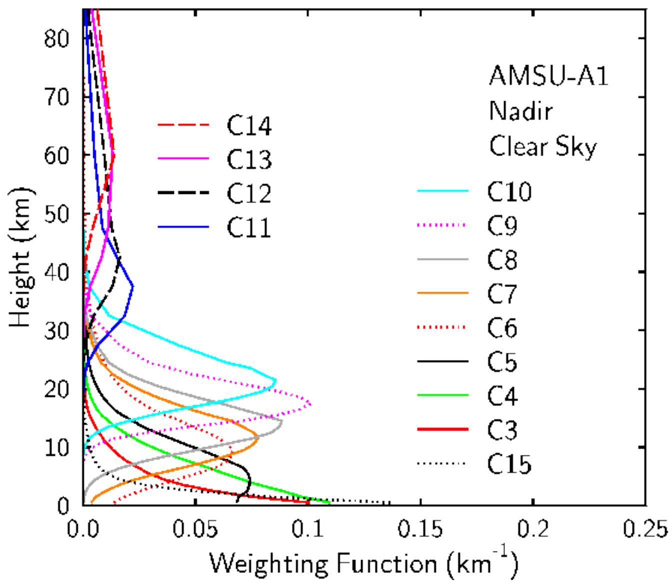






Satellite sensors are designed to make use of the frequency-dependent atmospheric absorption

Weighting functions



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

Weighting functions are frequency (channel) dependent

<u>Channel selection for NWP data assimilation</u>

- 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

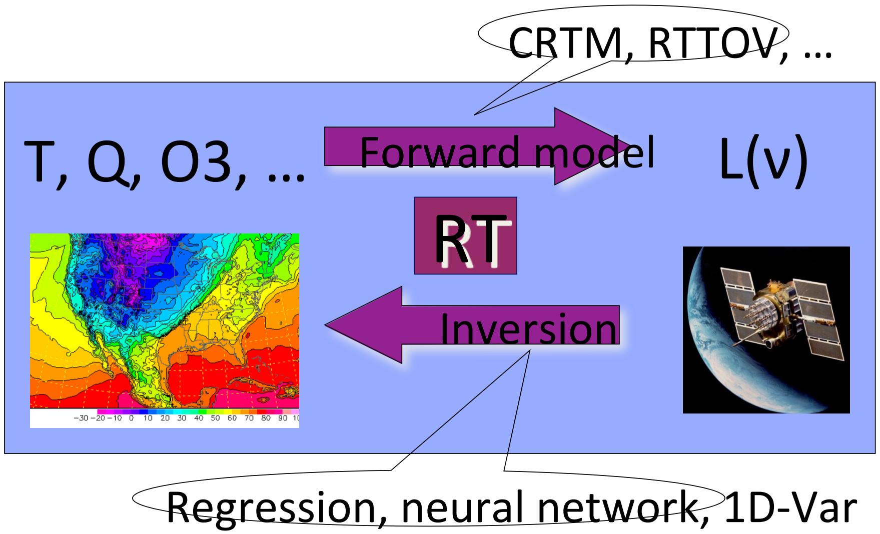
3DVAR cost function:

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

Observation operators include (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 aspects with WRFDA

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

Bias Correction

- Satellite measurements are prone to error
- Biases of satellite observations are measured with respect to the data assimilation system itself
- Biases arise for several reasons:
    - Satellite instrument errors
    - Scanning position/angles
    - Atmospheric thermodynamic profile
    - The background field
- Bias correction can be done several ways

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

J_b: background term for x

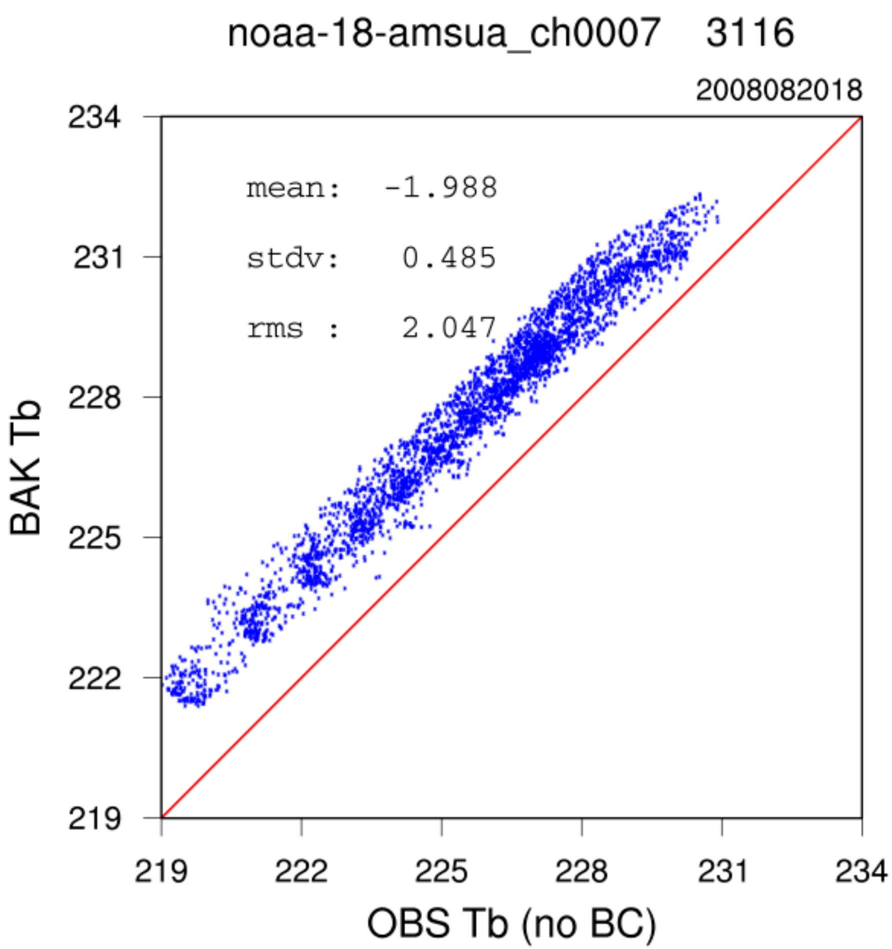
J_o: corrected observation term

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

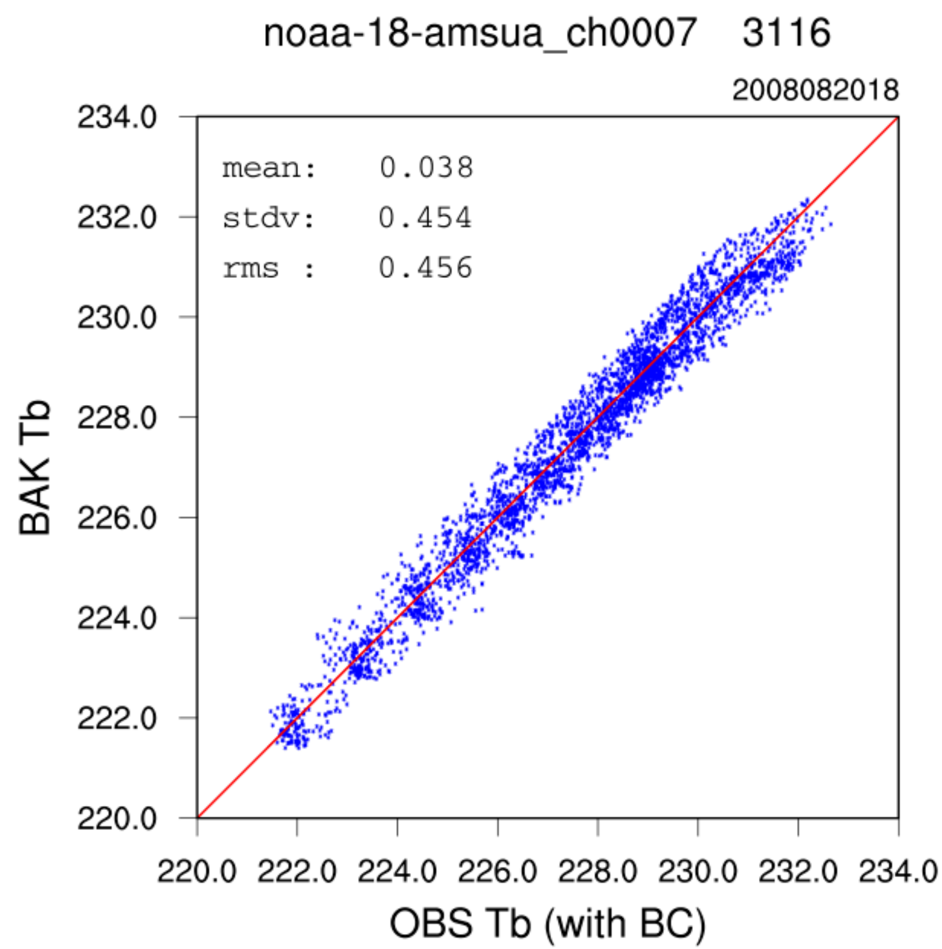
J_p: background term for β

Can be used for radiance offline monitoring by removing J_b term and other obs and using an analysis field as reference.

Bias Correction



No bias correction



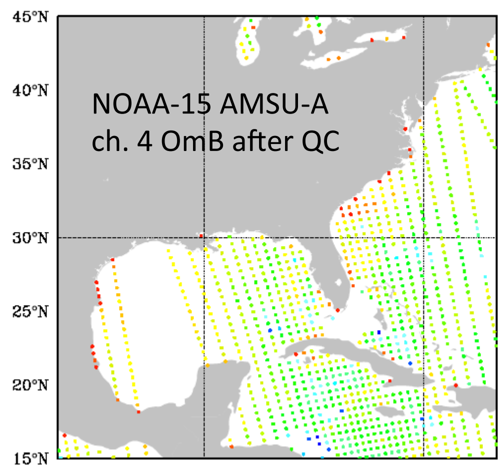
With bias correction

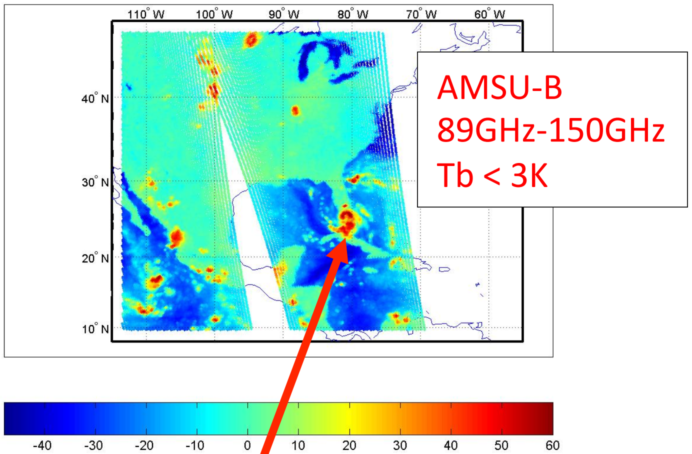
Quality control (QC)

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

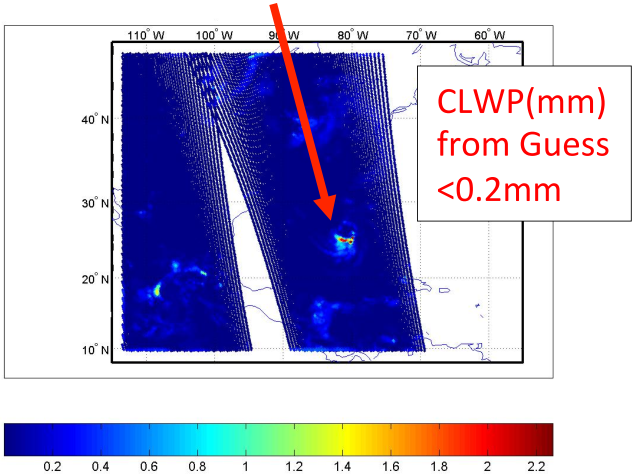
- **Pixel-level QC**
  - Reject **limb** observations
  - Reject pixels over **land** and **sea-ice**
  - **Cloud/Precipitation** detection
  - **Synergy** with imager (AIRS/VIS-NIR)

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



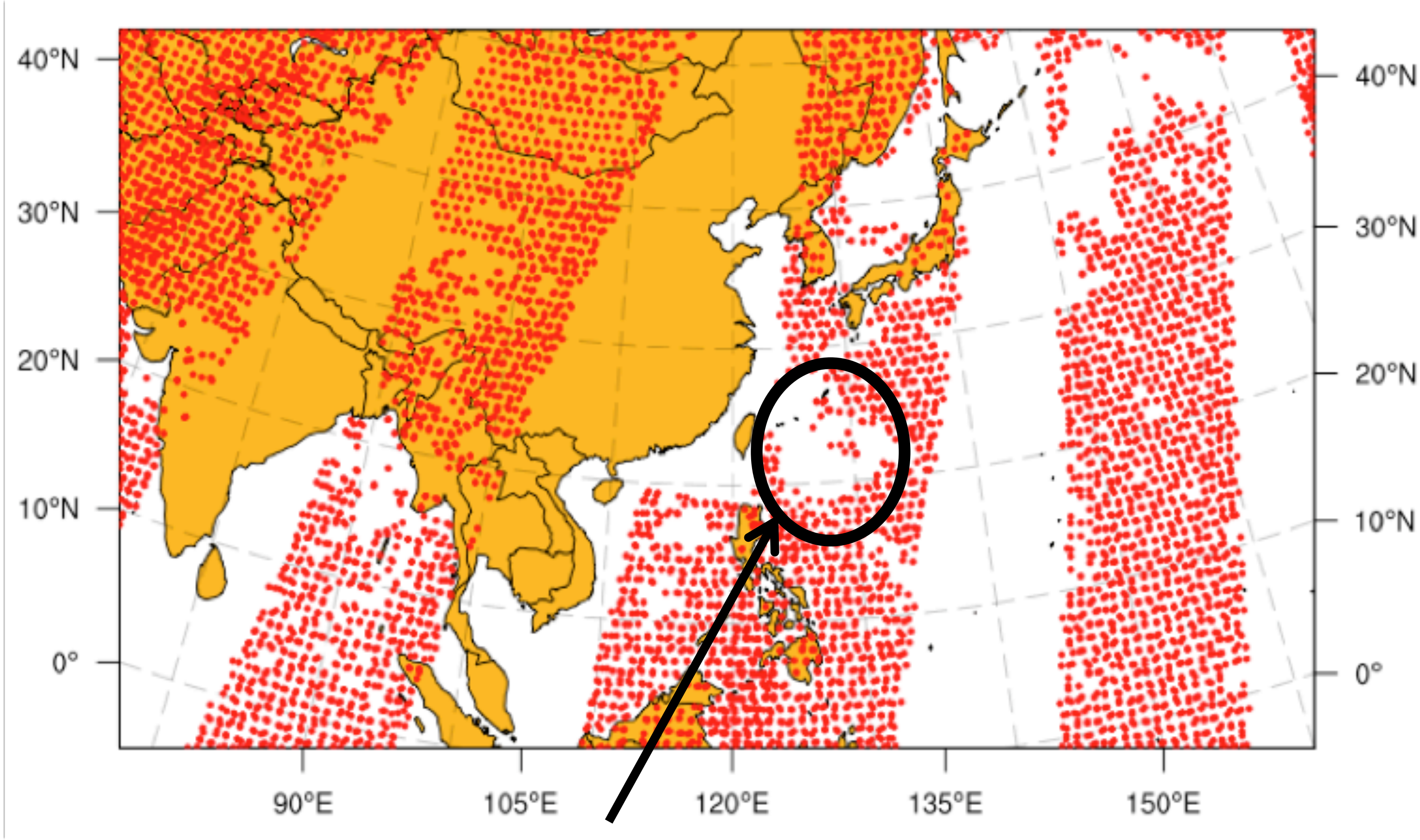


Katrina Location (2005/08/26/06Z)



Quality Control (QC)

- Each dot represents a grid box where at least one radiance observation was assimilated

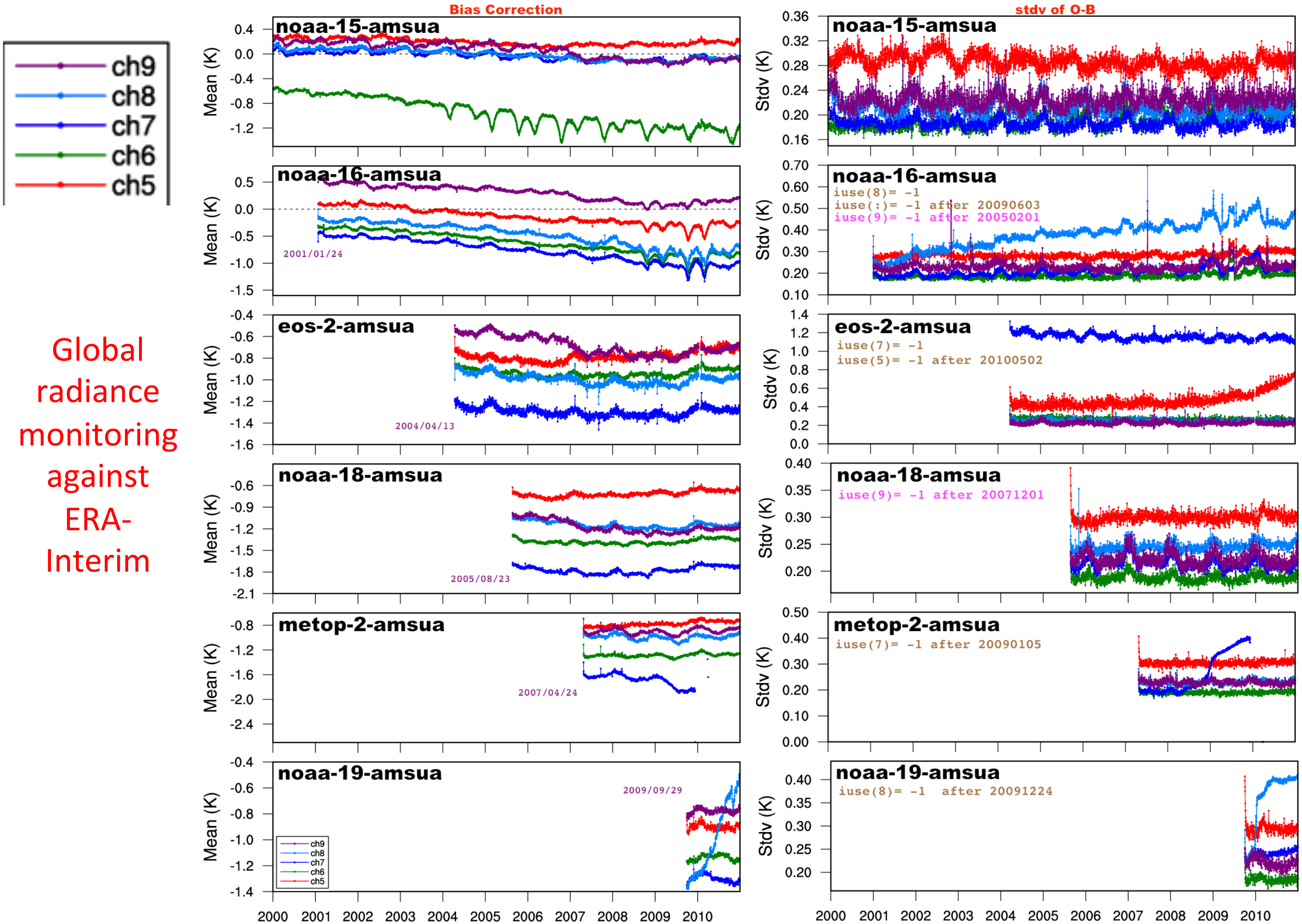


Location of a typhoon—precipitating there, so no radiances assimilated over that area

Quality control

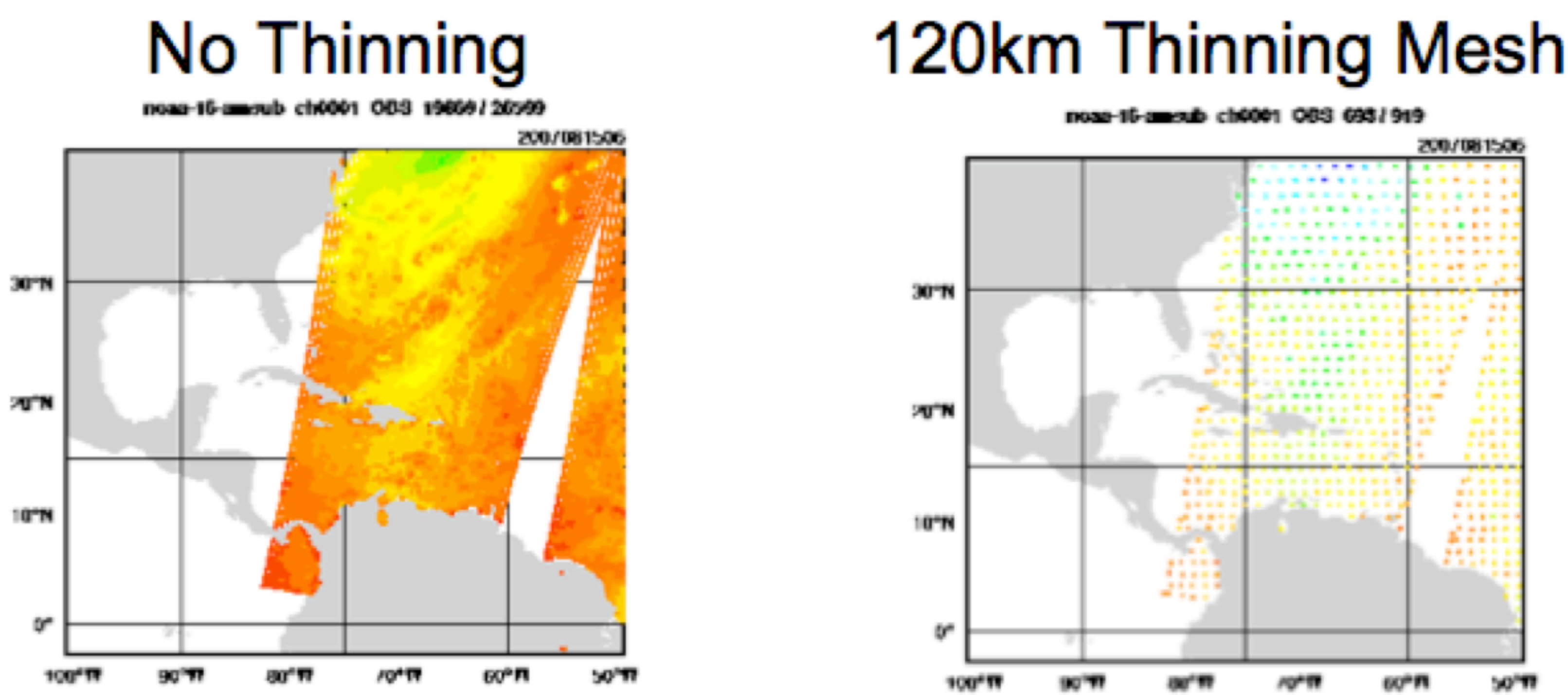
monitoring and blacklisting

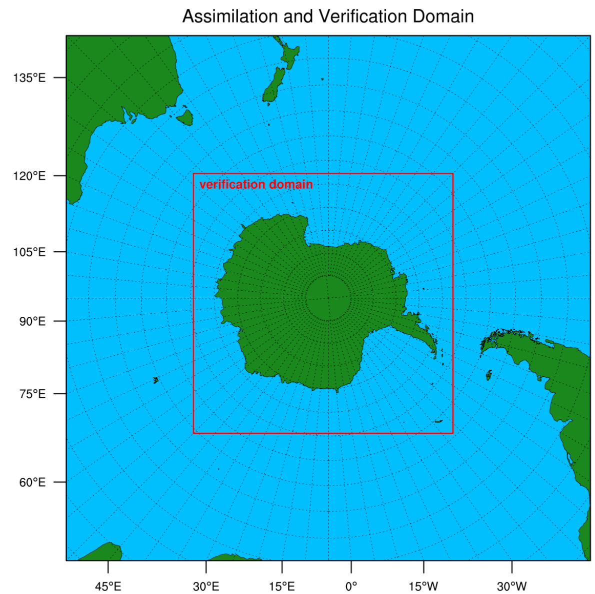
Global radiance monitoring against ERA-Interim



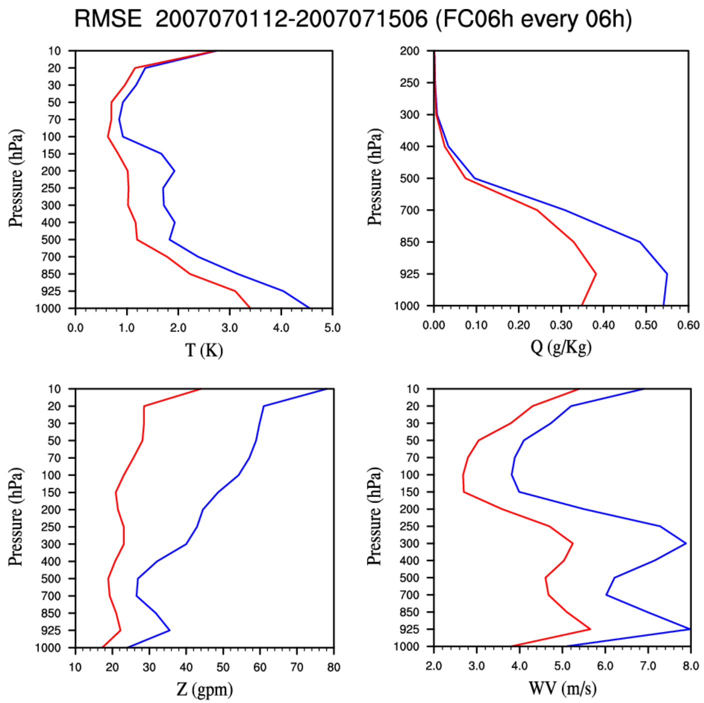
Data Thinning

- Raw satellite data are dense and likely correlated
- But the **R** matrix does not contain observation covariances
- So we must thin the data to remove (or at least diminish) correlation between the radiance observations

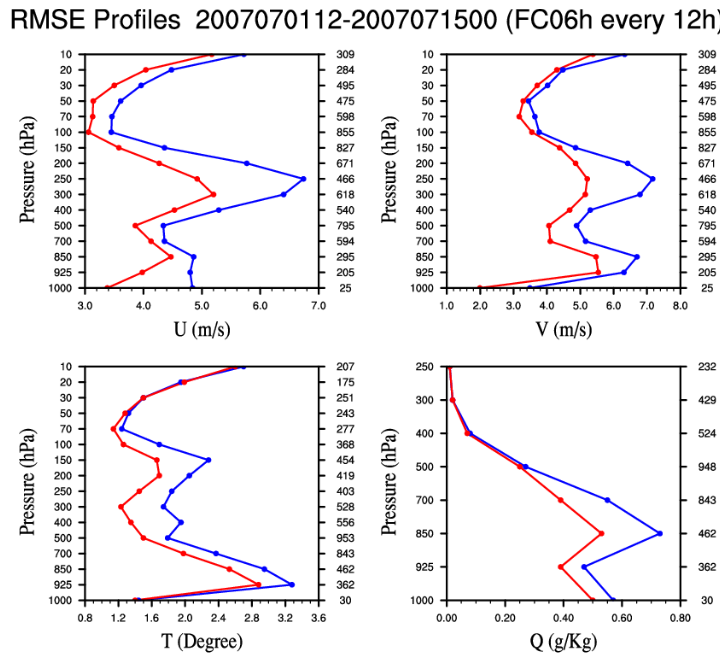




- WRF/WRFDA V3.6+ (V3.6 with modifications and fixes)
- 1-hPa model top, 71 levels, 60-km horizontal grid spacing
- low/lateral boundary conditions from ERA-interim
- Snow from NCEP FNL
- 6-hour cycling starting from 2007070100
- 240-second time step, 180-sec for a couple dates that exceeded CFL criteria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



verification against SOUNDs

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, and 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			

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 to 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

```
metop-2 = metop-a
metop-1 = metop-b
jpss-0  = npp
msg-1   = meteosat-8
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
AMSR2	63

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)

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-2.2.3

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 12.1,

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

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" (refers to the first row of 10000 values)

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

The implementation of other cloud_cv_options (with additional cloud variables included) 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 WRFDA 3.9.

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

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

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

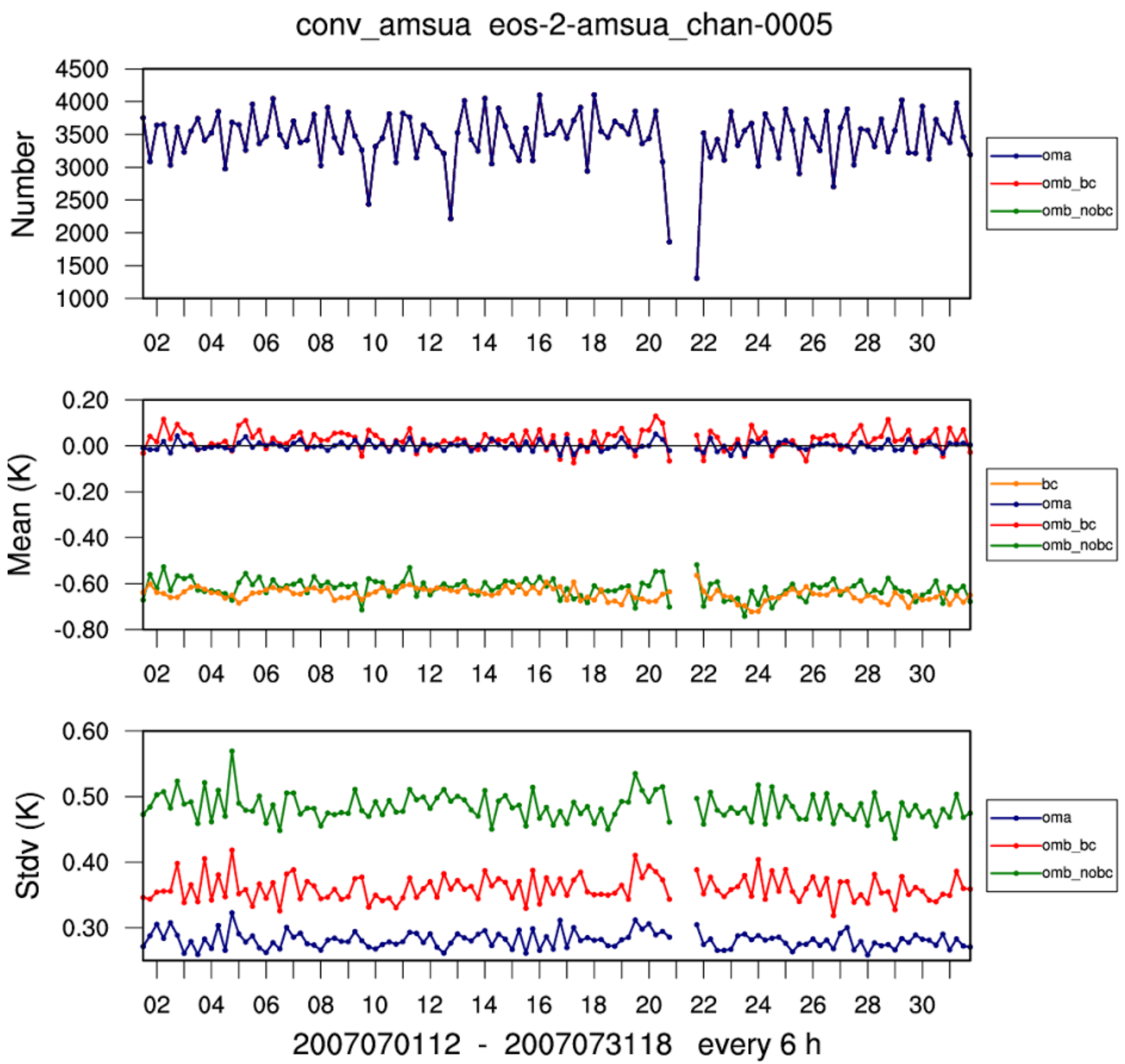
```
Diagnostics of OI for radiance          noaa-19-amsua

 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 OI for radiance          noaa-19-amsua
```

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
02 04 06 08 10 12 14 16 18 20 22 24 26 28 30
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
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