

Radiance Data Assimilation in WRFDA

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WRFDA tutorial
July 2019



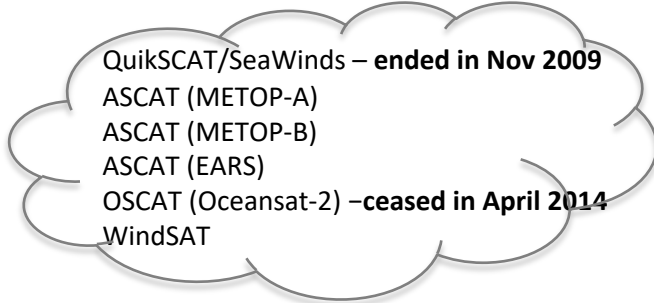
WRFDA can assimilate ...

❑ In-Situ conventional observations:

- Surface (SYNOP, METAR, SHIP, BUOY)
- Upper air (TEMP, PIBAL, AIREP, ACARS, AMDAR, TAMDAR)

❑ Remotely sensed observations:

- Atmospheric Motion Vectors (geo/polar) (SATOBS)
- 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

❑ Radiances (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/MWHS FY-3 A/B
- MWHS2 FY-3 C/D
- SEVIRI METEOSAT-8, METEOSAT-9, METEOSAT-10
- AMSR-2 GCOM-W1 (all-sky radiance DA)
- GOES-Imager and Himawari-AHI

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

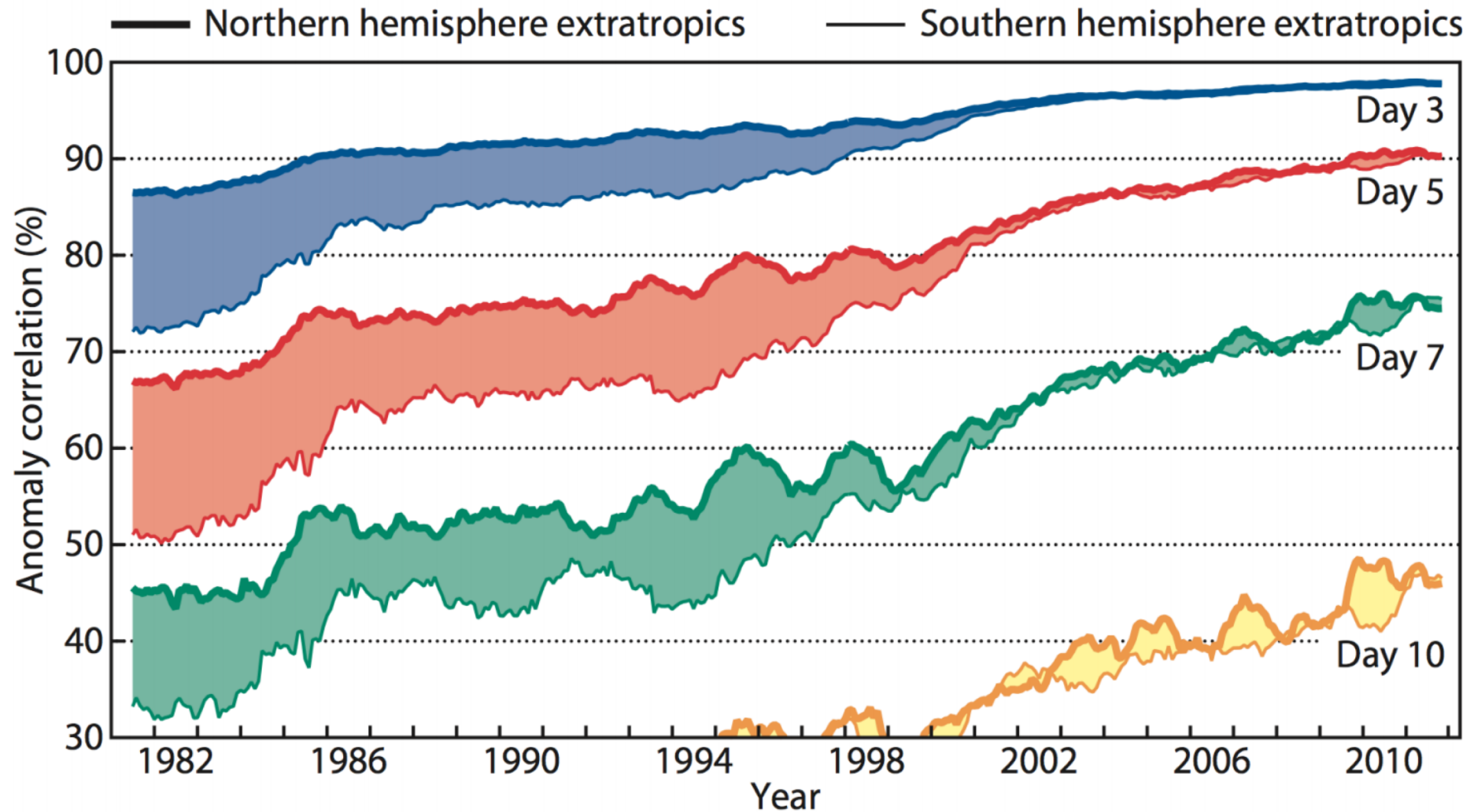
Part I: Introduction to radiance data assimilation

Global Analysis Systems

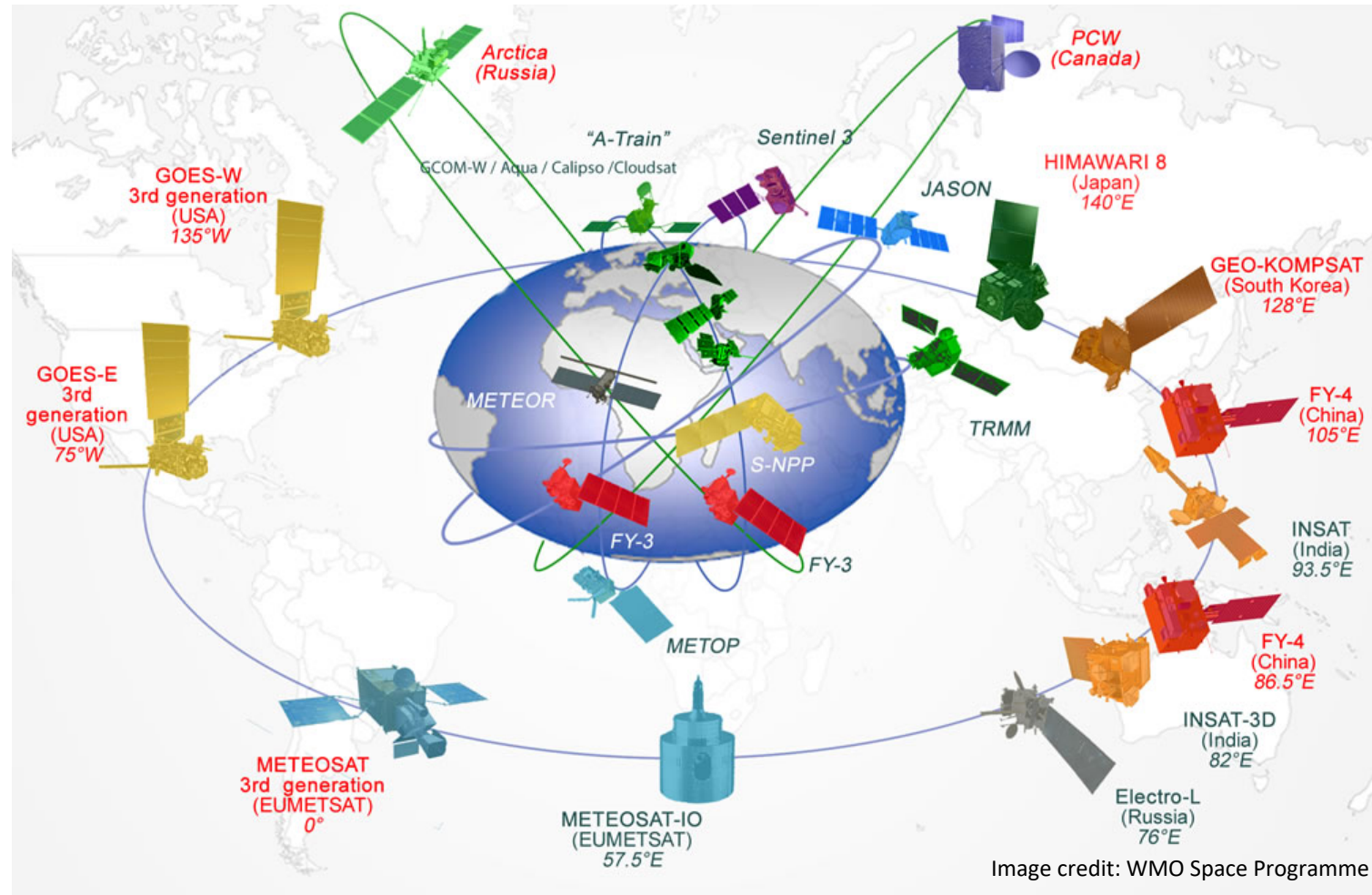
- Assimilation of satellite observations is a key component of analysis systems at nearly every operational center
 - Satellites provide observational data in regions where few conventional observations are available:
 - Marine areas
 - Deserts
 - Other unpopulated regions
- Greatest forecast benefit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

Global forecast improvement

- ECMWF improvement from radiance DA



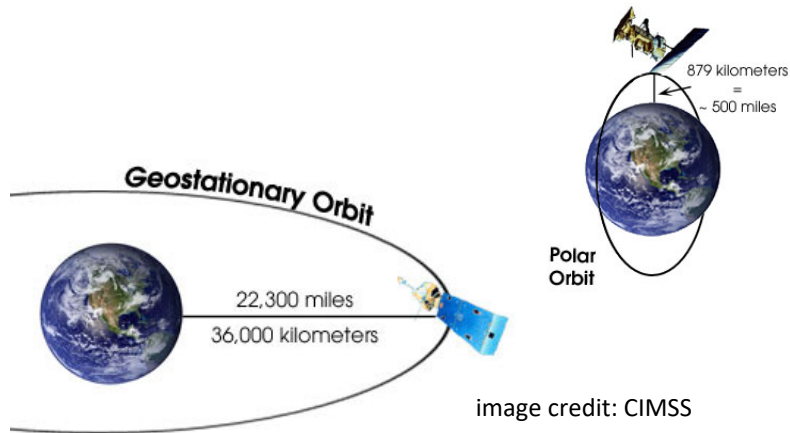
Environmental monitoring satellites



Valuable information from satellite measurements:

- Images, retrieved/derived products, **radiances**

Types of satellites

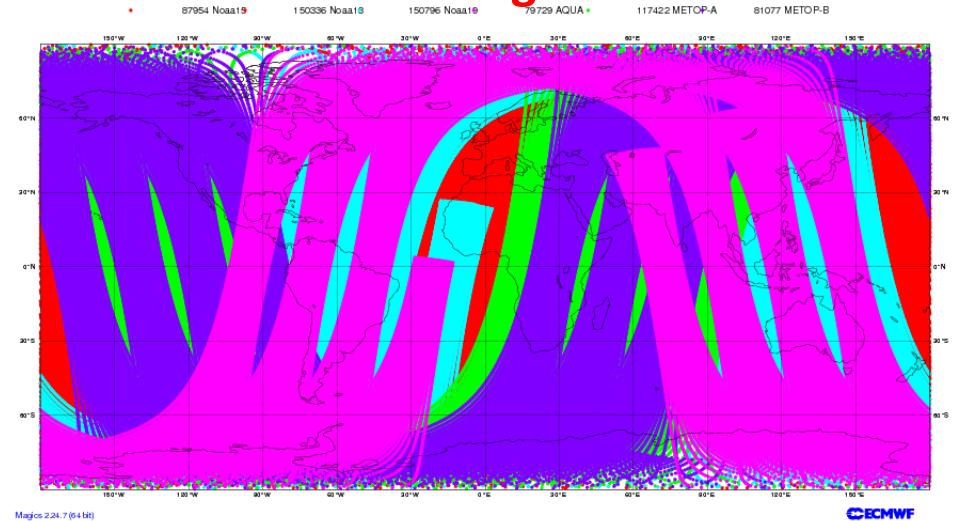


ECMWF Data Coverage (All obs DA) - AMSU-A

05/Jul/2015; 06 UTC

Total number of obs = 667314

Polar-orbiting satellites

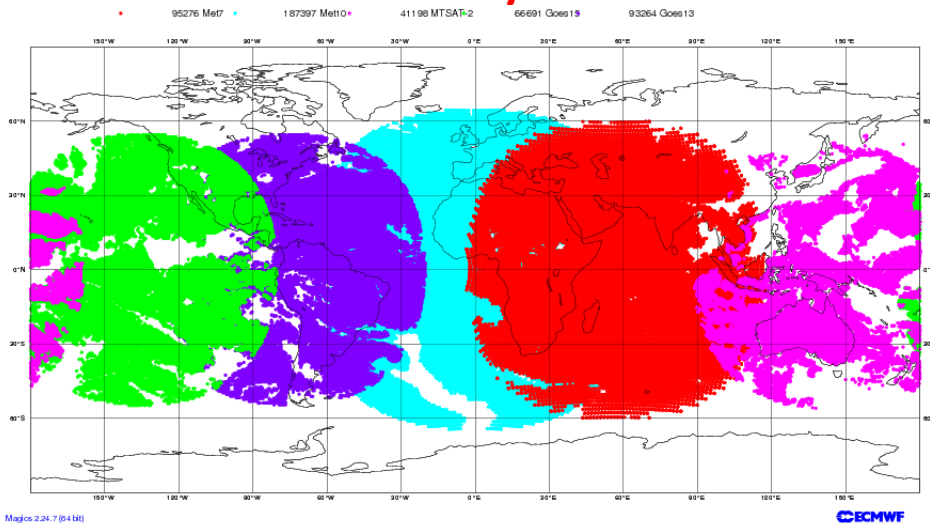


ECMWF Data Coverage (All obs DA) - GRAD

05/Jul/2015; 06 UTC

Total number of obs = 483826

Geostationary satellites

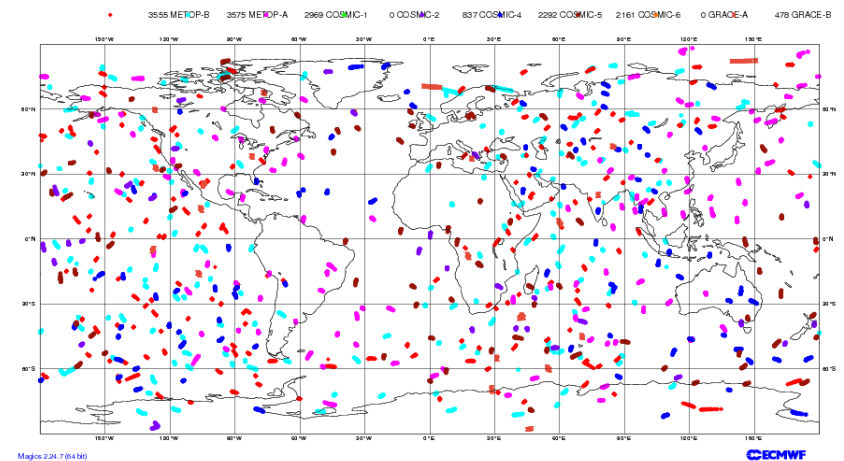


ECMWF Data Coverage (All obs DA) - GPSRO

05/Jul/2015; 06 UTC

Total number of obs = 15867

GPS satellites



Satellite instruments/sensors

Types of sensors

- Passive
- Active
- Occultation

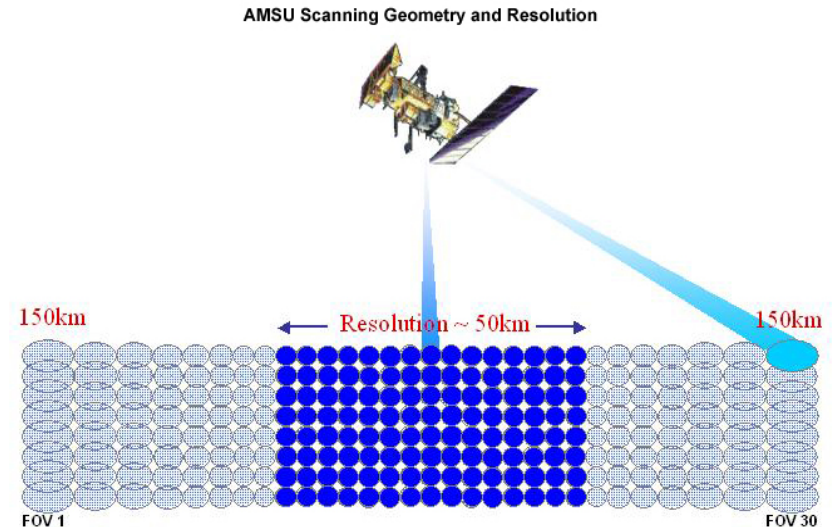
Scan strategies and viewing geometry affect coverage and field-of-view (FOV) resolution

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



CIMSS

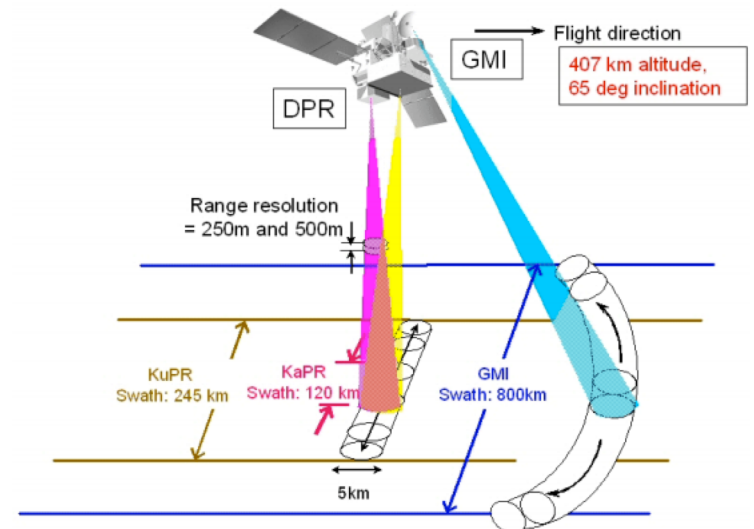
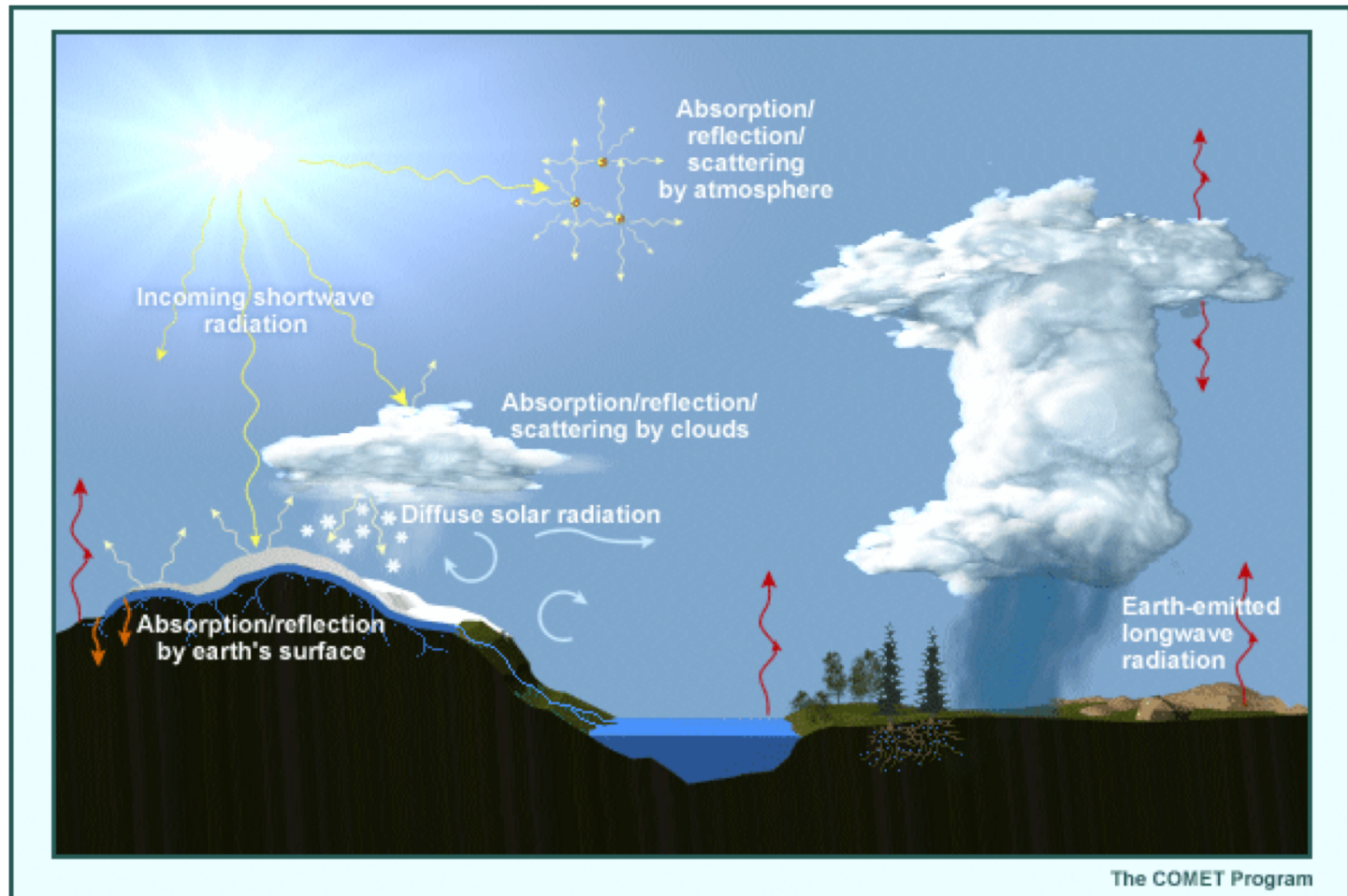


Figure 2. GPM swath measurements
image credit: NASA

What do satellite instruments measure?

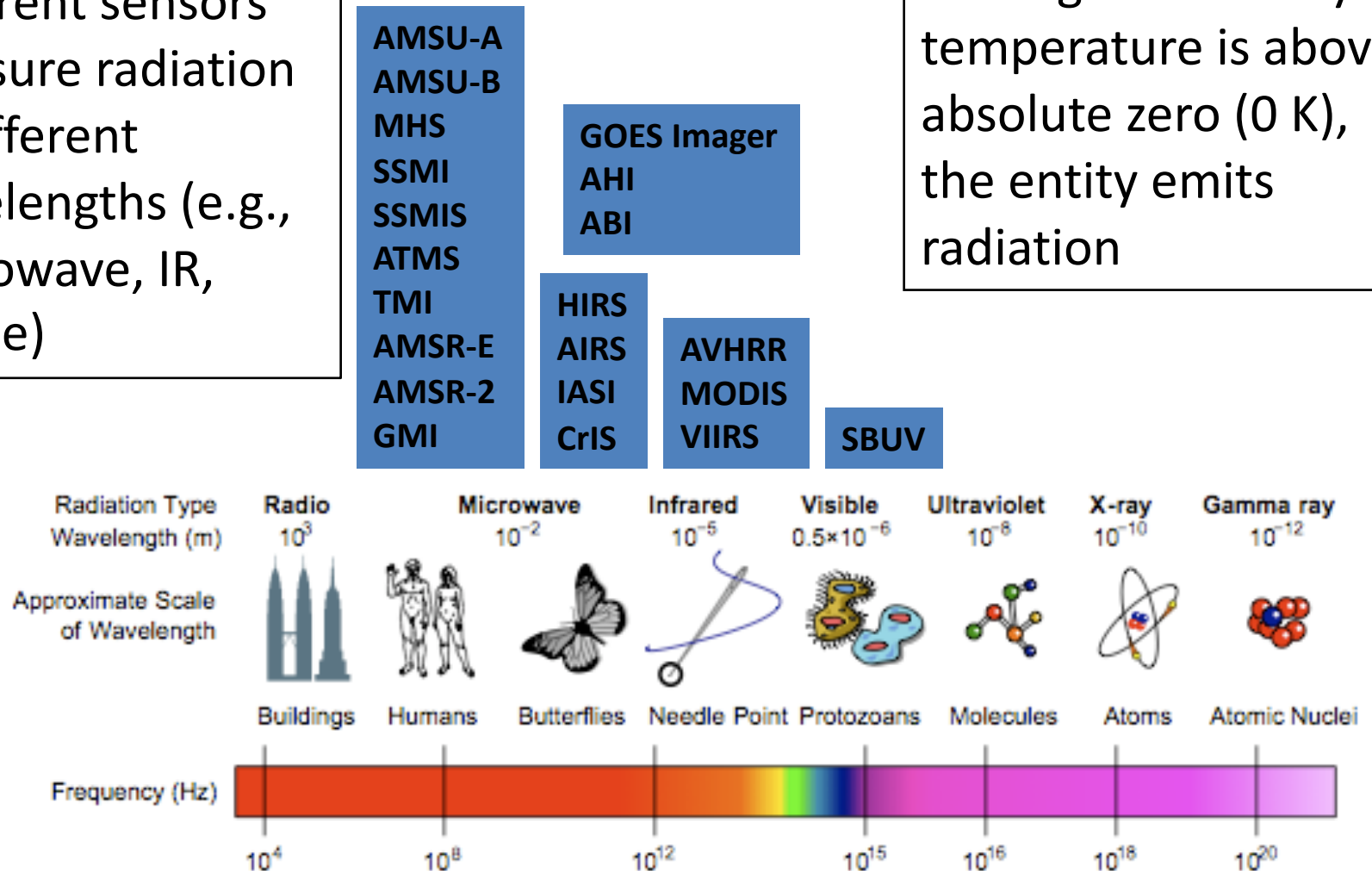
- **Satellite passive sensors** observe radiation emitted and scattered from Earth's surface and atmosphere at **discrete wavelength intervals**



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



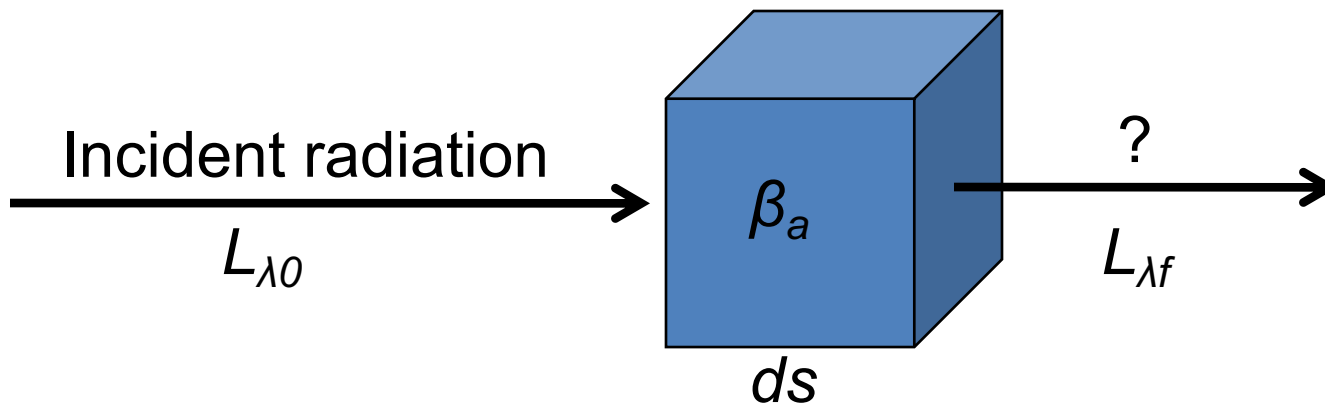
Electromagnetic Spectrum

What is radiance?

- Radiance (L) is the amount of energy per unit area per unit time per unit solid angle emitted at a wavelength λ (or frequency ν)
 - Recall, $c = \lambda\nu$, 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 Planck 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 emerging 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

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

$L(\nu)$: 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

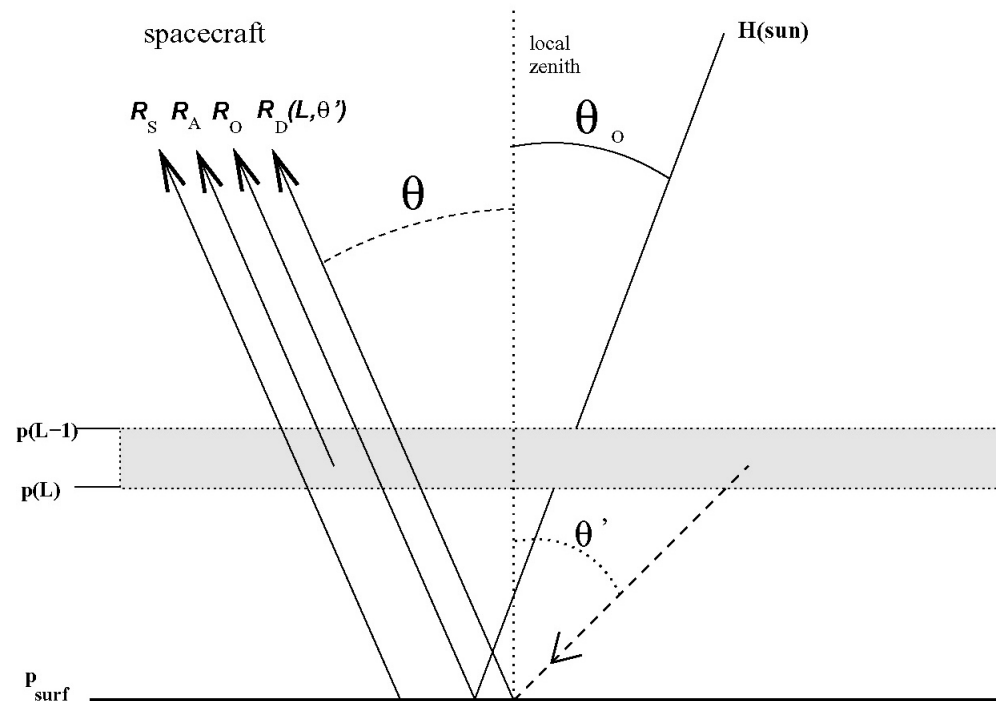
Surface emission R_s

Up-welling atmosphere emission R_A

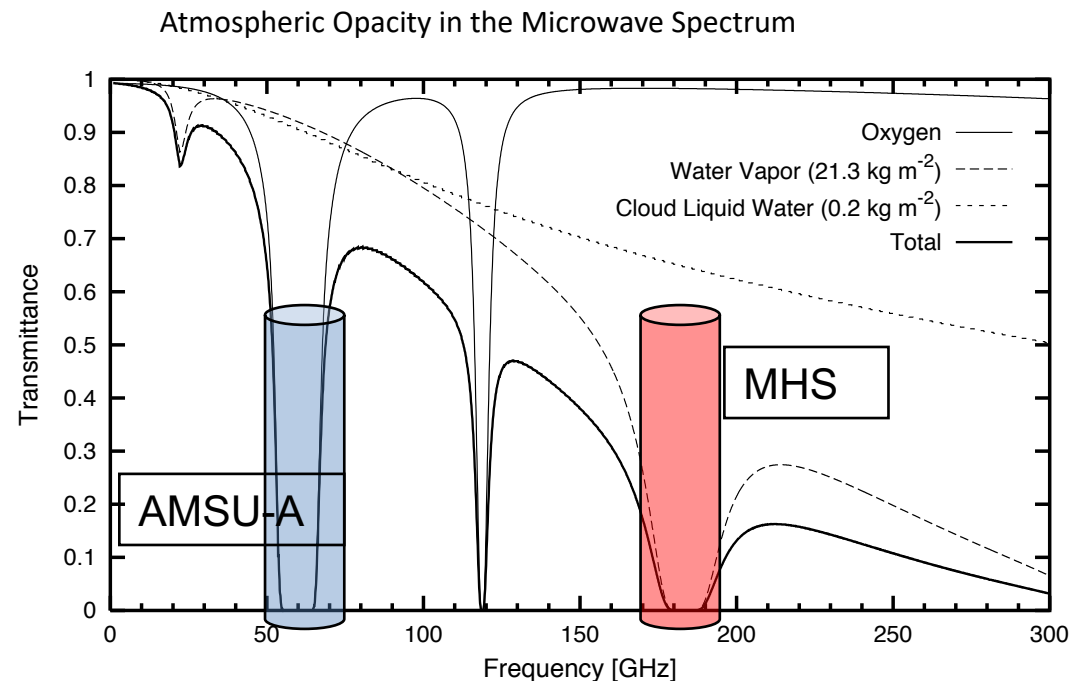
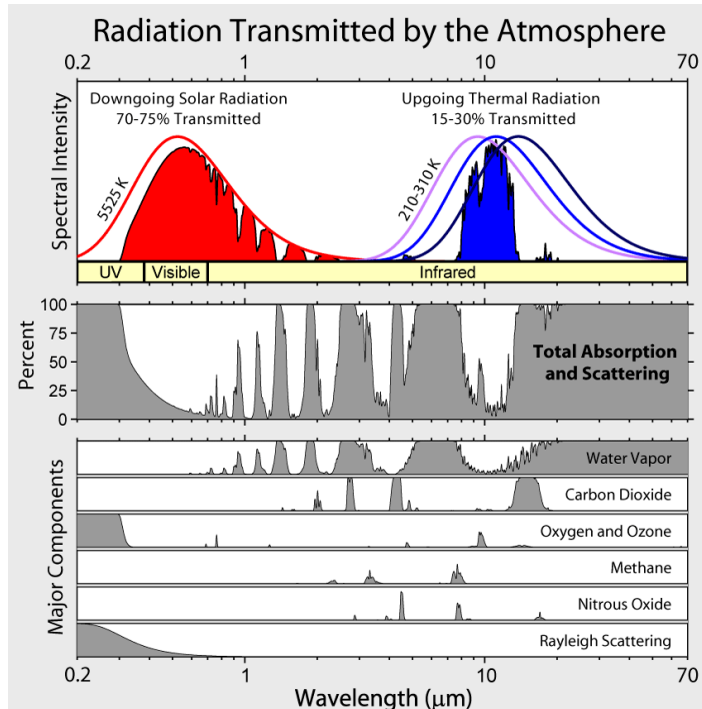
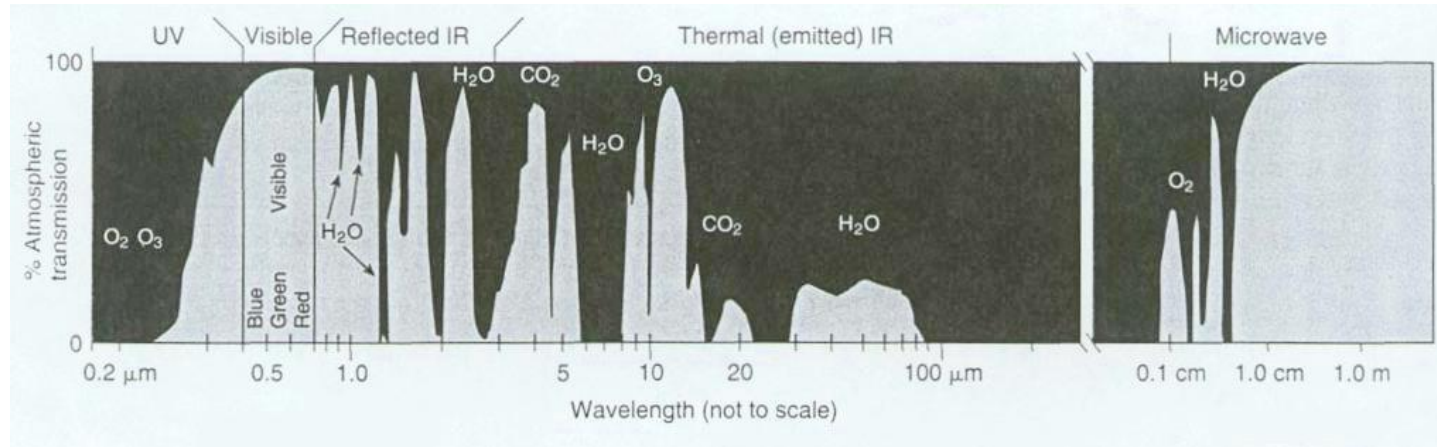
Reflected solar radiation R_O

Down-welling & reflected atmos.

Emission (R_D)

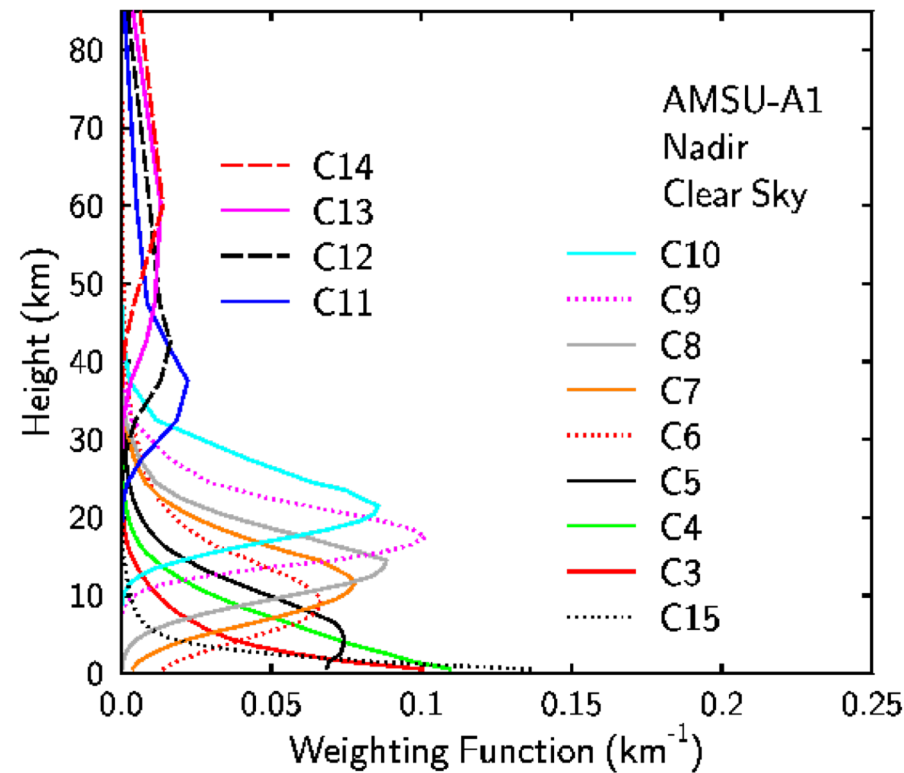


Atmospheric gas absorption-transmission



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

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

3DVAR cost function:

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



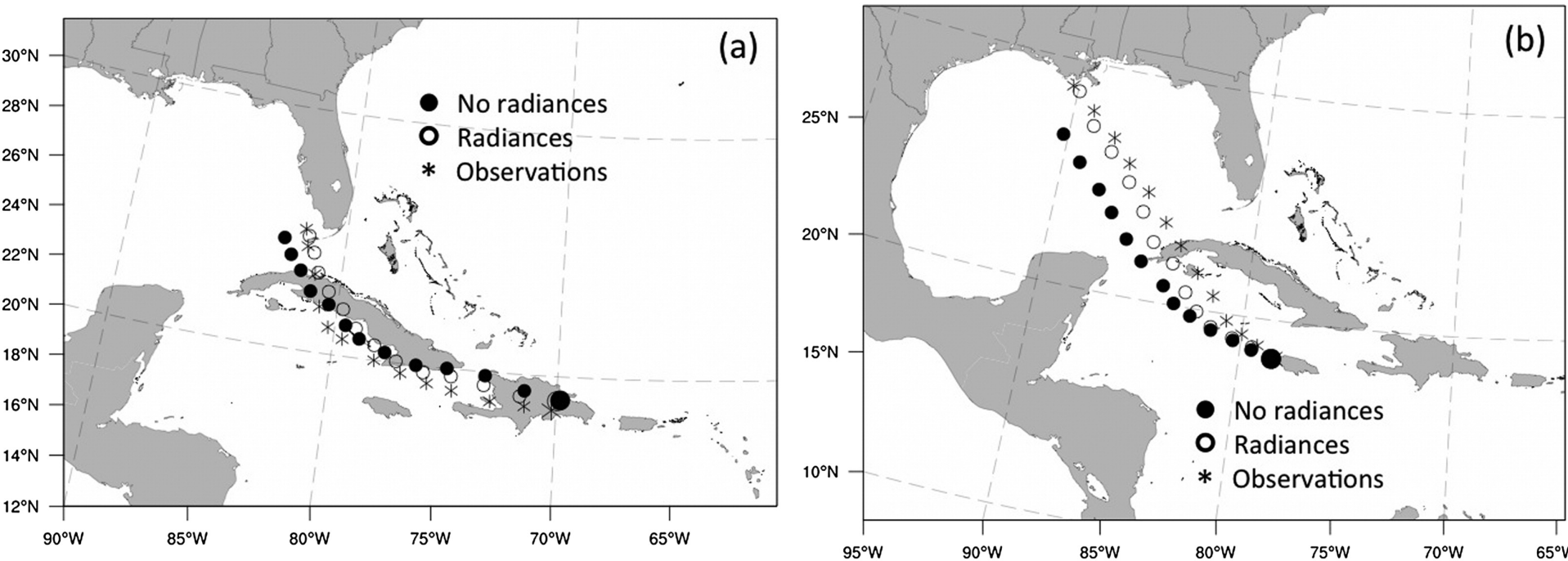
Observation operators include (Fast) Radiative Transfer Model

- **Radiance DA considerations:**
 - Radiative transfer model
 - Channel selection
 - Observation errors
 - Bias correction
 - Quality control
 - Thinning
 - Monitoring

Clear vs. cloudy (all-sky) radiances

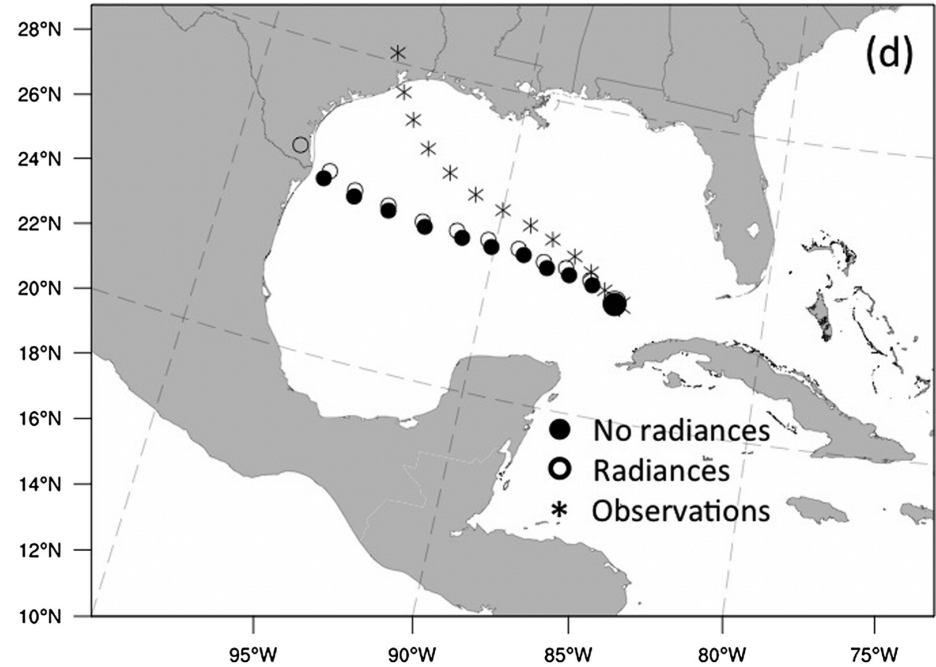
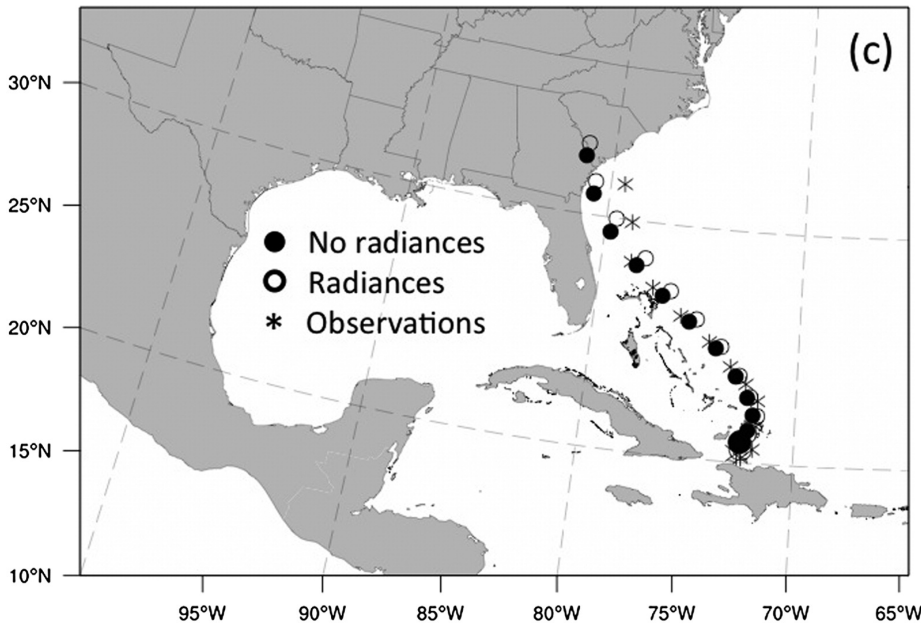
- Clear sky radiances
 - Forward operator a function of temperature and moisture
 - Don't assimilate observations at cloudy pixels
 - Relatively small observation errors
- Cloudy radiances
 - Forward operator a function of T, Q, and cloud variables
 - Observation errors potentially large and depends on correspondence of observed vs. forecast (i.e., background) clouds

Impacts of regional radiance DA



Liu et al. (2012); doi:10.1175/MWR-D-12-00083.1

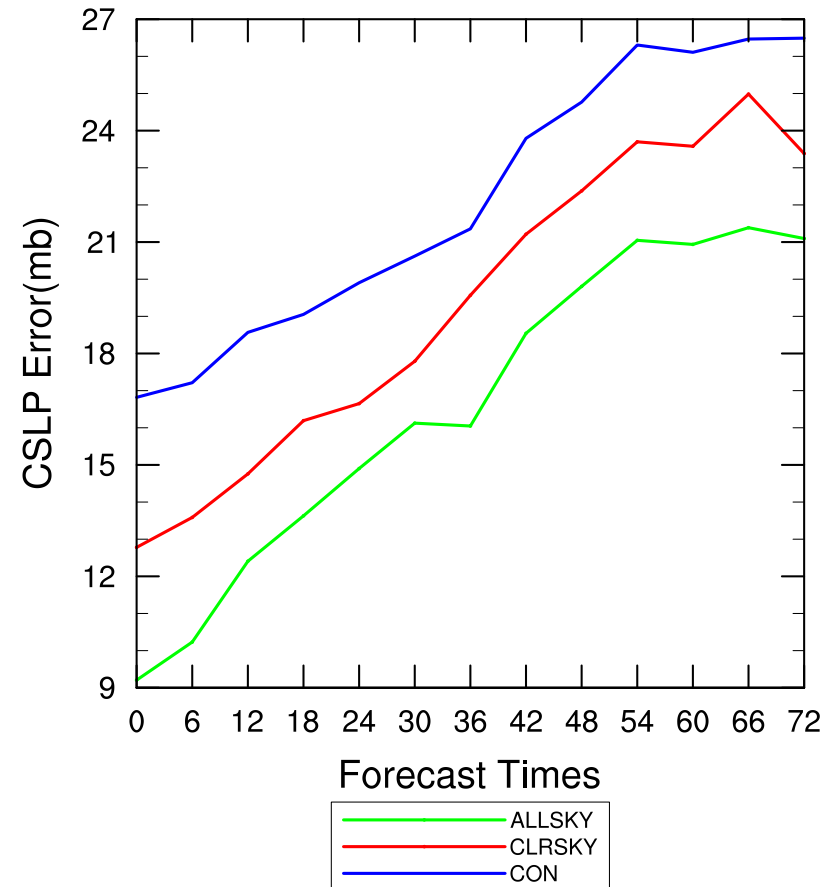
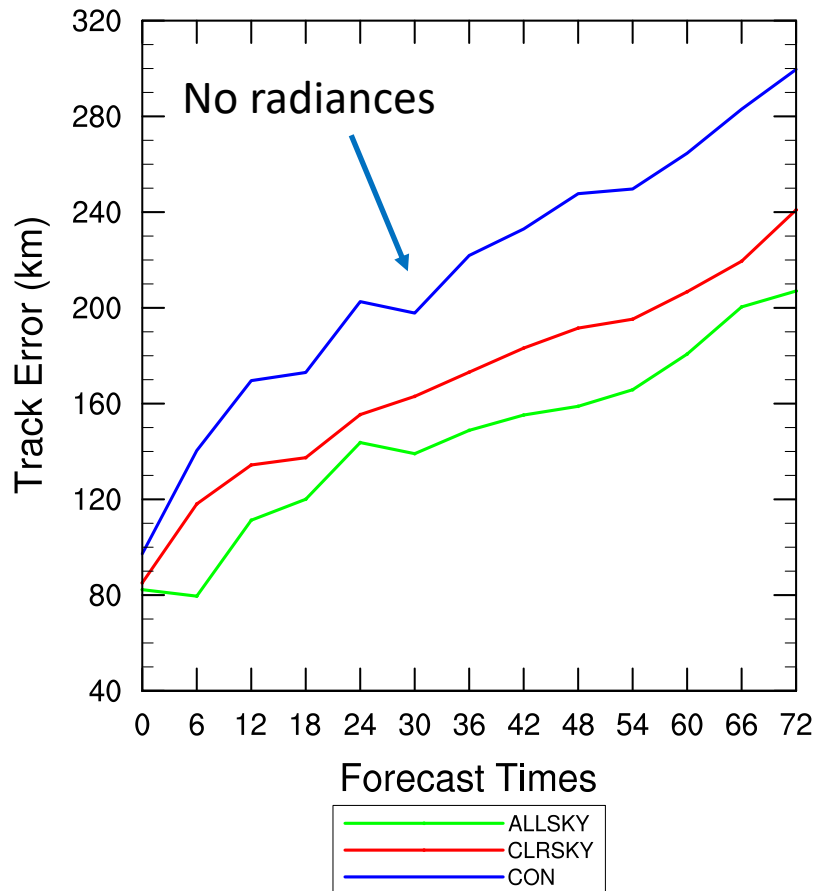
Impacts of regional radiance DA



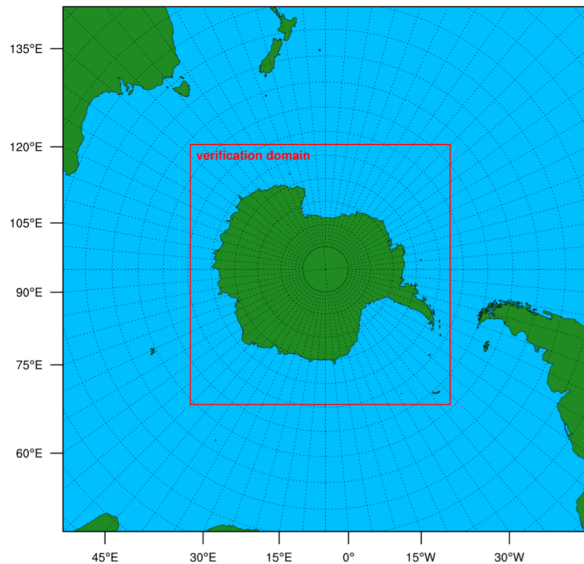
Liu et al. (2012); doi:10.1175/MWR-D-12-00083.1

Impacts of regional radiance DA

- Track and intensity forecasts for hurricane Sandy

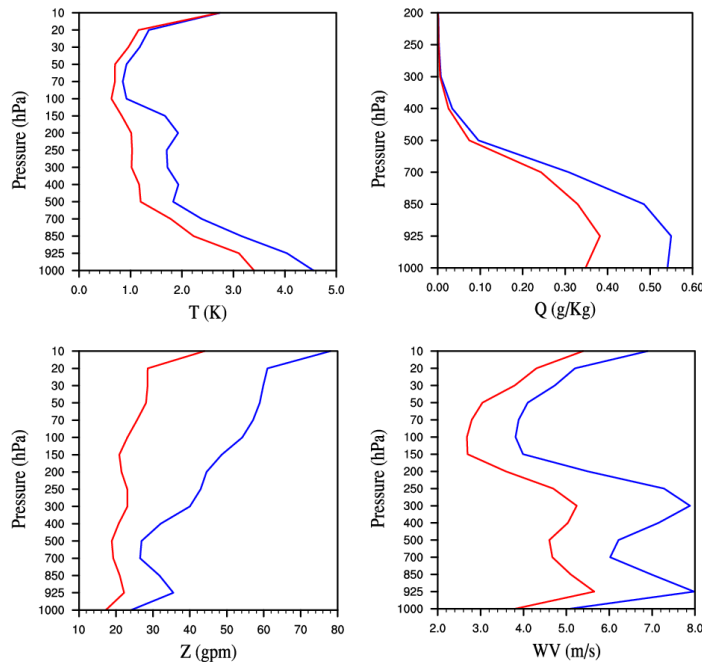


Yang et al. (2016) doi:10.3402/tellusa.v68.30917



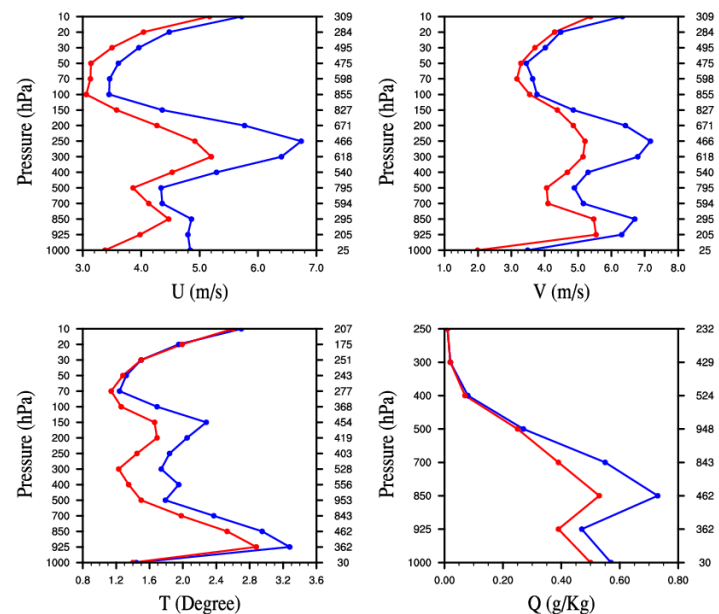
- WRF/WRFDA V3.6+ (V3.6 with modifications and fixes)
- 1-hPa model top, 71 levels, 60-km horizontal grid spacing
- low/lateral boundary conditions from ERA-interim
- Snow from NCEP FNL
- 6-hour cycling starting from 2007070100
- 240-second time step, 180-sec for a couple dates that exceeded CFL criteria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

RMSE 2007070112-2007071506 (FC06h every 06h)



verification against ERA-interim analysis

RMSE Profiles 2007070112-2007071500 (FC06h every 12h)



verification against SOUNDS

conv amsua

conv

conv amsua

conv

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 errors in satellite radiances:

$$y = H(x_t) + B(\beta) + \varepsilon \quad \left\{ \begin{array}{l} \langle \varepsilon \rangle = 0 \\ B(\beta) = \sum_{i=1}^N \beta_i p_i \end{array} \right.$$

Bias-correction coefficients

Predictors:

- Offset (i.e., 1)
- 1000-300mb thickness
- 200-50mb thickness
- Surface skin temperature
- Total column water vapor
- Scan, Scan², Scan³

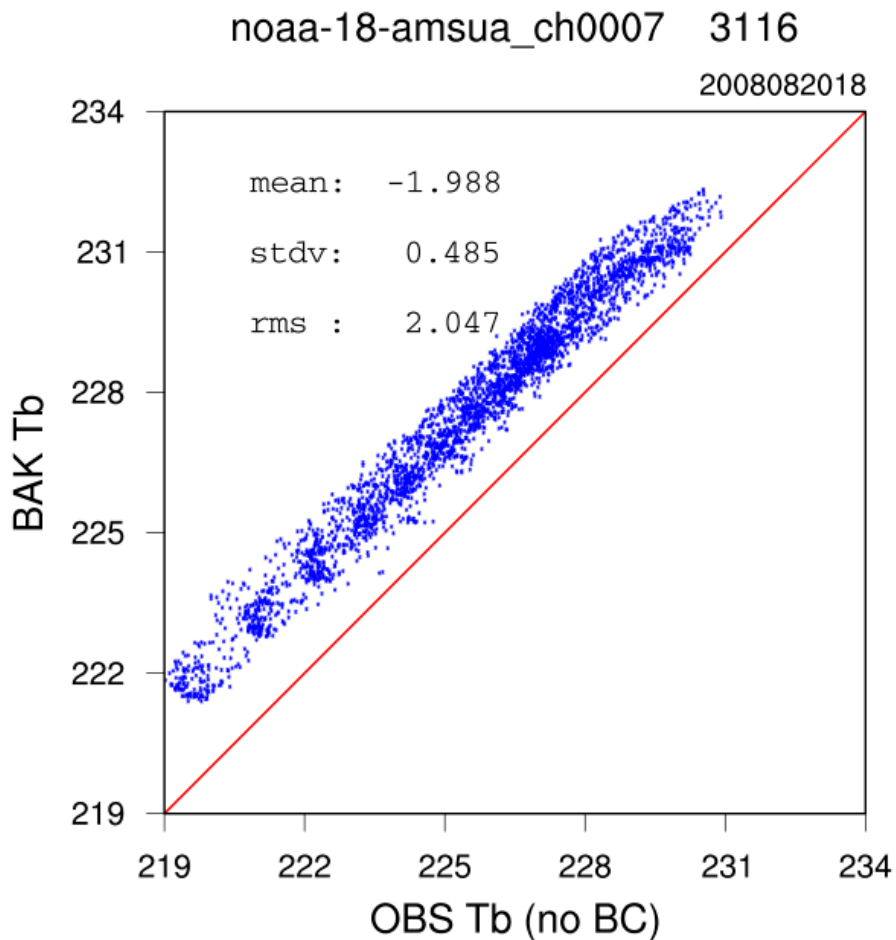
- Bias parameters can be estimated within the **variational assimilation** jointly with the atmospheric model state (Derber and Wu 1998; Dee 2005; Auligné et al. 2007)
- Inclusion of the bias parameters in the control vector : $x^T \rightarrow [x, \beta]^T$

$$\begin{aligned} & \text{J}_b: \text{background term for } x & \text{J}_o: \text{corrected observation term} \\ & \underbrace{(\mathbf{x}_b - \mathbf{x})^T \mathbf{B}_x^{-1} (\mathbf{x}_b - \mathbf{x})}_{\text{J}_b} + \underbrace{[\mathbf{y} - H(\mathbf{x}) - B(\beta)]^T \mathbf{R}^{-1} [\mathbf{y} - H(\mathbf{x}) - B(\beta)]}_{\text{J}_o} \\ & + \underbrace{(\beta_b - \beta)^T \mathbf{B}_\beta^{-1} (\beta_b - \beta)}_{\text{J}_p} \end{aligned}$$

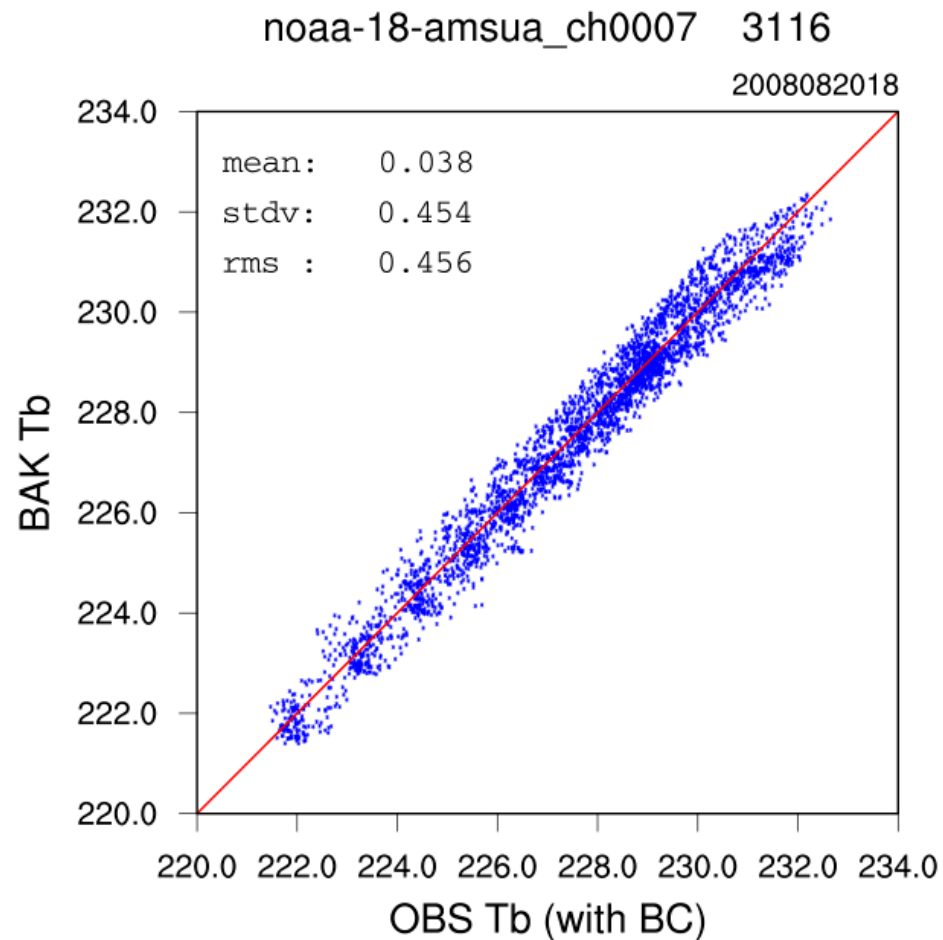
J_p: background term for β

- 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**

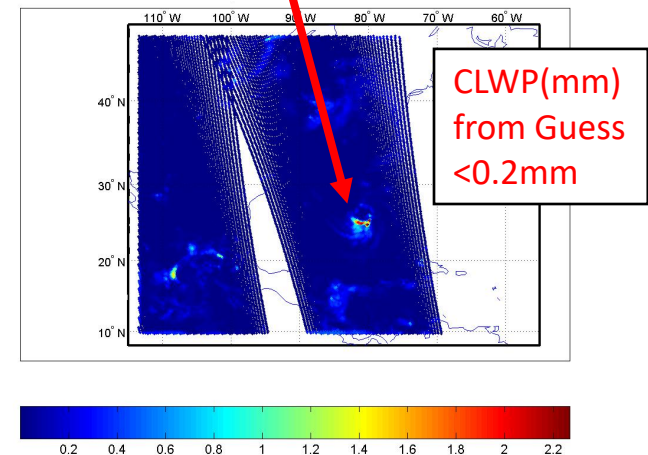
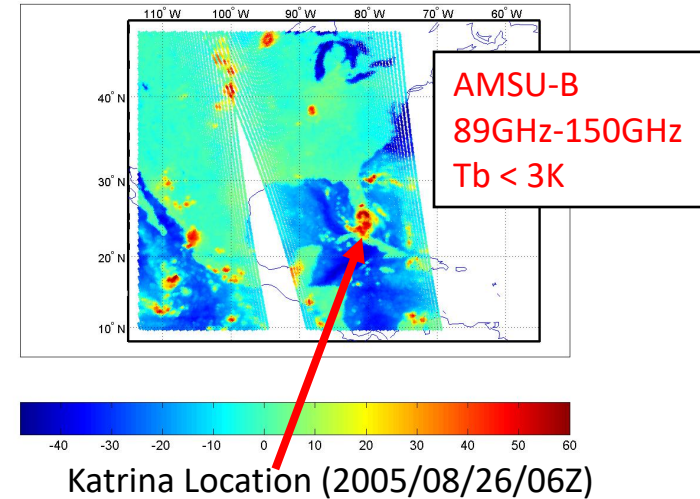
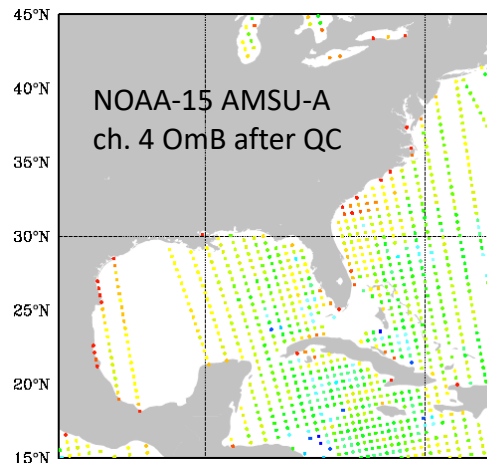
AMSU-A, AMSU-B, MHS, SSMIS, AIRS, AMSR2...

- **Pixel-level QC**

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

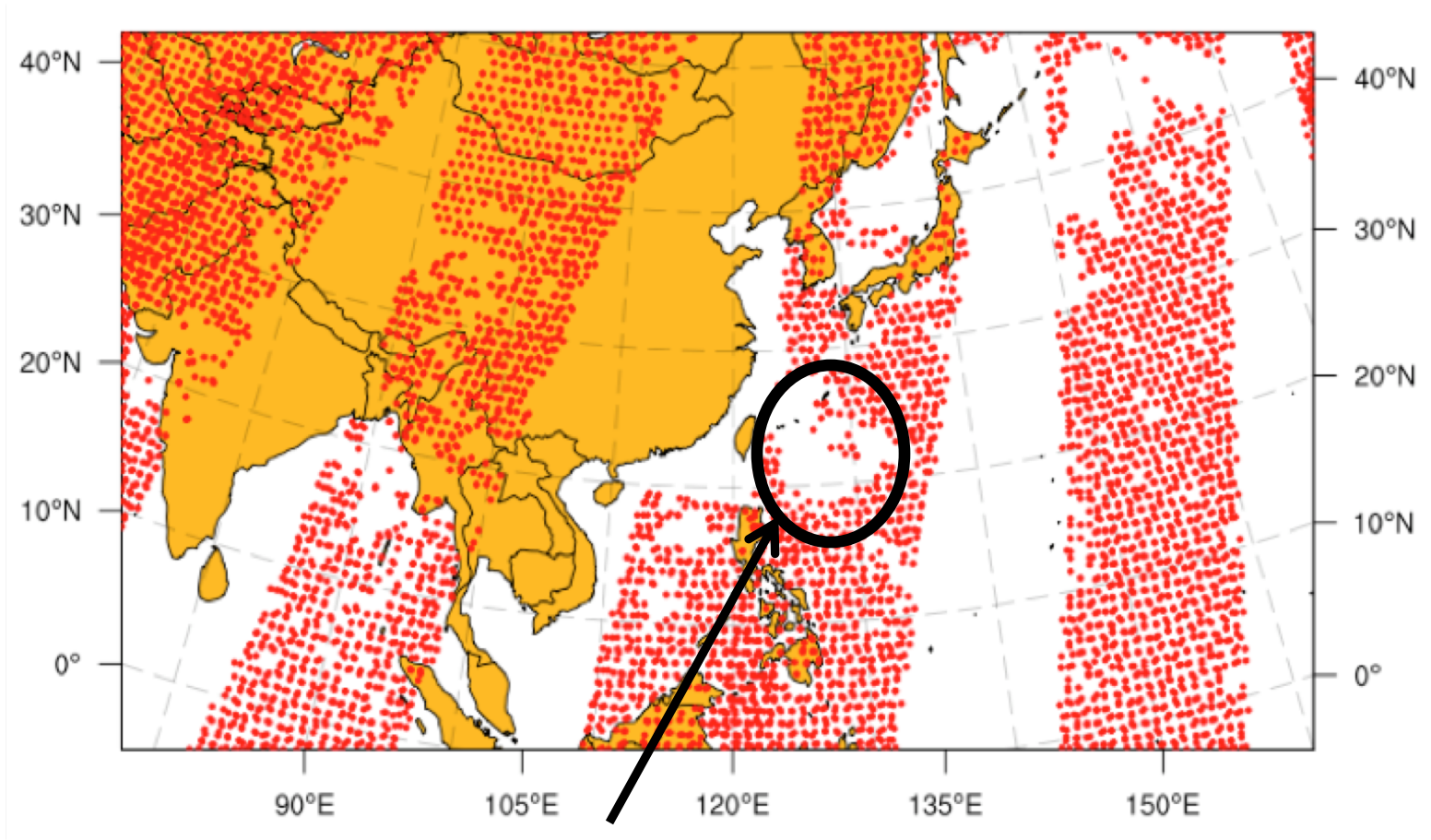
- **Channel-level QC**

- **Gross check**
(innovations < 15 K)
- **First-guess check**
(innovations $< 3\sigma_0$).



Quality Control (QC)

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

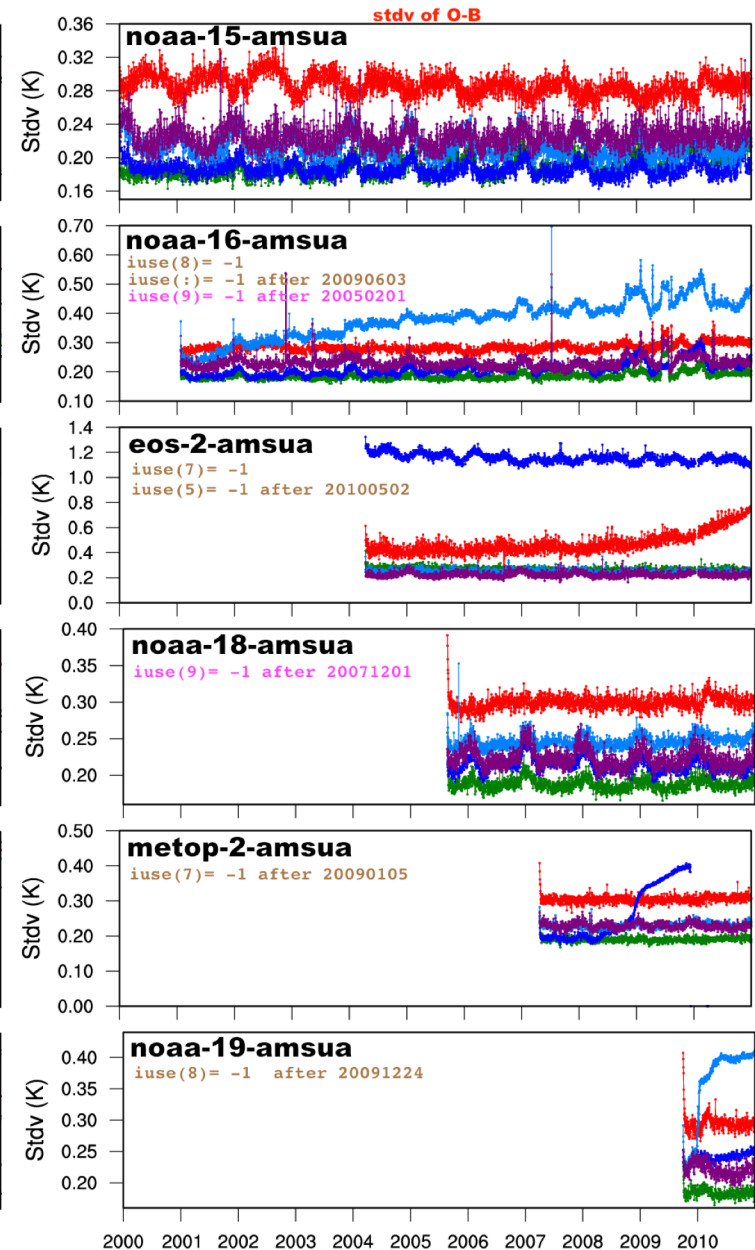
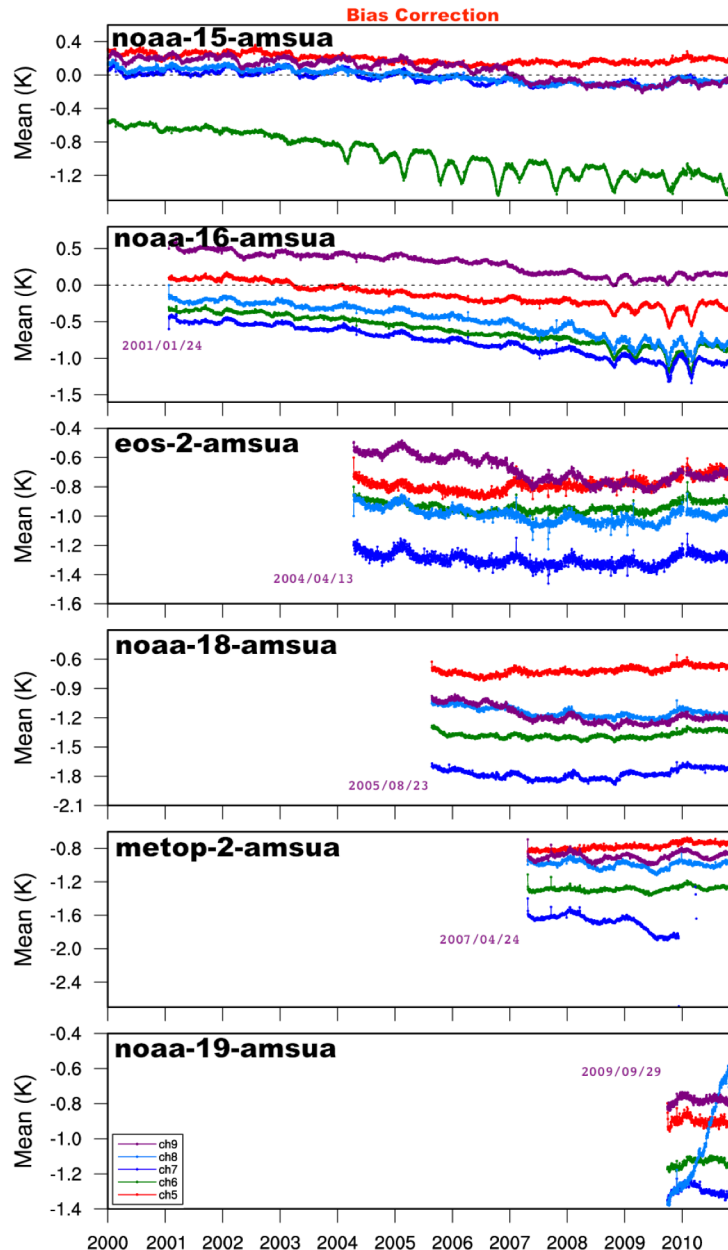


Location of a typhoon—precipitating there, so no clear-sky radiances assimilated over that area

Quality control

monitoring and blacklisting

Global
radiance
monitoring
against
ERA-
Interim



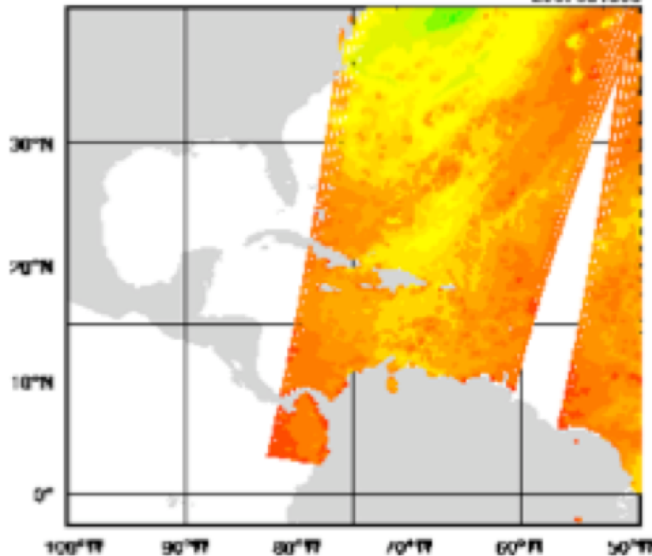
Data Thinning

- 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

No Thinning

noaa-16-amsr2b ch0001 OBS 19669/20799

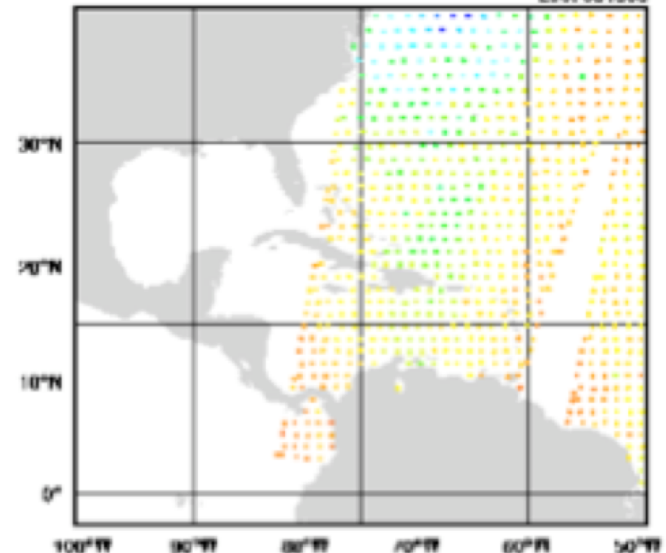
200/0815:06



120km Thinning Mesh

noaa-16-amsr2b ch0001 OBS 693/919

200/0815:06



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 A/B: MWTS and MWHS, CMA binary format
- FY-3 C/D: MWHS2, HDF format
- GOES-Imager in NC format
- Himawari-AHI in NC 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/qdas.\\${yyyymmdd}](http://www.ftp.ncep.noaa.gov/data/nccf/com/gfs/prod/qdas.${yyyymmdd})

NOAA archive: <http://nomads.ncdc.noaa.gov/data/qdas>

NCAR CISL archive: <http://rda.ucar.edu/datasets/ds735.0>

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

NCEP naming convention

gdas.thhz.1bamua.tm00.bufr_d
gdas.thhz.1bamub.tm00.bufr_d
gdas.thhz.1bhrs3.tm00.bufr_d
gdas.thhz.1bhrs4.tm00.bufr_d
gdas.thhz.1bmhs.tm00.bufr_d
gdas.thhz.airsev.tm00.bufr_d
gdas.thhz.atms.tm00.bufr_d
gdas.thhz.mtiasi.tm00.bufr_d
gdas.thhz.sevcsr.tm00.bufr_d

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

WRFDA naming convention

amsua.bufr
amsub.bufr
hirs3.bufr
hirs4.bufr
mhs.bufr
airs.bufr
atms.bufr
iasi.bufr
seviri.bufr

JAXA AMSR2 radiance HDF5 data

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

JAXA naming convention

GW1AM2_201210271433_082A_L1SGRTBR_1110110.h5

WRFDA naming convention

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_iasobs	
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

seviri_m10.SpcCoeff.bin

amsua_n19.SpcCoeff.bin

RTTOV

rtcoef_msg_3_seviri.dat

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

https://www.nwpsaf.eu/site/download/documentation/rtm/docs_rttov12/users_guide_rttov12_v1.3.pdf Tables 2 and 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
(AMS2 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-2.3.0
- Version included in WRFDA: CRTM REL-2.3.0
- CRTM code included in WRFDA, but you have to get the coefficients:
 - http://www2.mmm.ucar.edu/wrf/users/wrfda/download/crtm_coeffs.html (a subset)
 - ftp://ftp.emc.ncep.noaa.gov/jcsda/CRTM/REL-2.2.3/crtm_v2.2.3.tar.gz (full set)

1 = RTTOV (Radiative Transfer for TOVS)

- EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites)
- Latest released version: RTTOV 12.3, and RTTOV 12.3 is used in WRFDA

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** is an ASCII file controlling what goes into 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

6 6 0 0 0 0 0 0 0

7 7 0 0 0 0 0 0 0

8 8 0 0 0 0 0 0 0

9 9 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

4 4 0 0 0 0 0 0 0

5 5 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)

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)

In -sf WRFDA/run/LANDUSE.TBL ./LANDUSE.TBL

In -sf \$DAT_DIR/rc/2007010200/wrfinput_d01 ./fg (link first guess file as fg)

In -sf WRFDA/var/obsproc/obs_gts_2007-01-02_00:00:00.3DVAR ./ob.ascii (link OBSPROC processed observation file as ob.ascii)

In -sf \$DAT_DIR/be/be.dat ./be.dat (link background error statistics as be.dat)

In -sf WRFDA/var/da/da_wrfvar.exe ./da_wrfvar.exe (link executable)

In -sf \$DAT_DIR/2007010200/gdas1.t00z.1bamua.tm00.bufr_d ./amsua.bufr (link radiance bufr files)

In -sf WRFDA/var/run/radiance_info ./radiance_info (radiance_info is a directory)

In -sf WRFDA/var/run/VARBC.in ./VARBC.in

(CRTM only) > In -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) > In -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

```

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    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

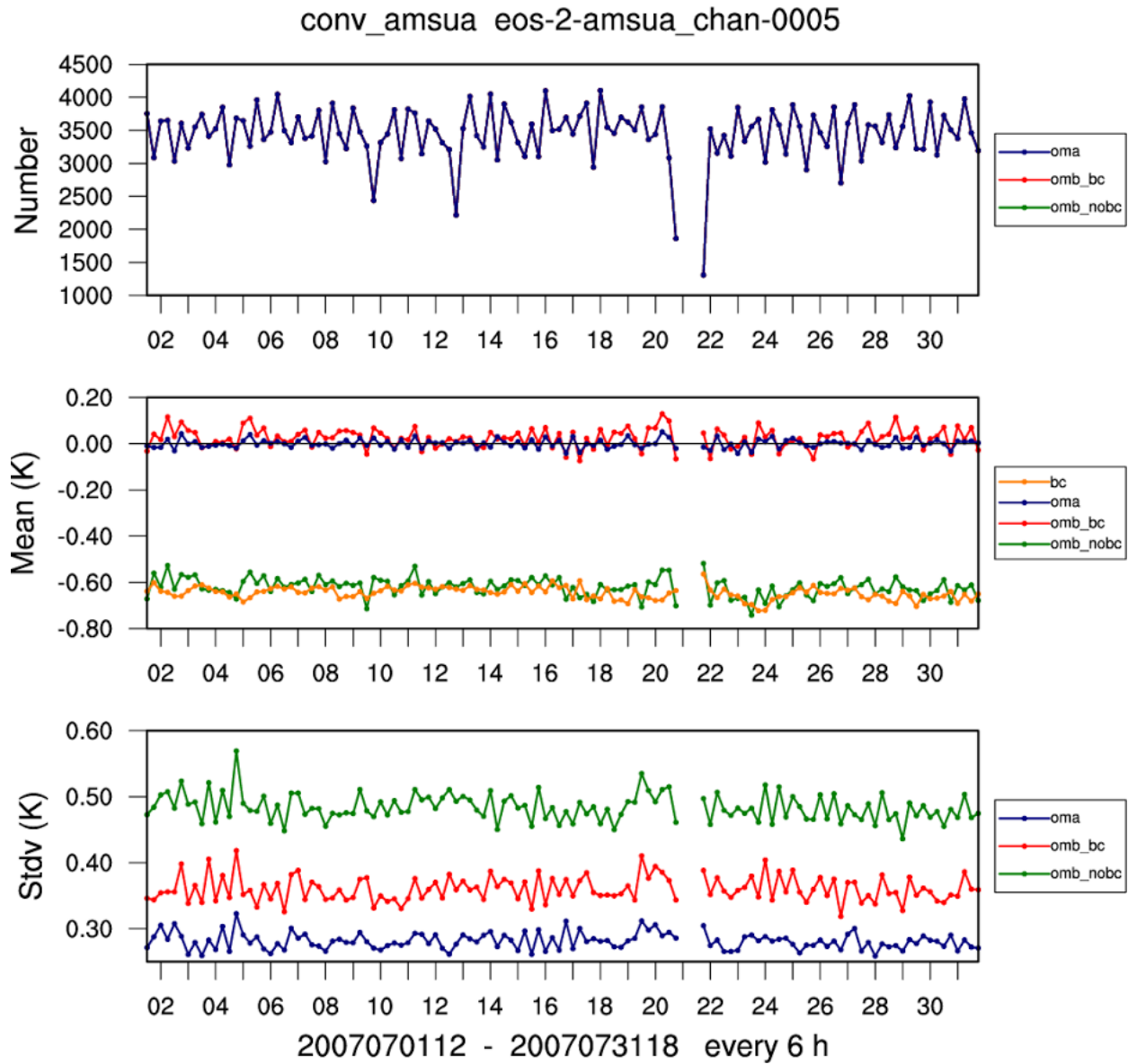
noaa-19-amsua

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 brightness temp, 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, QCd or no-QCd observations



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

References

- Liu, Z., C. S. Schwartz, C. Snyder, and S.-Y. Ha, 2012: Impact of assimilating AMSU-A radiances on forecasts of 2008 Atlantic tropical cyclones initialized with a limited-area ensemble Kalman filter. *Mon. Wea. Rev.*, **140**, 4017–4034, doi:10.1175/MWR-D-12-00083.1.
- Schwartz, C. S., Z. Liu, Y. Chen, and X.-Y. Huang, 2012: Impact of assimilating microwave radiances with a limited-area ensemble data assimilation system on forecasts of typhoon Morakot. *Wea. Forecasting*, **27**, 424–437, doi:10.1175/WAF-D-11-00033.1.
- Yang, C., Z. Liu, J. Bresch, S. R. H. Rizvi, X. Huang and J. Min, 2016: AMSR2 all-sky radiance assimilation and its impact on the analysis and forecast of Hurricane Sandy with a limited-area data assimilation system. *Tellus A*, **68**, 30917.
- Yang, C., Z. Liu, F. Gao, P. P. Childs, and J. Min (2017), Impact of assimilating GOES imager clear-sky radiance with a rapid refresh assimilation system for convection-permitting forecast over Mexico, *J. Geophys. Res. Atmos.*, **122**, 5472–5490, doi:10.1002/2016JD026436.
- Wang, Y., Liu, Z., Yang, S., Min, J., Chen, L., Chen, Y., and Zhang, T., (2018). Added value of assimilating Himawari-8 AHI water vapor radiances on analyses and forecasts for “7.19” severe storm over north China. *J. Geophys. Res. Atmos.*, **123**, <https://doi.org/10.1002/2017JD027697>.