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Observations (3):
Satellite Radiance Data Assimilation

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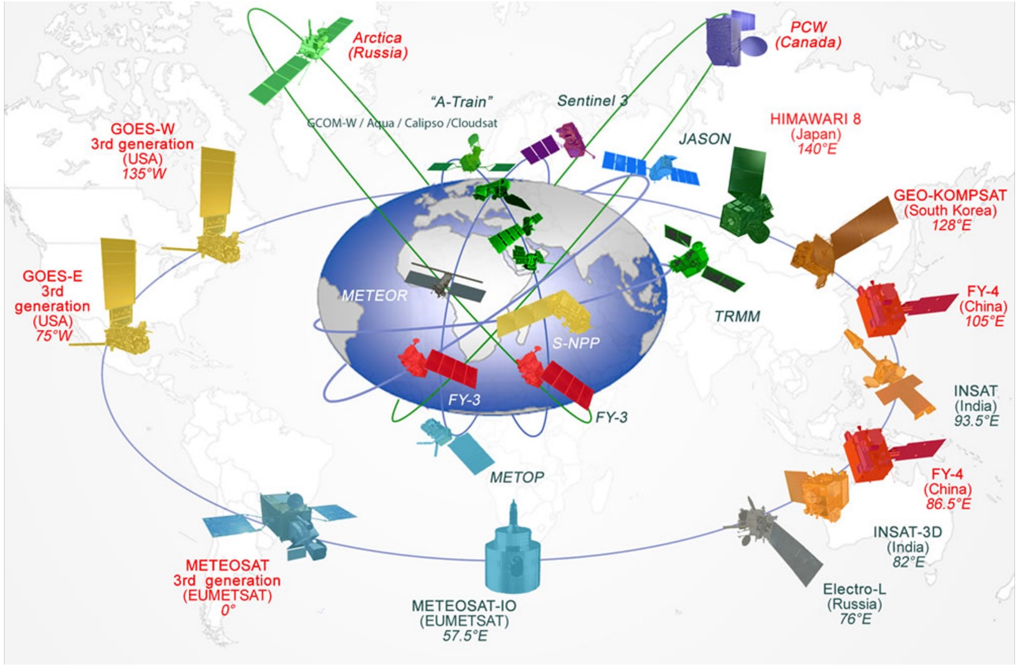
MONAN: INPE MPAS-JEDI Training 2024, Cachoeira Paulista, São Paulo, Brazil
August 15-16, 2024

Outline

1. Background
2. Principles of satellite measurements
3. Radiative Transfer Model
4. Radiance DA setting with MPAS-JEDI
5. Variational Bias Correction
6. All-sky radiance DA

Background

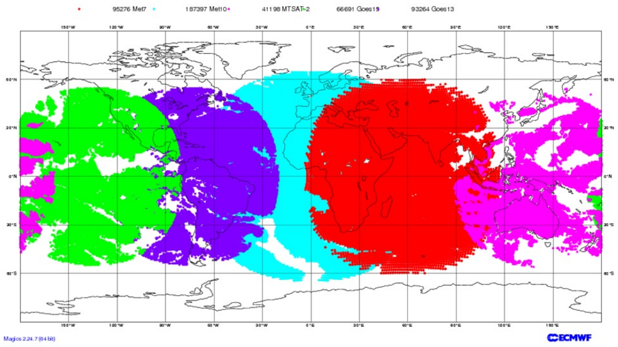
Environmental monitoring satellites



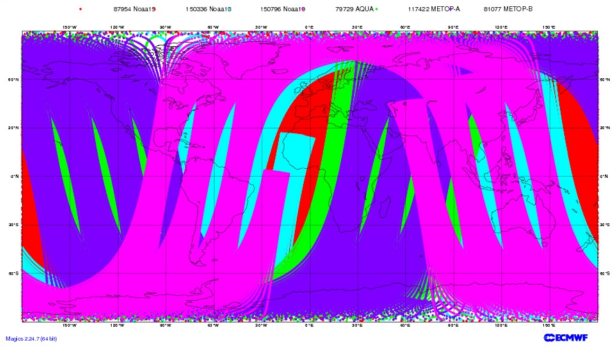
Polar-orbiting satellites vs. Geostationary satellites

Background

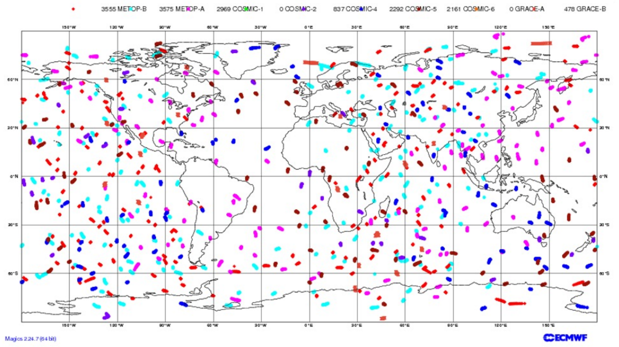
ECMWF data coverage for 06 UTC 05/Jul/2015 (All obs DA)



GRAD
Total obs: 483826



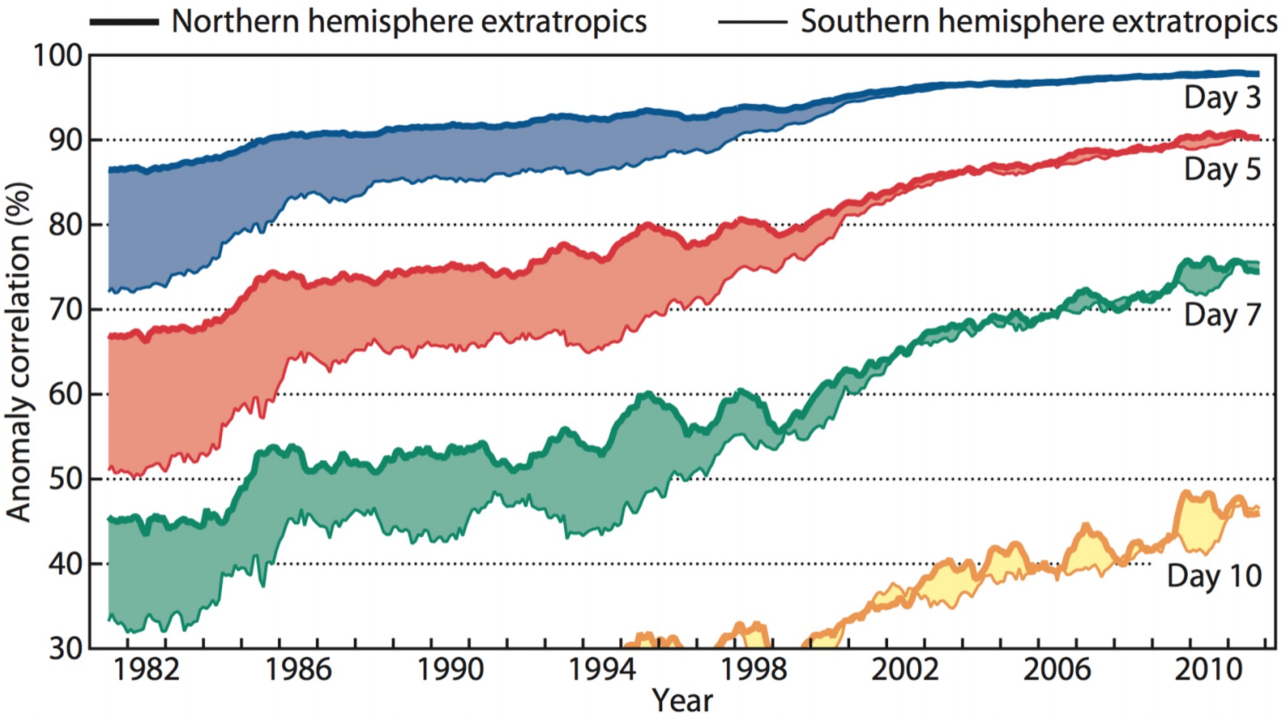
AMSU-A
Total obs: 777314



GPSRO
Total obs: 15867

Background

Global forecast improvement over time at ECMWF 2012



Background

Current status (2023) of satellite radiance DA at ECMWF

(Courtesy of Niels Bormann, ITSC-24)

Satellite	Present orbit position (LTAN, approx.)	MW temperature sounder	MW humidity sounder	MW imager	IR broadband sounder or imager	IR hyper-spectral sounder
NOAA-15	19:30	A 🌦	X		X	
NOAA-18	22:30	A 🌦	X		X	
NOAA-19	20:30	A 🌦	A 🌦		P	
NOAA-20	13:30	A	A			A
NOAA-21	13:30	E	E			
Aqua	13:30	X	X			A
S-NPP	13:30	A	A			A
Metop-B	21:30	A 🌦	A 🌦		X	A
Metop-C	21:30	A 🌦	A 🌦			A
FY-3C	19:00	X	A 🌦	X		
FY-3D	14:00	P 🌦	A 🌦	P 🌦 & X		E
FY-3E	17:30	E 🌦	A 🌦			
DMSP-F17	18:30		A 🌦	A 🌦		
DMSP-F18	16:00		A 🌦	P 🌦 & E		
GCOM-W1	13:30			A 🌦		
GPM	Mid-incl.		A 🌦	A 🌦		
Meteosat-9	45.5ºE				A	
Meteosat-11	0º				A	
GOES-16	75.2ºW				A	
GOES-18	137ºW				A	
Himawari-9	140.7ºE				A	
FY-4A	104.7ºE					E
FY-4B	133ºE					E

A – Assimilated; P – Passively monitored; E – Under evaluation; X – Failed or data excluded due to quality/transmission issues; 🌦 – All-sky treatment

Changes since ITSC-23 are highlighted through orange shading.

Principles of satellite measurements

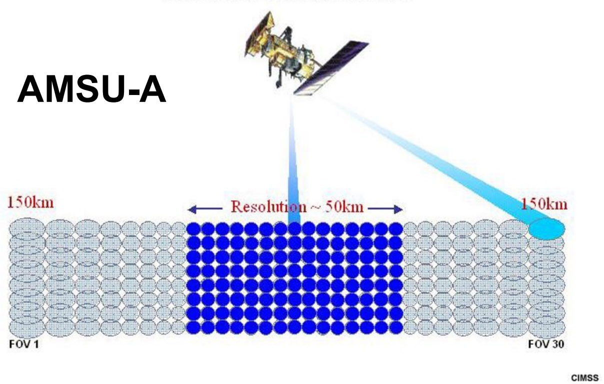
Types of sensors → Passive | Active | GNSS radio occultation

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

AMSU-A



conical scan

- Constant ground resolution
- Generally narrower swaths than cross-track scan swaths

GMI

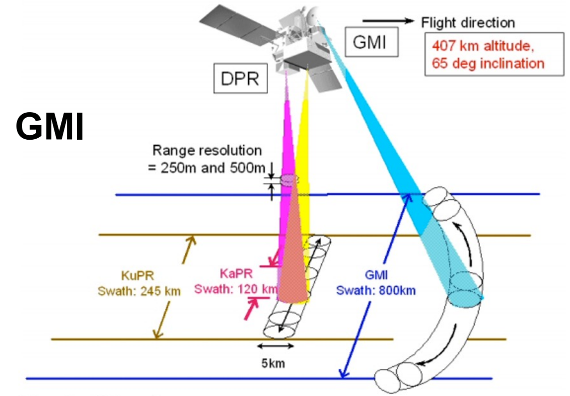
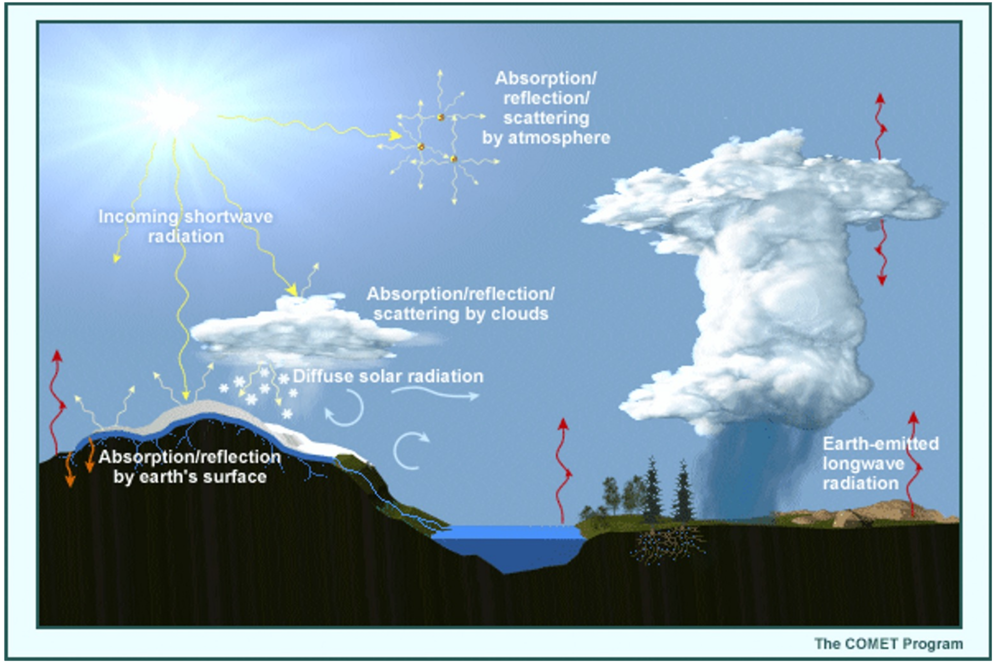


Figure 2. GPM swath measurements

Principles of satellite measurements

What do satellite instruments measure?

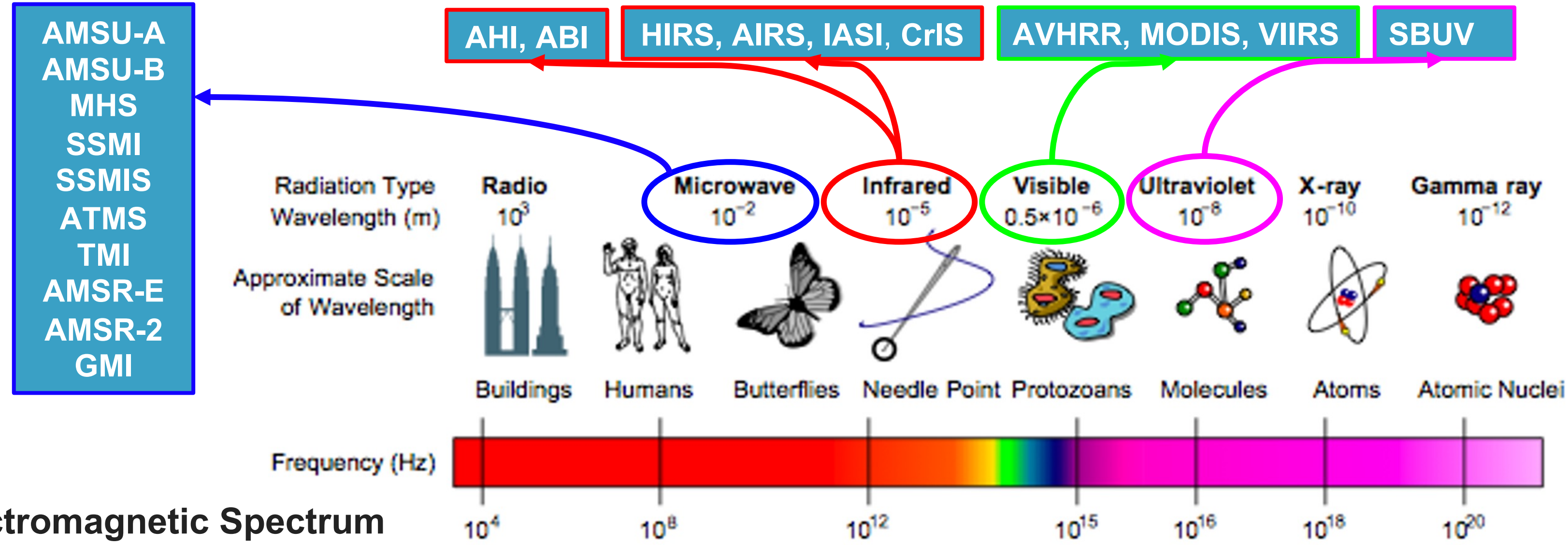
- **Satellite passive sensors** observe radiation emitted and scattered from Earth's surface and atmosphere at discrete wavelength intervals



Principles of satellite measurements

What do satellite instruments measure?

⇒ Different sensors measure radiation at different wavelengths (e.g., MW, IR, VIS)



Electromagnetic Spectrum

Principles of satellite measurements

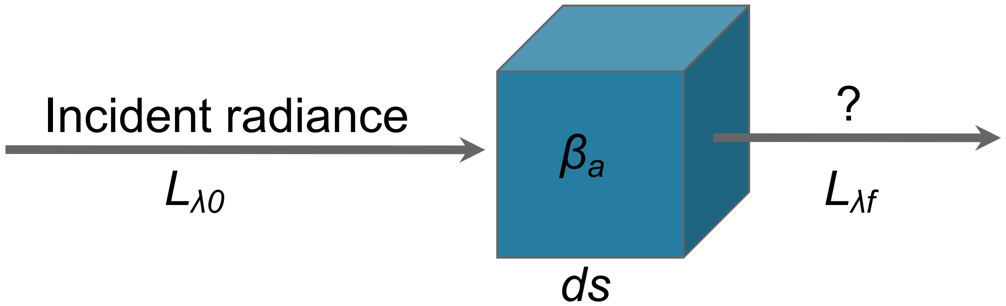
What is radiance?

- Radiance (L) is the amount of energy per unit area per unit time per unit solid angle emitted at a wavelength λ (or frequency v)
  - Recall, c = λv, 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)

Principles of satellite measurements

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 on the other side of the surface?



Principles of satellite measurements

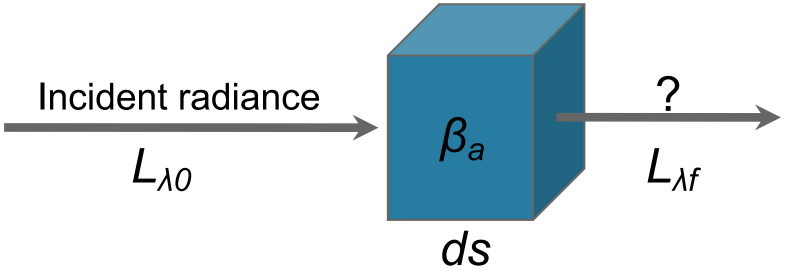
Atmospheric Transmittance

- 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:

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



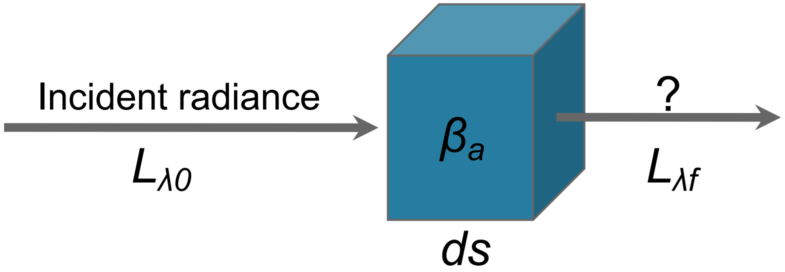
Principles of satellite measurements

Atmospheric Transmittance

- 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:

$$a_\lambda + \tau_\lambda = 1$$



Radiative Transfer Model

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

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

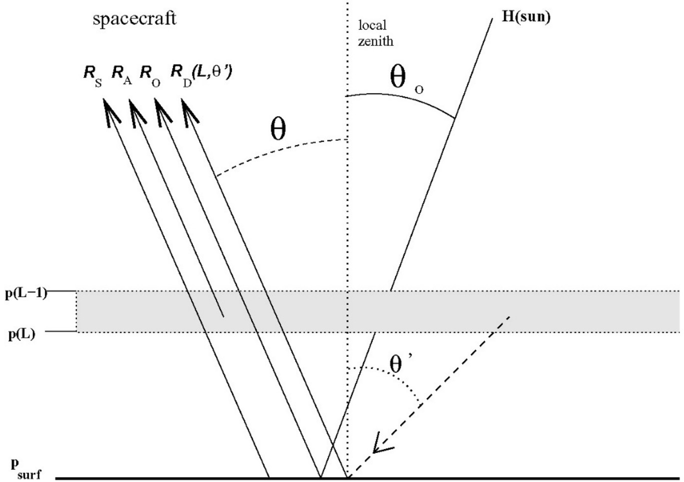
Surface emission R_s

Upwelling atmosphere emission R_A

Reflected solar radiation R_O

Down-welling & reflected atmos.

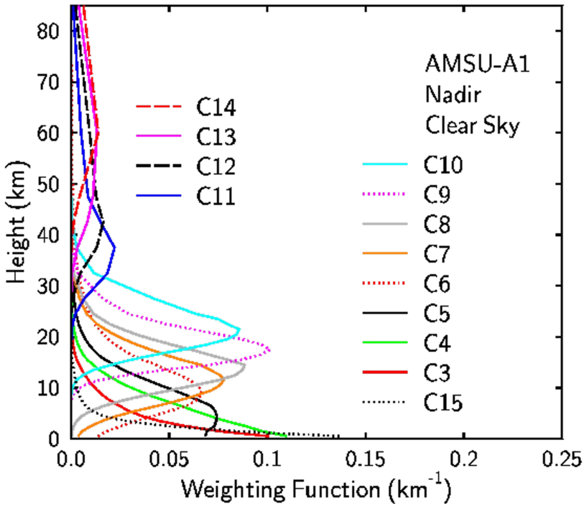
Emission (R_D)



Radiative Transfer Model

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)
- **Window channels** are sensitive to properties associated with earth and ocean surfaces as well as clouds

Radiance DA setting with MPAS-JEDI

YAML setting for radiative transfer model

```yaml
_clear crtm: &clearCRTMObsOperator
  name: CRTM
  SurfaceWindGeoVars: uv
  Absorbers: [H2O, O3]
  linear obs operator:
    Absorbers: [H2O]
  obs options: &CRTMObsOptions
    EndianType: little_endian
    CoefficientPath: ./crtm_coeffs_v2/
    IRVISlandCoeff: USGS
```

```yaml
- obs space:
    <<: *ObsSpace
    name: amsua_n18
    obsdatain:
      engine:
        type: H5File
        obsfile: ./amsua_n18_obs_2018041500.h5
    obsdataout:
      engine:
        type: H5File
        obsfile: ./obsout_da_amsua_n18.h5
    simulated variables: [brightnessTemperature]
    channels: &amsua_n18_channels 1-15
  obs error: *ObsErrorDiagonal
  obs operator:
    <<: *clearCRTMObsOperator
    obs options:
      <<: *CRTMObsOptions
      Sensor_ID: amsua_n18
  get values:
```

Radiance DA setting with MPAS-JEDI

YAML settings for channel selection and quality control

```yaml
  obs filters:
  - filter: PreQC
    maxvalue: 0
#  Useflag check #amsua-n18
  - filter: Bounds Check
    filter variables:
    - name: brightnessTemperature
      channels: *amsua_n18_channels
    test variables:
    - name: ObsFunction/ChannelUseflagCheckRad
      channels: *amsua_n18_channels
      options:
        channels: *amsua_n18_channels
        use_flag: [-1, -1, -1, -1,  1,
                    1,  1,  1,  1, -1,
                   -1, -1, -1, -1, -1 ]
    minvalue: 1.0e-12
    action:
      name: reject
  - filter: Background Check
    threshold: 3.0
    <<: *multiIterationFilter
```

Much more you can set
for quality control, but not able
to cover too much this time

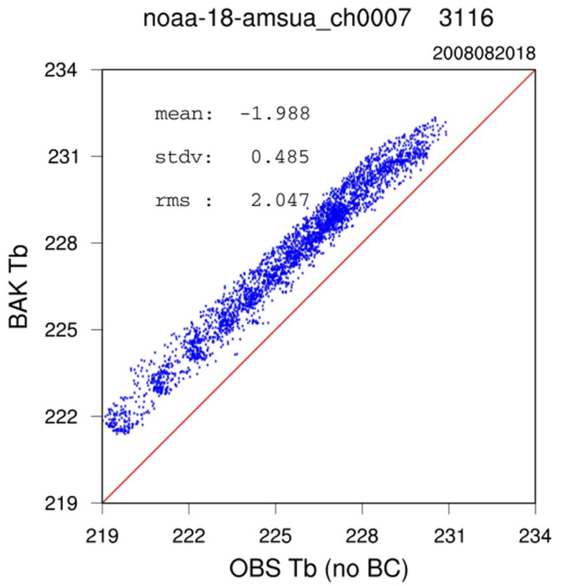
Variational Bias Correction (VarBC)

Modeling errors for satellite radiances

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

Bias-correction coefficients

Predictors: e.g.,
- **Offset (i.e., 1)**
- **Temperature lapse rate**
- **Scan, Scan^2, Scan^3**



J_b: background term for x
J_o: corrected observation term

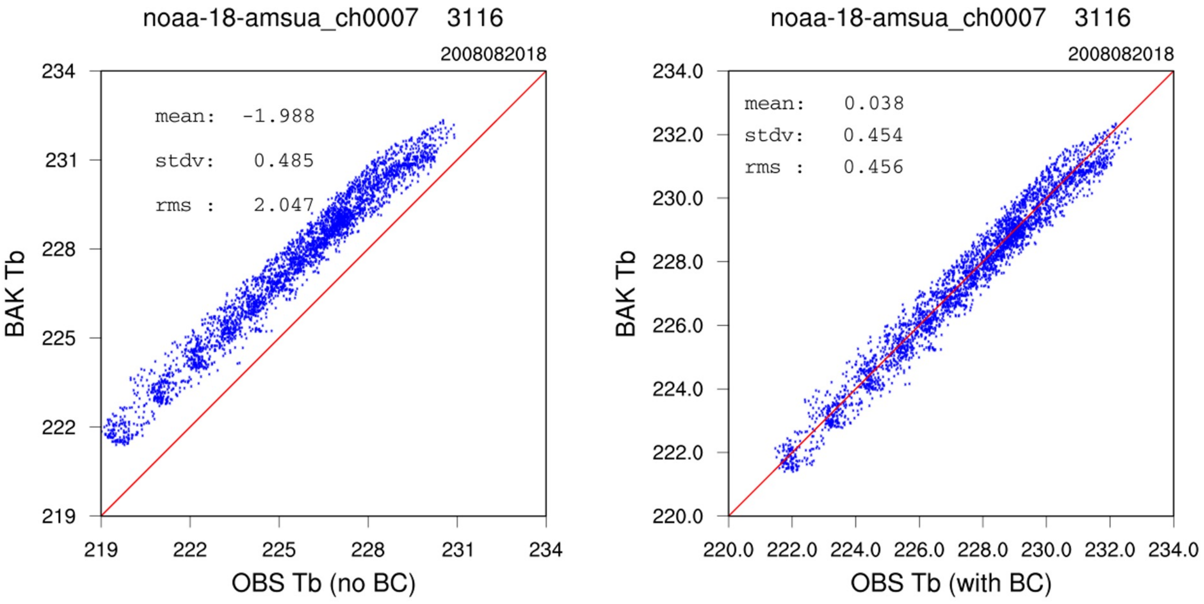
$$\mathbf{J}(\mathbf{x},\beta) = \underbrace{(\mathbf{x}_b - \mathbf{x})^T \mathbf{B}_x^{-1} (\mathbf{x}_b - \mathbf{x})}_{J_b} + \underbrace{[\mathbf{y} - H(\mathbf{x}) - B(\beta)]^T \mathbf{R}^{-1} [\mathbf{y} - H(\mathbf{x}) - B(\beta)]}_{J_o}$$
$$+ \underbrace{(\beta_b - \beta)^T \mathbf{B}_\beta^{-1} (\beta_b - \beta)}_{J_p}$$

J_p: background term for β

Variational Bias Correction (VarBC)

Modeling errors for satellite radiances

No bias correction



With bias correction

Variational Bias Correction (VarBC)

JEDI's bias correction coefficient file

```
netcdf satbias_amsua_n18 {
dimensions:
        nchannels = 15 ;
        npredictors = 12 ;
variables:
        float bias_coeff_errors(npredictors, nchannels) ;
        float bias_coefficients(npredictors, nchannels) ;
        int channels(nchannels) ;
        int nchannels(nchannels) ;
                nchannels:suggested_chunk_dim = 15LL ;
        int npredictors(npredictors) ;
                npredictors:suggested_chunk_dim = 12LL ;
        float number_obs_assimilated(nchannels) ;
        string predictors(npredictors) ;

// global attributes:
                string :_ioda_layout = "ObsGroup" ;
                :_ioda_layout_version = 0 ;
```

satbias_amsua_n18.h5
satbias_cov_mhs_n18.h5

```
predictors = "constant", "zenith_angle", "cloud_liquid_water",
   "lapse_rate_order_2", "lapse_rate",
   "cosine_of_latitude_times_orbit_node", "sine_of_latitude", "emissivity",
   "scan_angle_order_4", "scan_angle_order_3", "scan_angle_order_2",
   "scan_angle" ;
```

Variational Bias Correction (VarBC)

YAML setting for VarBC

```yaml
obs bias:
  input file: {{biasCorrectionDir}}/satbias_amsua_n18.h5
  output file: {{OutDBDir}}{{MemberDir}}/satbias_amsua_n18.h5
  variational bc:
    predictors: &predictors3
    - name: constant
    - name: lapse_rate
      order: 2
      tlapse: &amsua18tlap {{fixedTlapmeanCov}}/amsua_n18_tlapmean.txt
    - name: lapse_rate
      tlapse: *amsua18tlap
    - name: emissivity
    - name: scan_angle
      order: 4
    - name: scan_angle
      order: 3
    - name: scan_angle
      order: 2
   covariance:
     minimal required obs number: 20
     variance range: [1.0e-6, 10.]
     step size: 1.0e-4
     largest analysis variance: 10000.0
     prior:
       input file: {{biasCorrectionDir}}/satbias_cov_amsua_n18.h5
       inflation:
         ratio: 1.1
         ratio for small dataset: 2.0
     output file: {{OutDBDir}}{{MemberDir}}/satbias_cov_amsua_n18.h5
```

$$B(\beta) = \sum_{i=1}^{N} \beta_i p_i$$

J_b: background term for x

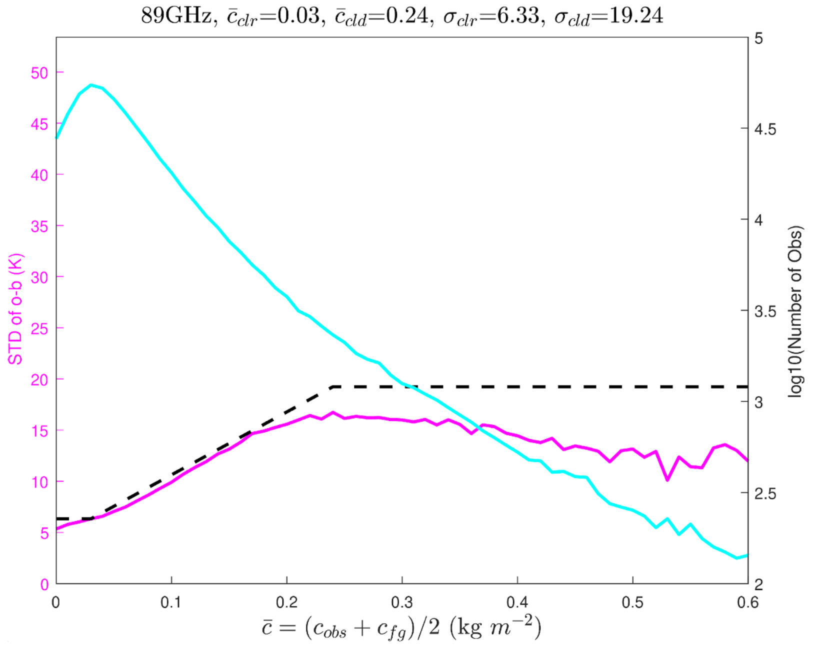
J_o: corrected observation term

$$\mathbf{J}(\mathbf{x},\beta) = \underbrace{(\mathbf{x}_b - \mathbf{x})^T \mathbf{B}_x^{-1} (\mathbf{x}_b - \mathbf{x})}_{J_b} + \underbrace{[\mathbf{y} - H(\mathbf{x}) - B(\beta)]^T \mathbf{R}^{-1} [\mathbf{y} - H(\mathbf{x}) - B(\beta)]}_{J_o}$$
$$+ \underbrace{(\beta_b - \beta)^T \mathbf{B}_\beta^{-1} (\beta_b - \beta)}_{J_p}$$

J_p: background term for β

All-sky radiance DA

Situation-dependent all-sky obs error model

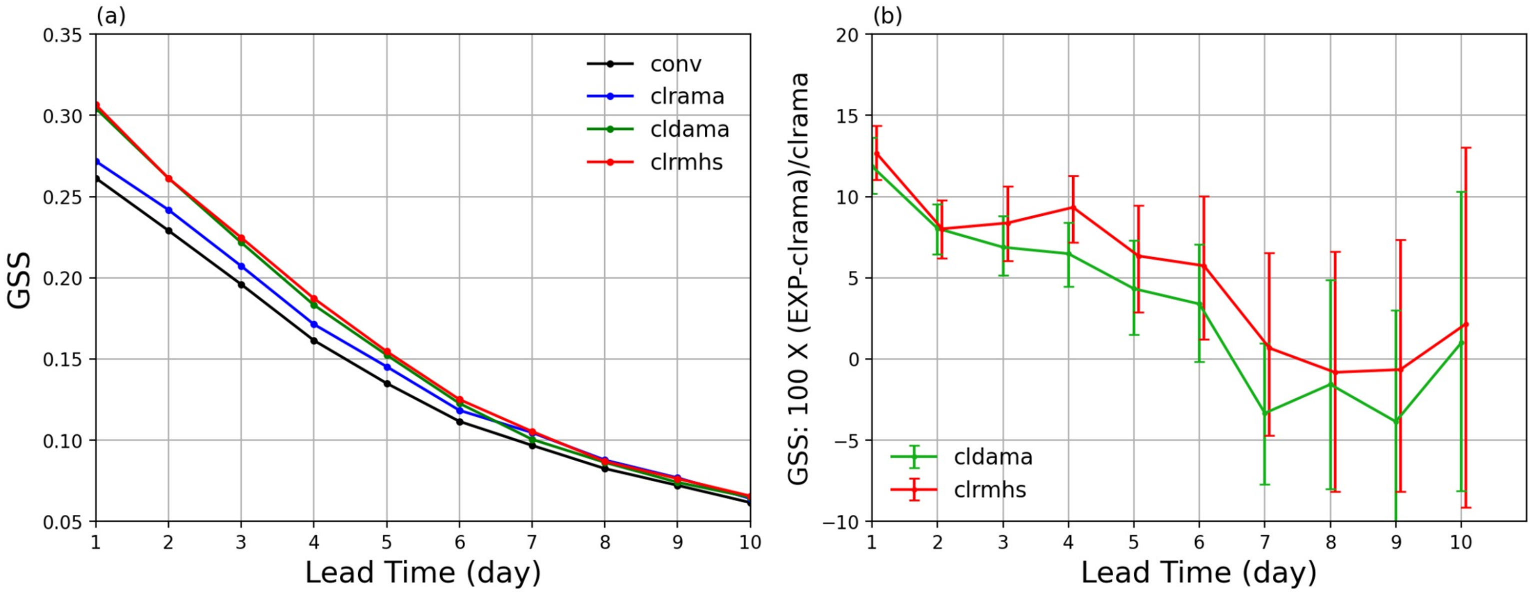


All-sky obs error model for AMSU-A channel 15:

- ❑ Observation error is a function of cloud liquid water path retrieved from channel 1 and 2's brightness temperature

All-sky radiance DA

Gilbert Skill Score of 1-10-day rainfall FC w.r.t. CMORPH obs

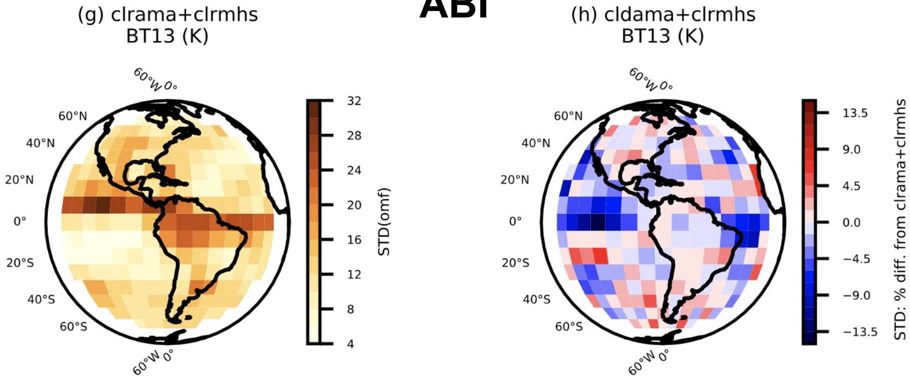


Liu et al., 2022

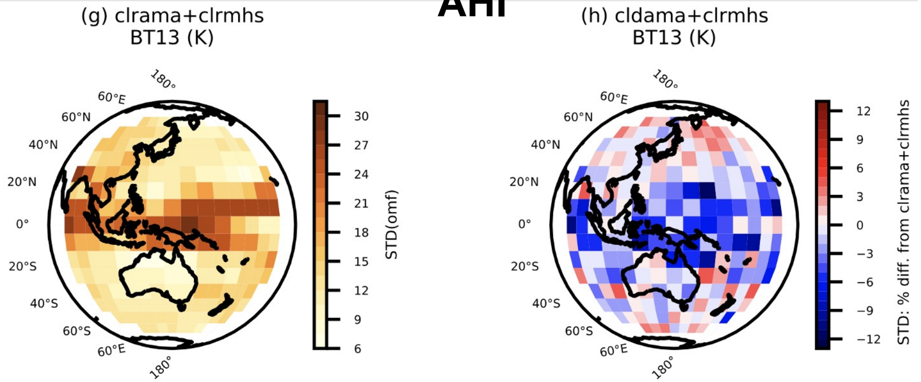
All-sky radiance DA

Added value of all-sky AMSU-A

ABI



AHI



Day-1 forecast

Error STD reduction

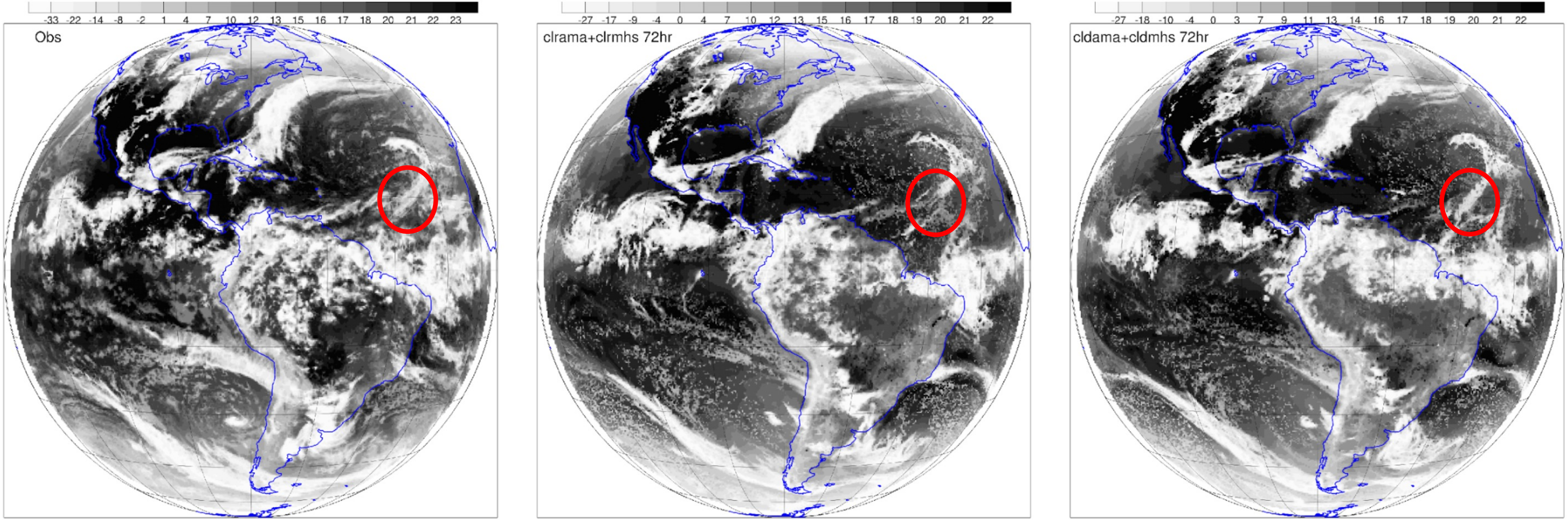
Improvement concentrated in cloudy regions of Tropics Up to 12-14%

All-sky radiance DA

ABI channel 13 BTs (degree C) valid at 00 UTC 9 May 2018

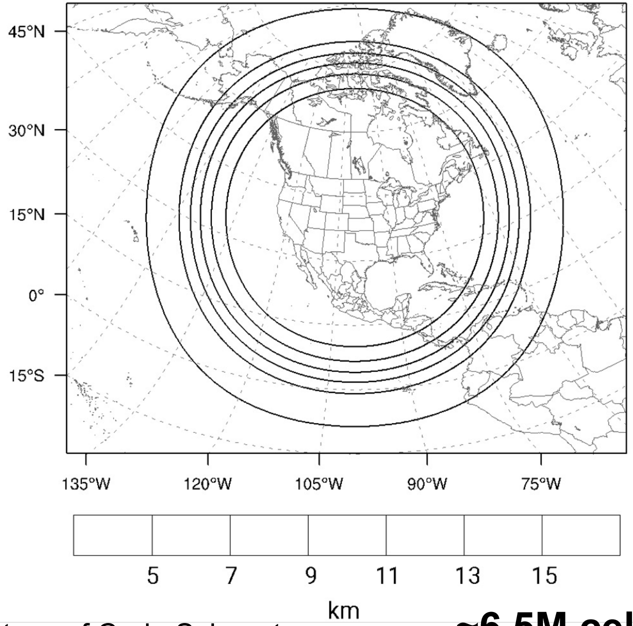
Observations vs. Day-3 forecast

Observations | Clear-sky DA | All-sky DA



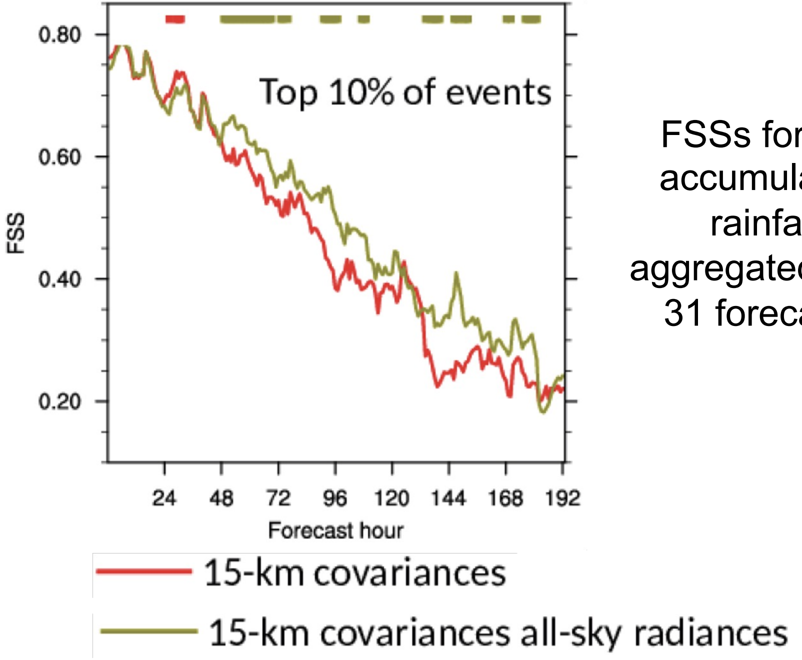
All-sky radiance DA

3DEnVar exps @ global 15km-3km variable-resolution mesh (centered over US) with the 80-member 15km ensemble input



Courtesy of Craig Schwartz

~6.5M cells



FSSs for 1-h accumulated rainfall aggregated over 31 forecasts

Concluding Remarks

- Radiance DA is complex
  - Cloudy radiative transfer, QC, bias correction, all-sky obs error model
  - Different complexity for assimilating different sensors' data

- Much more to explore for satellite DA in general
  - Visible band, near IR, active sensors, small satellites, …

- JEDI framework allows much greater flexibility to configure/tune without code change, ease science discovery
  - e.g., you can combine the use of CRTM and RTTOV in the same run!