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Observations (3):
Satellite Radiance Data Assimilation

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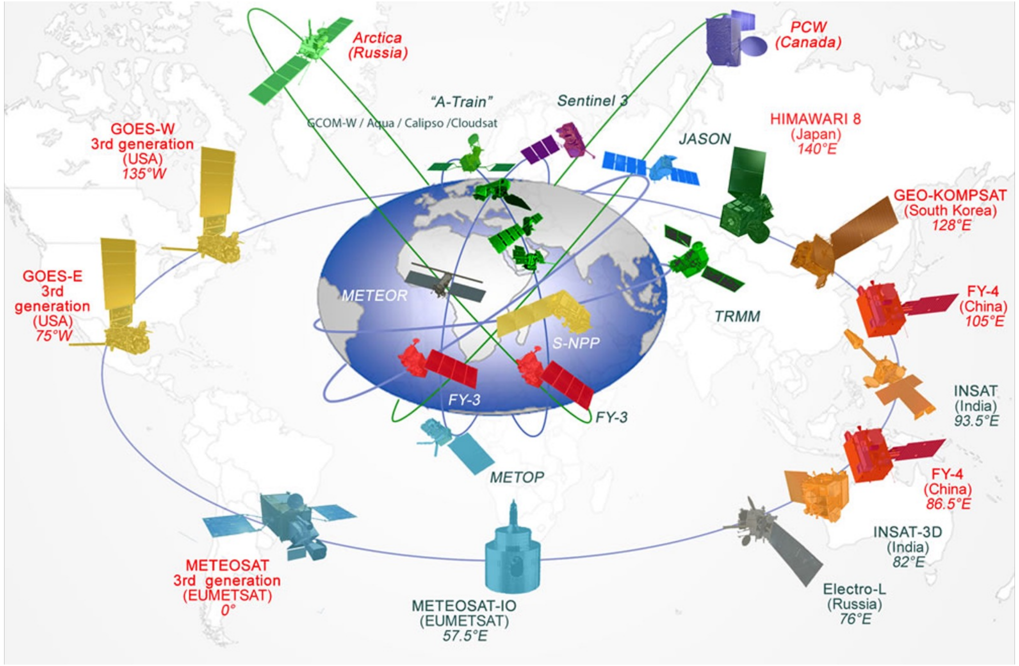
NCAS MPAS-JEDI Tutorial, St Andrews, UK
June 25-26, 2025

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

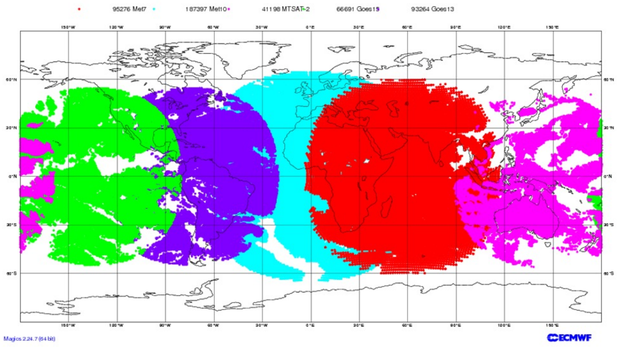
Environmental monitoring satellites



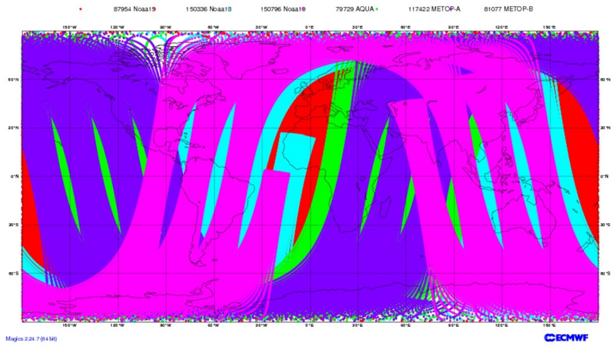
Polar-orbiting satellites vs. Geostationary satellites

Background

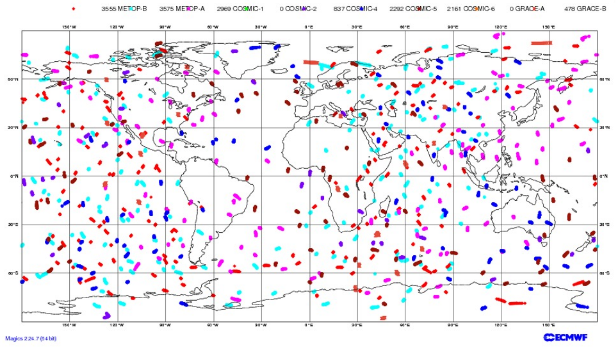
ECMWF data coverage for 06 UTC 05/Jul/2015 (All obs DA)



GRAD
Total obs: 483826

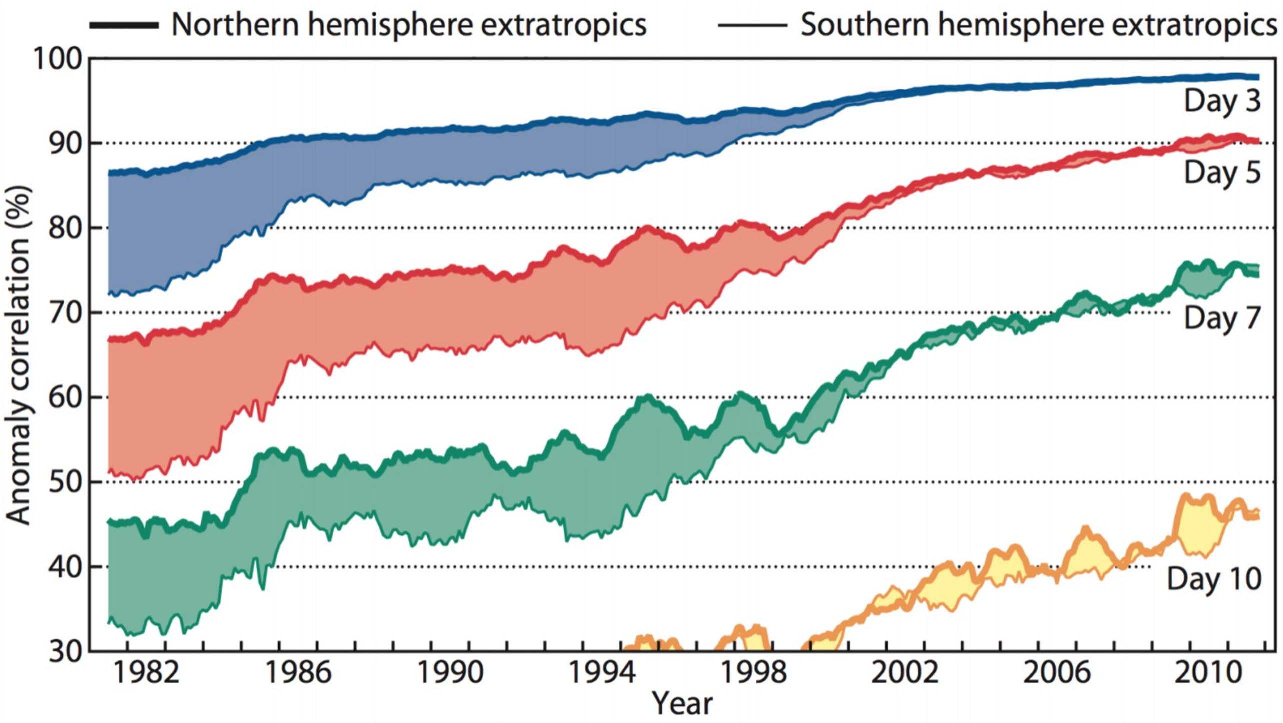


AMSU-A
Total obs: 777314



GPSRO
Total obs: 15867

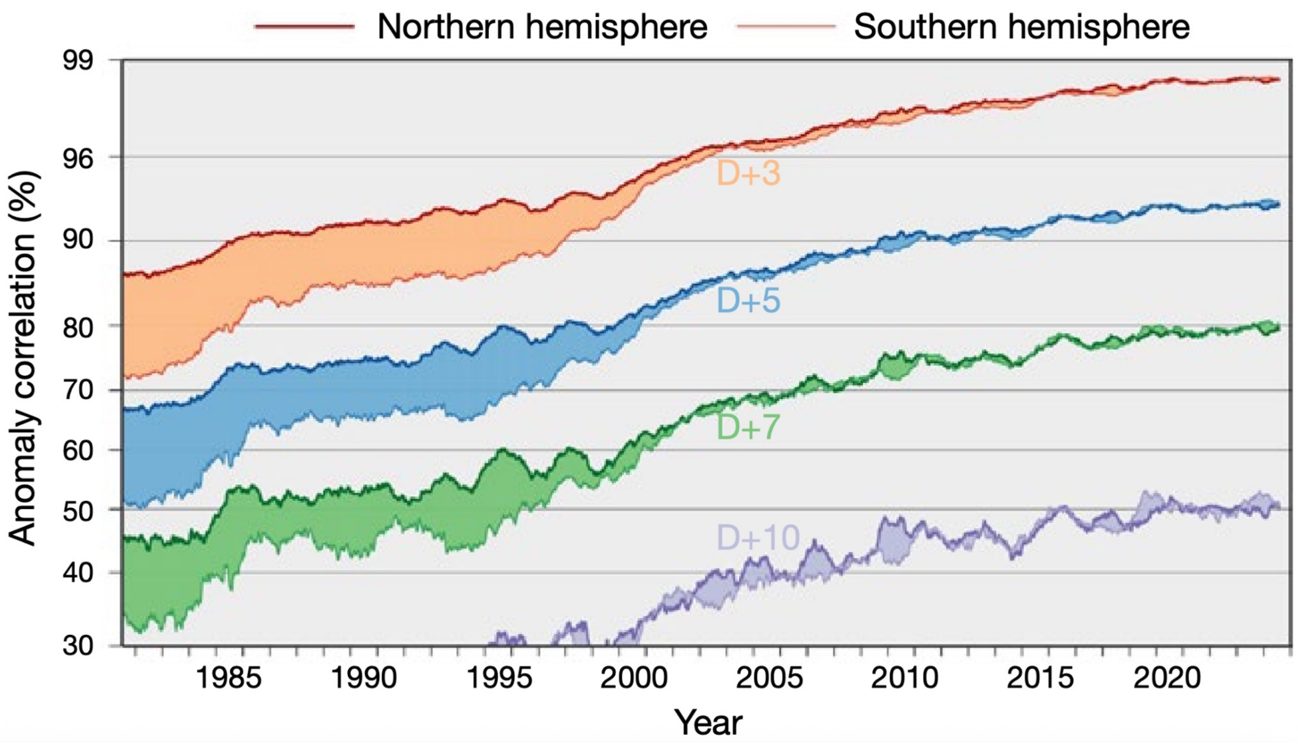
Background



Global forecast improvement over time at ECMWF 2012 (Kirtman et al. 2013)

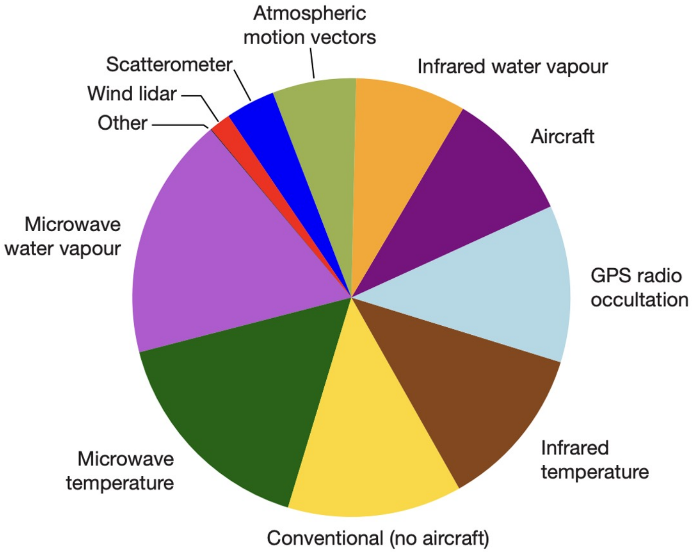
Background

Global forecast improvement over time at ECMWF 2025 (ECMWF 2025)

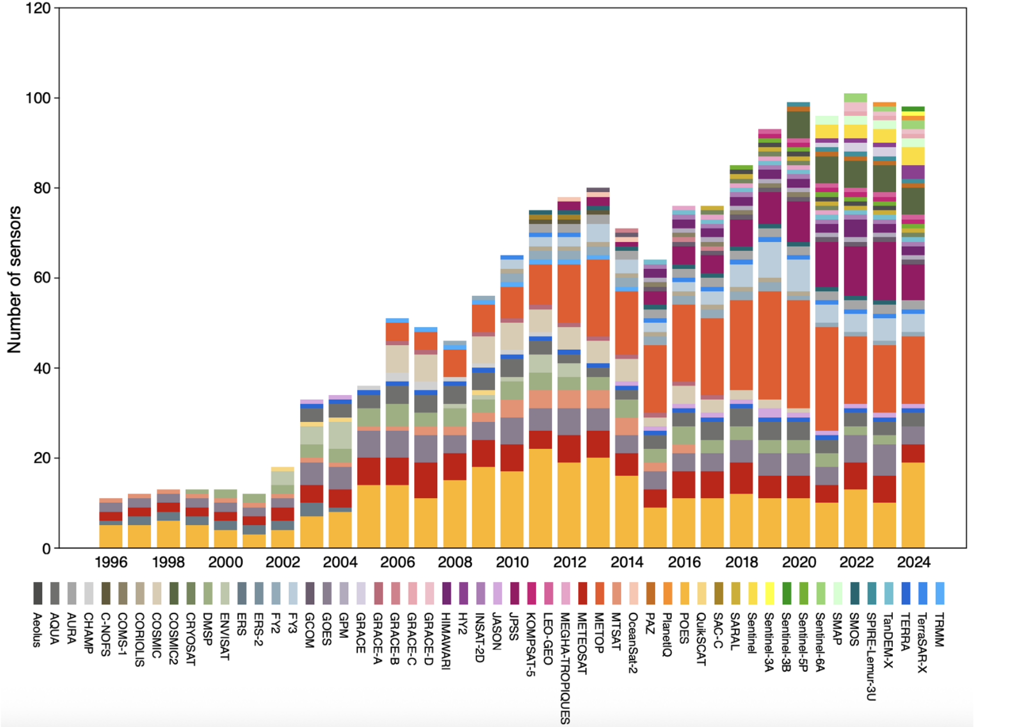


Background

Relative impact of observing systems on 24h forecasts (2020-2024)



Increase in satellite sensors monitored at ECMWF 1996-2024



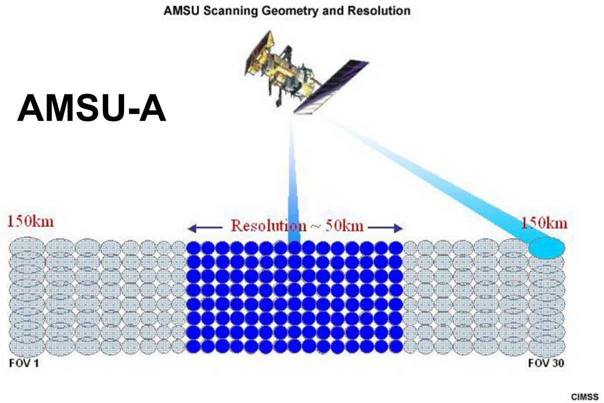
Principles of satellite measurements

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

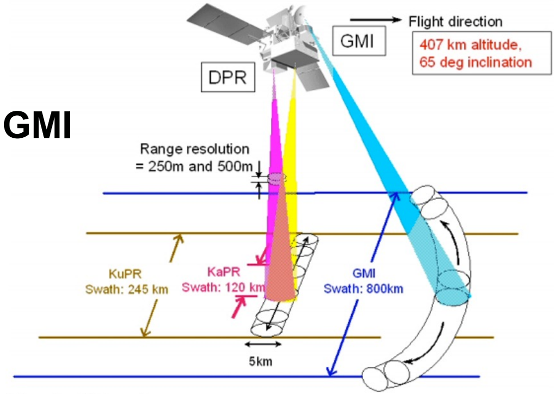
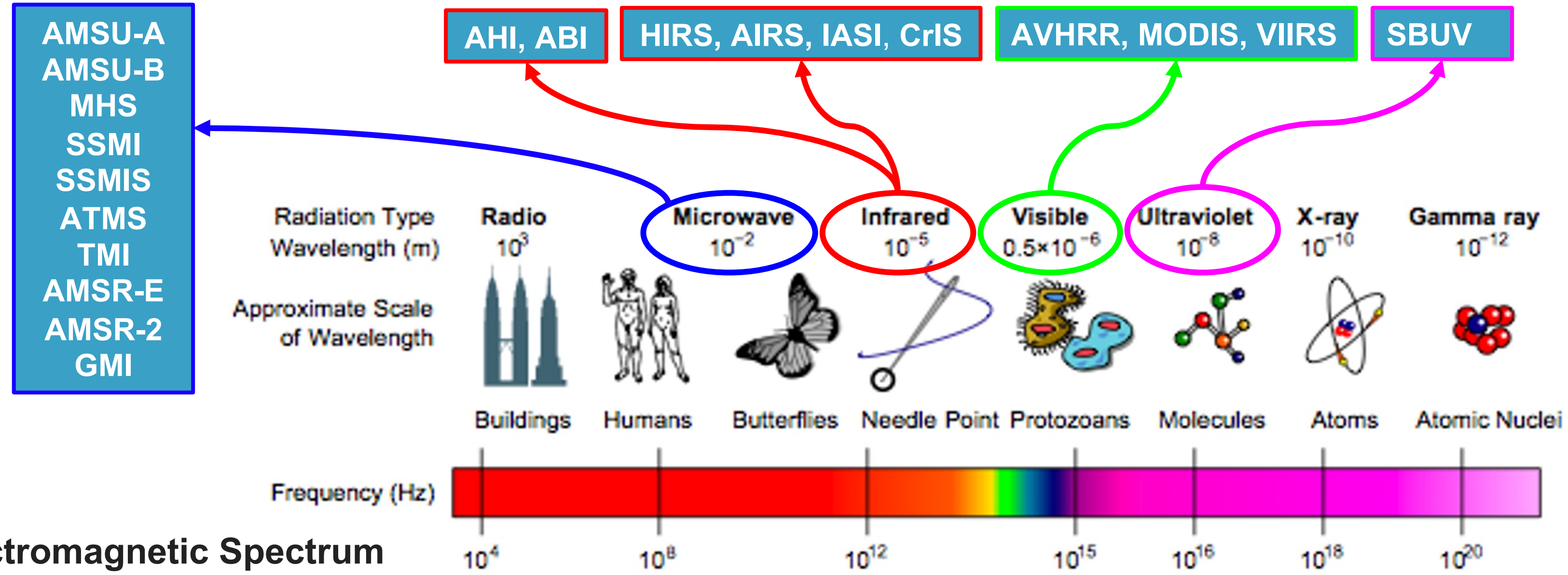


Figure 2. GPM swath measurements

Principles of satellite measurements

What do satellite instruments measure?

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

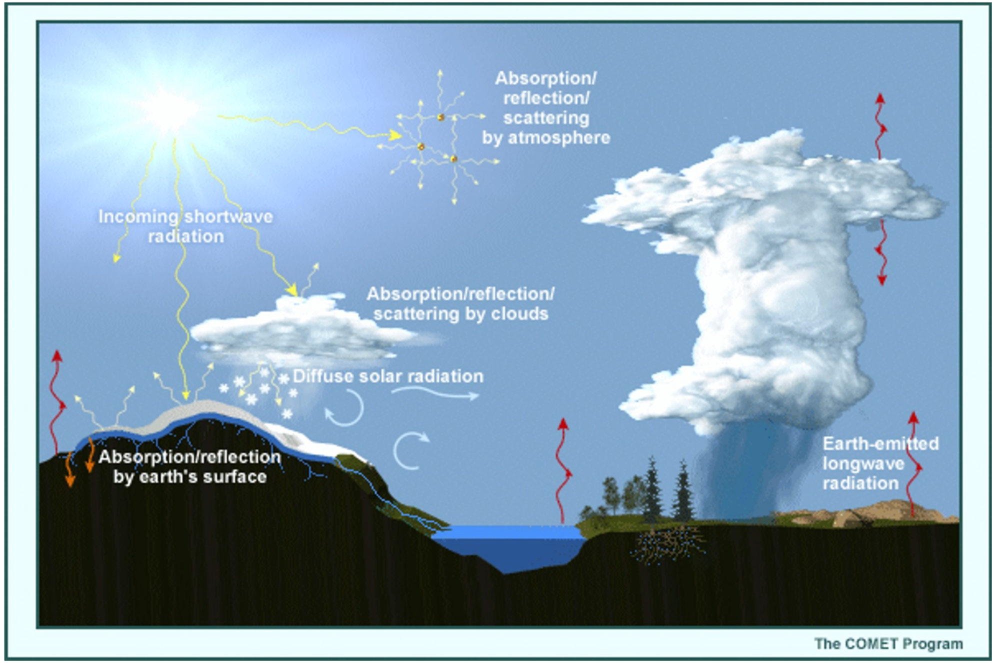


Electromagnetic Spectrum

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

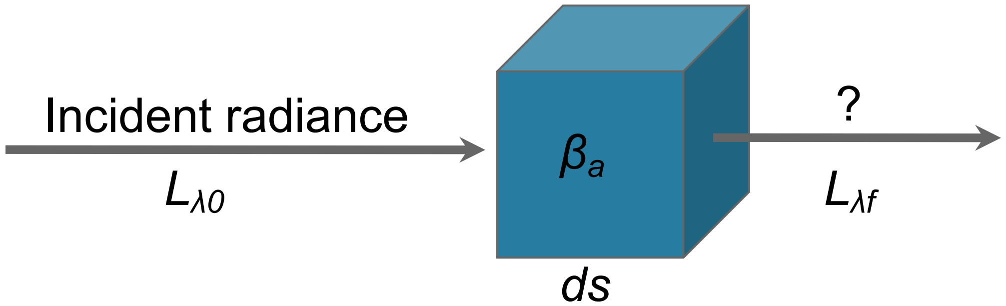
What is radiance?

- 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, we 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

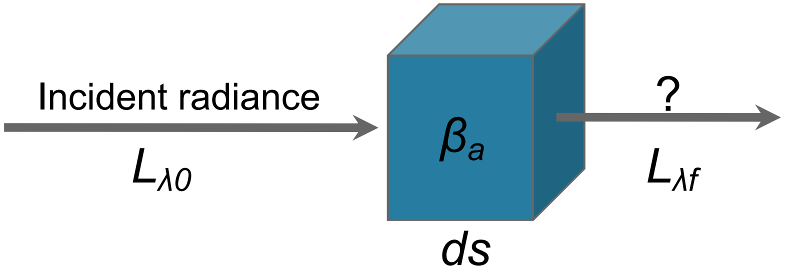
Atmospheric Transmittance

- 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:

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



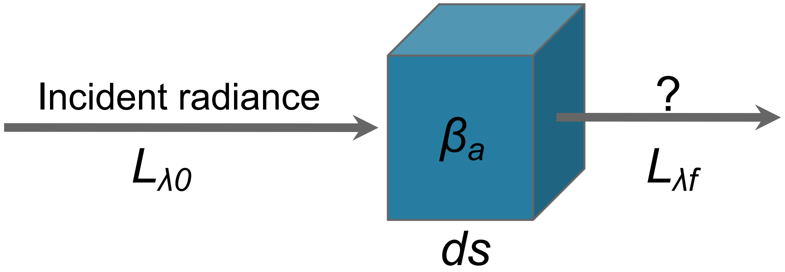
Principles of satellite measurements

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:

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



Radiative Transfer Model

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

TOA radiance at frequency ν

Planck function

Atmospheric Absorption (weighting function)

Emission/reflection

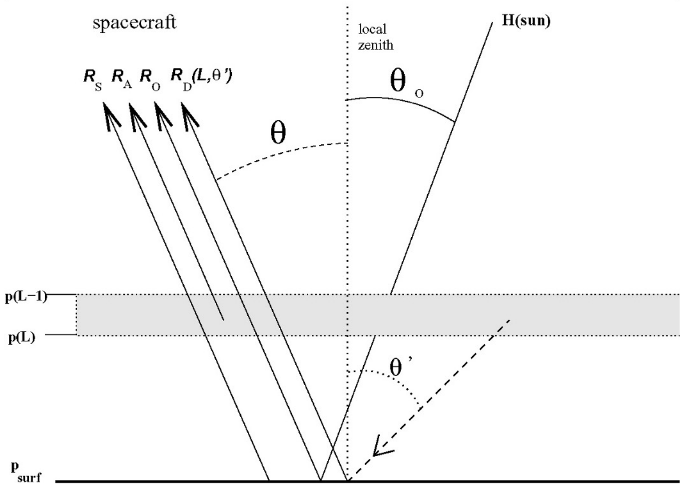
Diffusion/scattering

Surface emission R_s

Upwelling atmosphere emission R_A

Reflected solar radiation R_O

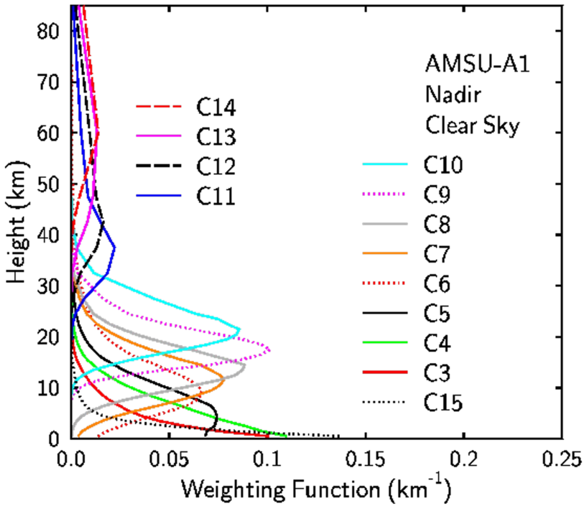
Down-welling & reflected atmos. Emission (R_D)



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 land and ocean surfaces as well as clouds

Radiance DA setting with MPAS-JEDI

YAML setting for radiative transfer model

```
_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
```

```
- 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

```
  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

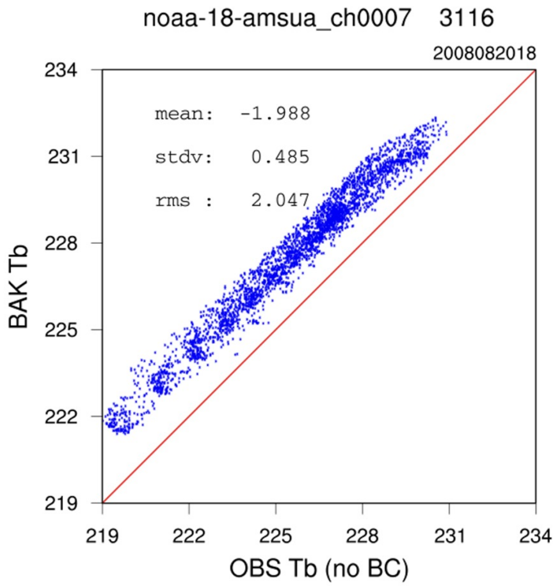
$$y = H(x_t) + B(\beta) + \varepsilon$$

$$\langle \varepsilon \rangle = 0$$

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

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

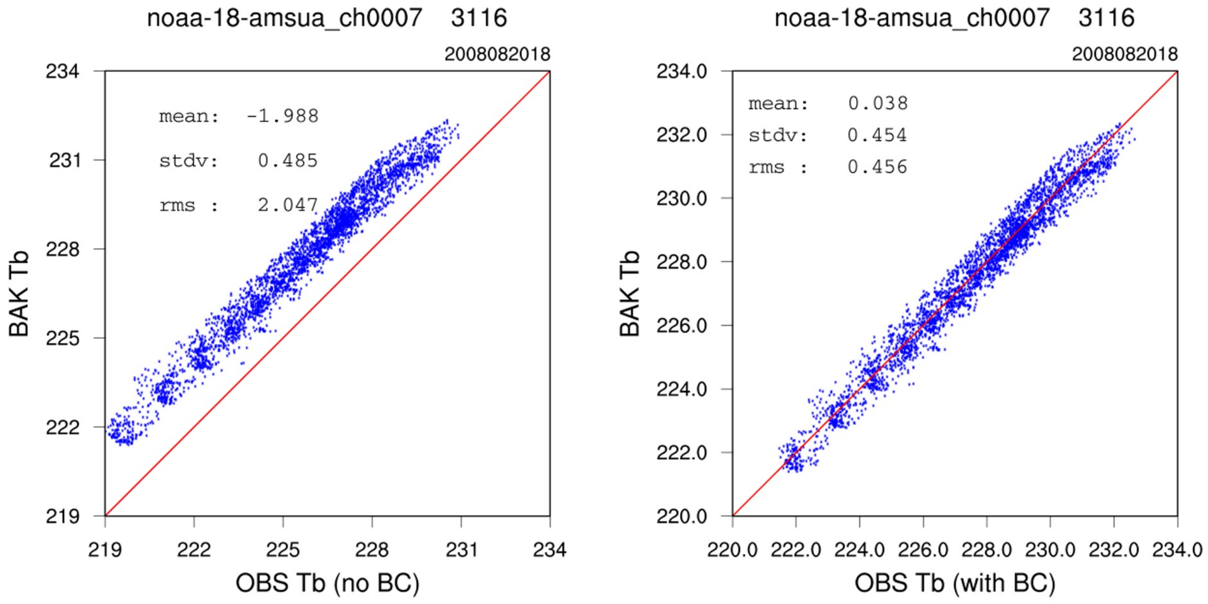
$$\mathbf{J}(\mathbf{x},\beta) = (\mathbf{x}_b - \mathbf{x})^T \mathbf{B}_x^{-1} (\mathbf{x}_b - \mathbf{x}) + [\mathbf{y} - H(\mathbf{x}) - B(\beta)]^T \mathbf{R}^{-1} [\mathbf{y} - H(\mathbf{x}) - B(\beta)]$$
$$+ (\beta_b - \beta)^T \mathbf{B}_\beta^{-1} (\beta_b - \beta)$$

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

satbias_amsua_n18.h5
satbias_cov_mhs_n18.h5

```
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 ;
```

Variable names in file may be changed with the latest JEDI code.

```
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

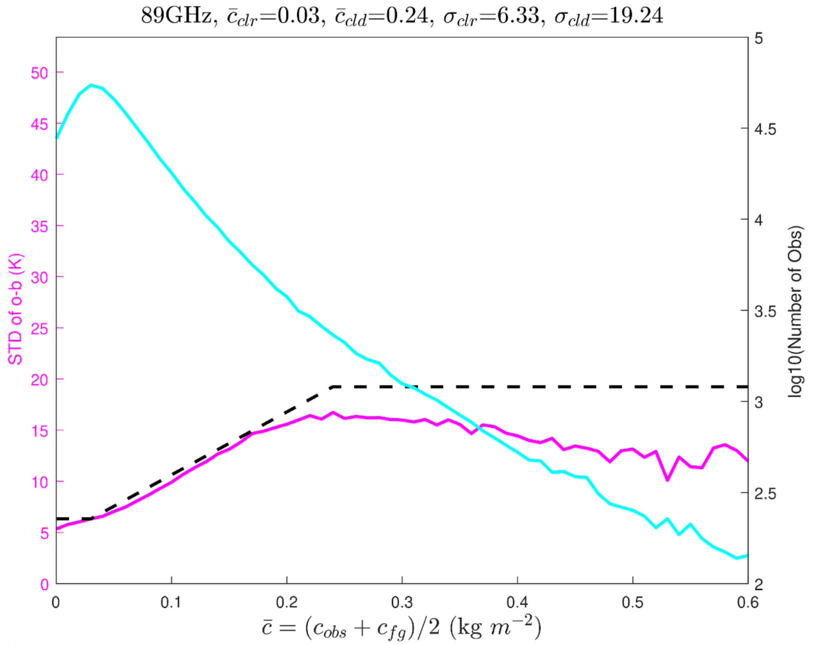
J_o: corrected observation term

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

J_p: background term for β

All-sky radiance DA

Situation-dependent all-sky obs error model

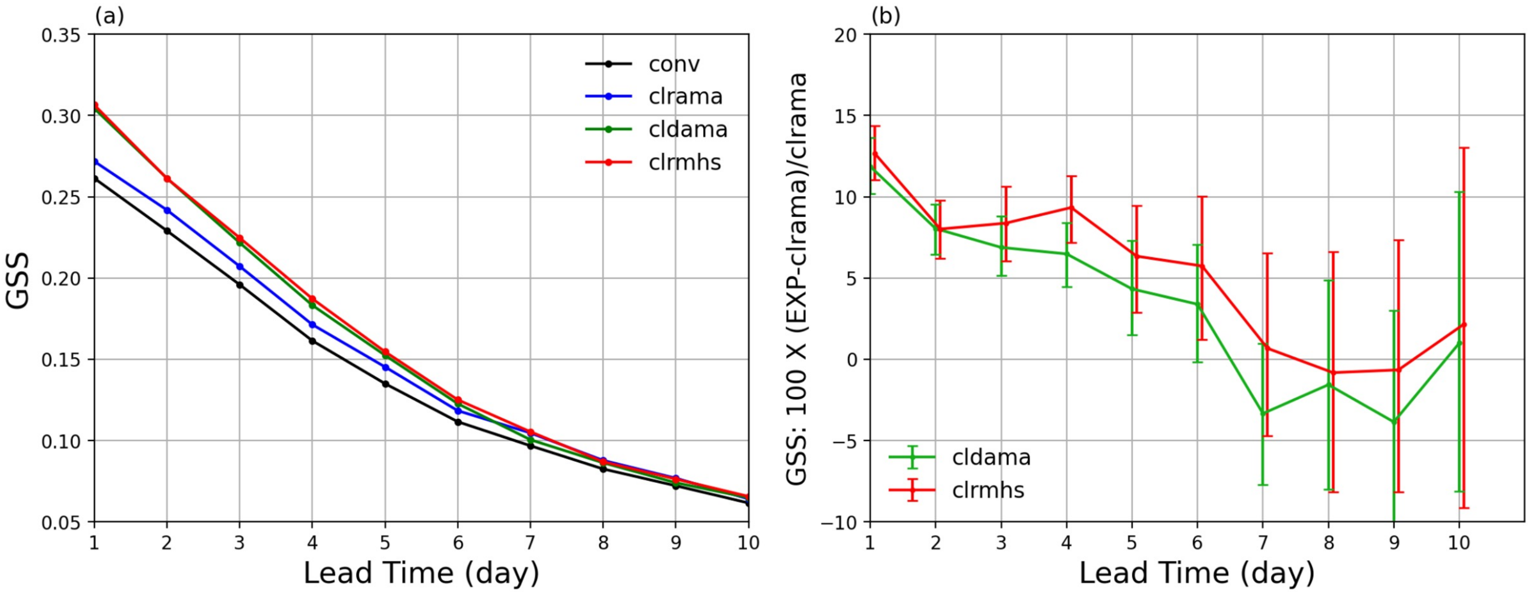


All-sky obs error model for AMSU-A channel 15:

- ❑ 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

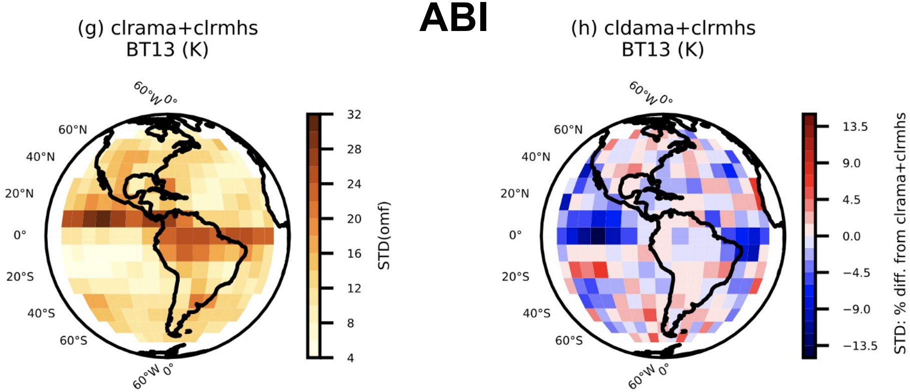


Liu et al., 2022

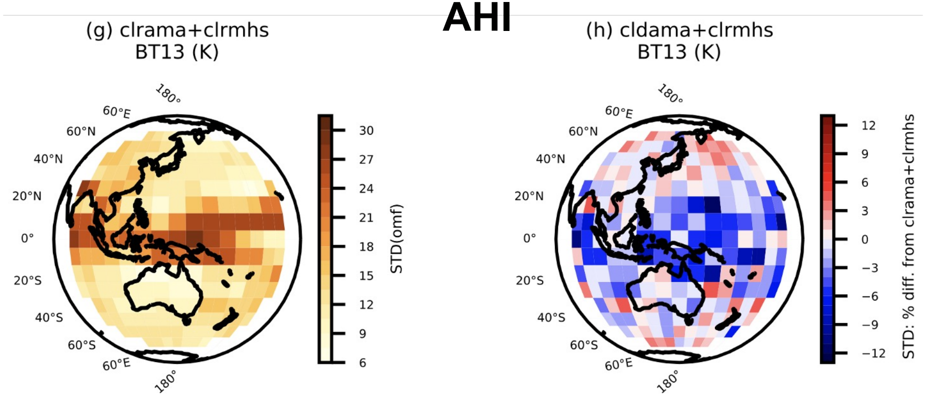
All-sky radiance DA

Added value of all-sky AMSU-A

ABI



AHI



Day-1 forecast

Error STD reduction

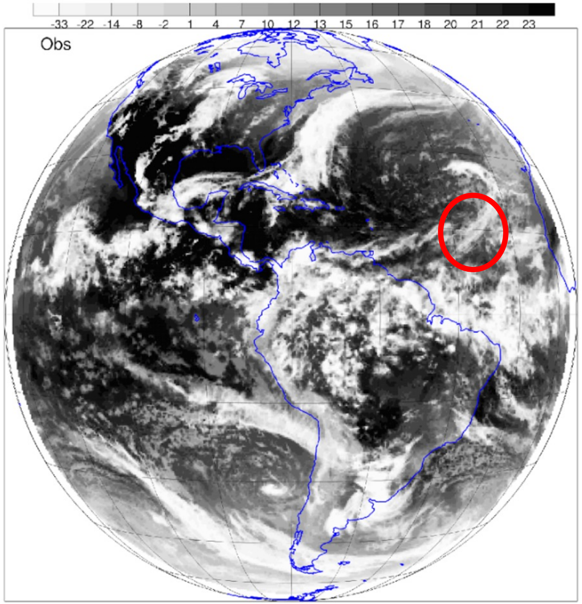
Improvement concentrated in cloudy regions of Tropics
Up to 12-14%

All-sky radiance DA

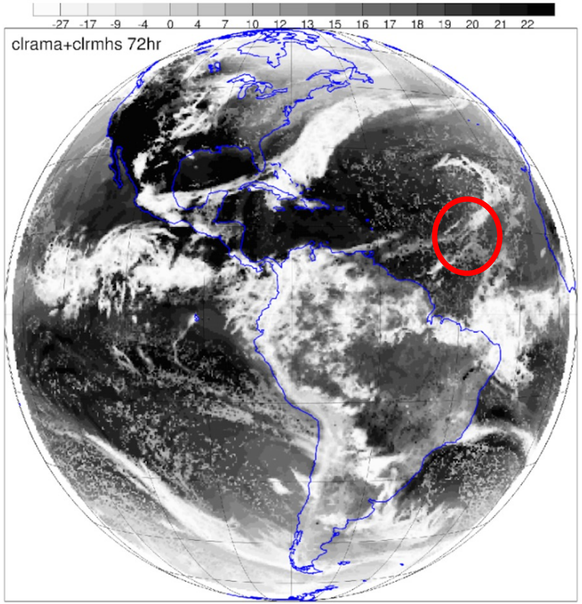
Observations vs. Day-3 forecast

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

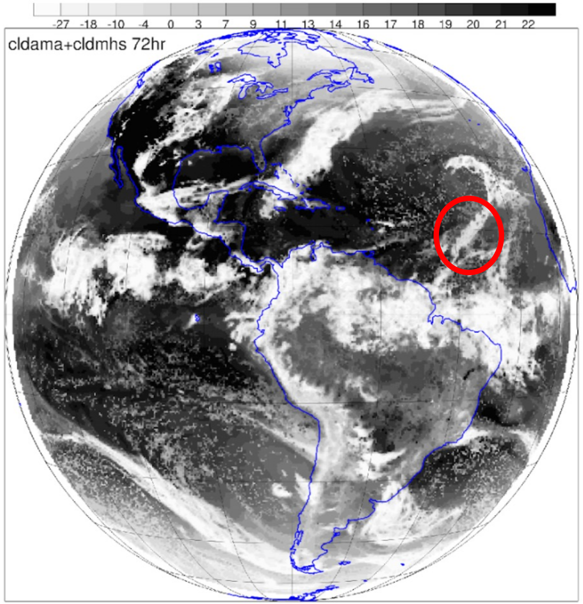
Observations



Clear-sky DA

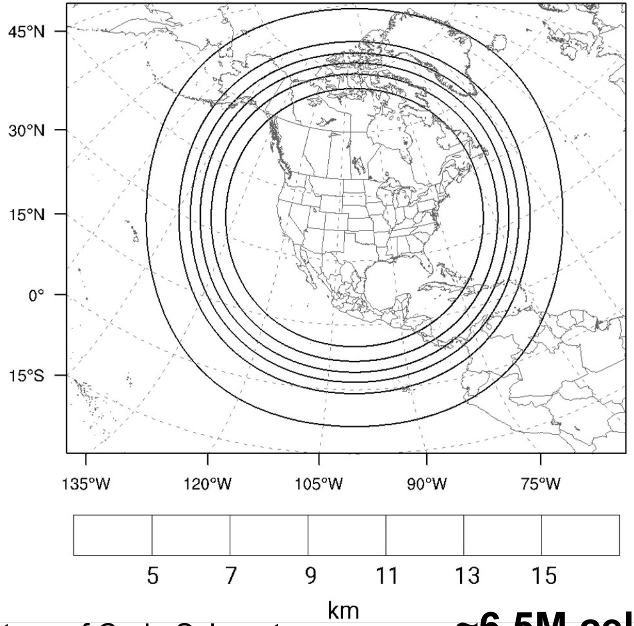


All-sky DA



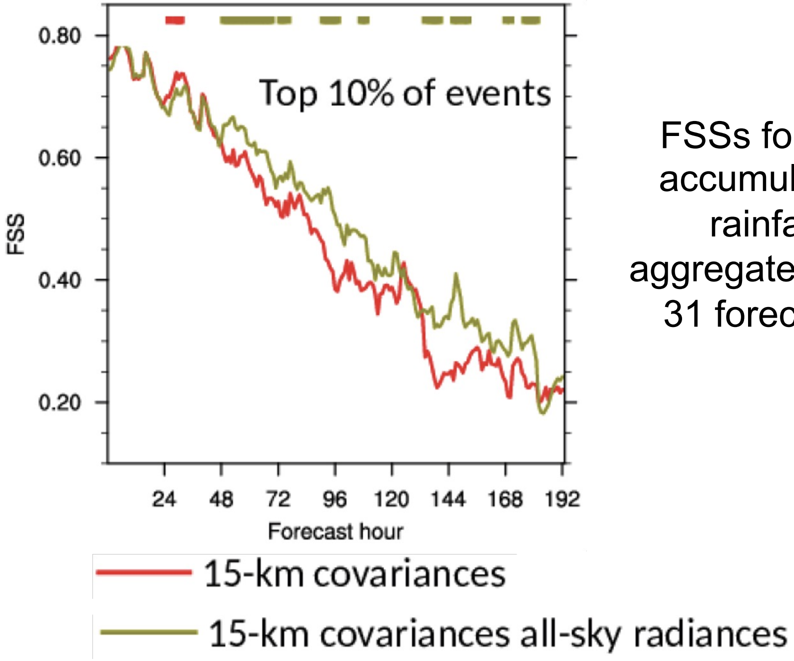
All-sky radiance DA

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!