OBSERVATIONS (4)

Satellite Radiance Data Assimilation

Ivette Hernández Baños

Contributor: Zhiquan (Jake) Liu

Mesoscale & Microscale Meteorology Laboratory
National Center for Atmospheric Research

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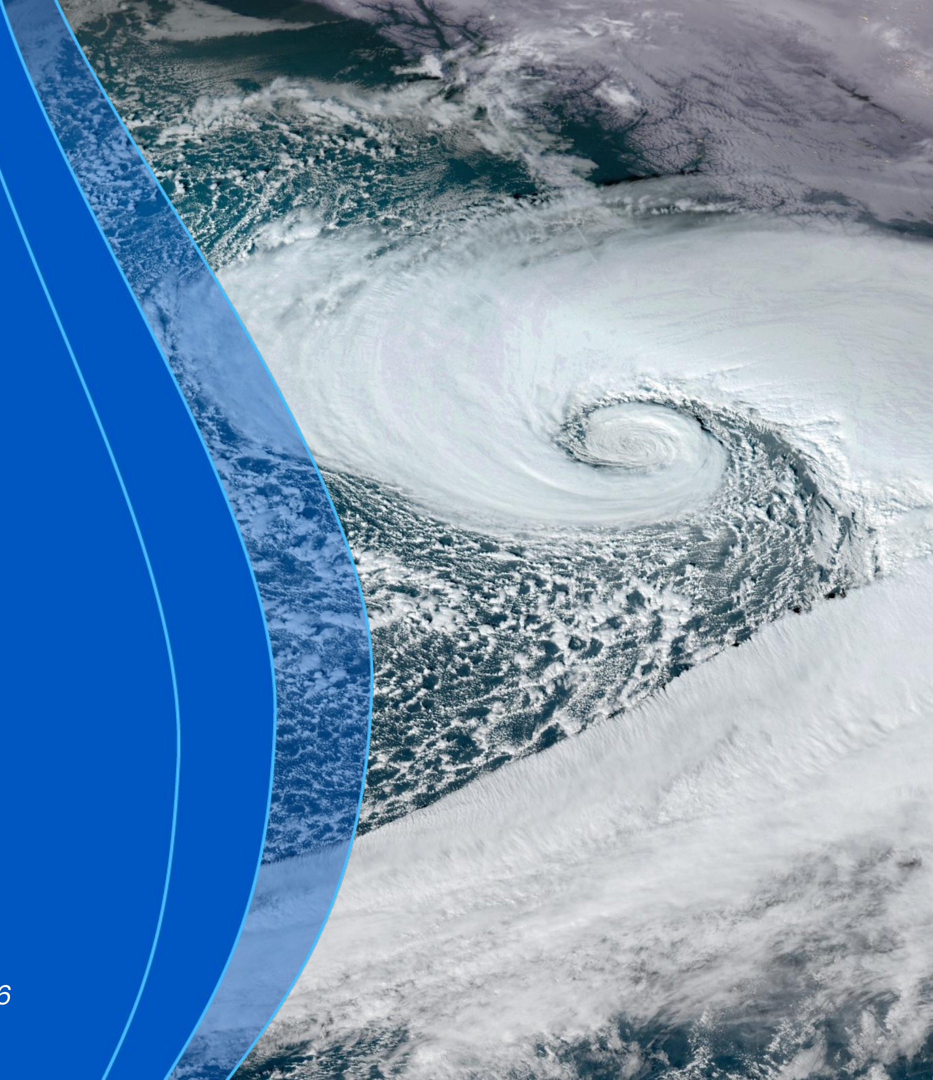
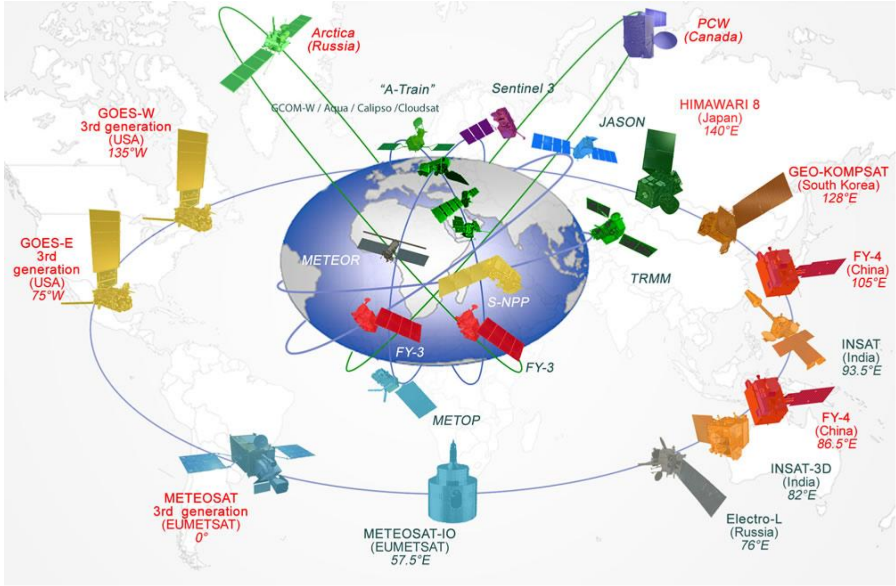


Outline

Environmental monitoring satellites

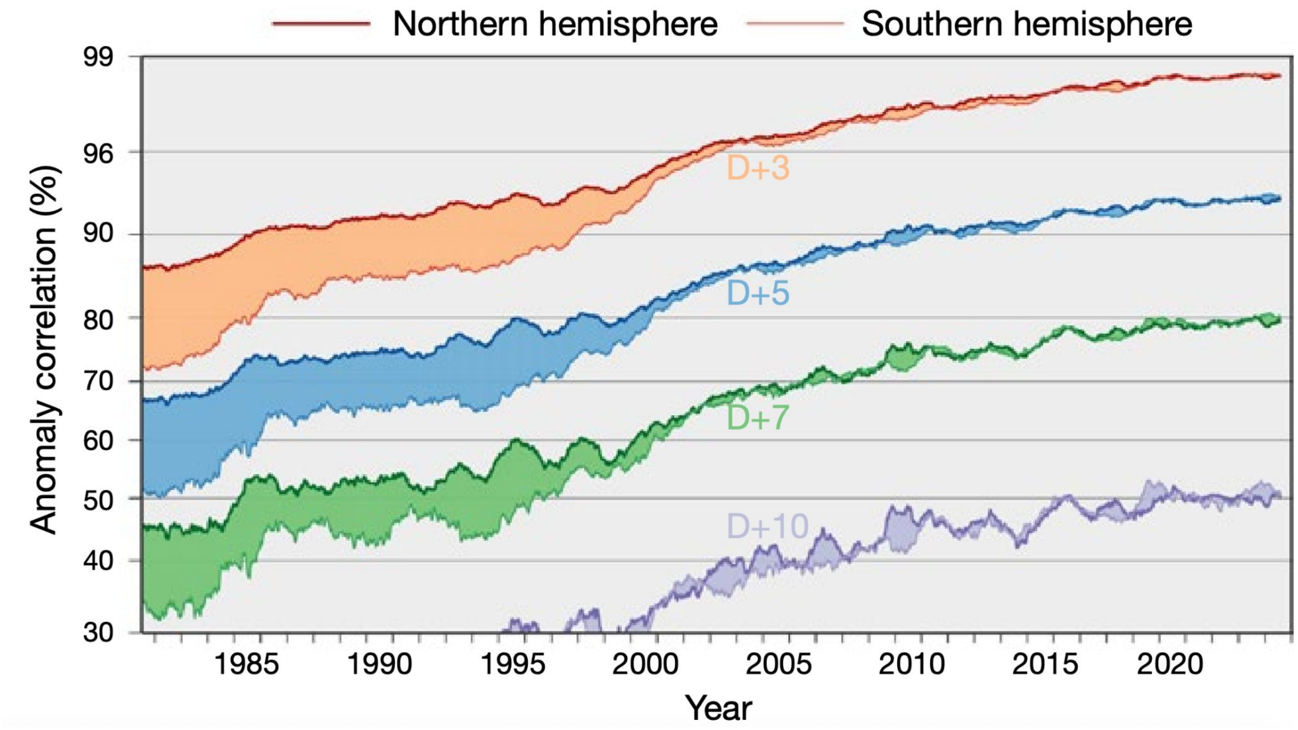
- Polar-orbiting satellites cross at fixed local times and build global coverage over a day. They carry most of the sounding instruments used in NWP.
- Geostationary satellites hold one view of the disc and revisit the same scene every few minutes, so they capture rapidly developing weather.
- Together they provide the only continuous, genuinely global source of atmospheric information.

Satellite imagery reveals structure in regions with no conventional observations.



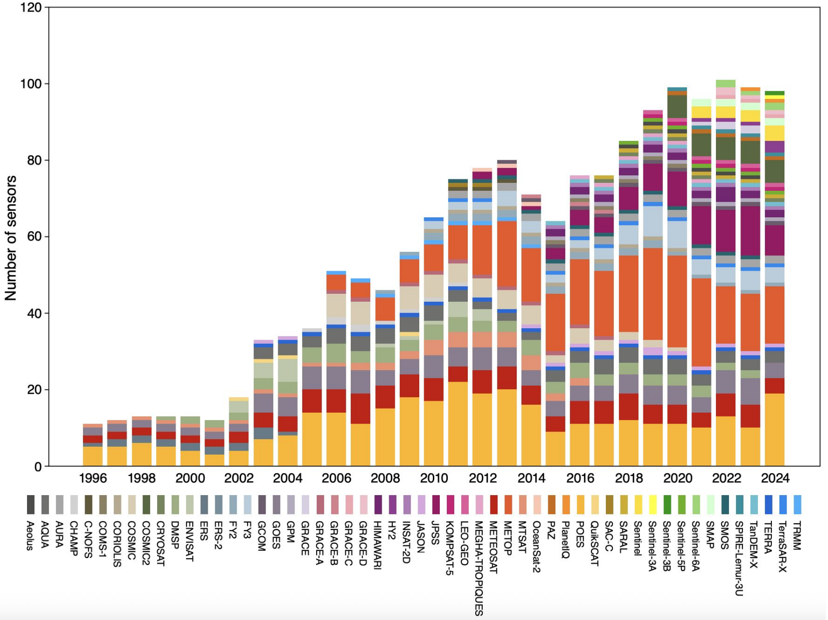
Polar-orbiting and geostationary platforms.

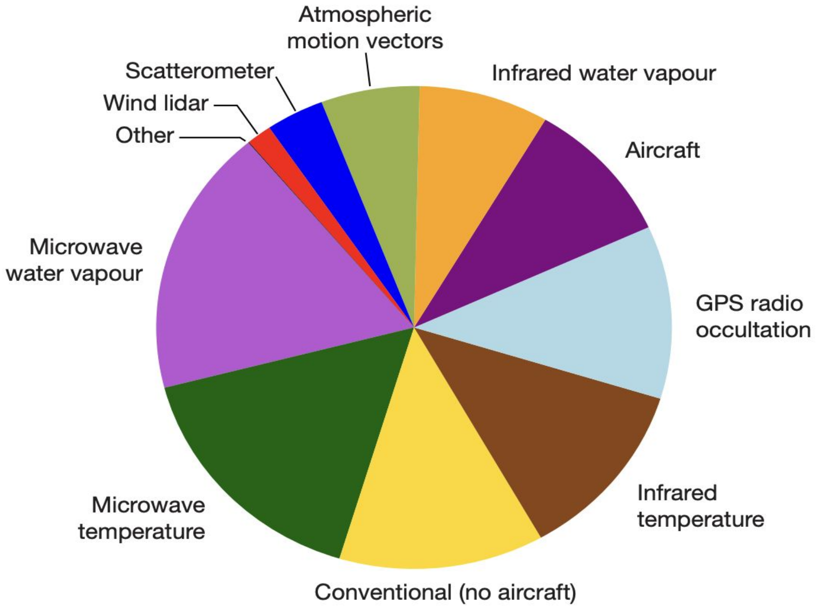
Forecast skill over four decades



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

Impact, and how much of the system is satellite data





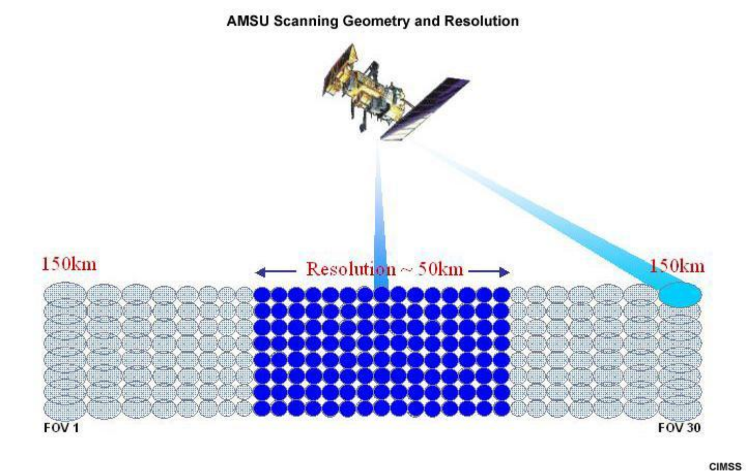
Relative impact of observing systems on 24 h forecasts, 2020–2024.

Growth in satellite sensors monitored at ECMWF, 1996–2024 (ECMWF 2025).

Scan strategy and viewing geometry

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

Cross-track scan



AMSU-A. Resolution degrades towards the edge of the swath as the viewing angle changes, so scan position matters for both QC and bias correction.

Conical scan

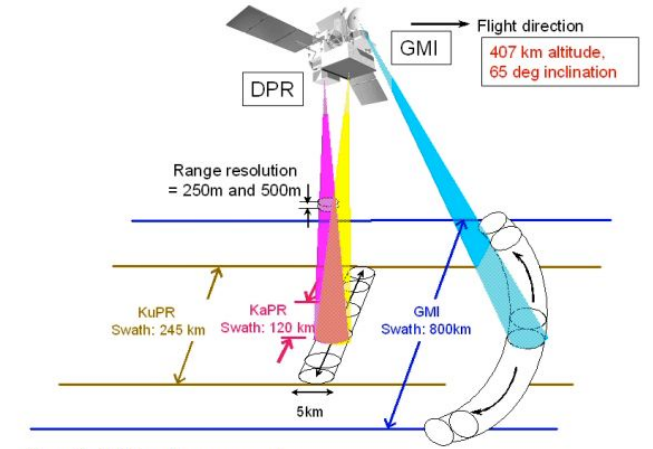


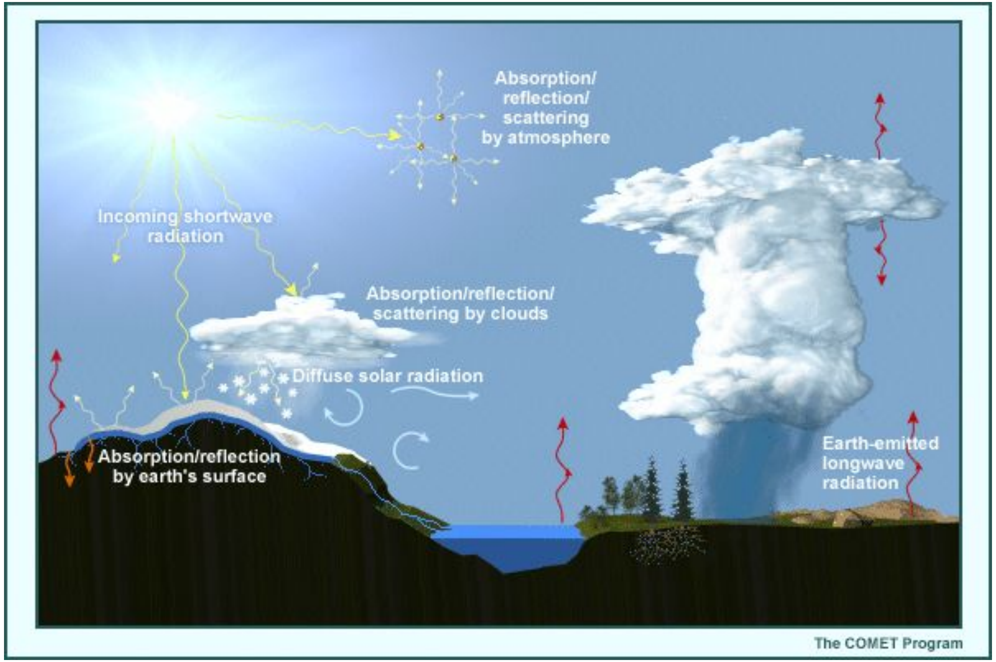
Figure 2. GPM swath measurements

GMI. Constant ground resolution across the swath, but generally narrower swaths than cross-track scanning.

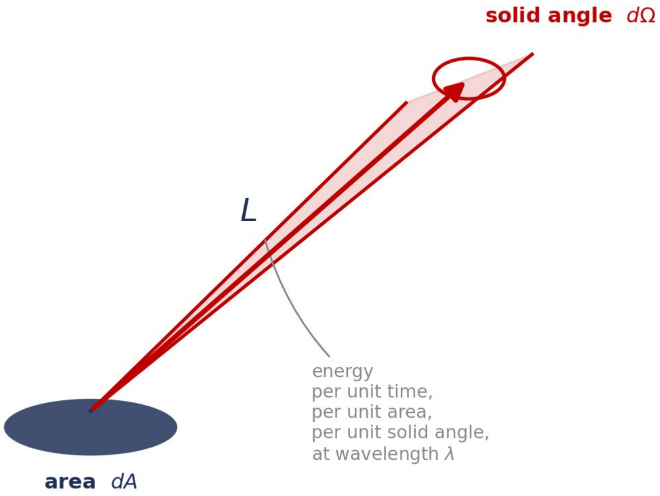
What satellite instruments measure

Different sensors measure radiation at different wavelengths and frequencies.

- Passive sensors observe radiation emitted and scattered by the surface and the atmosphere, in discrete spectral intervals.
- Microwave sounders use oxygen and water-vapour absorption bands; infrared sounders use carbon dioxide and water-vapour bands.
- Which gas absorbs, and how strongly, determines how deep into the atmosphere that channel can see.



Radiance, and brightness temperature



Radiance L

Energy per unit area, per unit time, per unit solid angle, at wavelength λ (or frequency v); recall c = λv

Physically

Think of L as the "brightness" of an object

Governed by

The radiative transfer equation, which links L to the atmosphere's temperature, gas, and cloud state

Often converted to

Brightness temperature: the equivalent blackbody temperature, found by inverting the Planck function

Units: L in $W \cdot m^{-2} \cdot sr^{-1} \cdot Hz^{-1}$ (per-frequency, common for MW) or $W \cdot m^{-2} \cdot sr^{-1} \cdot (cm^{-1})^{-1}$ (per-wavenumber, common for IR sounders)

The radiative transfer equation

$$I_\nu(\mathrm{TOA}) = \varepsilon_\nu B_\nu(T_s)\,\tau_\nu(0) + \int_0^\infty B_\nu(T(z))\,\frac{\partial \tau_\nu(z)}{\partial z}\,dz + (1-\varepsilon_\nu)\,\tau_\nu(0)\,I_\nu^{\downarrow}$$

1 — 2 — 3

1

Surface emission

ε□ B(v,T□) τ(v,p□). The surface emits according to its temperature and emissivity; only the fraction that survives the column above reaches the satellite.

2

Upwelling atmospheric emission

The integral above. Every layer emits at its own temperature, weighted by its share of ∂τ/∂z, the part of that emission that escapes to space.

3

Reflected downwelling emission

(1−ε□) τ(v,p□) × downwelling radiance. Matters for window channels and low-emissivity surfaces such as water.

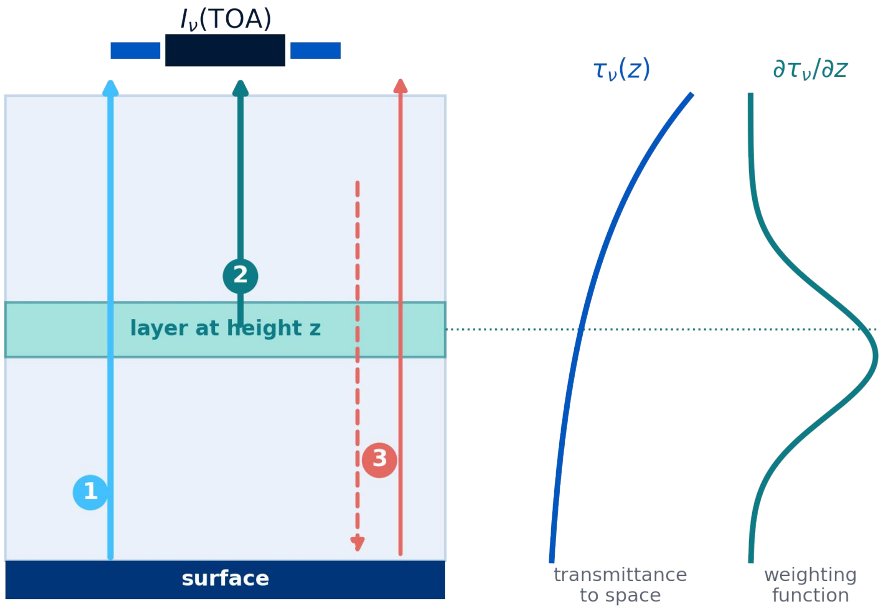
4

Cloud, rain and aerosol

Emission, reflection and scattering by hydrometeors. Neglected in clear-sky assimilation, and the subject of the all-sky section.

Clear-sky, monochromatic, no scattering. Brightness temperature is this radiance inverted through the Planck function. CRTM evaluates these terms for every observation, channel by channel.

Clear-sky: where each term comes from?



Schematic. Arrow numbers match the three terms on the previous slide.

τ(z), transmittance to space

The fraction of radiation leaving height z that reaches the satellite. Close to one near the top, small near the surface for an opaque channel.

∂τ/∂z, the weighting function

How much each layer contributes. Its peak is the level the channel is most sensitive to. This is the curve on the next slide.

Opaque channel, τ(0) near zero

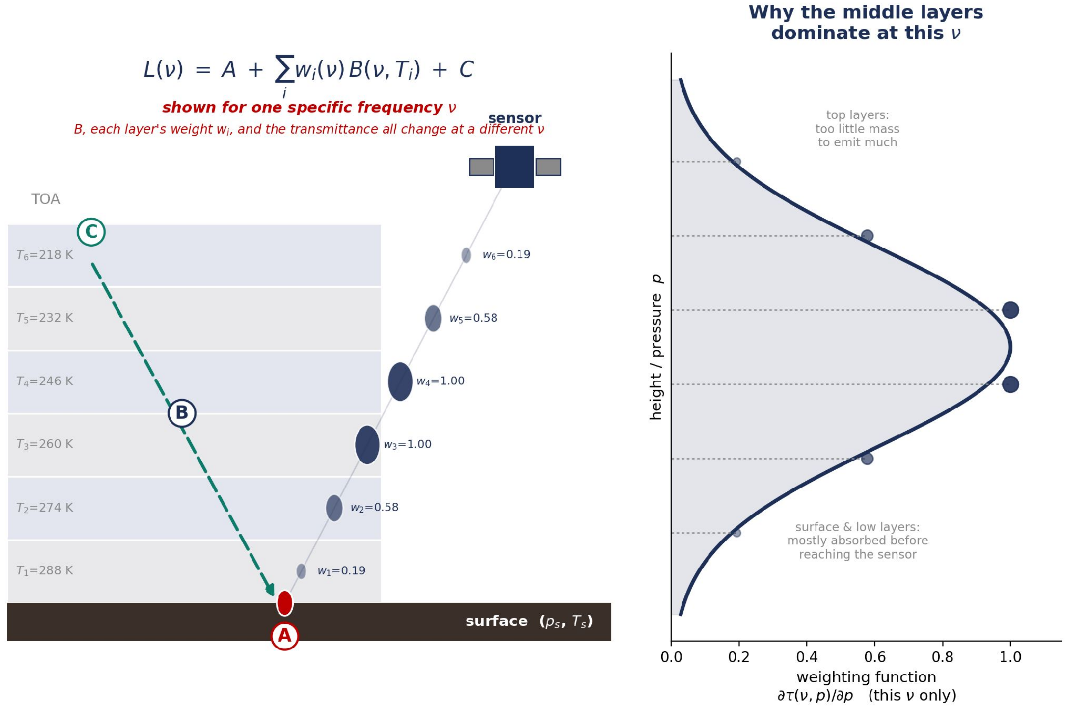
Term 1 disappears. The channel sees the atmosphere only, and surface emissivity stops mattering.

Transparent channel, τ(0) near one

Term 1 dominates and term 3 becomes significant. Surface temperature and emissivity now control the observation.

Channel selection is the choice of where ∂τ/∂z peaks.

Clear-sky: where each term comes from?



Contributions for one frequency, and the weighting function that results.

A · surface

Emitted at the surface and attenuated by the whole column. Large only when $\tau(p_s)$ is appreciable.

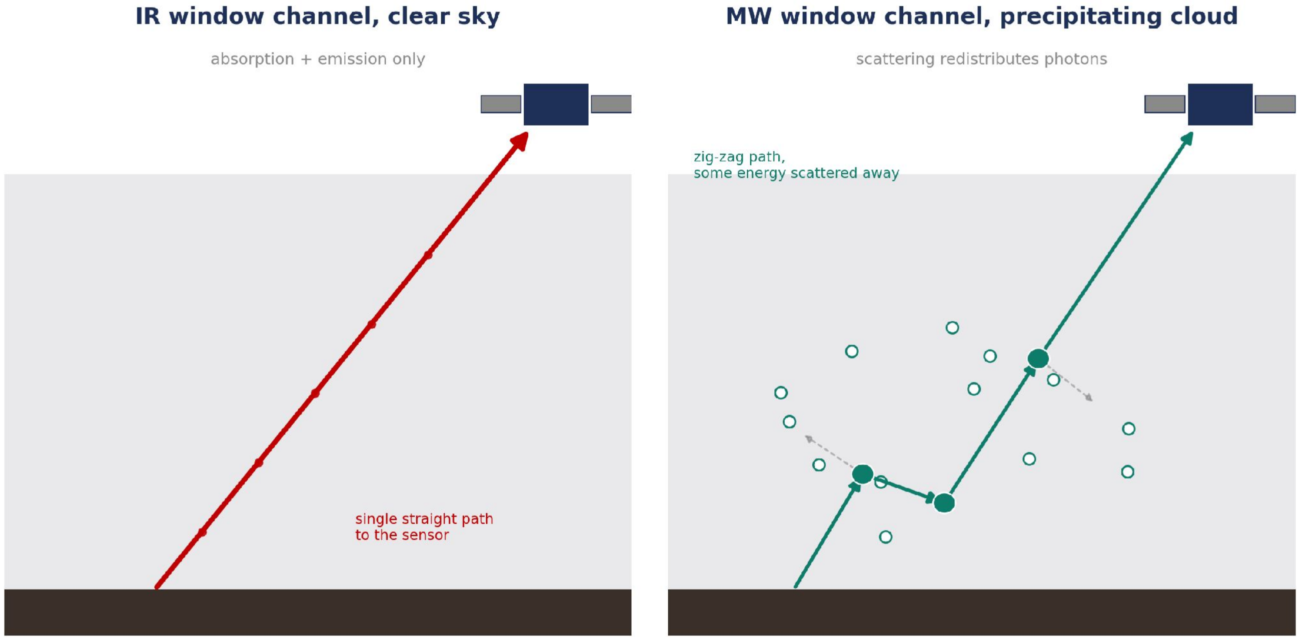
B · each layer

Each layer contributes its own emission, scaled by how much the transmittance changes across it.

C · reflected

Downwelling radiation returned by a surface with emissivity below one.

What changes when there is cloud?



Left: infrared window channel, clear sky, absorption and emission along a single straight path. Right: microwave window channel in precipitating cloud, where scattering redistributes photons.

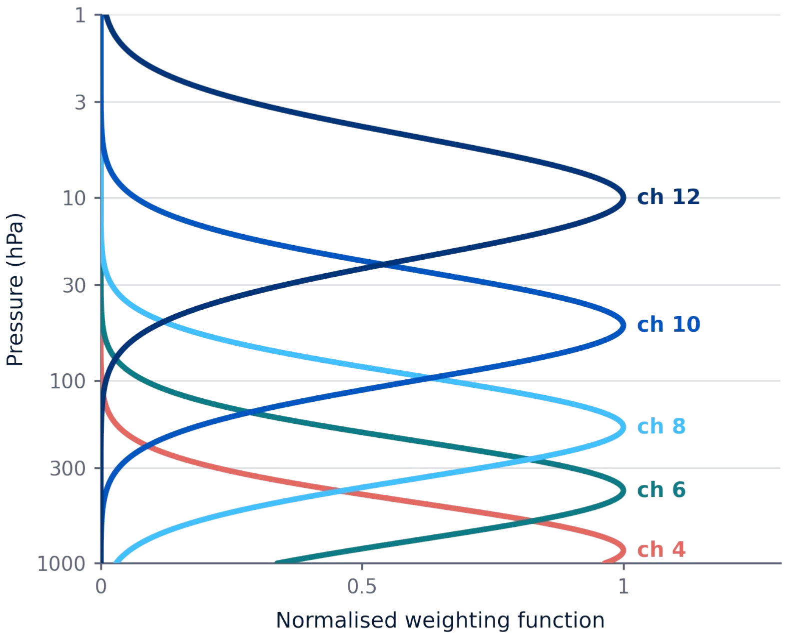
Weighting functions and channel selection

- The weighting function gives the contribution to the outgoing radiance from each layer of the atmosphere.
- It is channel dependent, because each channel sits at a different point in an absorption band.
- Its peak is the level the channel constraints most; its width is how coarse that constraint is.

Channel selection for NWP data assimilation

Atmospheric sounding channels measured radiance has no contribution from the surface, so they can be used almost anywhere.

Window channels are sensitive to land and ocean surface properties and to cloud, which is exactly why they need the heaviest quality control.



Schematic, idealized curves for illustration

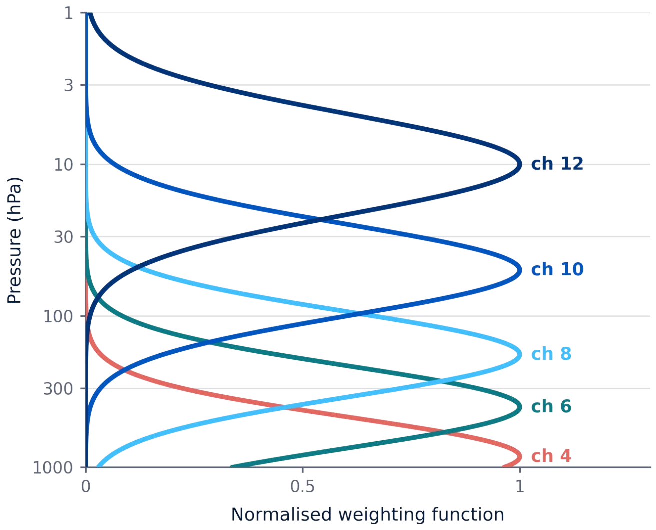
Over to you: reading a weighting function

Which of these channels is most exposed to surface emissivity error?

A ch 4	B ch 6	C ch 10	D ch 12

Same instrument, thick cloud in the field of view. Which channel changes least?

A ch 4	B ch 6	C ch 10	D ch 12



From radiative transfer to data assimilation

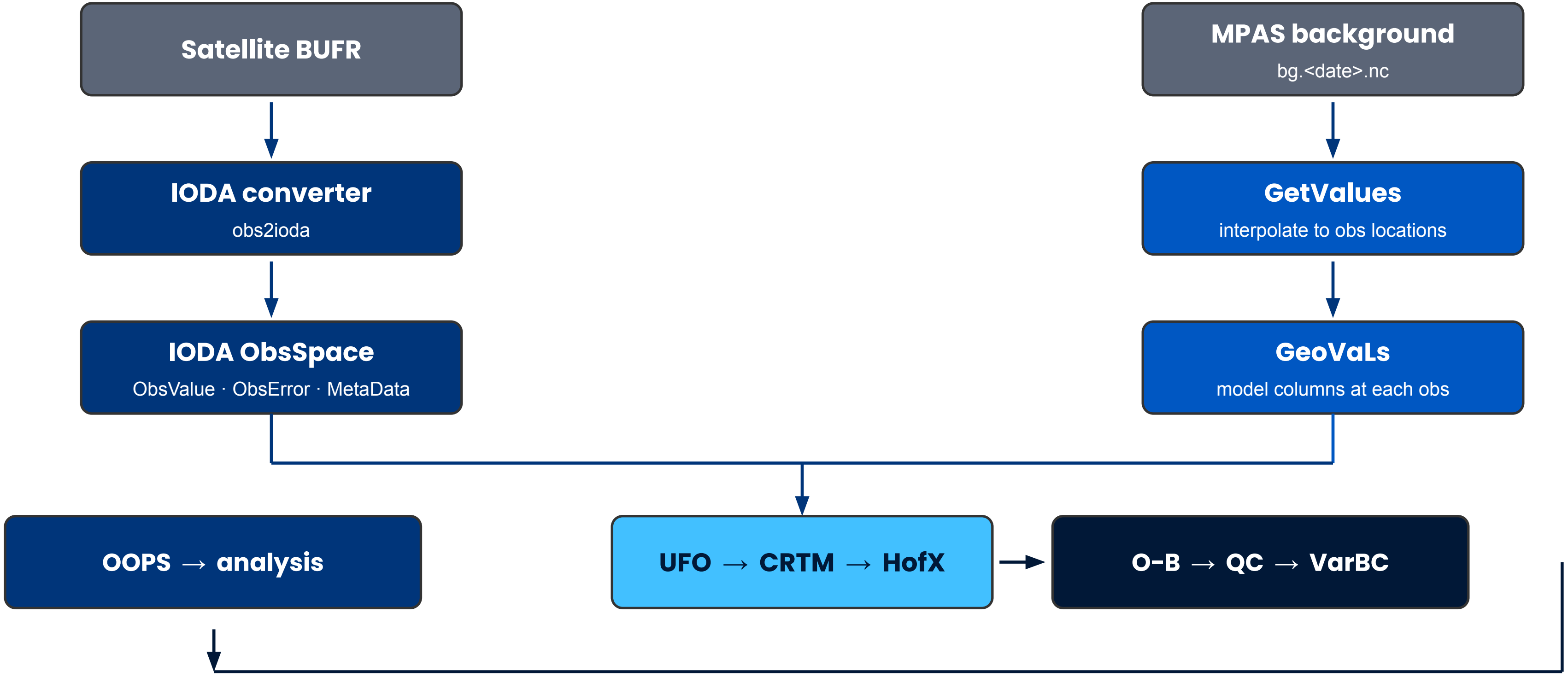
$$y = H(x) + \varepsilon$$

observed radiance = radiance simulated from the model state + error

y	The observation. In IODA, ObsValue/brightnessTemperature, one value per channel per location.
H(x)	The observation operator. For radiances this is CRTM or RTTOV solving the radiative transfer equation on the model column. In IODA it comes back as HofX.
x	The atmospheric and surface state, which for us is the MPAS background.
ε	Instrument noise, forward-model error and representativeness error combined. Specified as ObsError.

The departure `d = y − H(x)` is what the assimilation consumes. Everything that follows exists to make d trustworthy.

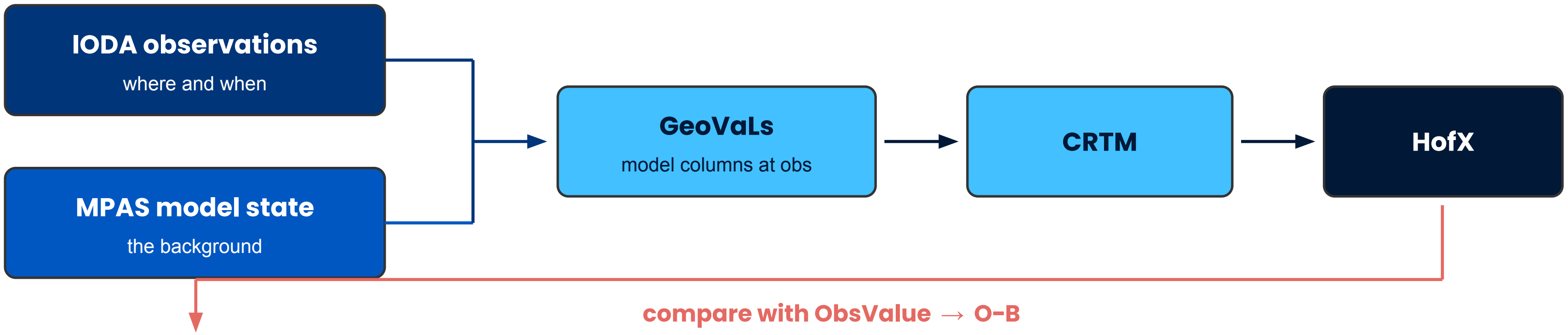
Where a radiance goes inside MPAS-JEDI?



Observations enter from the left, the model state from the right. They meet only inside the observation operator.

GeoVaLs

CRTM needs an atmospheric column and a surface underneath it.



- GeoVaLs are the model fields interpolated to each observation location and time, one column per observation.
- UFO declares which GeoVaLs each operator requires; OOPS and the model interface supply them.
- In MPAS-JEDI, the mapping between JEDI variable names and MPAS fields is set in geovars.yaml.
- If a required GeoVaL is missing or has the wrong units, the operator fails, usually with a message that points at the variable name.

What the CRTM operator requires from the model?

Atmosphere

- Temperature profile
- Water vapour (H_2O)
- Ozone (O_3)
- Pressure on levels and layers

Absorbers

- H_2O and O_3 are always required
- CO_2 also implemented
- Set via the Absorbers option
- CO_2 can come from background, a constant, or a Mauna Loa estimate

Clouds (optional)

- Water, Ice, Rain, Snow, Graupel, Hail
- Water content and effective radius
- Cloud fraction: from the model, or fixed via Cloud_Fraction

Surface & geometry

- Surface type and skin temperature
- Surface wind (vector or u/v)
- Sensor zenith angle, scan position
- Emissivity model coefficients

What has to be on disk before it will run?

Observations

amsua_n18_obs_2018041500
.h5

…and any other sensor you add

CRTM coefficients

`crtm_coeffs_v3/`

must contain the SpcCoeff and TauCoeff sets for your Sensor_ID

Variable mappings

`geovars.yaml`

`keptvars.yaml`

`obsop_name_map.yaml`

Model and B

bg.<date>.nc and an.<date>.nc

templateFields.<mesh>.nc

static B or ensemble, plus localisation

Standalone forward operator

MPAS-JEDI provides mpasjedi_hofx3d.x. It reads the background and the observations, runs the operator, writes obsout_hofx_*.h5, and never touches the minimisation. If something is wrong with your radiance setup, it will surface here, in seconds, instead of inside a variational run.

Why radiances need so much quality control?

An observation being physically available is not the same as an observation being appropriate for assimilation.

Cloud and precipitation

Clear-sky operators have no way to represent them; the departure is meaningless.

Surface contamination

Window and low-peaking channels see the surface, where emissivity is poorly known.

Land, sea and ice

Emissivity behaviour differs so much that channels are often screened by surface type.

Large viewing angles

Long slant paths and limb effects degrade the forward model.

Instrument flags

The provider already knows about calibration problems, which is what PreQC carries.

Gross errors

Values that are simply impossible for the channel.

Excessive departures

A departure far larger than the assumed error is either a bad observation or a bad background.

Channel-specific issues

Some channels are monitored but never assimilated, per sensor and per system.

QC in practice: the UFO filter framework

- Filters are listed in YAML under obs filters and run in order.
- Each filter acts on chosen filter variables, optionally restricted to specific channels.
- A where clause restricts a filter to observations meeting stated conditions.
- An action decides what happens: reject, inflate error, accept, or reduce obs space.
- Decisions are recorded in EffectiveQC, so you can always find out why an observation was dropped.

Filters you will meet first

`Bounds Check`	reject values outside a range
`PreQC`	honour the provider's flags
`Background Check`	reject large departures
`Domain Check / BlackList`	keep or drop by condition
`Variable Assignment`	derive a new variable or flag

```yaml
obs filters:
- filter: Bounds Check
  filter variables:
  - name: brightnessTemperature
    channels: 4-6
  minvalue: 240.0
  maxvalue: 300.0

- filter: Background Check
  filter variables:
  - name: brightnessTemperature
    channels: 1-15
  absolute threshold: 3.5
  action:
    name: reject

- filter: Perform Action
  action:
    name: inflate error
    inflation factor: 2.0
  where:
  - variable:
      name: GeoVaLs/water_area_fraction
    maxvalue: 0.99
```

Syntax after the UFO generic QC filter documentation (JEDI 8.0.0).

YAML setting for the radiative transfer model

```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:
```

```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
```

`obsfile`	the IODA radiance file for this sensor
`simulated variables`	brightnessTemperature
`channels`	the subset to simulate
`Sensor_ID`	prefix of the coefficient files, e.g. amsua_n18
`CoefficientPath`	where those coefficient files live

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
```

- Filters are listed under obs filters and run in order.
- Each filter acts on chosen filter variables, and can be restricted to specific channels.
- A where clause restricts a filter to observations meeting stated conditions.
- An action decides the outcome: reject, inflate error, accept, or reduce the obs space.
- Decisions are recorded in EffectiveQC, so you can always find out why an observation was dropped.

`PreQC`	pregenerated flags
`Bounds Check`	reject values outside a range
`Background Check`	reject large departures
`Domain Check / BlackList`	keep or drop by condition

There is far more available for quality control than one session can cover.

What goes into ObsError?

Instrument noise

The only part the manufacturer quotes. Usually the smallest term for a sounding channel.

Forward-model error

Spectroscopy, the emissivity model, the cloud treatment, the discretisation of the column.

Representativeness

The footprint averages over an area the model cannot resolve; the model column is not the real column.

Unresolved processes

Anything real that the background model simply does not contain.

A situation-dependent error model, in which the error grows with cloud amount, is the standard approach for all-sky radiances.

Errors between channels are correlated

Two channels on the same instrument view the same footprint, through overlapping weighting functions, using the same radiative transfer, the same surface and the same cloud assumption. When any one of those is wrong, both departures move together.

Treating them as independent tells the analysis it has more information than it really does, so it draws too hard towards the observations.

Two common responses

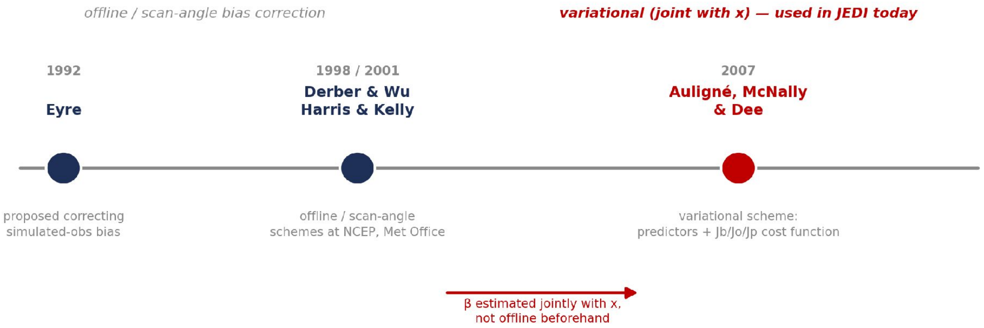
- Inflate the diagonal error and thin the data. Simple, standard, and wasteful of information.
- Model the correlated error matrix directly. Better, and the reason correlated-error support exists in UFO.

Variational bias correction

- Variational DA assumes departures are unbiased. Radiance departures are not.
- A systematic offset between y and H(x) is indistinguishable, to the minimization, from a genuine model error, so an uncorrected bias is projected into the analysis cycle after cycle.
- Radiance biases come from the instrument, from the radiative transfer, and from the model background. **In practice they cannot be cleanly separated.**

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

The bias is modelled as a linear combination of predictors. The coefficients β join the control vector and are estimated by the same minimization that produces the analysis.

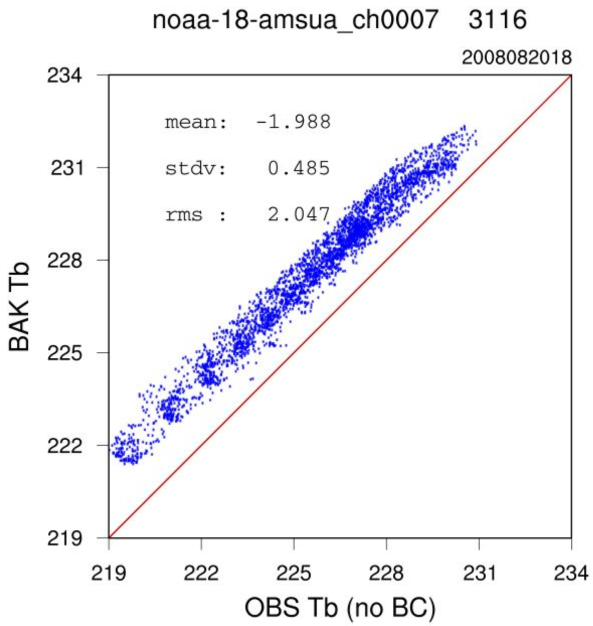


Bias depends on

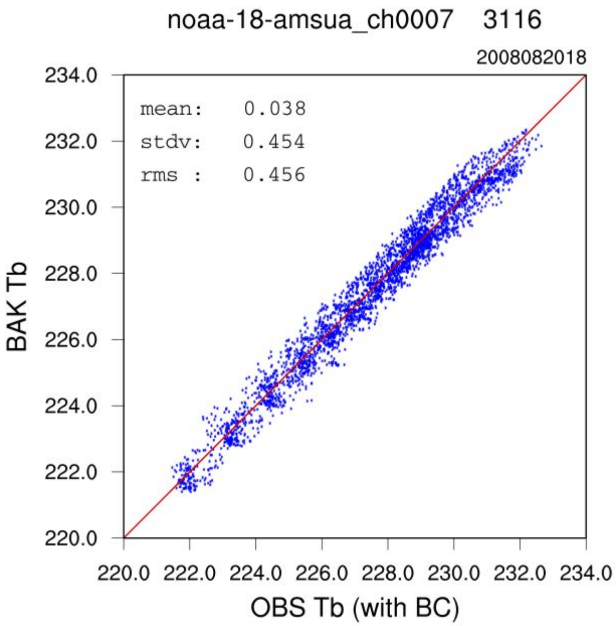
Channel	Scan position	Lapse rate
Emissivity	Latitude	Cloud water

...

What bias correction does to the departures?



No bias correction



With bias correction

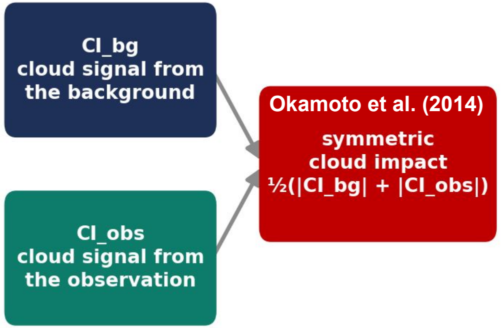
NOAA-18 AMSU-A channel 7, background versus observed brightness temperature.

Predictor classes available in UFO

Predictor	What it captures
Constant	Offset term, one per channel
Lapse rate (order 1, 2)	Sensitivity to the mean atmospheric temperature lapse rate
Sensor scan angle (order 1–4)	Cross-track scan-angle dependence
Emissivity	Surface emissivity sensitivity, mainly for window channels
Cosine of latitude	Residual latitudinal or seasonal structure
Cloud liquid water path	All-sky cloud-versus-clear departure, from retrieved cloud liquid water
SymmCldImpact	Unified symmetric cloud-impact predictor for all-sky

Predictor names changed between JEDI releases. Check ufo/src/ufo/predictors for your build.

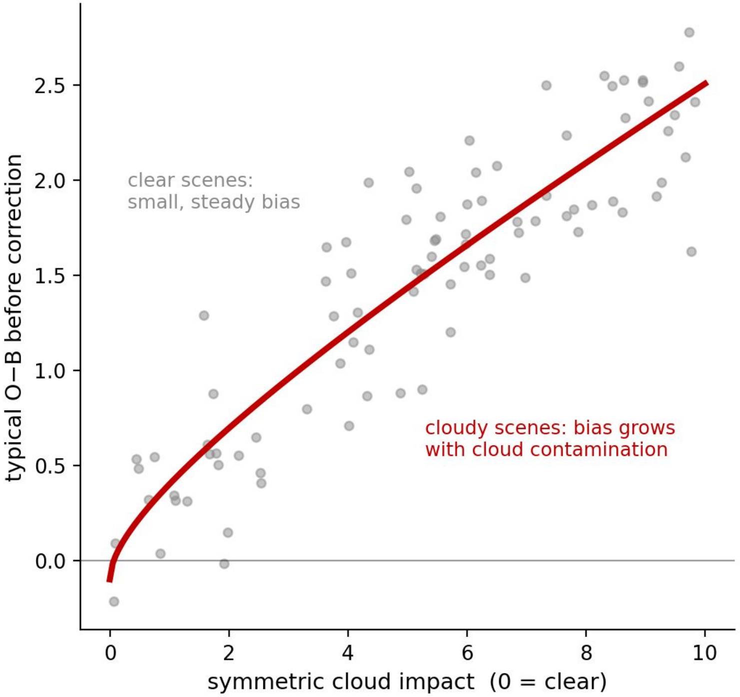
SymmCldImpact



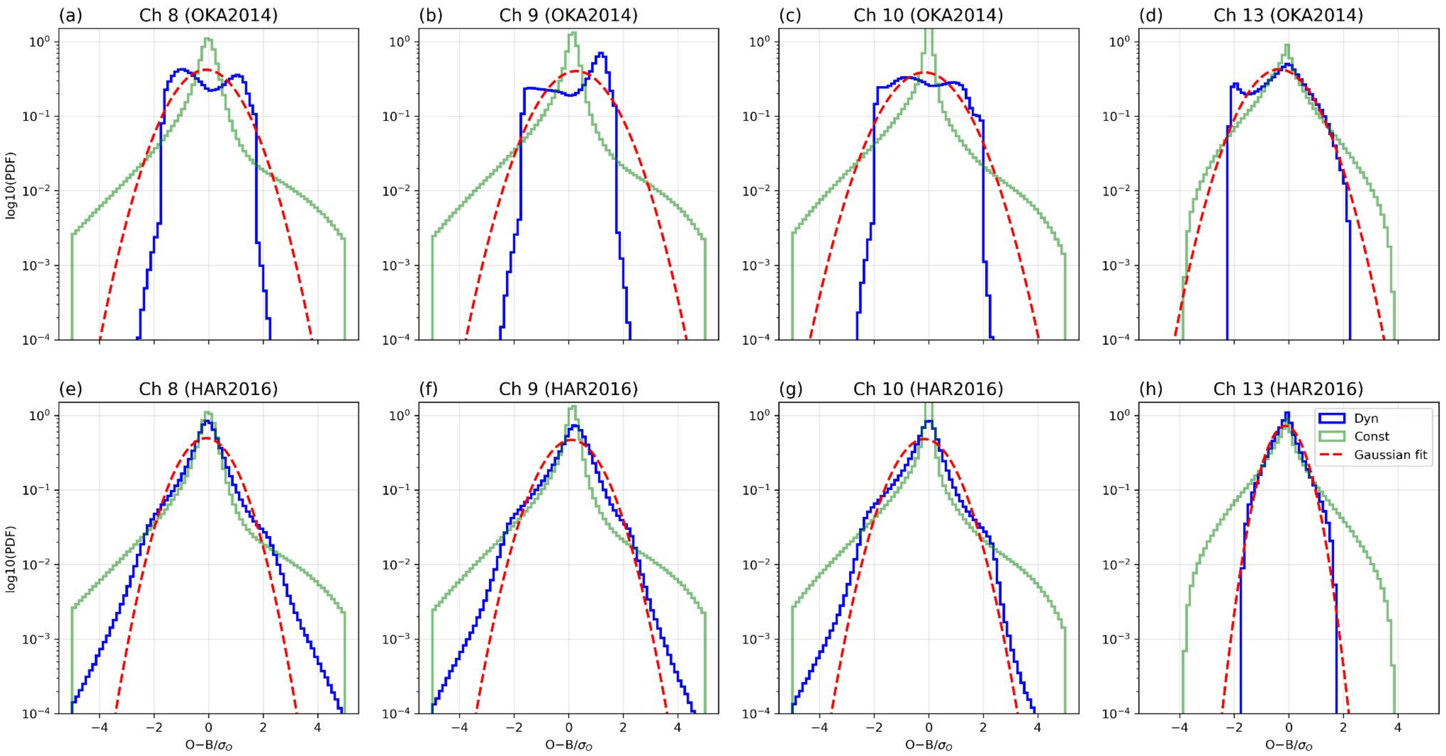
Harnish et al. (2016)

$$CI_O = \max(0, BT_{lim} - BT_{y,bc}), \quad CI_M = \max(0, BT_{lim} - BT_x)$$

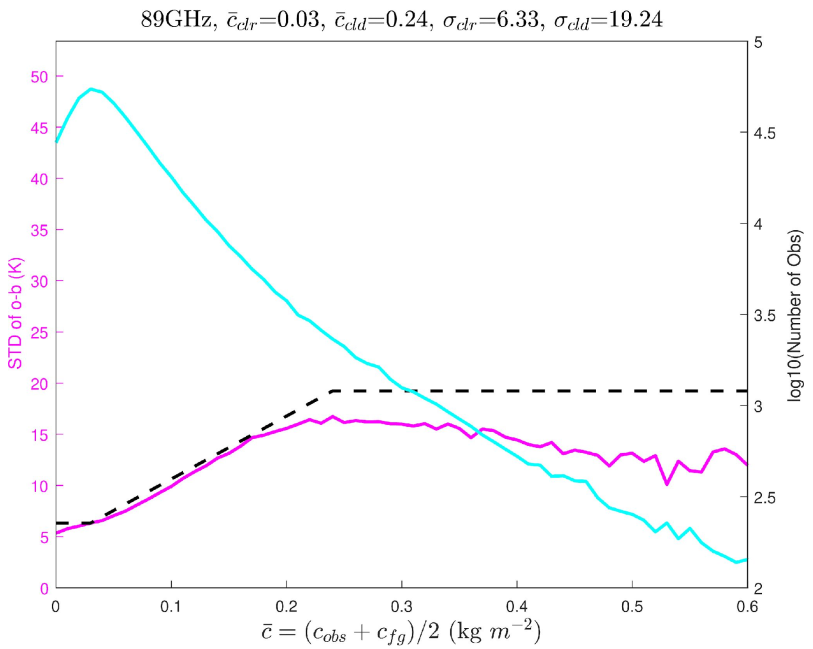
$$C_A = \frac{1}{2}(CI_O + CI_M)$$



SymmCldImpact



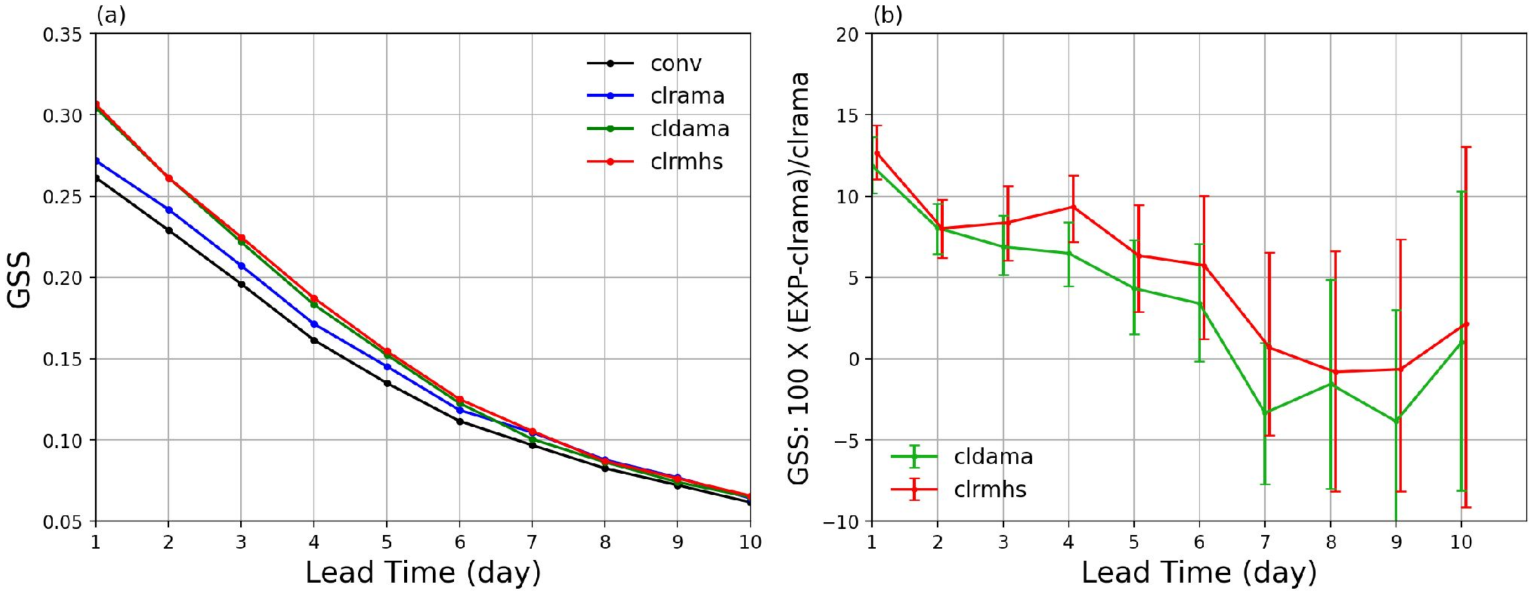
Situation-dependent all-sky obs error model



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

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

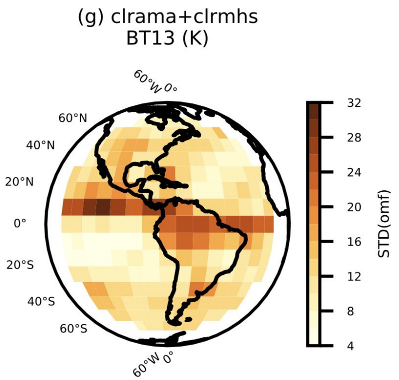


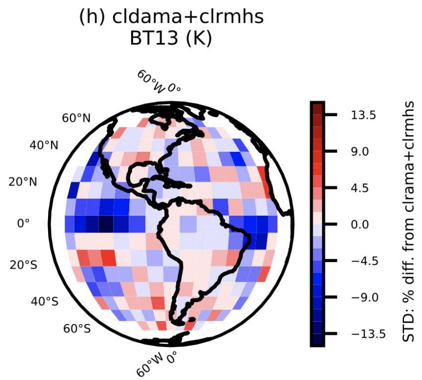
Liu et al., 2022

All-sky radiance DA

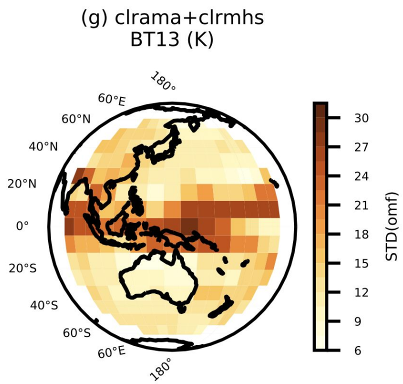
Added value of all-sky AMSU-A

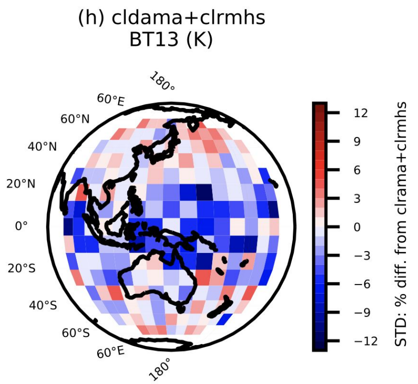
ABI





AHI





Day-1 forecast

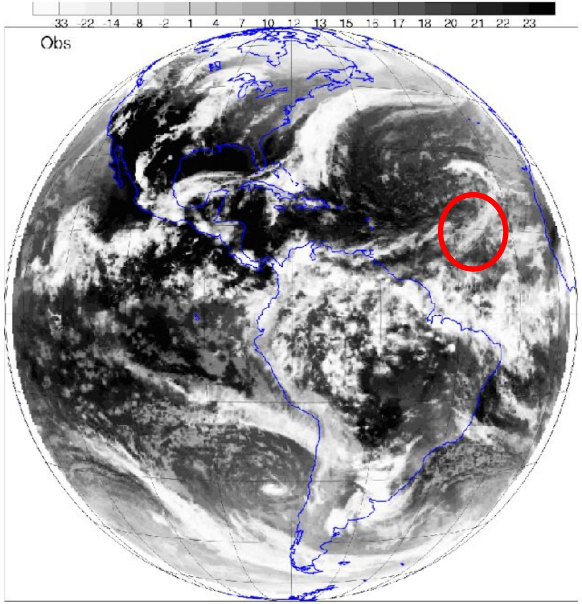
Error STD reduction

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

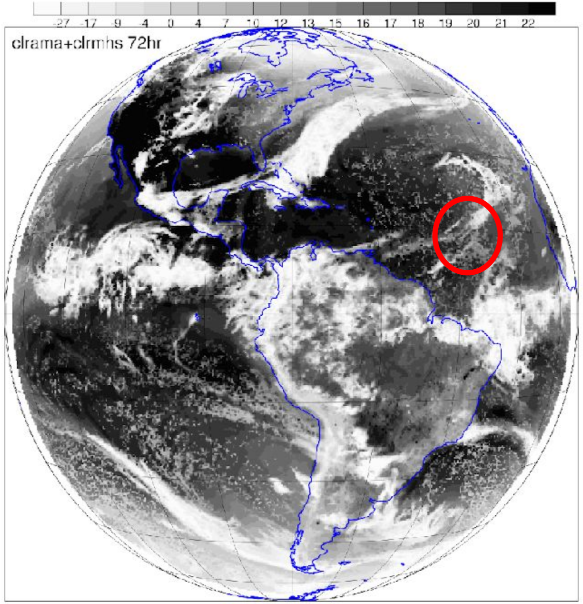
All-sky radiance DA

Observations vs. Day-3 forecast

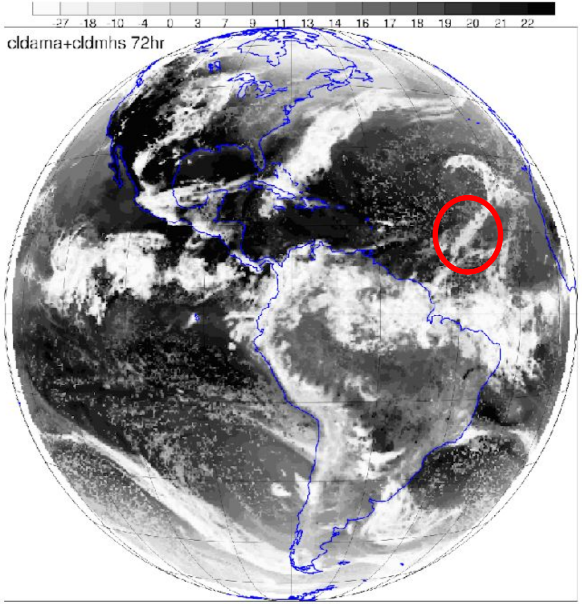
Observations



Clear-sky DA



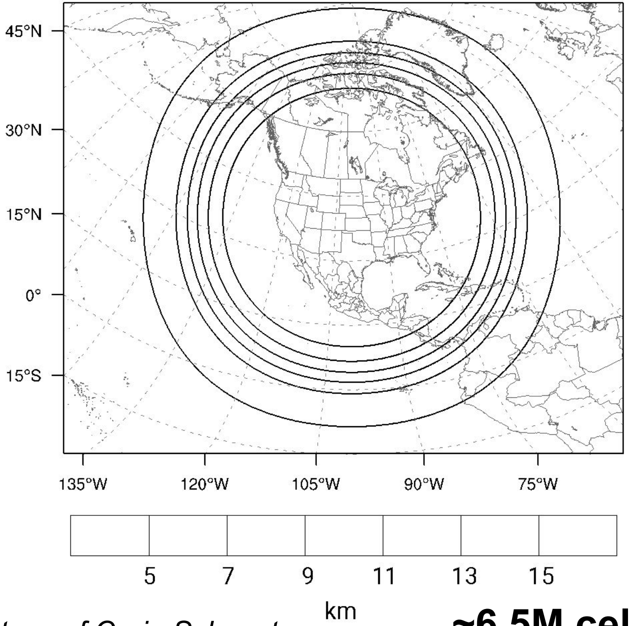
All-sky DA



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

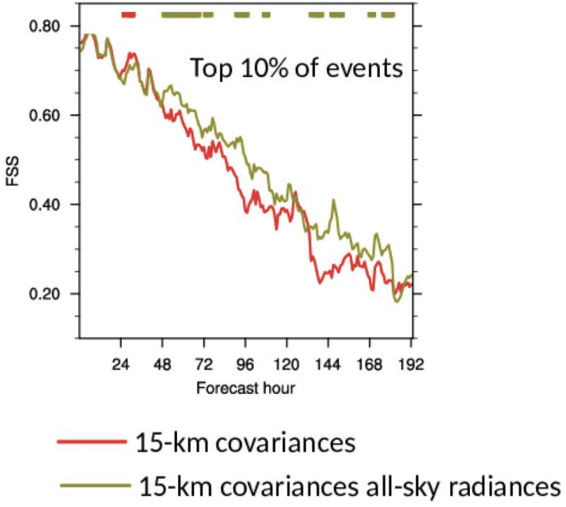
All-sky radiance DA

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

A satellite radiance is an observation that is related to the atmospheric state through a radiative transfer model

Radiance DA is complex

Cloudy radiative transfer, quality control, bias correction and the all-sky observation error model all have to work together, and the complexity differs from sensor to sensor.

There is much more to explore

Visible and near-infrared bands, active sensors, small satellite constellations, and correlated observation error.

JEDI is built for this

Configuration rather than code changes: you can compare CRTM and RTTOV in the same run, which makes the science easier to do.

Satellite observation → IODA → QC → GeoVaLs → UFO / CRTM → HofX → O-B → VarBC → OOPS → analysis