TRAINING
COURSE

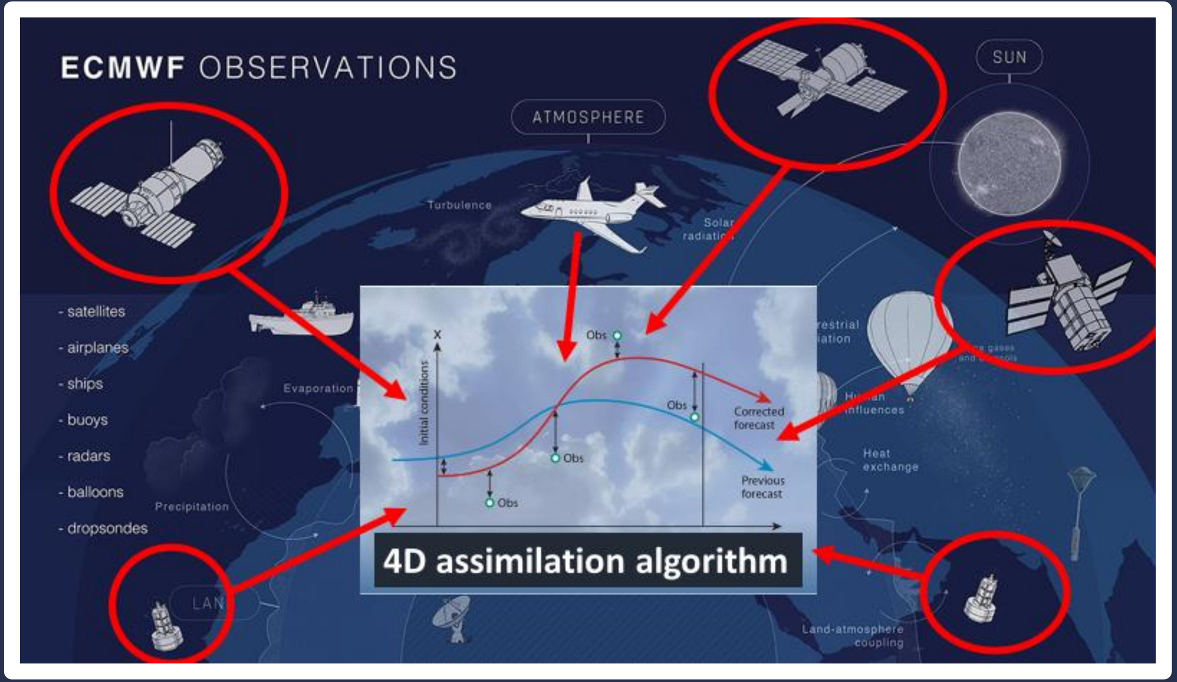
The assimilation of satellite radiance observations

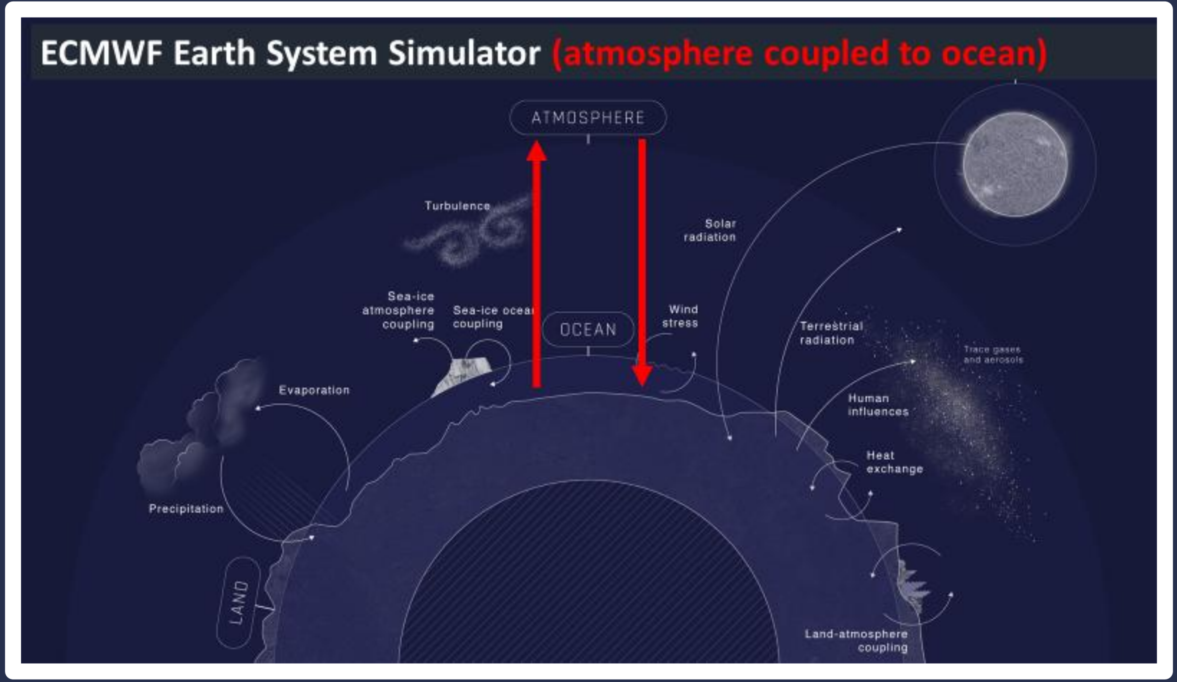
Tony McNally

Overview:

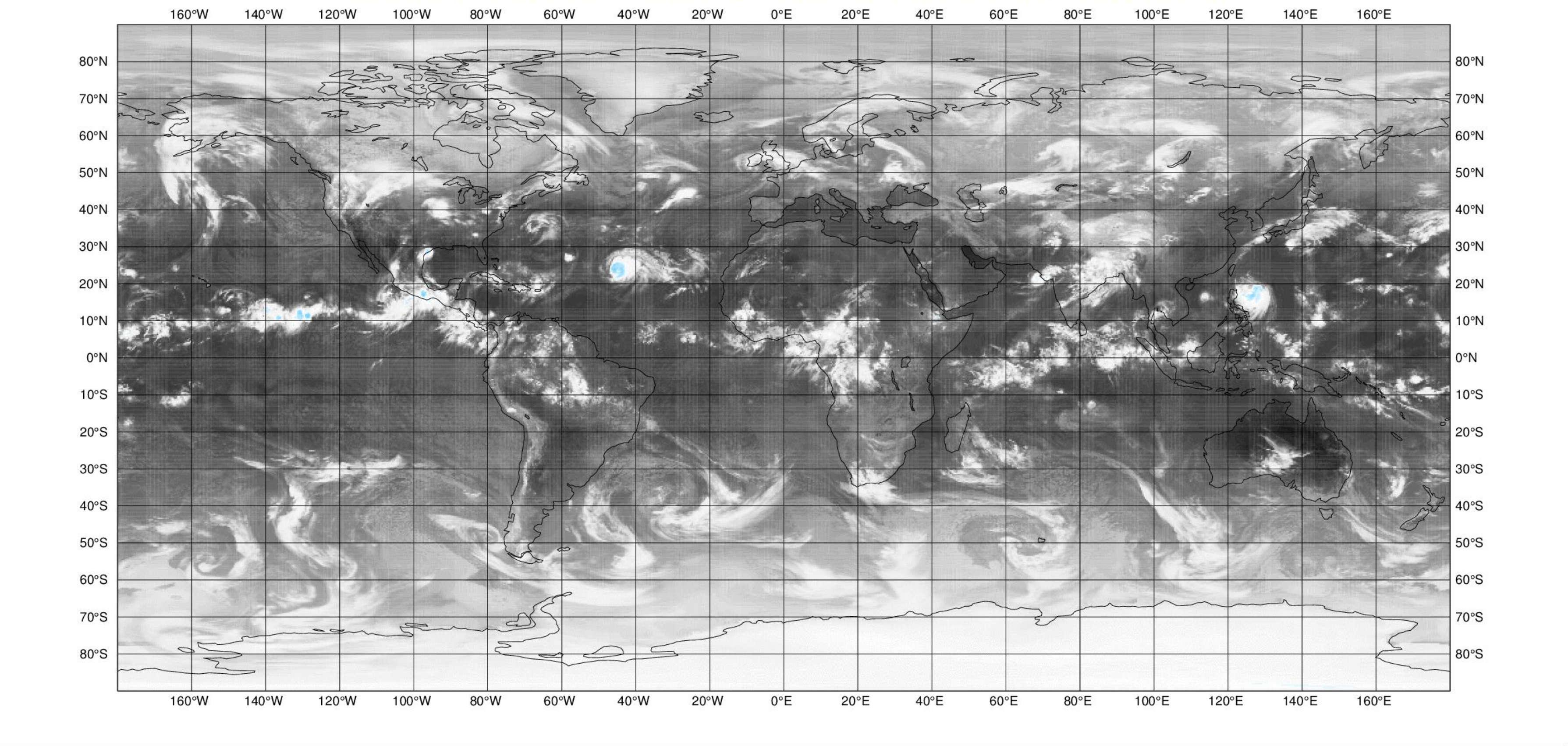
- Why do we need satellites ?
- What do we have and which are most important ?
- What is actually measured ?
- Key elements of satellite data assimilation

The Satellites and other observations provide **<u>initial conditions</u>** (what the atmosphere doing now) from which forecasts are launched

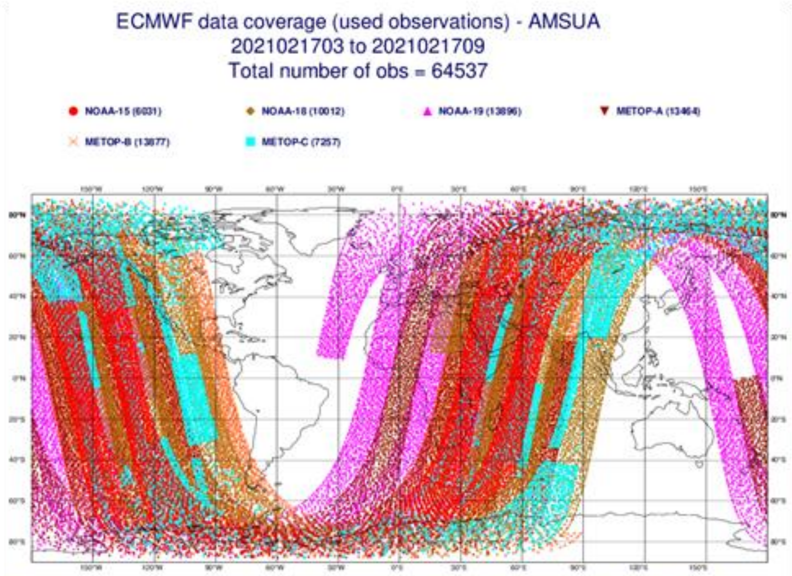


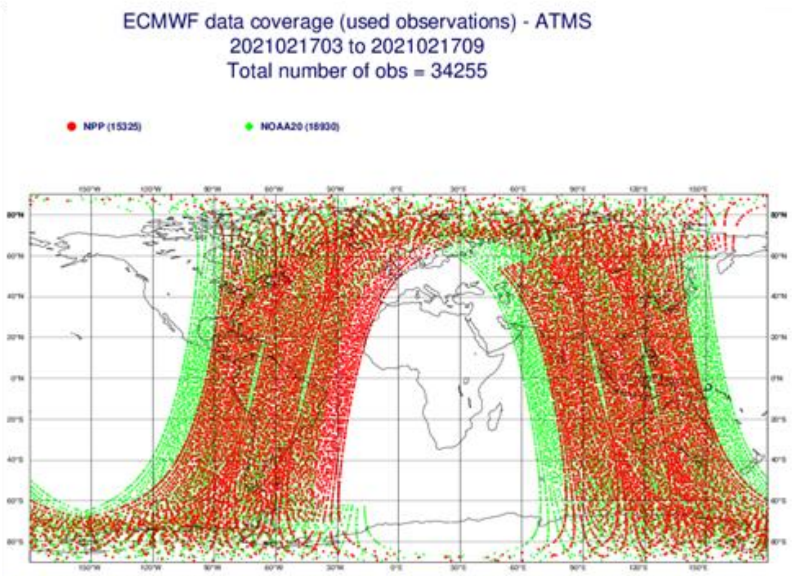


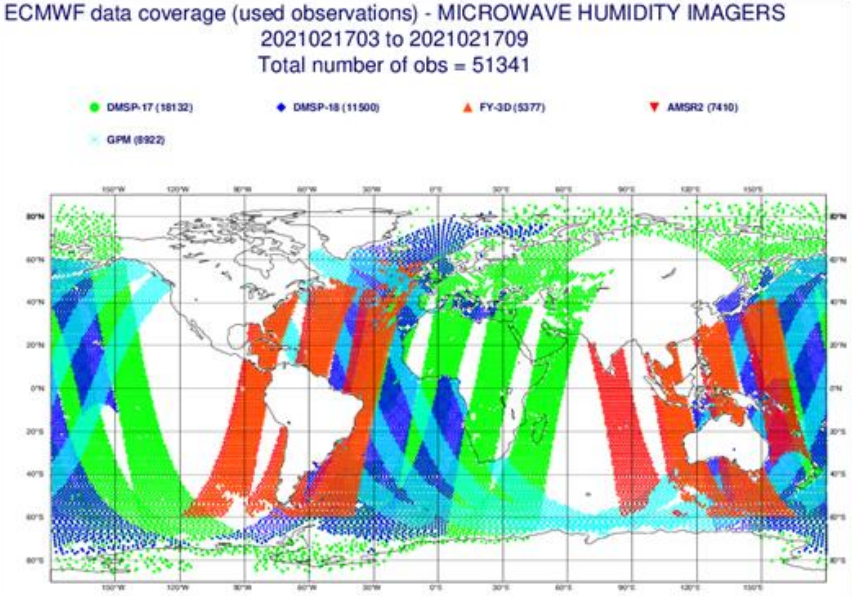
To forecast many days into the future, we need global initial conditions…and only satellites can provide this

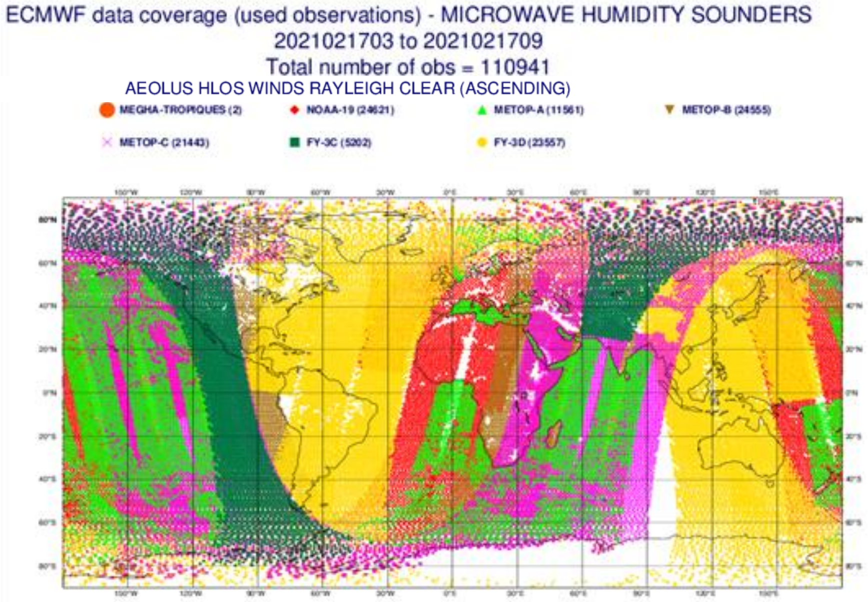


Passive microwave (LEO)

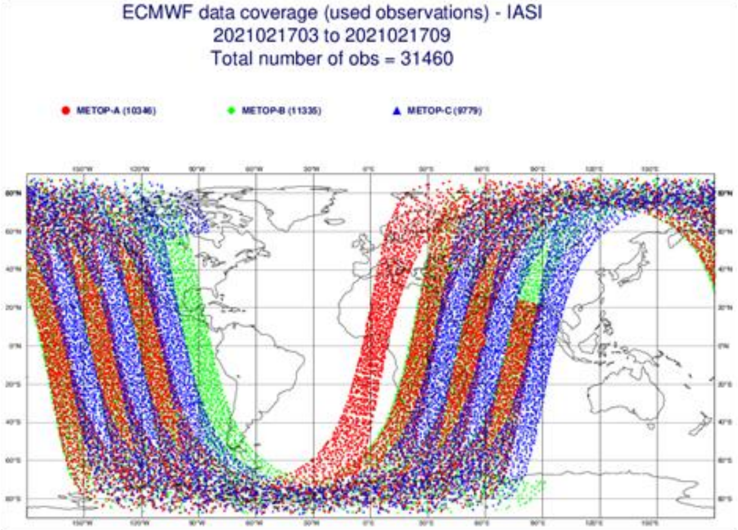


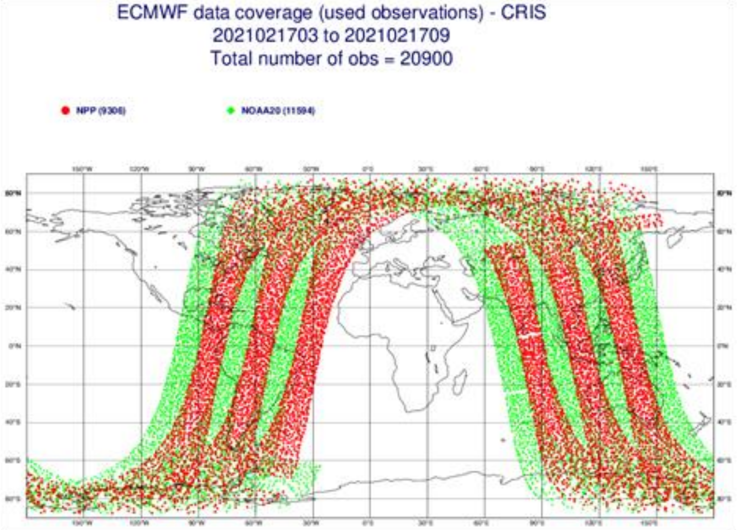


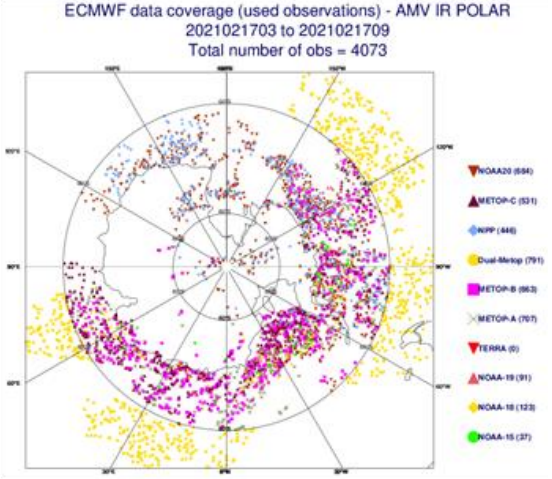


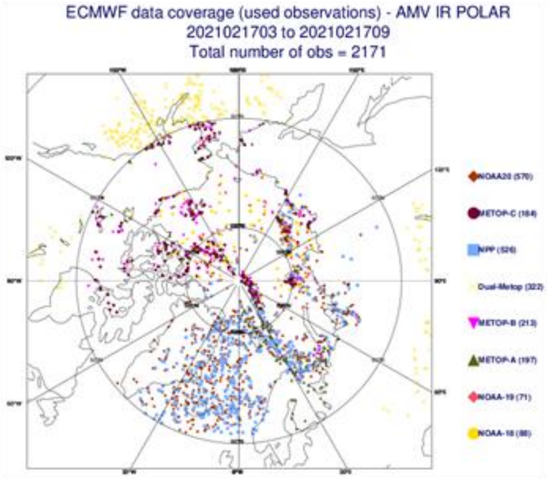


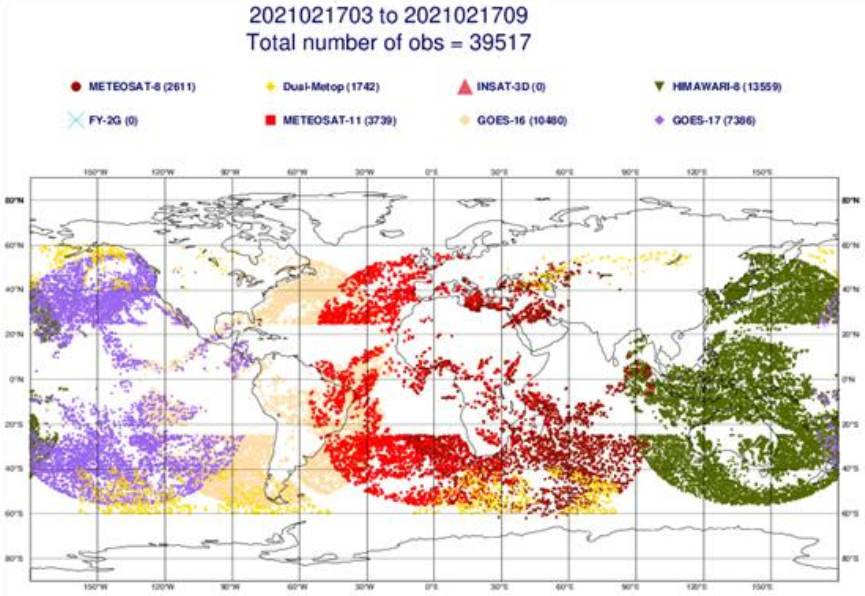
Passive infrared (LEO and GEO)



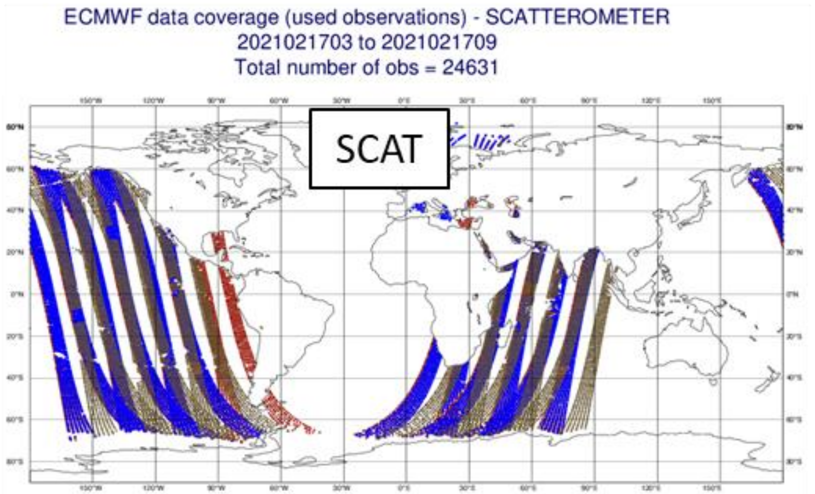


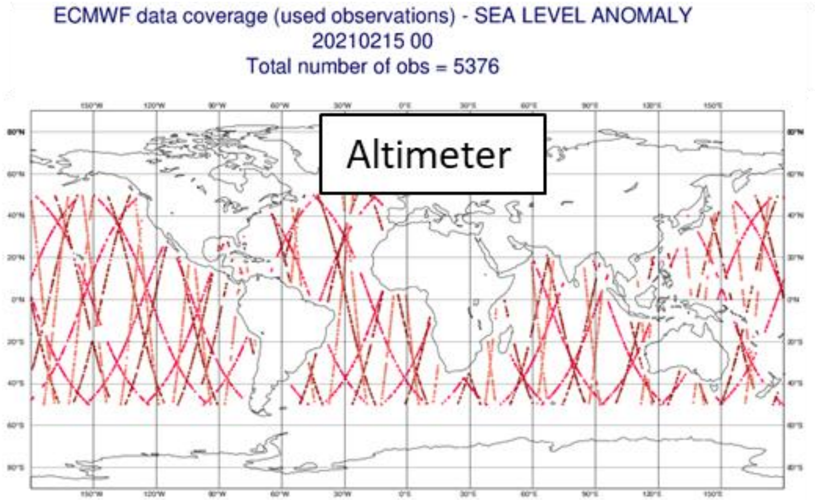


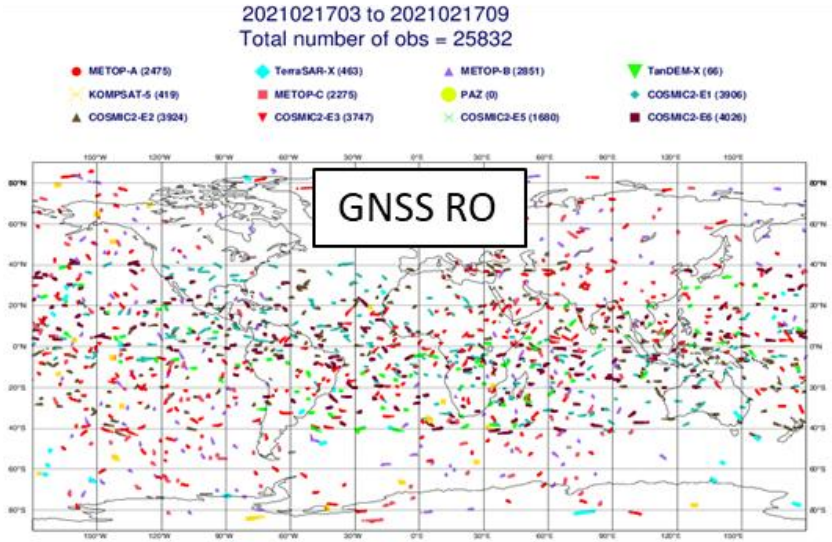


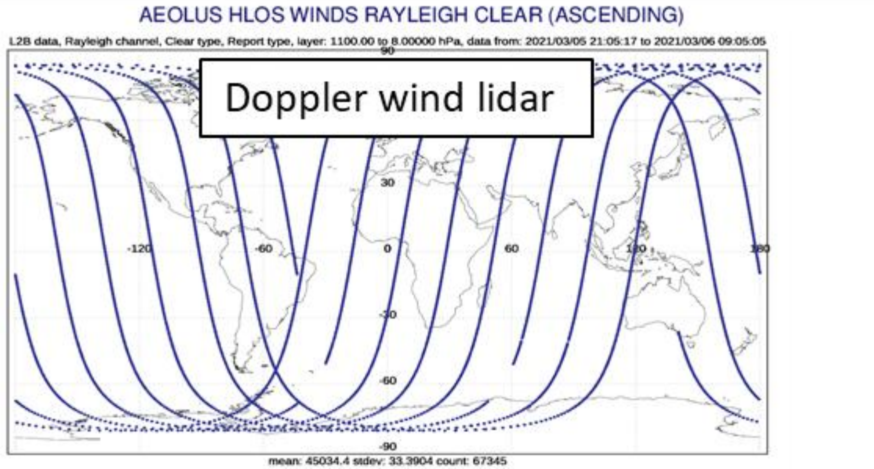


Active sensors









Can we quantify how important are satellites for NWP ?

…denial experiments…

Can we quantify how important are satellites for NWP ?

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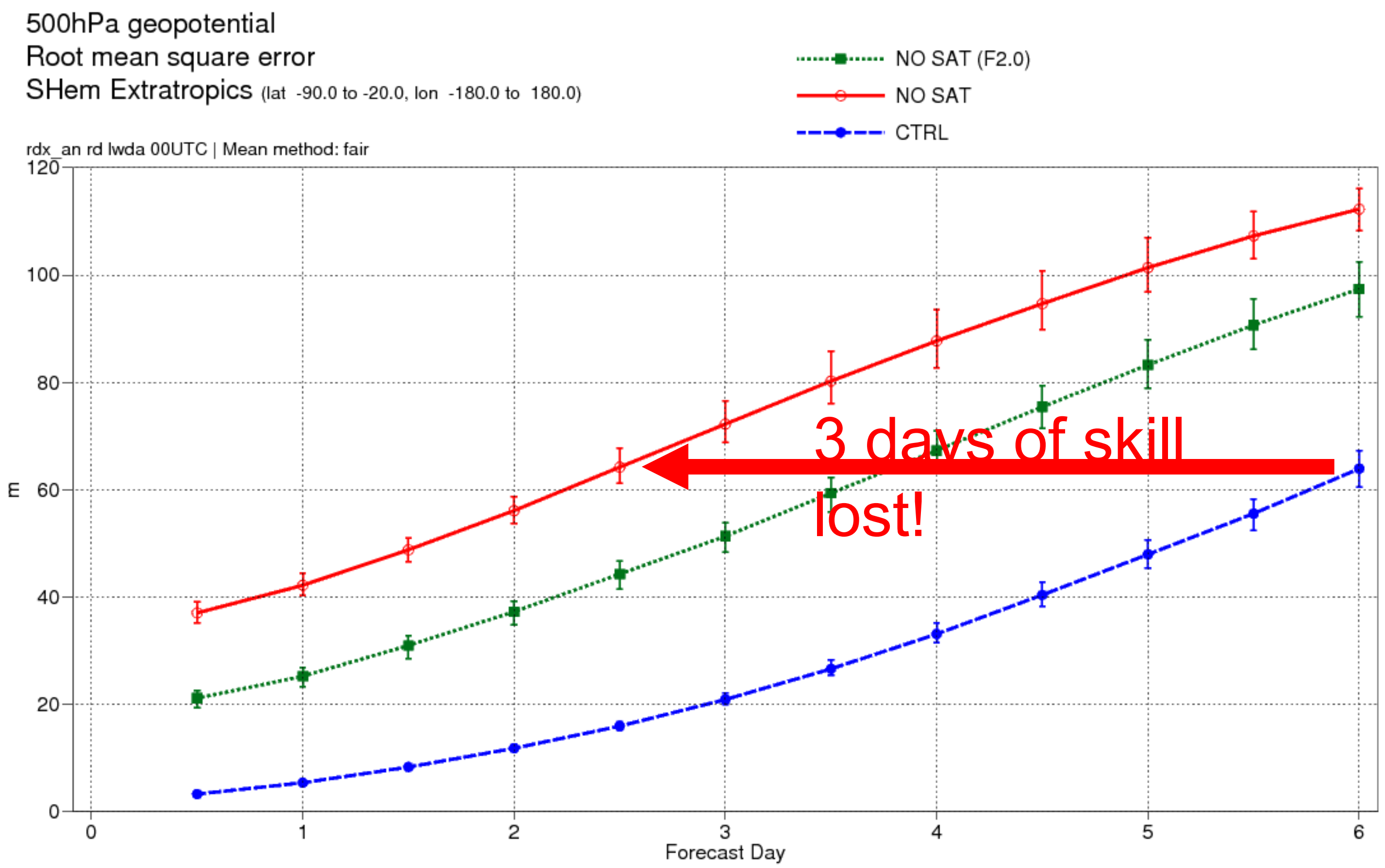


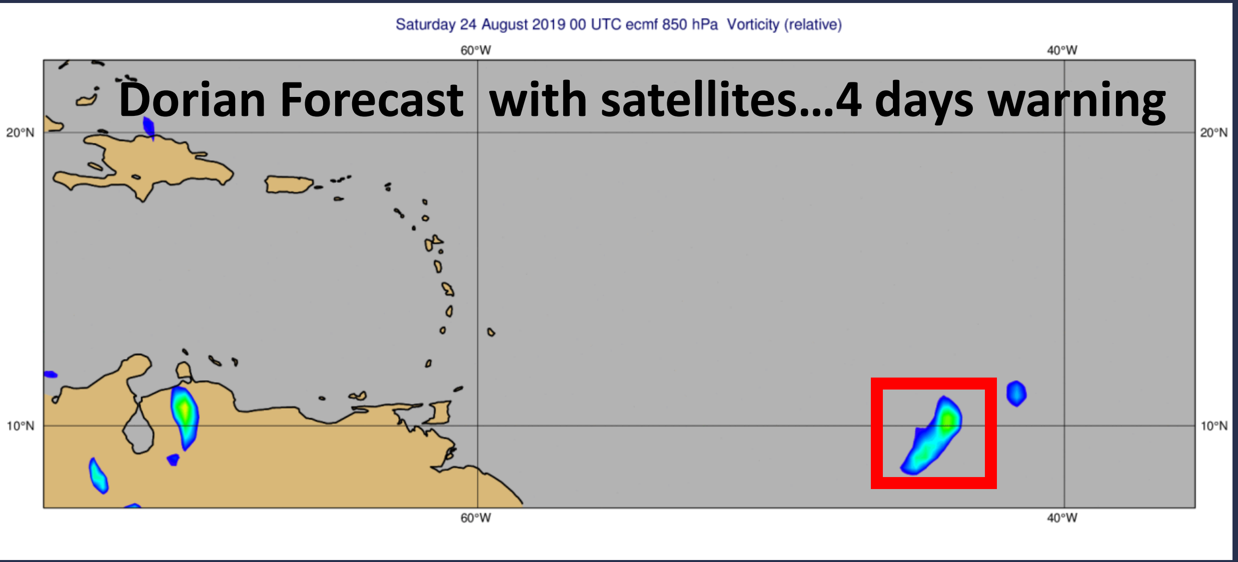
Dorian viewed from the Sentinel-3 satellite

Dorian viewed from the Sentinel-3 satellite

Dorian viewed from the Bahamas

Most deadly event in recent history is Nargis (2008) that claimed ~ 130,000 lives

Early identification of storm genesis with satellites saves many thousands of lives

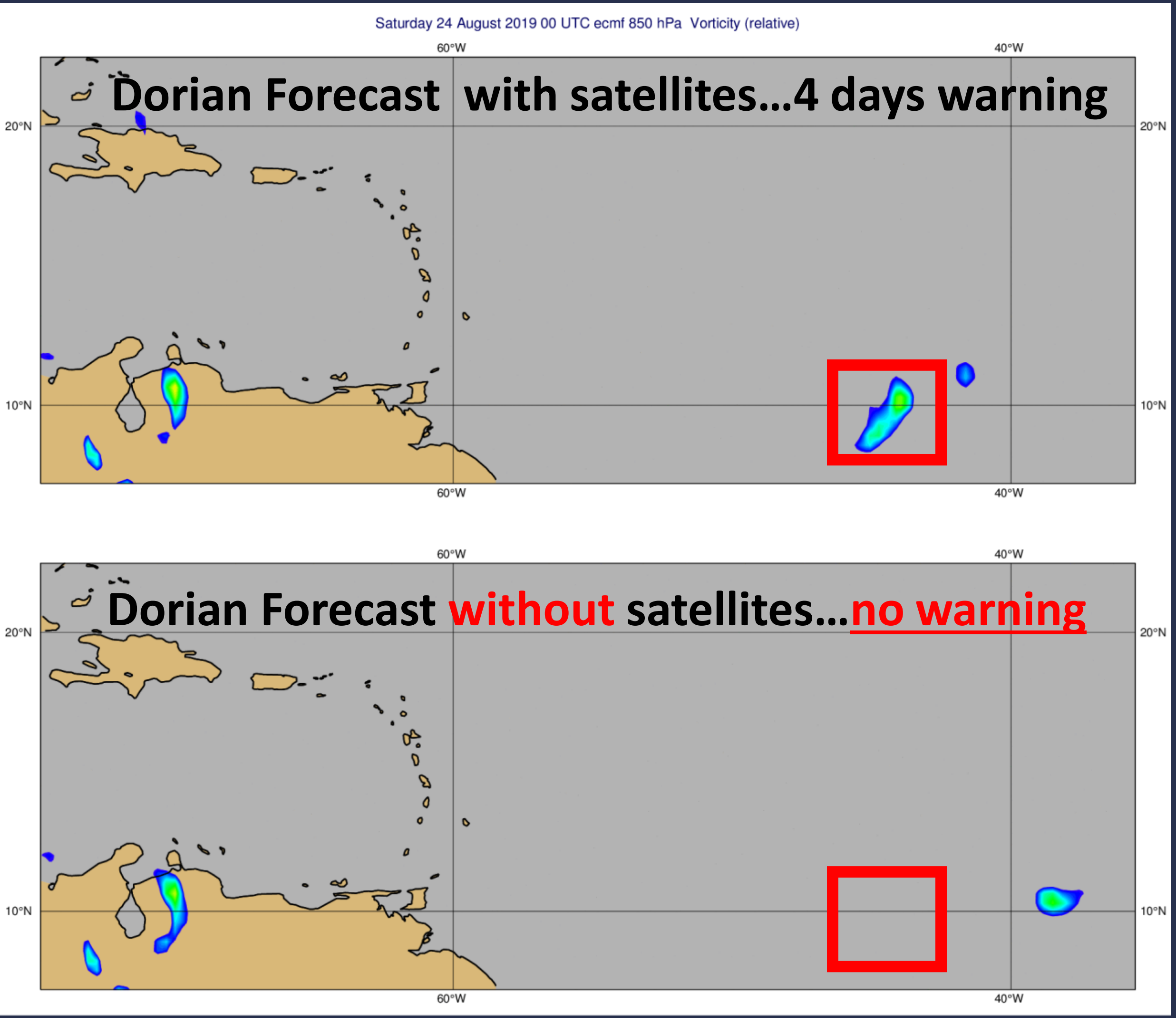


Key information

1. Ocean surface temperature
2. mid level humidity
3. wind sheer

Satellites provide this …

Without satellites we would often give no warning of severe weather!



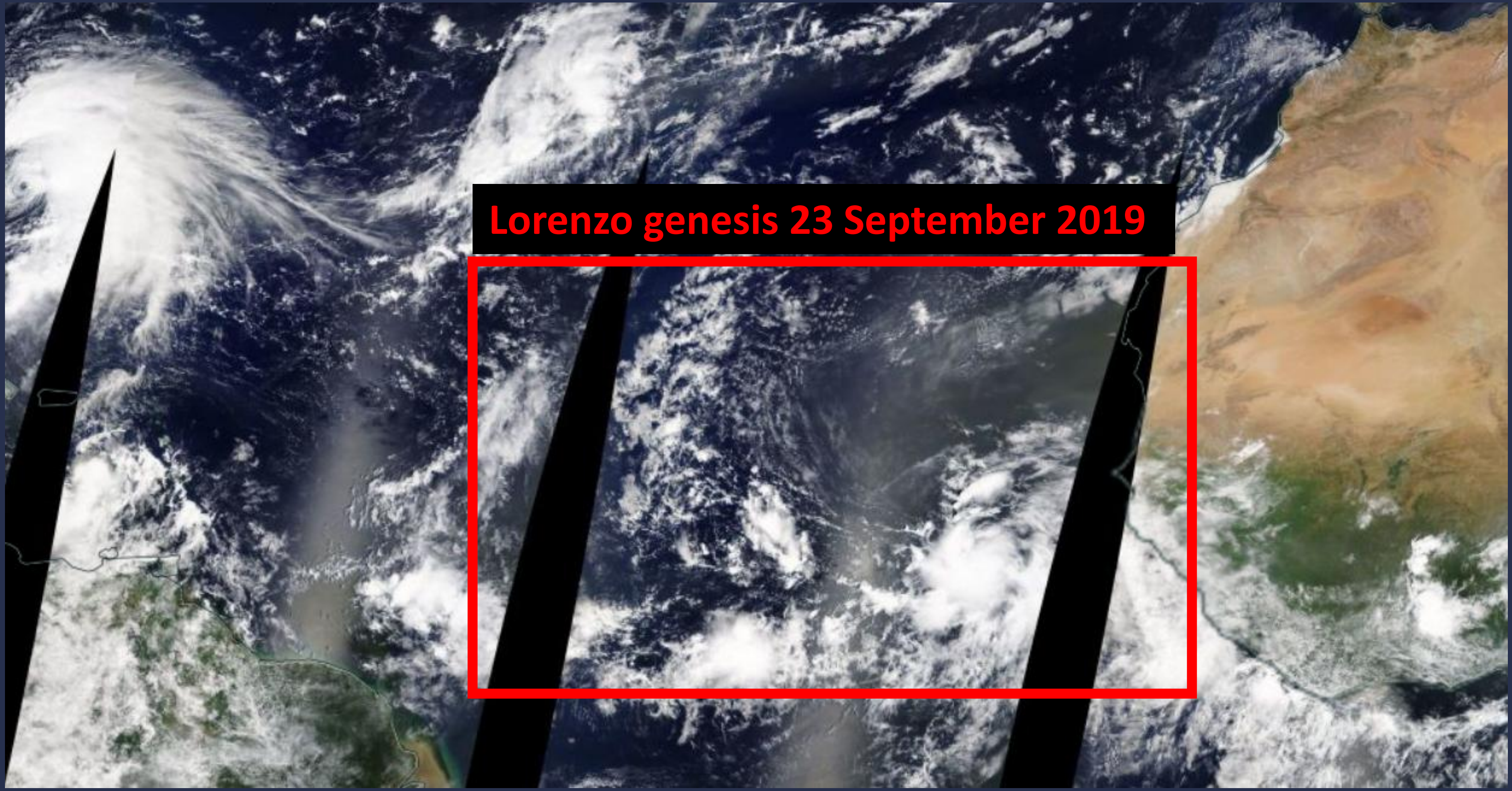
~~Key observations~~

1. ~~Ocean surface temperature~~
2. ~~mid level humidity~~
3. ~~wind sheer~~

Early identification of storm genesis…Lorenzo

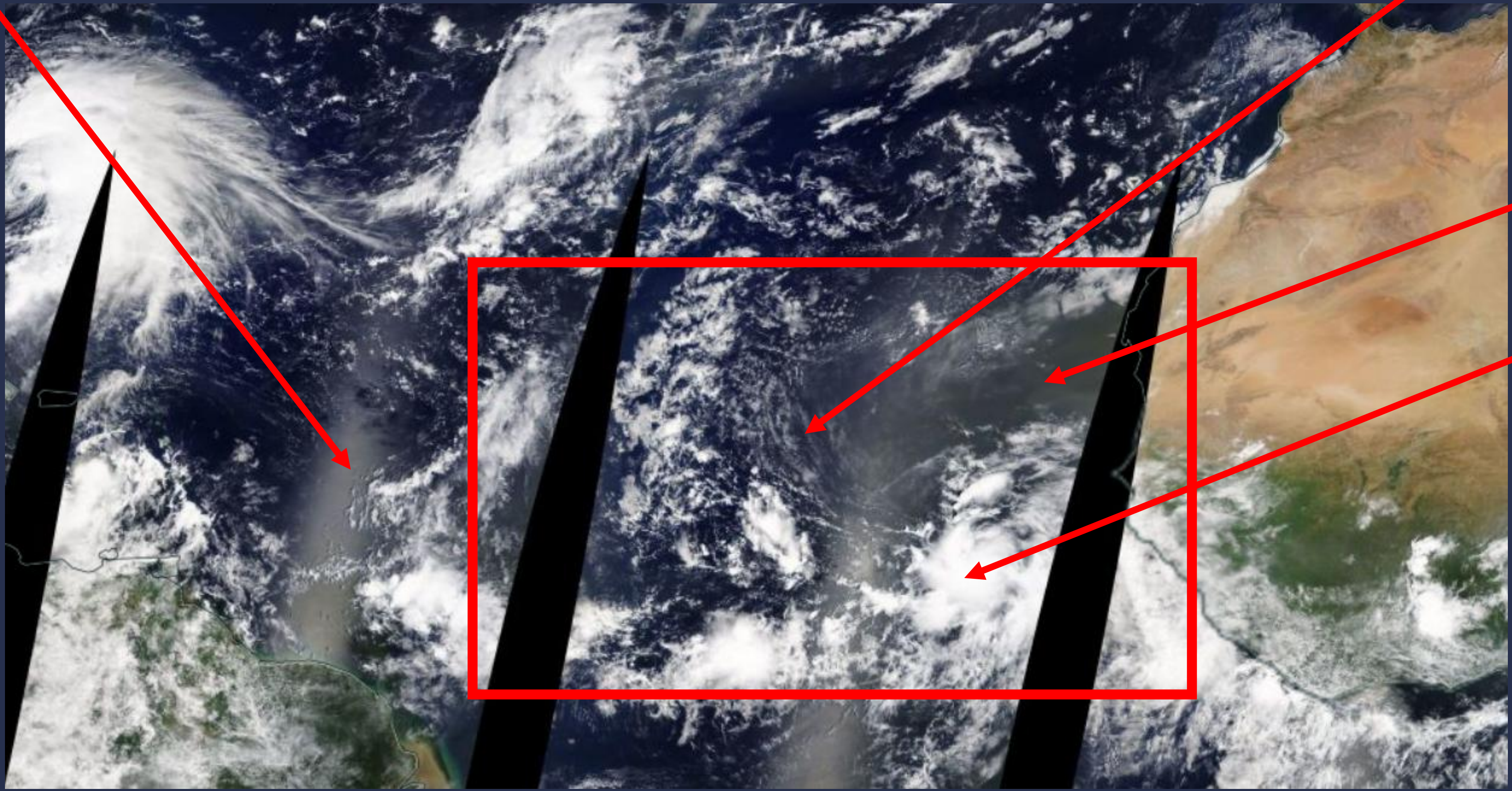
Key observations

- Ocean surface temperature ?
- mid level humidity ?
- wind sheer ?



Early identification of storm genesis…in a challenging environment

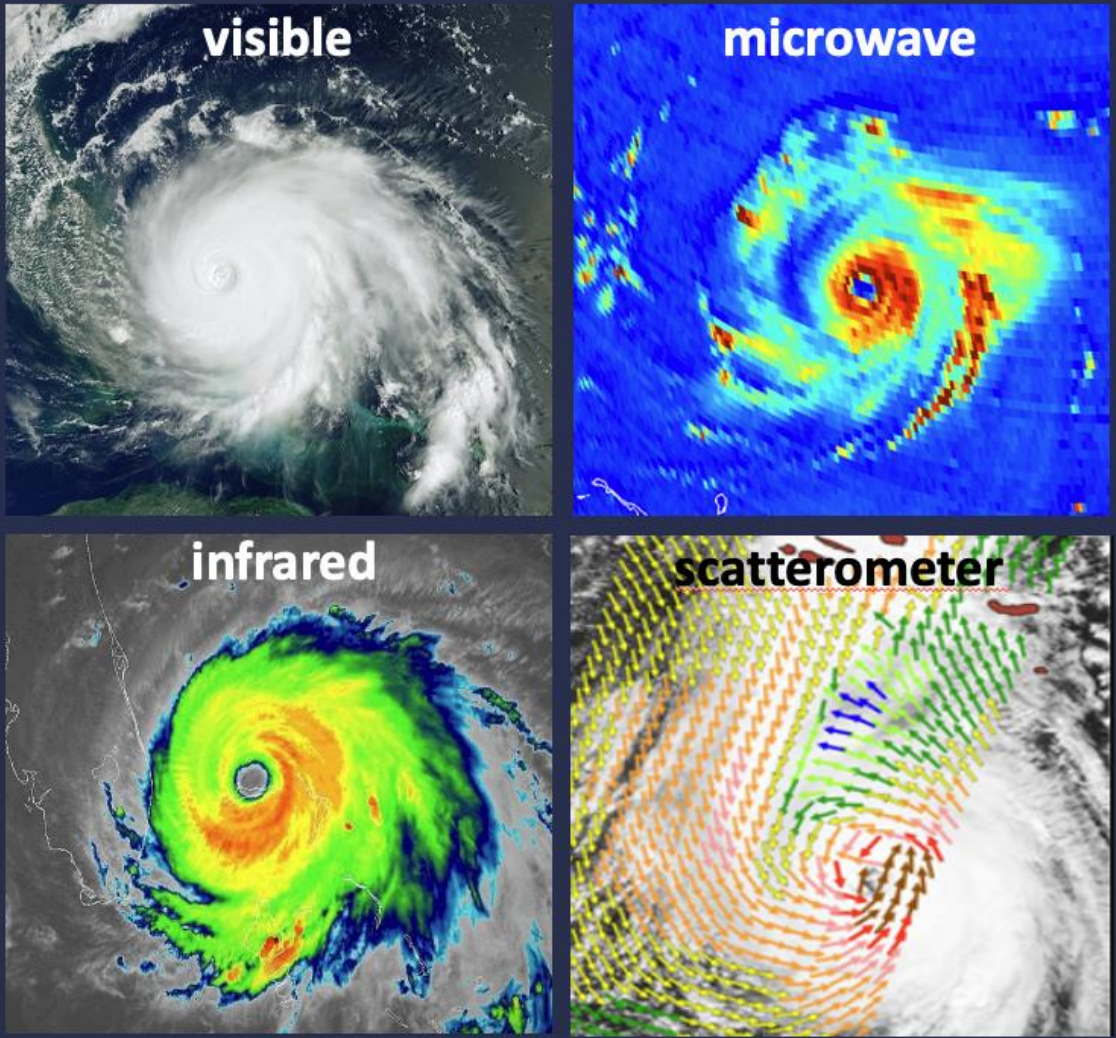
- Ocean surface temperature ?
- mid level humidity ?
- wind sheer ?



Satellite sensors operating at different frequencies are used to understand the full atmospheric state…

Cloud phase and motion (wind)

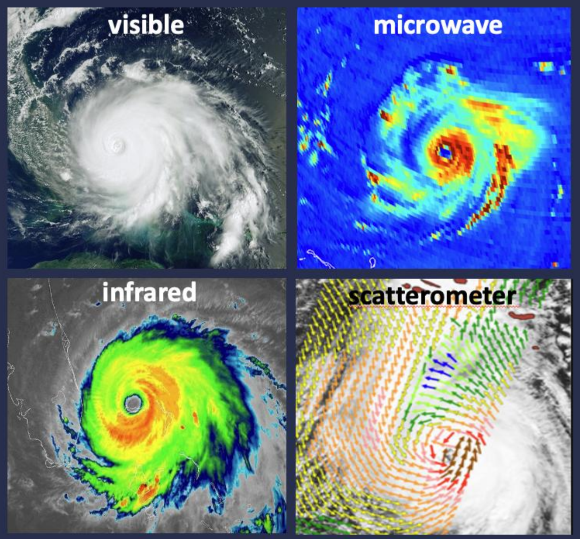
Temperature and height of clouds, humidity in clear sky

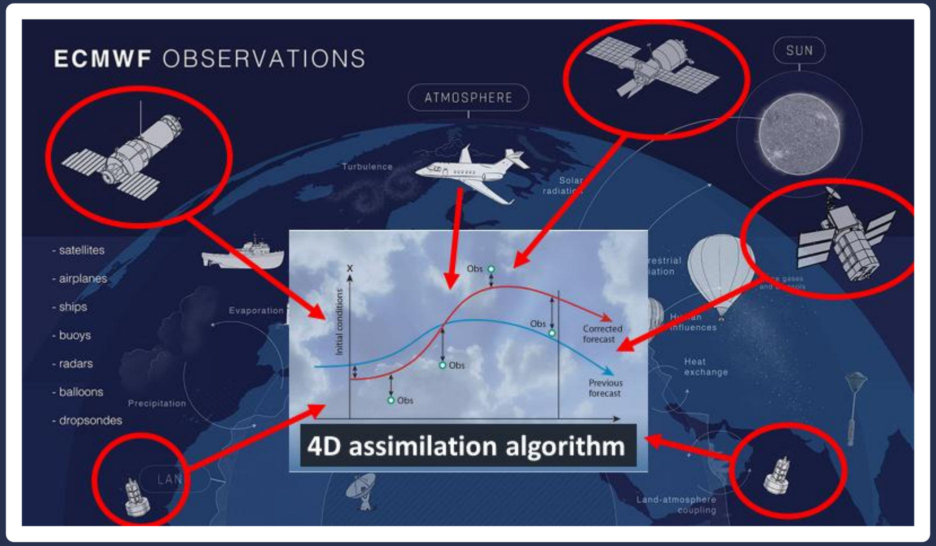


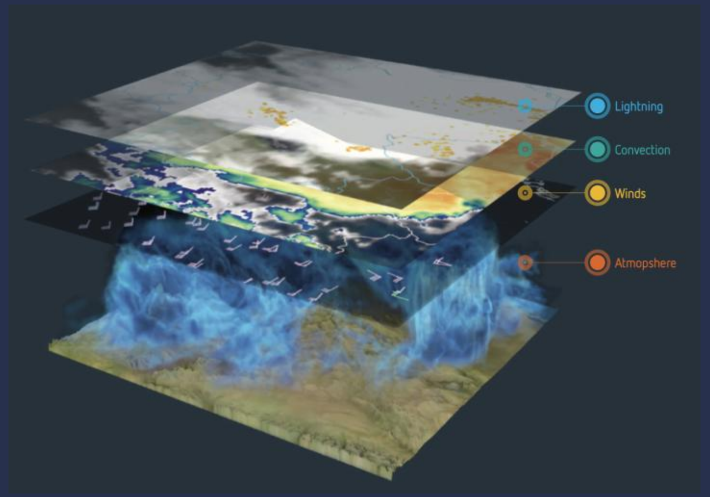
Water and rain content within clouds

Penetrating the clouds to look at ocean roughness and land state

…But require highly sophisticated Data Assimilation Systems to combine these into a coherent 3D picture

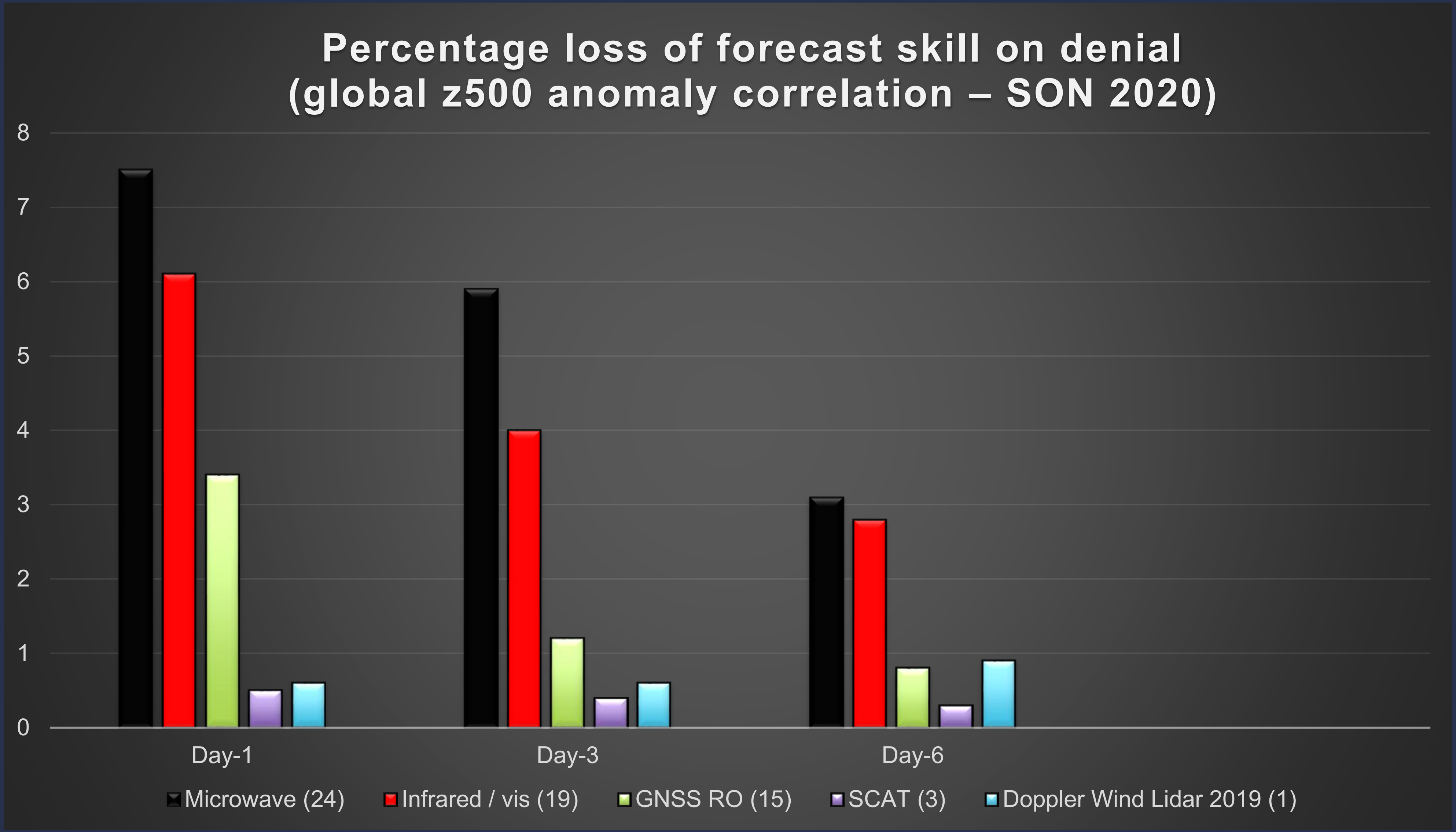






Which satellite observations are most important for NWP ?

Impact of different sensor technologies



Which satellite observations are most important for NWP ?

Sensor technology	Processing route
Passive microwave	L1 Radiances
Passive infrared	L1 Radiances / AMV
Radio occultation	Bending angles
SCAT / Altimeter	L2 wind / SLA / SWH
Doppler wind lidar	L2 LOS wind

Note that sensors available for NWP are **typically downward** looking instruments (**not limb viewing**)

What do passive microwave and infrared satellite instruments measure …?

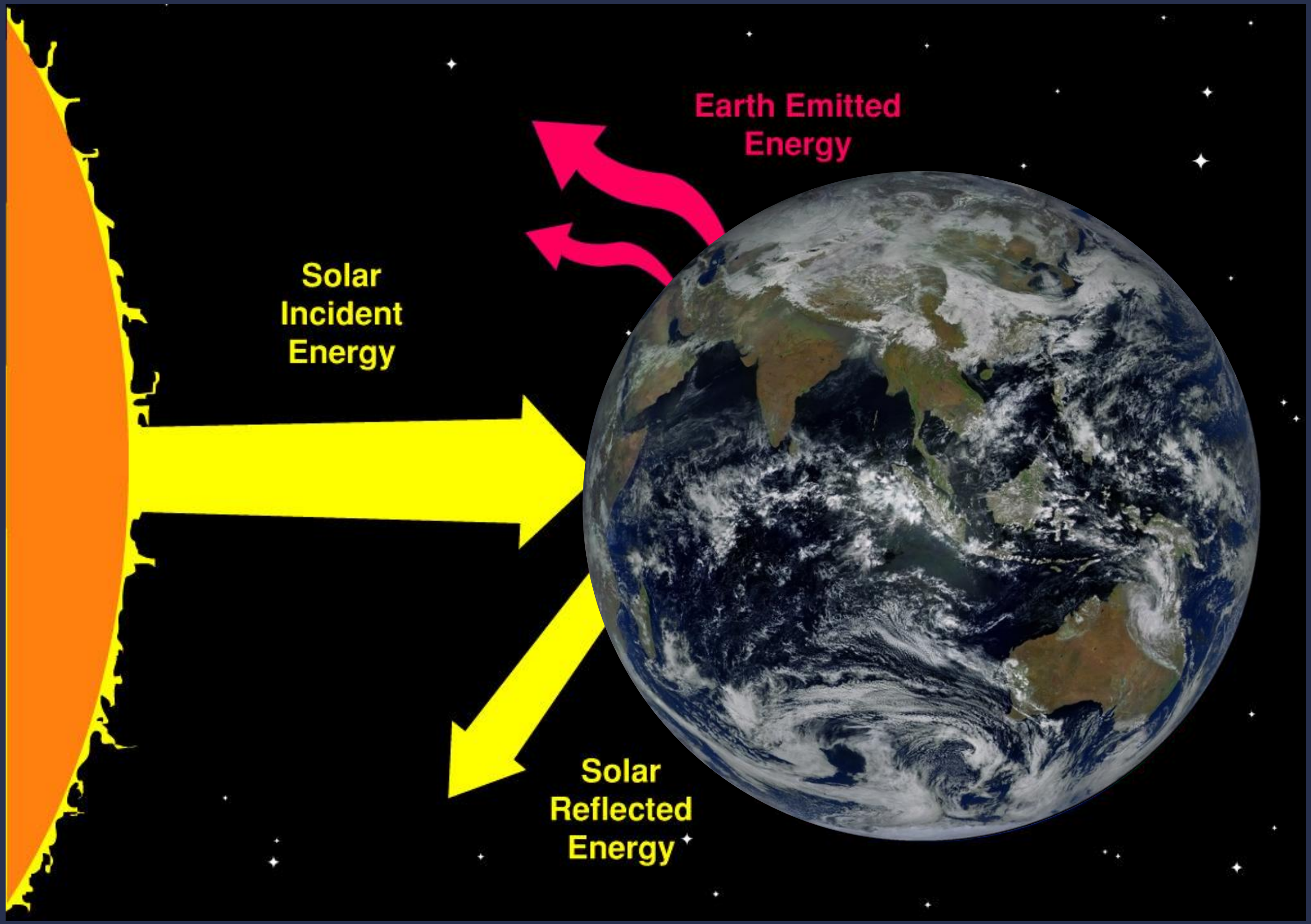
What do passive microwave and infrared satellite instruments measure …?

They DO NOT measure TEMPERATURE

They DO NOT measure HUMIDITY or OZONE

They DO NOT measure WIND

SATELLITES CAN ONLY MEASURE OUTGOING THERMAL RADIATION FROM THE ATMOSPHERE



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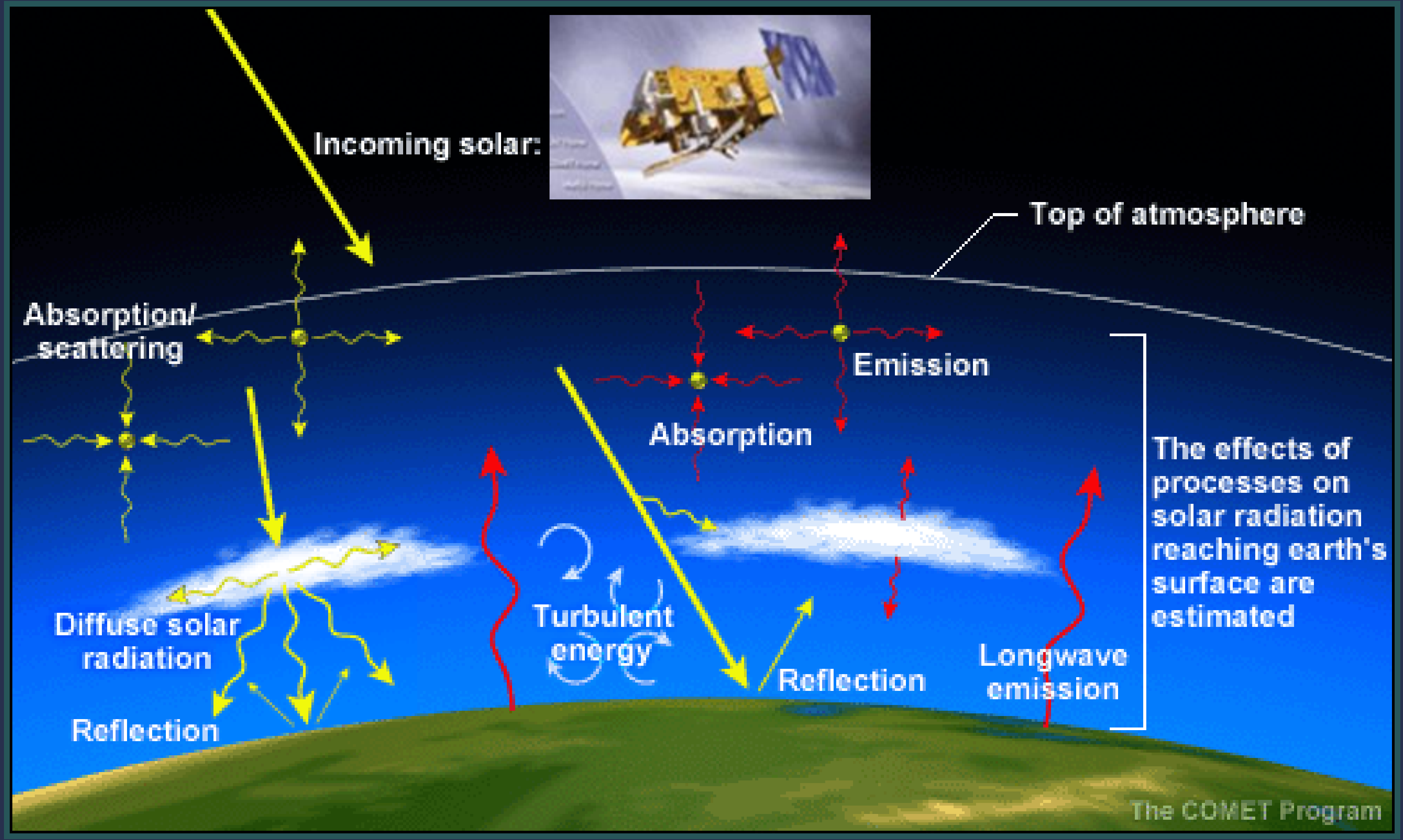


What do satellite instruments measure ?

Satellite instruments measure the radiation *L* that reaches the top of the atmosphere at given frequency *v* .

The measured radiance is related to geophysical atmospheric variables (T,Q,O_3, clouds etc…) by the

Radiative Transfer Equation

measured by the satellite

Our description of the atmosphere

$$L(\nu) = \int_0^\infty B(\nu, T(z)) \left[\frac{d\tau(\nu)}{dz} \right] dz + \text{Surface emission} + \text{Surface reflection/scattering} + \text{Cloud/rain contribution} + \ldots$$

Planck source term* depending on temperature *T(z)* of the atmosphere

Transmittance / Absorption in the atmosphere

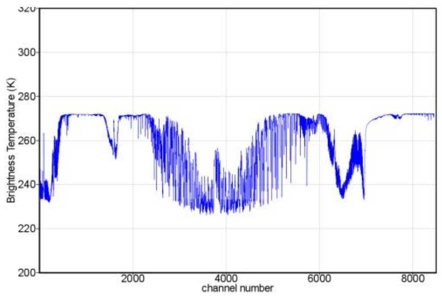
Other contributions to the measured radiances

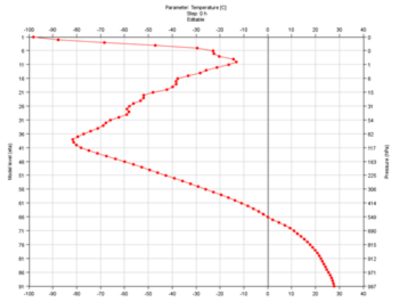
The Radiative Transfer (RT) equation

measured by the satellite

depends on the state of the atmosphere

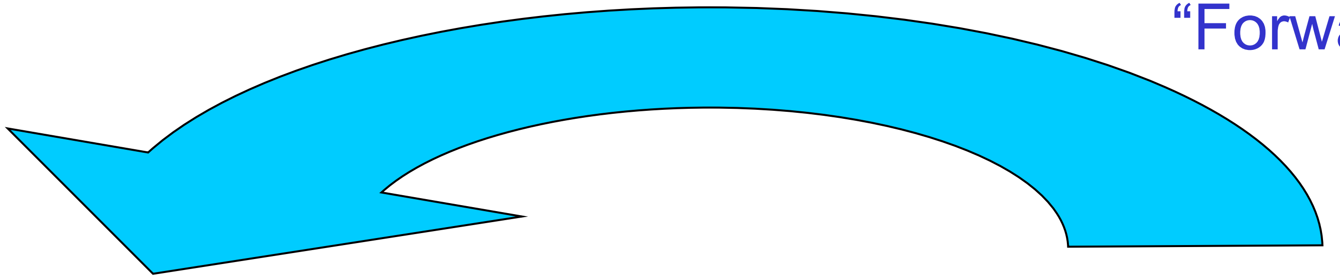
$$L(\nu) = \int_0^{\infty} B(\nu, T(z)) \left[\frac{d\tau(\nu)}{dz} \right] dz$$ + Surface emission + Surface reflection/ scattering + Cloud/rain contribution + ...





The Radiative Transfer (RT) equation

"Forward problem"



measured by the satellite — depends on the state of the atmosphere

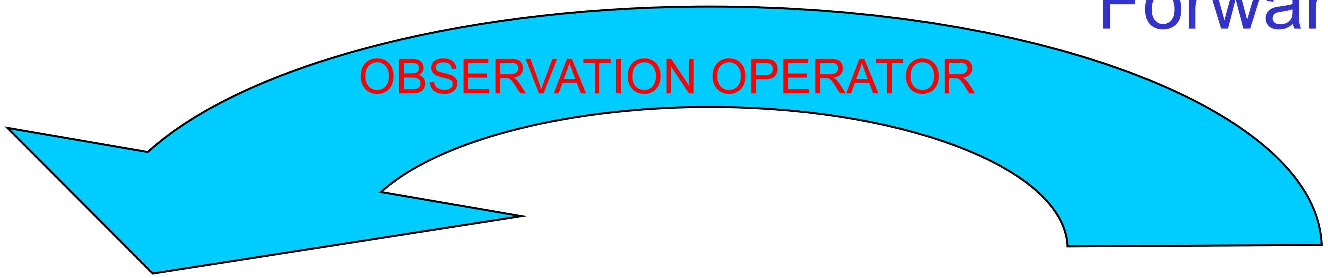
$$L(\nu) = \int_0^\infty B(\nu, T(z)) \left[\frac{d\tau(\nu)}{dz} \right] dz + \text{Surface emission} + \text{Surface reflection/scattering} + \text{Cloud/rain contribution} + \ldots$$

…given the state of the atmosphere, what is the radiance…?

*i.e. we can **simulate** what radiation would reach the satellite from a particular atmosphere…*

The Radiative Transfer (RT) equation

"Forward problem"



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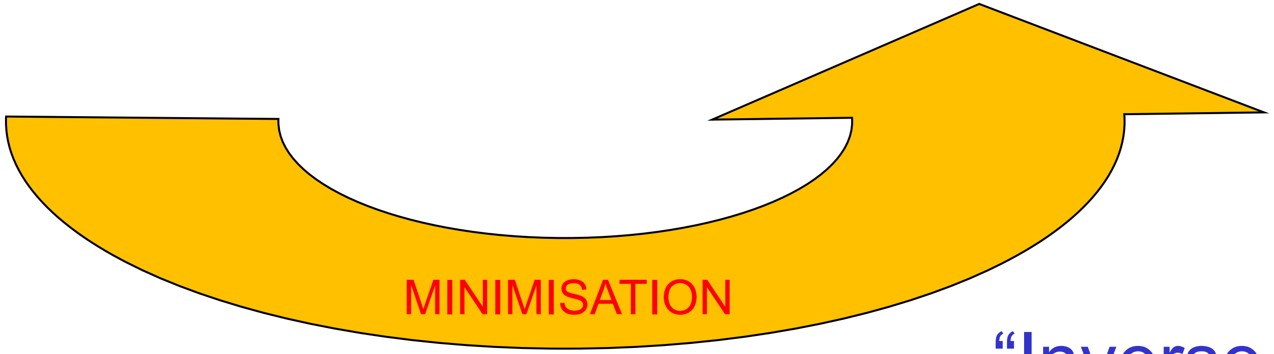
$$L(\nu) = \int_0^\infty B(\nu, T(z)) \left[\frac{d\tau(\nu)}{dz} \right] dz + \text{Surface emission} + \text{Surface reflection/scattering} + \text{Cloud/rain contribution} + \ldots$$



"Inverse problem"

…but first we have to simplify things a bit…

"Channel selection" …

…designing satellite instruments to measure atmospheric radiation at very specific frequencies (channels)

Atmospheric sounding channels…

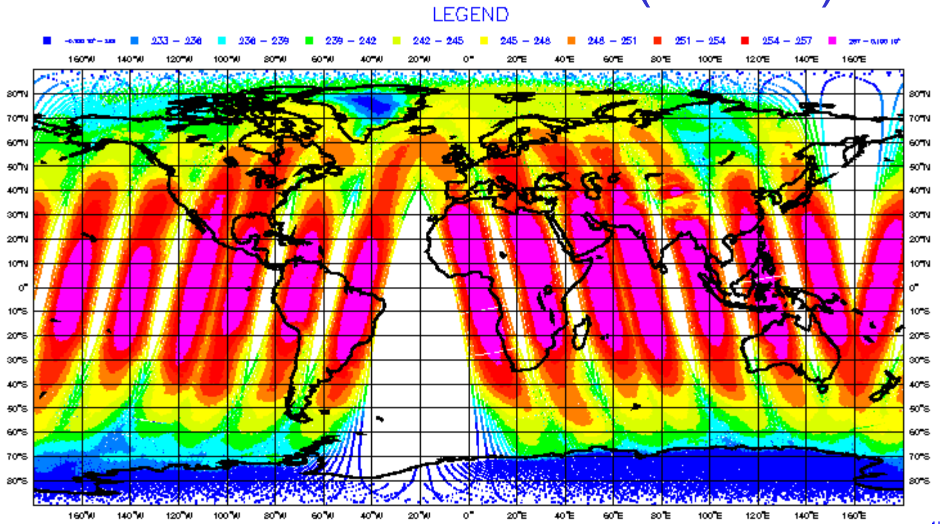
These channels are located in parts of the infra-red and microwave spectrum for which the main contribution to the measured radiance is from the atmosphere and can be written:

$$L(\nu) \approx \int_0^\infty B(\nu, T(z)) \left[\frac{d\tau(\nu)}{dz} \right] dz$$

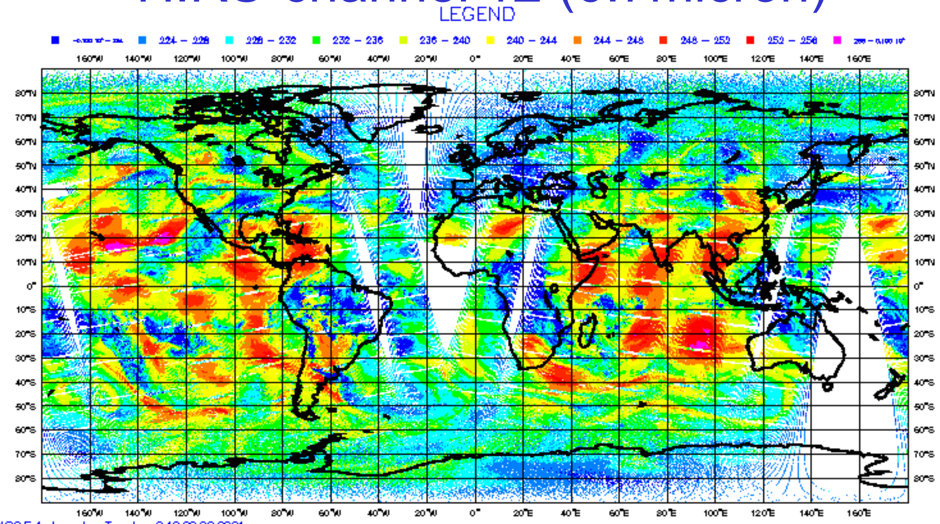
Where B=Planck function
t = transmittance
T(z) is the temperature
z is a height coordinate

That is they try to avoid frequencies for which surface radiation and cloud contributions are important. They are primarily used to obtain information about atmospheric temperature and humidity (or other constituents that influence the transmittance e.g. CO_2).

AMSUA-channel 5 (53GHz)



HIRS-channel 12 (6.7micron)



Surface sensing Channels

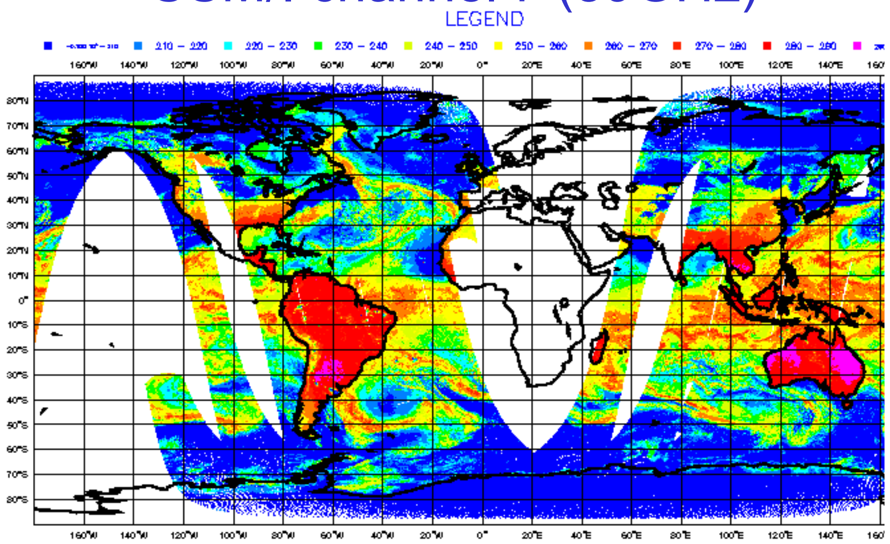
These are located in window regions of the infra-red and microwave spectrum at frequencies where there is very little interaction with the atmosphere and the primary contribution to the measured radiance is:

$$L(\nu) \approx B[\nu, T_{surf}]\varepsilon(u,v) \quad \text{(i.e. surface emission)}$$

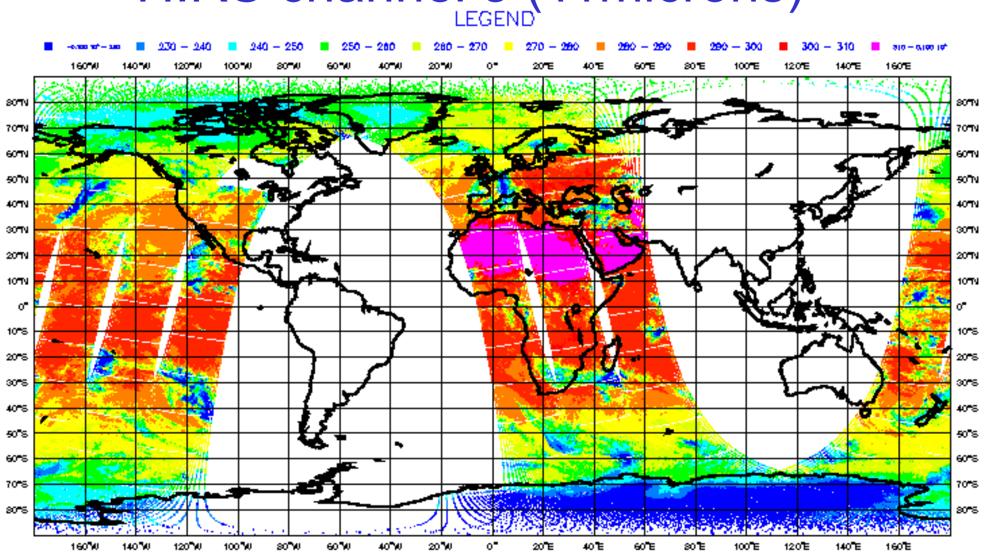
Where T_{surf} is the surface skin temperature and E the surface emissivity

These are primarily used to obtain information on the surface temperature and quantities that influence the surface emissivity such as wind (ocean) and vegetation (land). They can also be used to obtain information on clouds/rain and cloud movements (to provide wind information)

SSM/I channel 7 (89GHz)



HIRS channel 8 (11microns)



What type of channels are most important for NWP ?

Atmospheric temperature sounding…

Atmospheric temperature sounding – *weighting functions*

If radiation is selected in an atmospheric sounding channel for which

$$L(\nu) = \int_0^{\infty} B(\nu, T(z)) \left[\frac{d\tau(\nu)}{dz} \right] dz$$

and we define a function $H(z) = \left[\frac{d\tau}{dz} \right]$

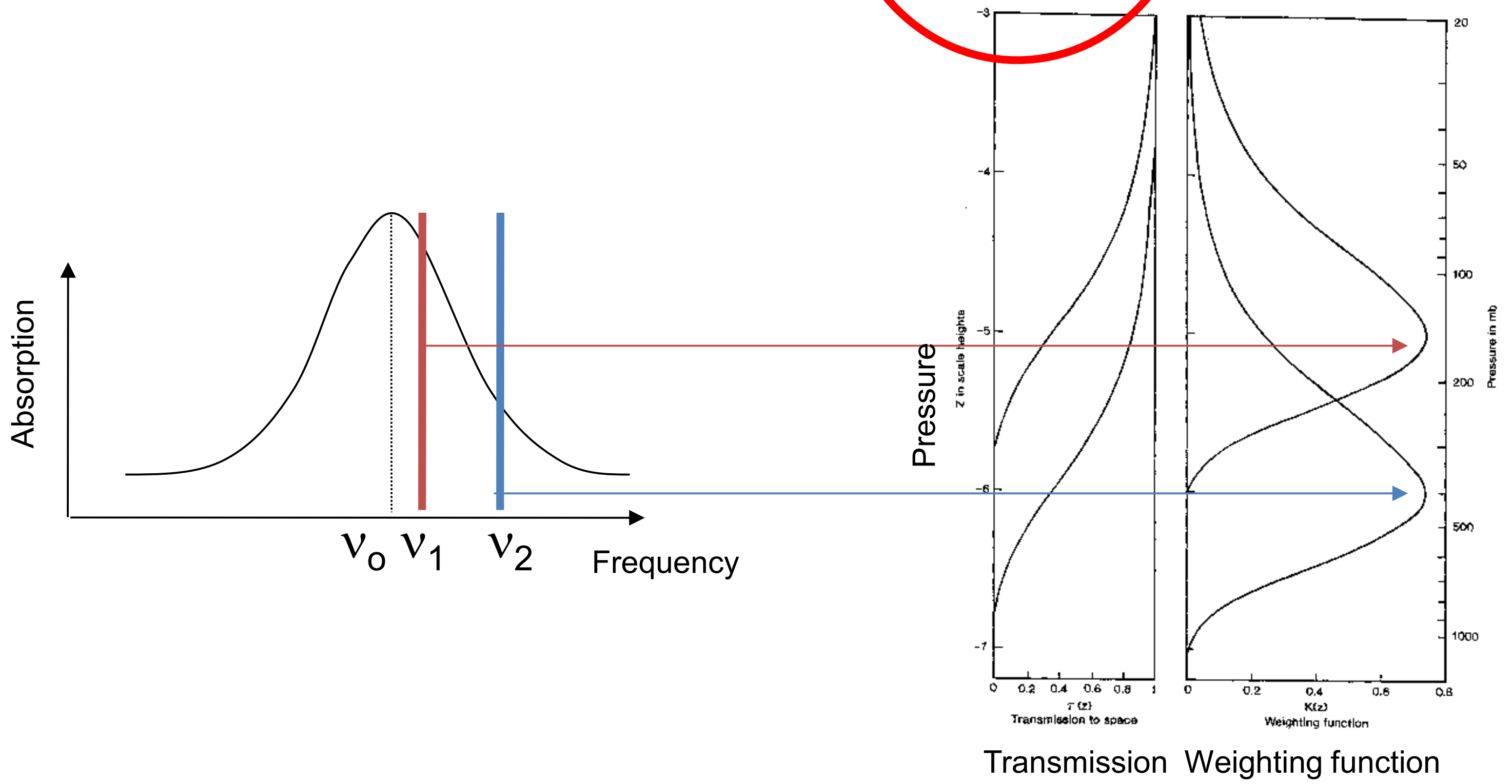
When the primary absorber is a well mixed gas (e.g. oxygen or CO_2) with known concentration it can be seen that the measured radiance is essentially a weighted average of the atmospheric temperature profile, or

$$L(\nu) = \int_0^{\infty} B(\nu, T(z)) \, H(z) dz$$

The function *H(z)* that defines this vertical average is known as a WEIGHTING FUNCTION

What do weighting functions look like ?

$$L(\nu) = \int_0^\infty B(\nu, T(z)) \left[\frac{d\tau(\nu)}{dz} \right] dz$$



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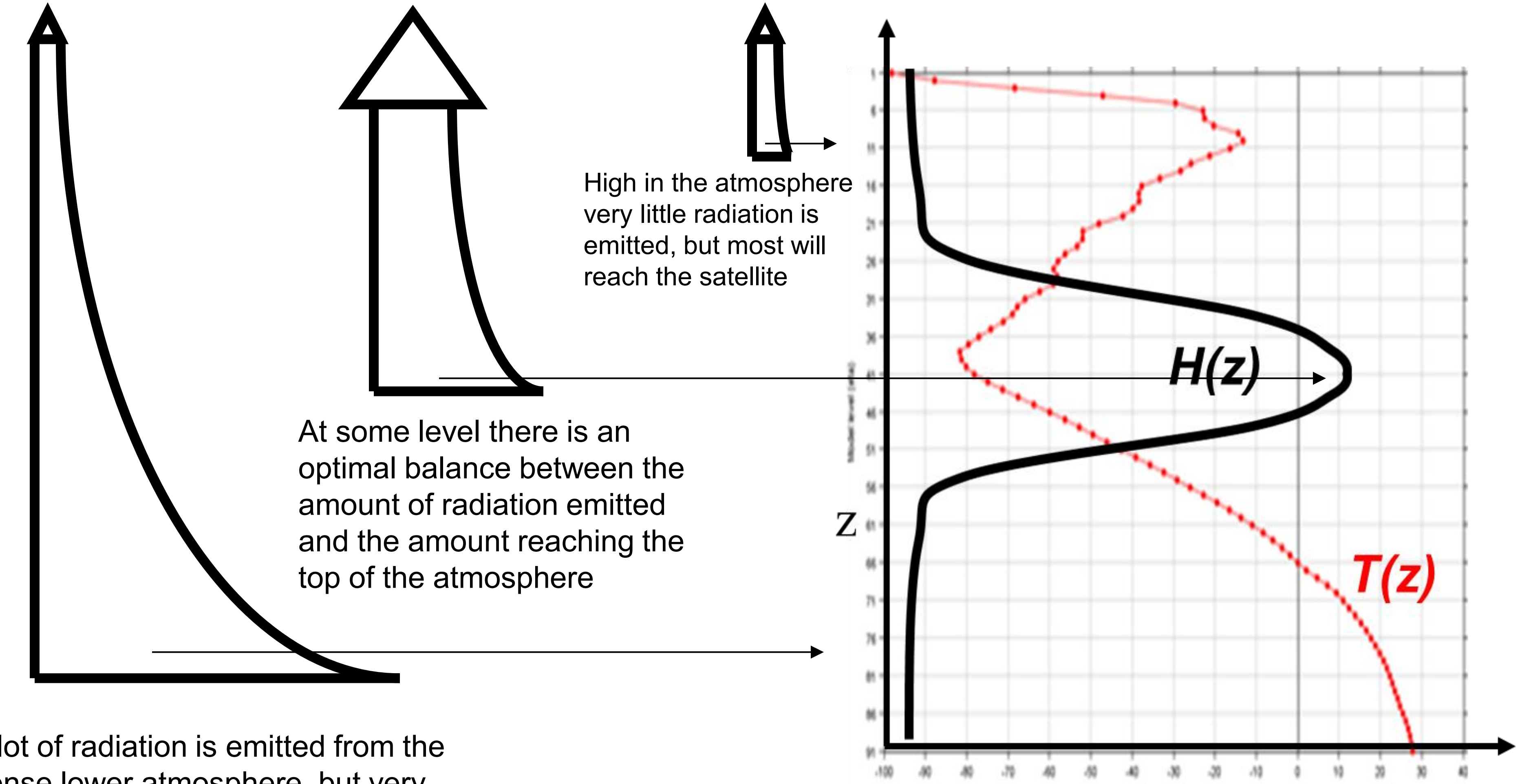
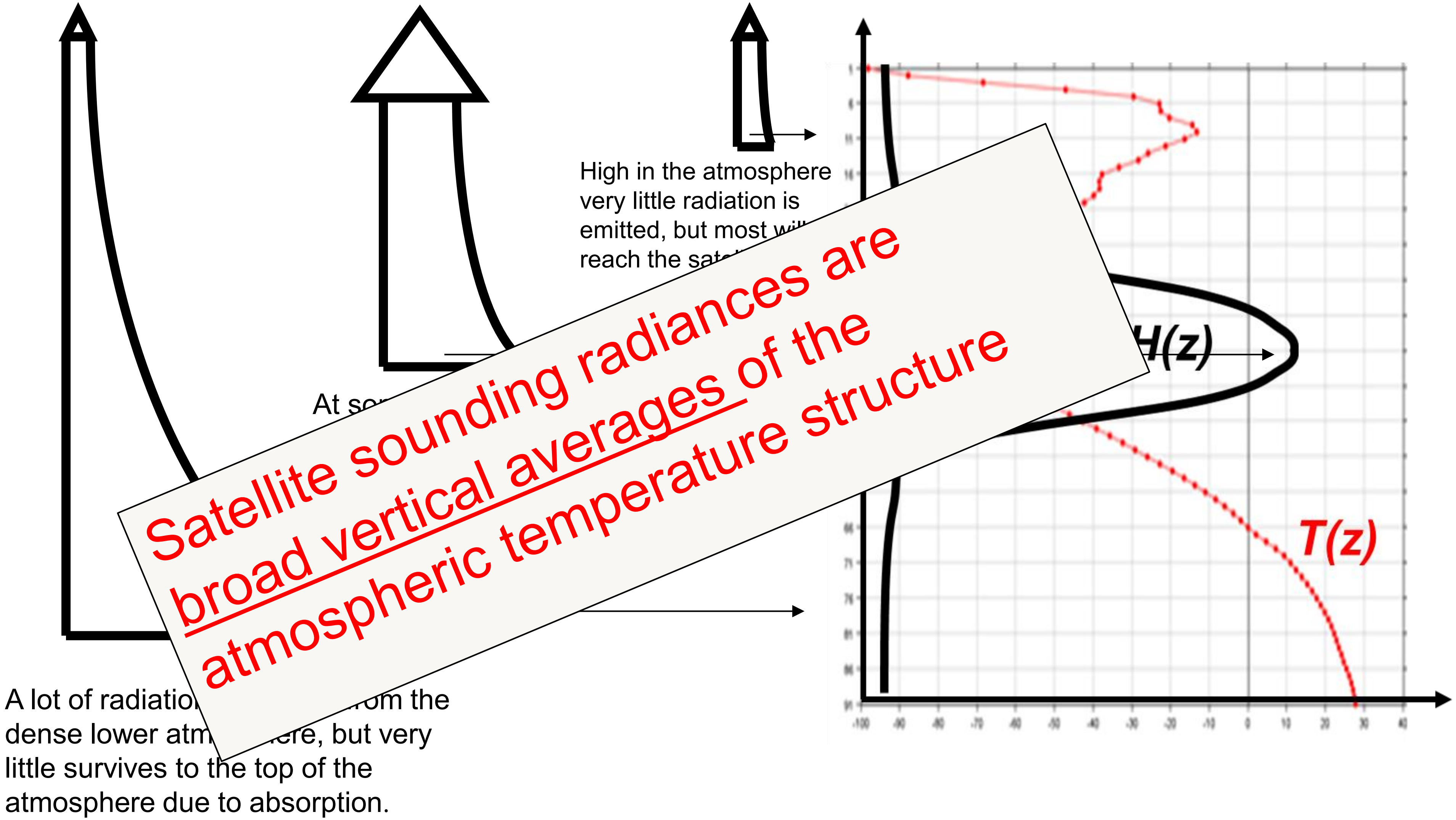


High in the atmosphere very little radiation is emitted, but most will reach the satellite

At some level there is an optimal balance between the amount of radiation emitted and the amount reaching the top of the atmosphere

A lot of radiation is emitted from the dense lower atmosphere, but very little survives to the top of the atmosphere due to absorption.

What do weighting functions look like ?



What do weighting functions look like ?

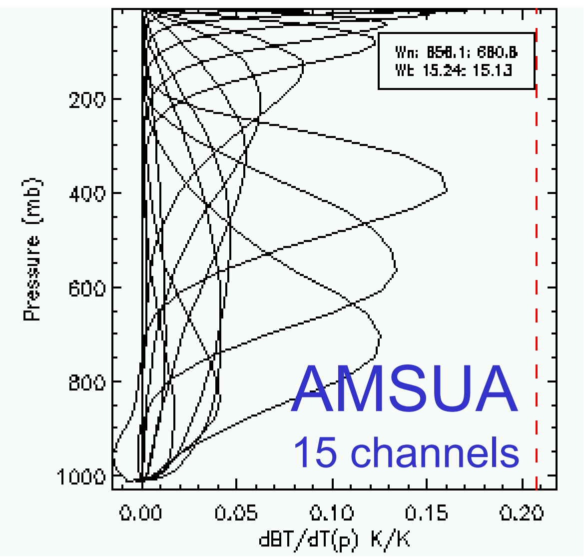
For any given channel the altitude at which the peak of the weighting function occurs depends on the strength of atmospheric absorption :

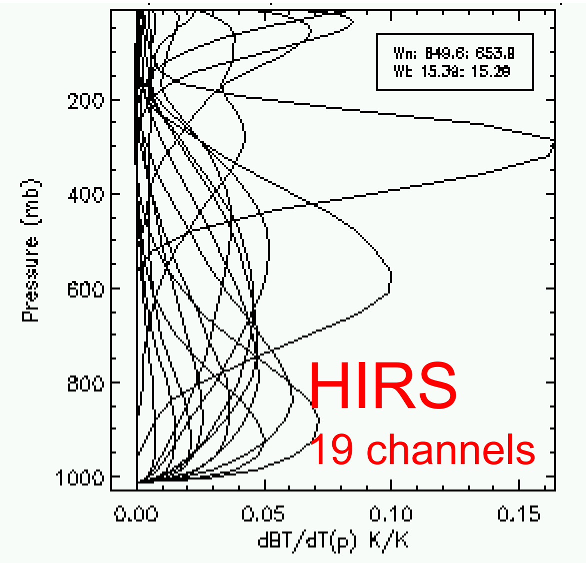
•Channels in parts of the spectrum where the absorption is strong (e.g. near the centre of CO2 or O2 lines) peak high in the atmosphere

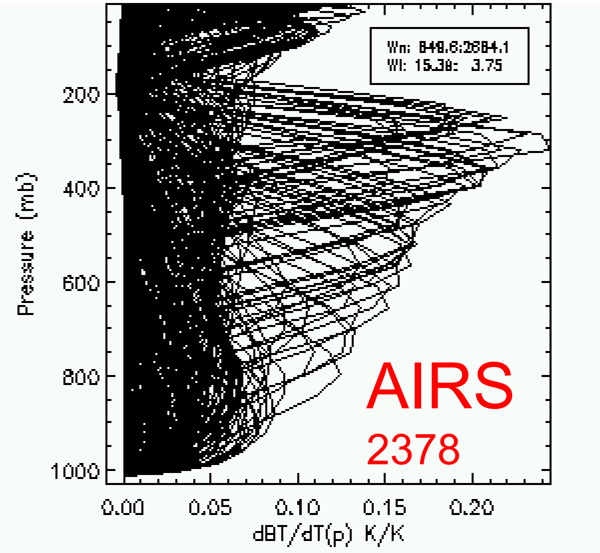
•Channels in parts of the spectrum where the absorption is weak (e.g. in the wings of CO_2 O_2 lines) peak low in the atmosphere

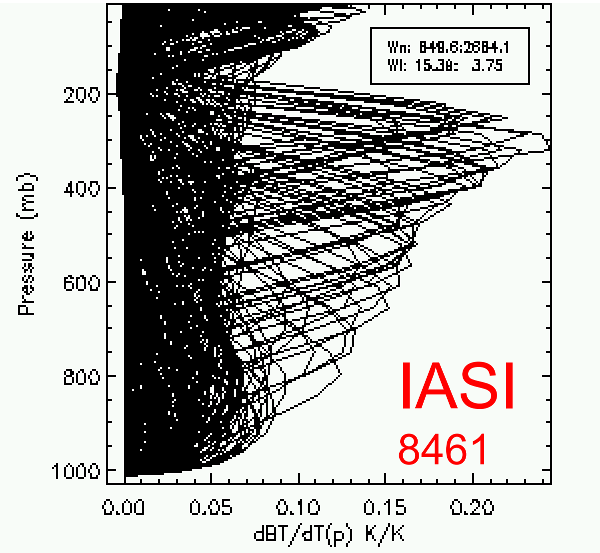
By building a satellite instrument that measures radiation in many different channels, all with varying absorption strengths we sample the atmospheric temperature profile at different altitudes (but of course not independently!)

What do real weighting functions look like ?



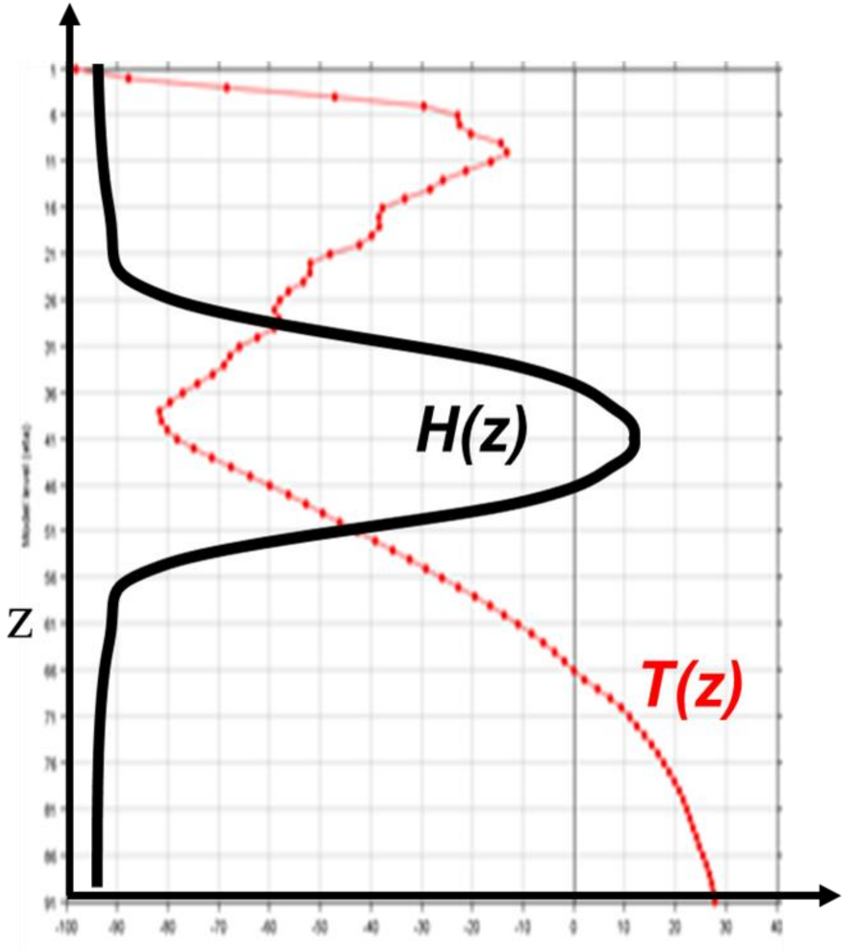






What are the implications of these broad weighting functions for Data Assimilation ?

The implications of broad weighting functions *H(z)*

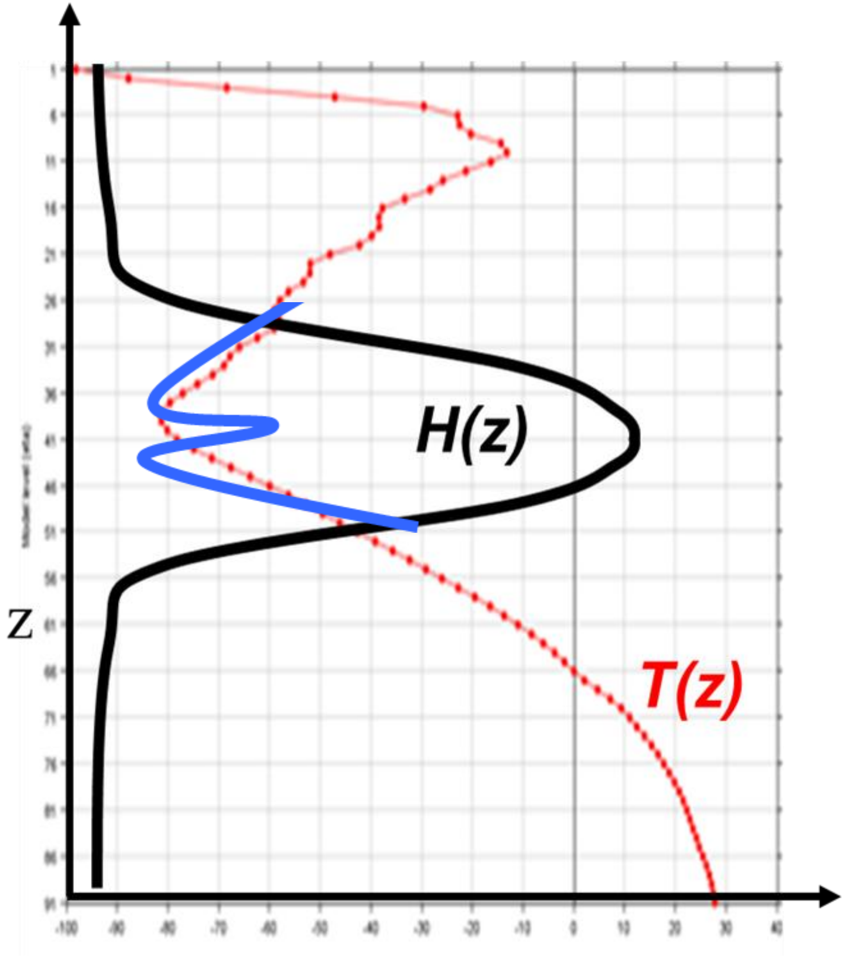


In principle for a single channel an infinite number of different temperature profiles could produce exactly the same measured radiance…

The extraction of temperature information within the data assimilation for these observations is mathematically ill-posed

See paper by Rodgers 1976 Retrieval of atmospheric temperature and composition from remote measurements of thermal radiation. Rev. Geophys.Space. Phys. 14, 609-624

The implications of broad weighting functions *H(z)*



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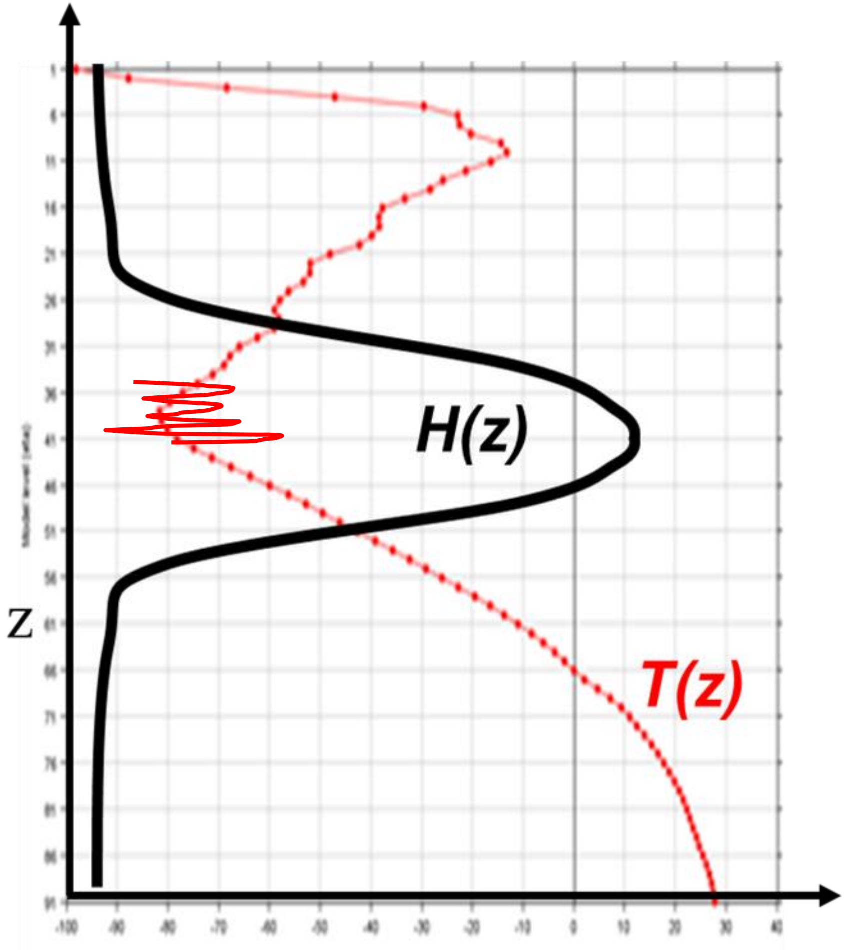

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The extraction of temperature information within the data assimilation for these observations is mathematically ill-posed

But having lots of different channels improves resolution…see later lecture

See paper by Rodgers 1976 Retrieval of atmospheric temperature and composition from remote measurements of thermal radiation. Rev. Geophys.Space. Phys. 14, 609-624

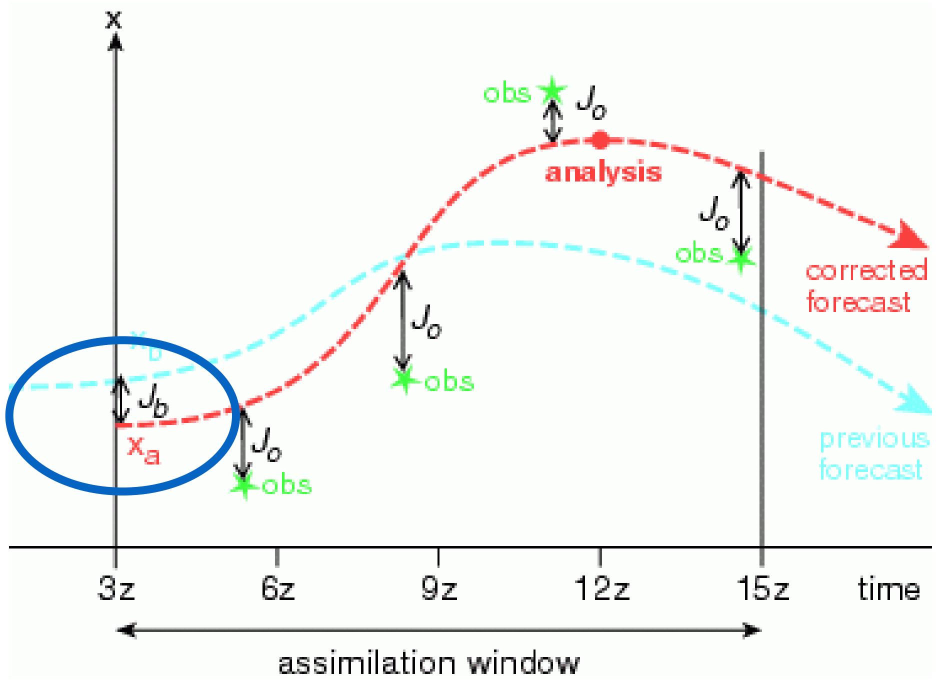
What are the implications of these broad weighting functions for Data Assimilation …?

…there are some vertical scales we cannot measure…

…the assimilation of satellite radiance data relies heavily on prior or background information …

The 4D-Var Algorithm J_b

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



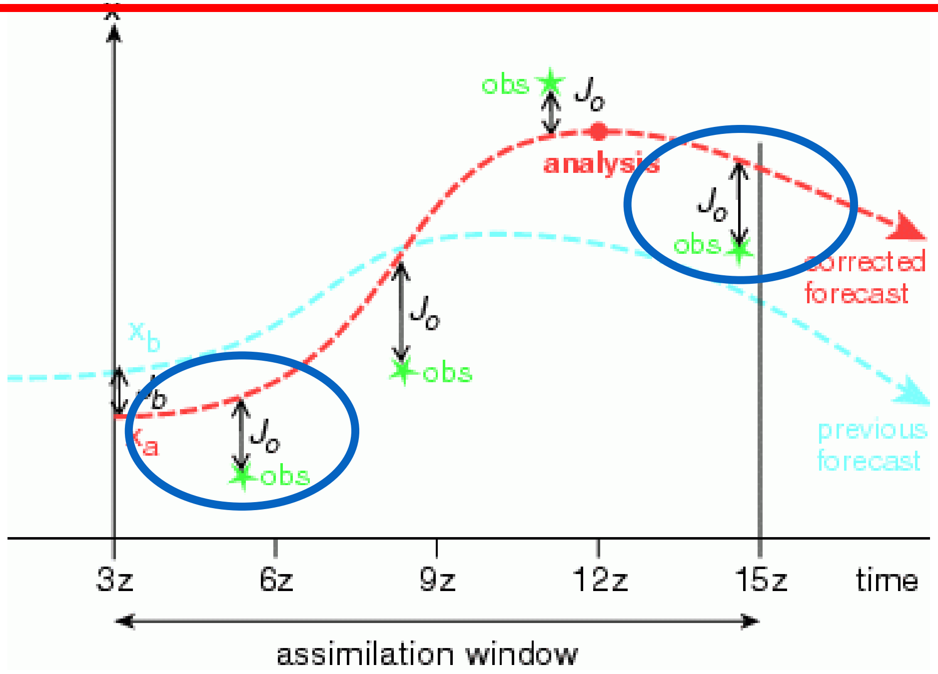
The key elements of a satellite radiance assimilation system

Key elements of a data assimilation system

- observation operator
- background errors
- observation errors
- bias correction
- data selection and quality control

The 4D-Var Algorithm J_o

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



Key elements of a data assimilation system

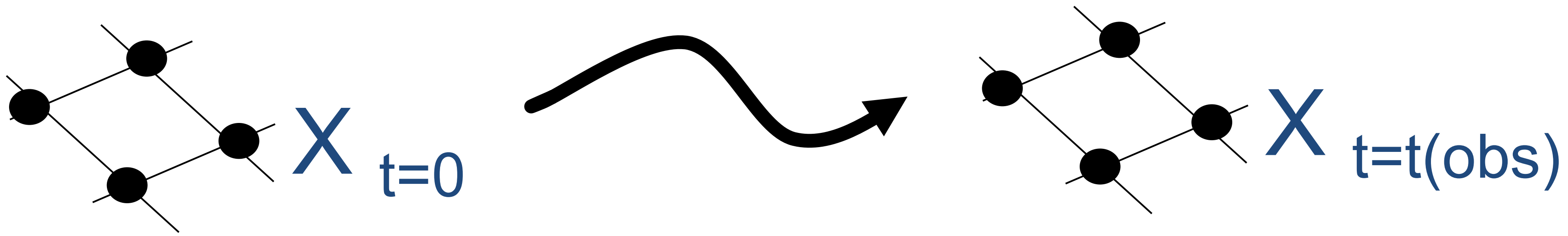
- **observation operator**
- **background errors**
- **observation errors**
- **bias correction**
- **data selection and quality control**

Observation operator

- The observation operator must map the model state at beginning of the assimilation window (t=0) to the observation time and location.
- In the **direct assimilation of radiance observations**, the observation operator must incorporate an additional step to compute radiances from the model state variables (radiative transfer model RTTOV).
- This means that radiance observations are significantly more computationally expensive than conventional observations (e.g. radiosonde temperature data)

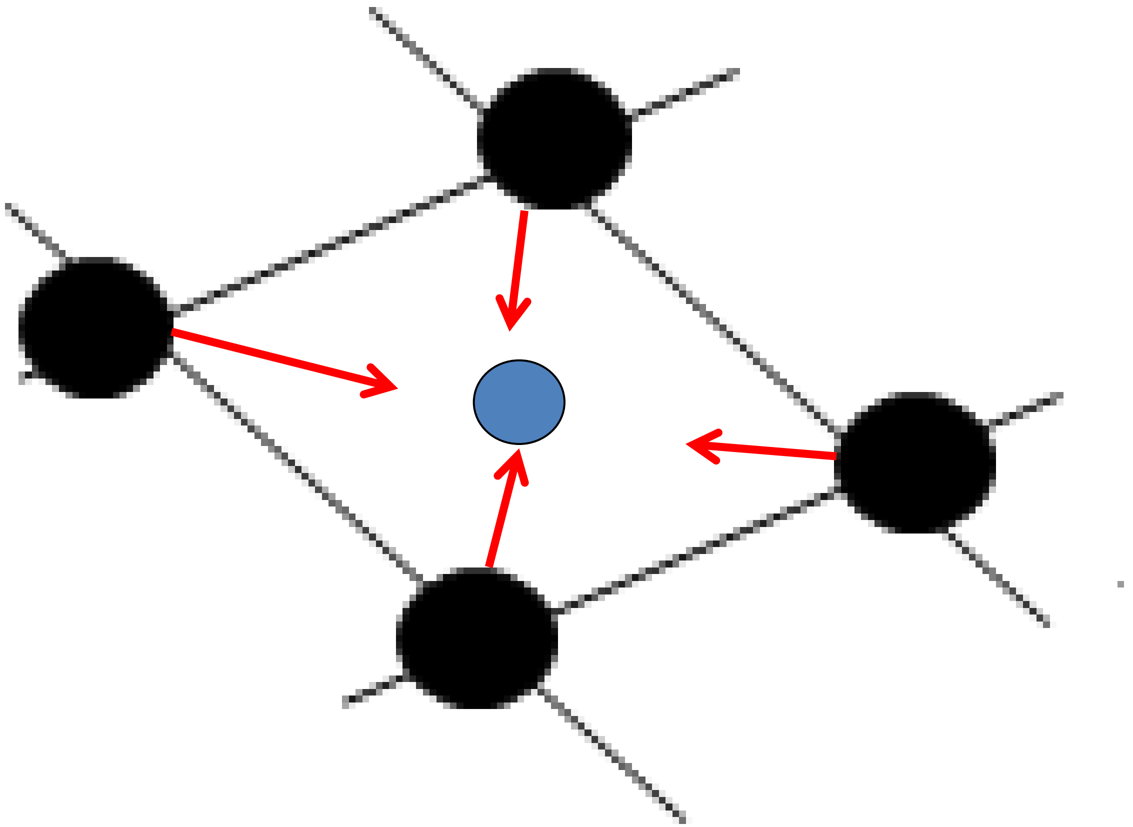
Observation operator

1) Time evolution of forecast model field to OBS time



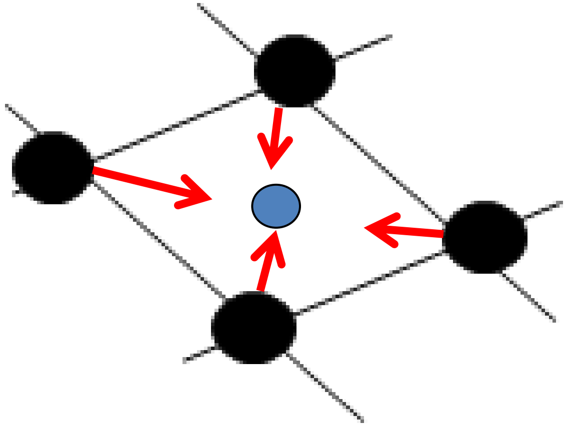
Observation operator

2) Spatial interpolation of model grid to OBS location

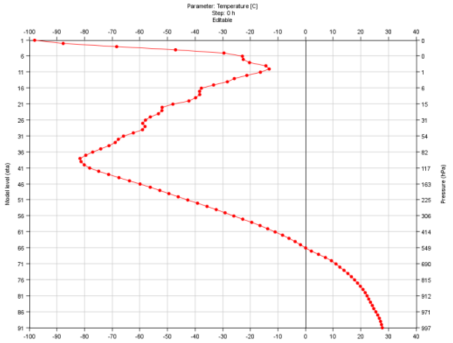


Observation operator

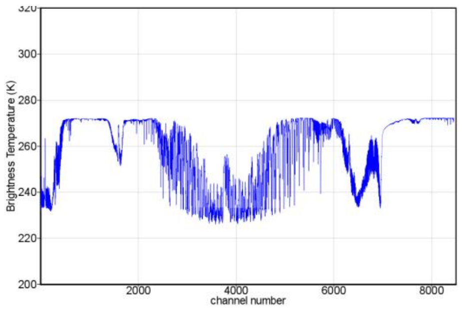
3) Radiative transfer calculation from model state at that location to radiances at that location



$$(y - \mathrm{H}[x])^T \mathbf{R}^{-1} (y - \mathrm{H}[x])$$

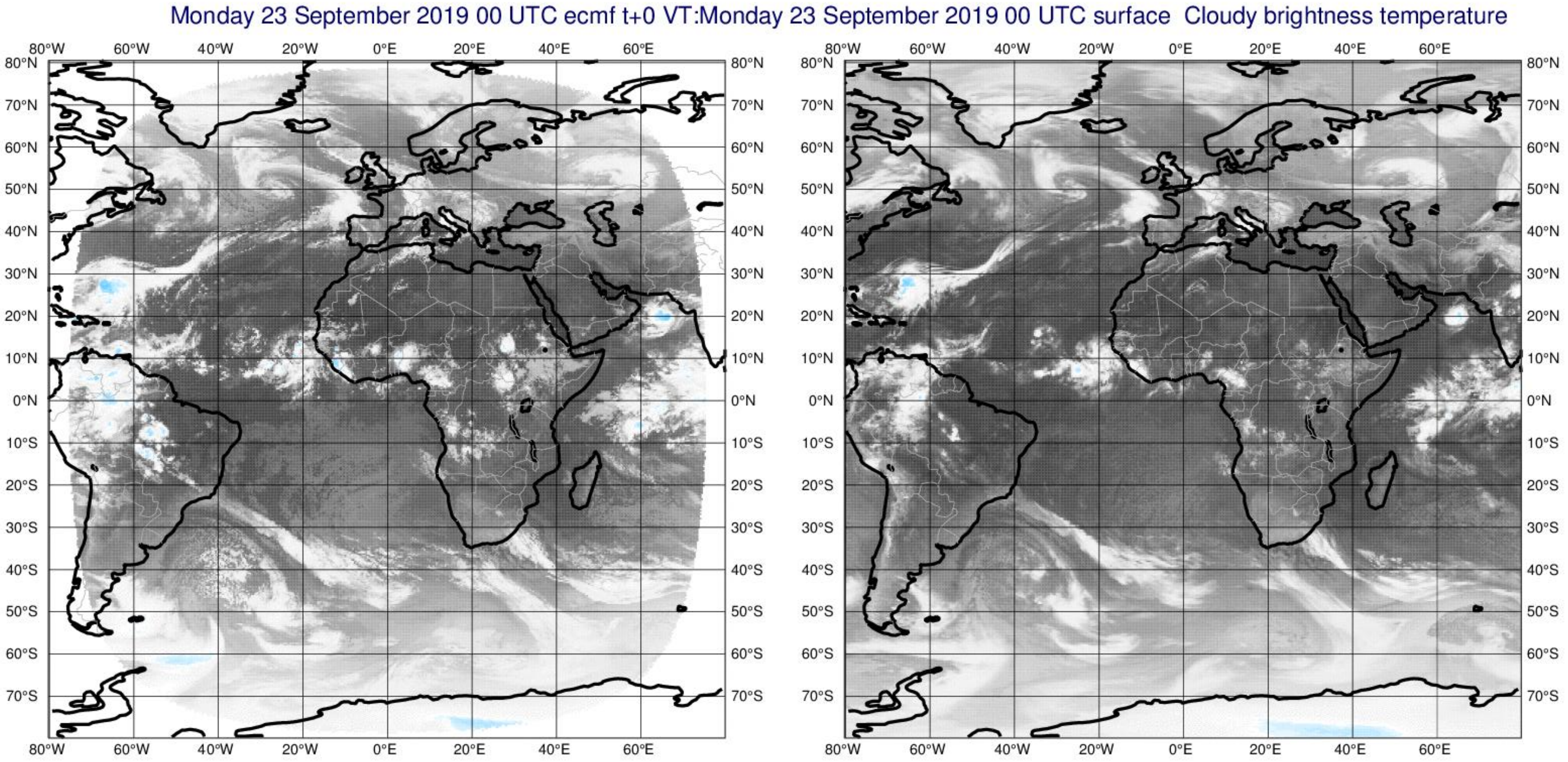


RTTOV



Comparing observations with background in radiance space

Observations from Meteosat-11 Simulated by RTTOV from model state



Key elements of a data assimilation system

- observation operator
- background errors
- observation errors
- bias correction
- data selection and quality control

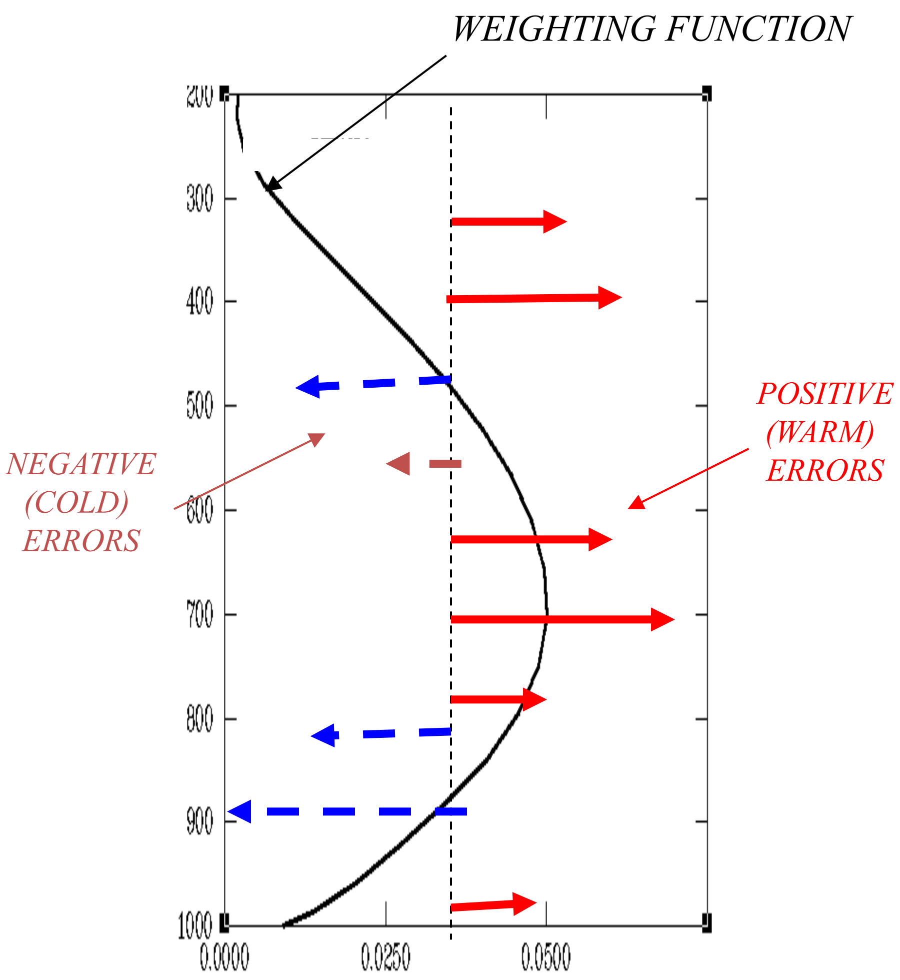
Background errors (and vertical resolution)

- The matrix B must accurately describe errors in the background estimate of the atmospheric state. It determines the weight given to the background information.

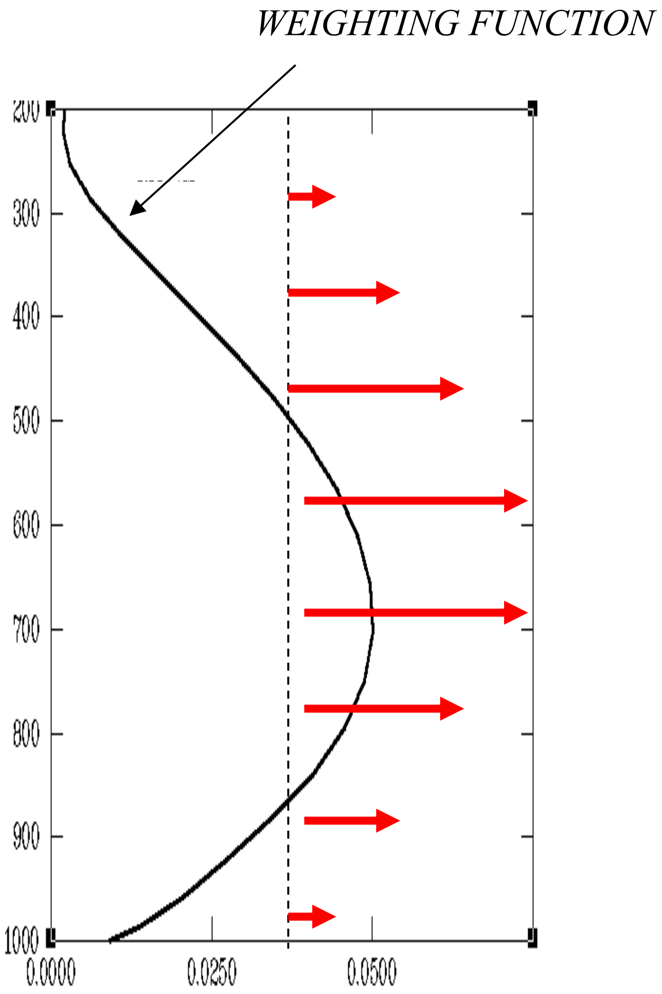
- A very important aspect of B for the assimilation of downward viewing satellite radiances are the **vertical correlations** that describe how background errors are distributed in the vertical (sometimes called structure functions)

- These are important because satellite radiances have very **limited vertical resolution** (previous lecture)

Background errors (and vertical resolution)



"Difficult" to correct



"Easy" to correct

…a helpful linear analogue …

It can be shown that the state that minimizes the cost function is equivalent to a linear **correction** of the background using the observations:

$$x_a = x_b + [\mathbf{HB}]^T [\mathbf{HBH}^T + \mathbf{R}]^{-1} (y - \mathbf{H} x_b)$$

correction term

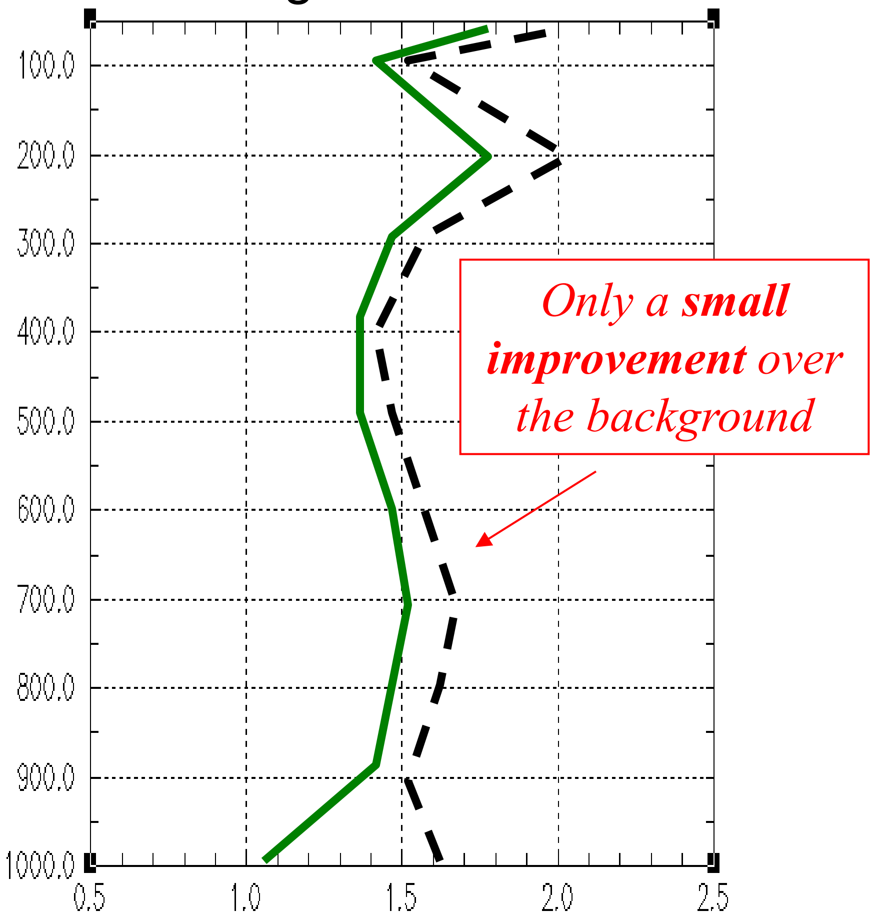
…and the **improvement** can be quantified in terms of the key parameters of the assimilation…(i.e. **B**, **R**, **H**)

$$S_a = B - [\mathbf{HB}]^T [\mathbf{HBH}^T + \mathbf{R}]^{-1} HB$$

improvement term

Background errors (and vertical resolution)

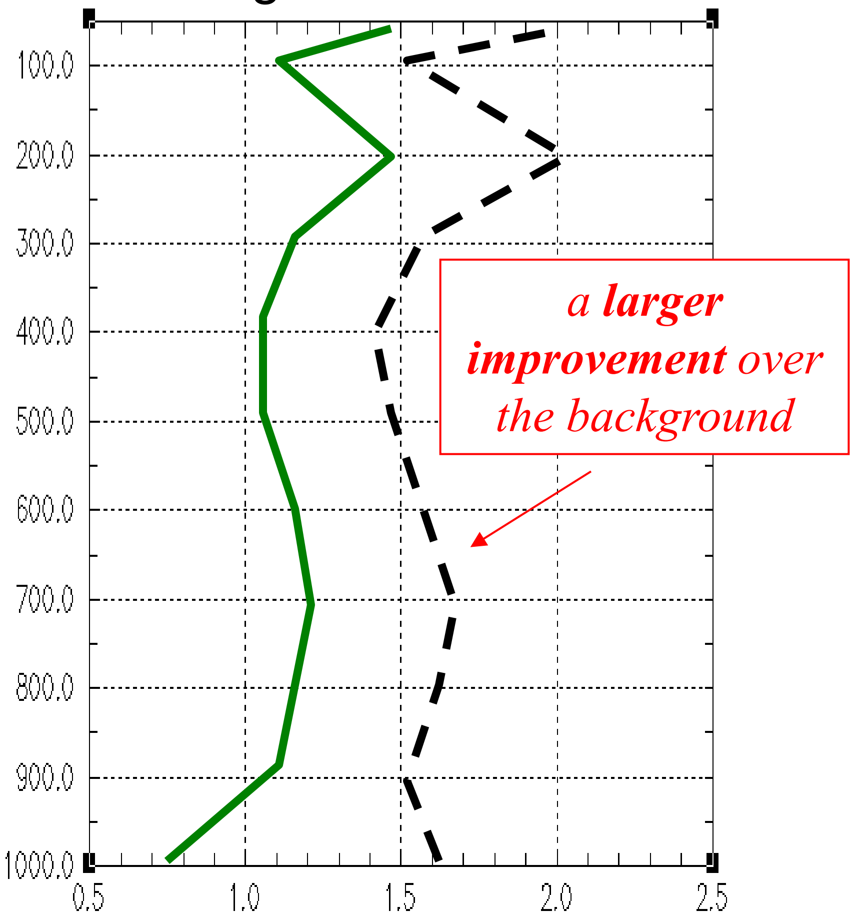
Sharp / anti-correlated background errors



Error standard deviation (K)

S_a

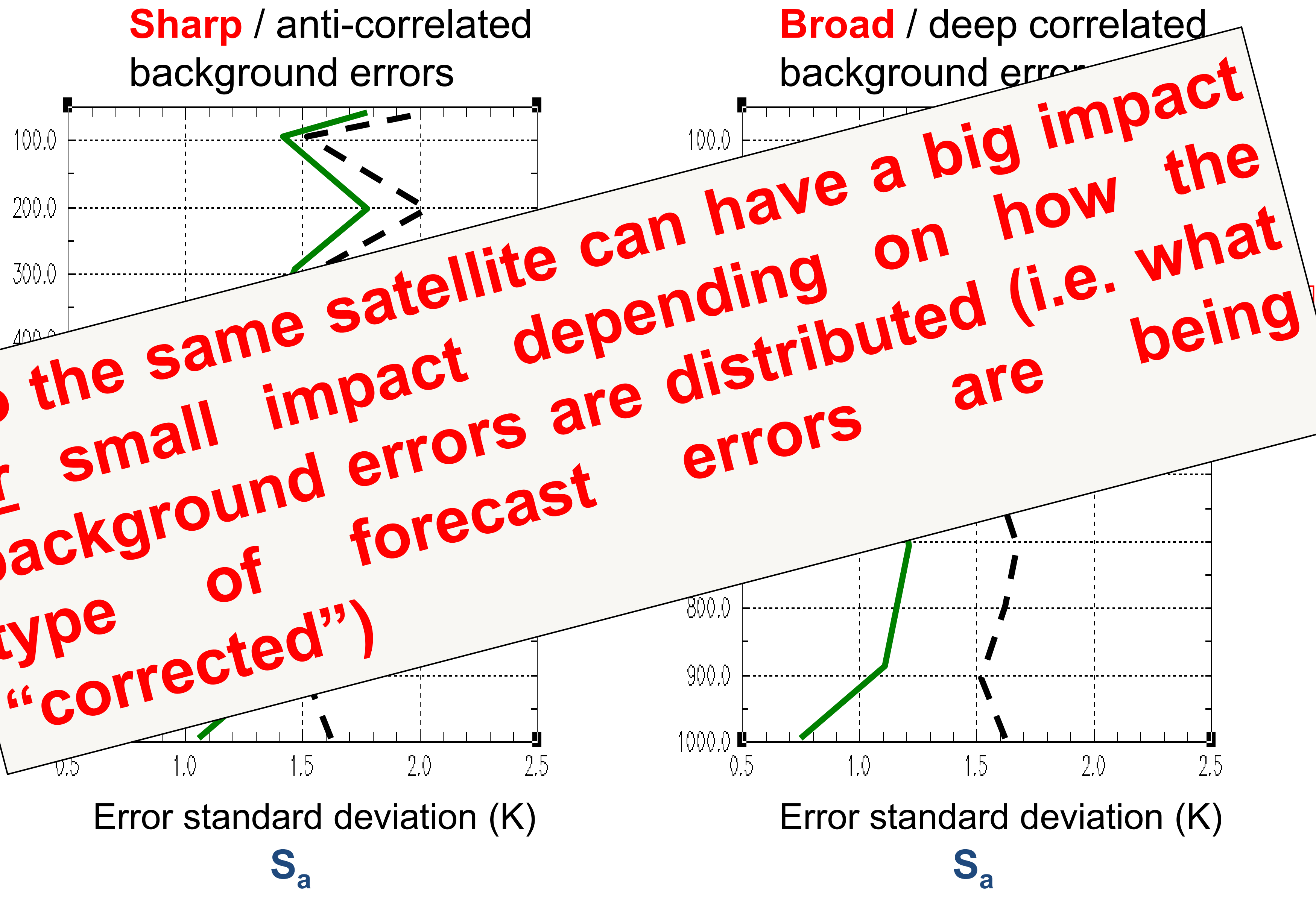
Broad / deep correlated background error



Error standard deviation (K)

S_a

Background errors (and vertical resolution)



So the same satellite can have a big impact or small impact depending on how the background errors are distributed (i.e. what type of forecast errors are being "corrected")

Key elements of a data assimilation system

- observation operator
- background errors
- observation errors
- bias correction
- data selection and quality control

Observation errors:

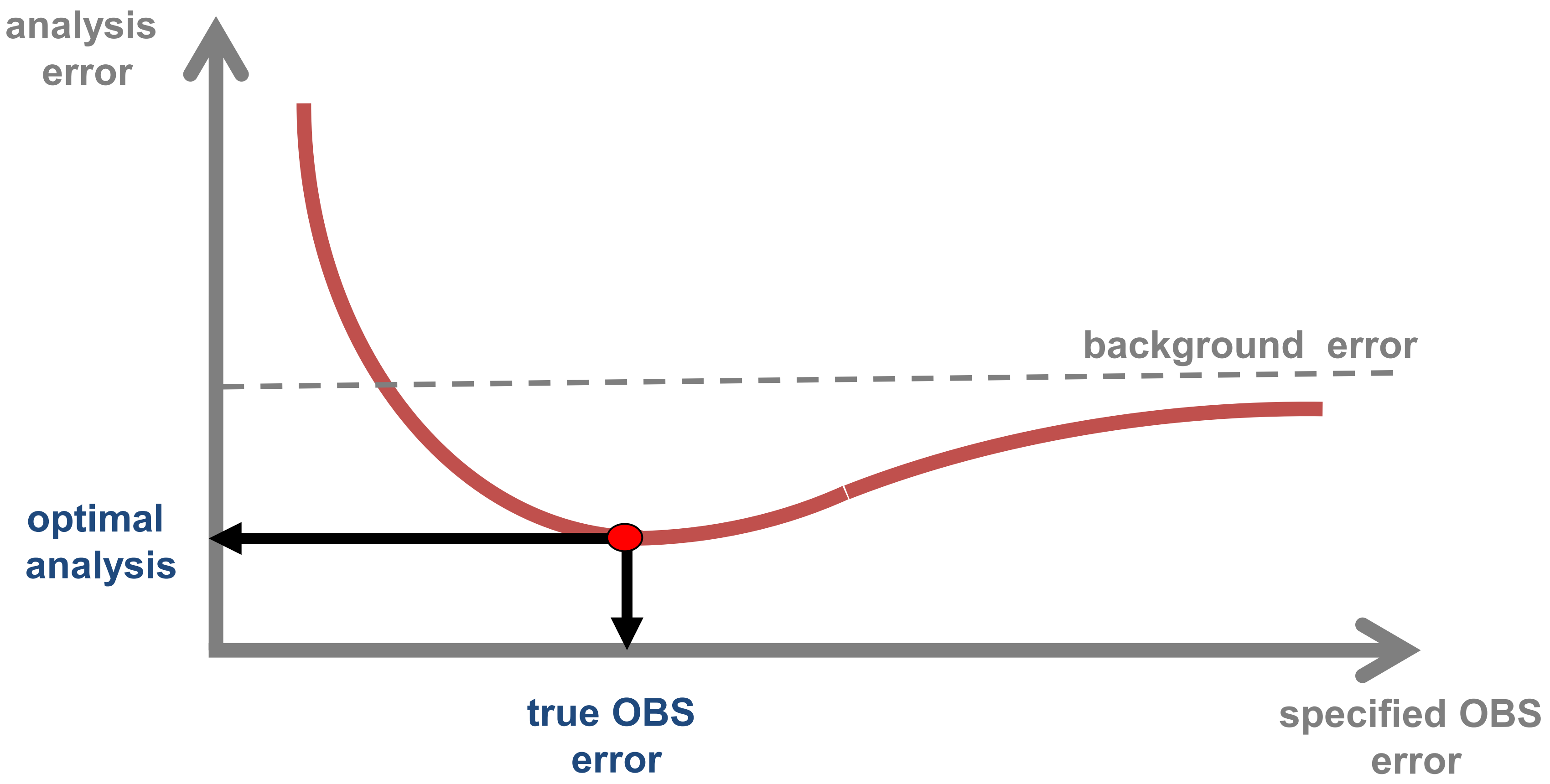
- These determine the weight we give to the radiance observations. The observation error must account for **instrument noise**, random uncertainties in the **observation operator** (e.g. RT model), errors in data **screening** (e.g. residual clouds) and errors of representativeness (e.g. scale mismatch).

- It is important to model both the magnitude of errors (diagonals of R) and **any inter-channel correlations**

- Wrongly specified observation errors can lead to an analysis with **larger errors than the background**!

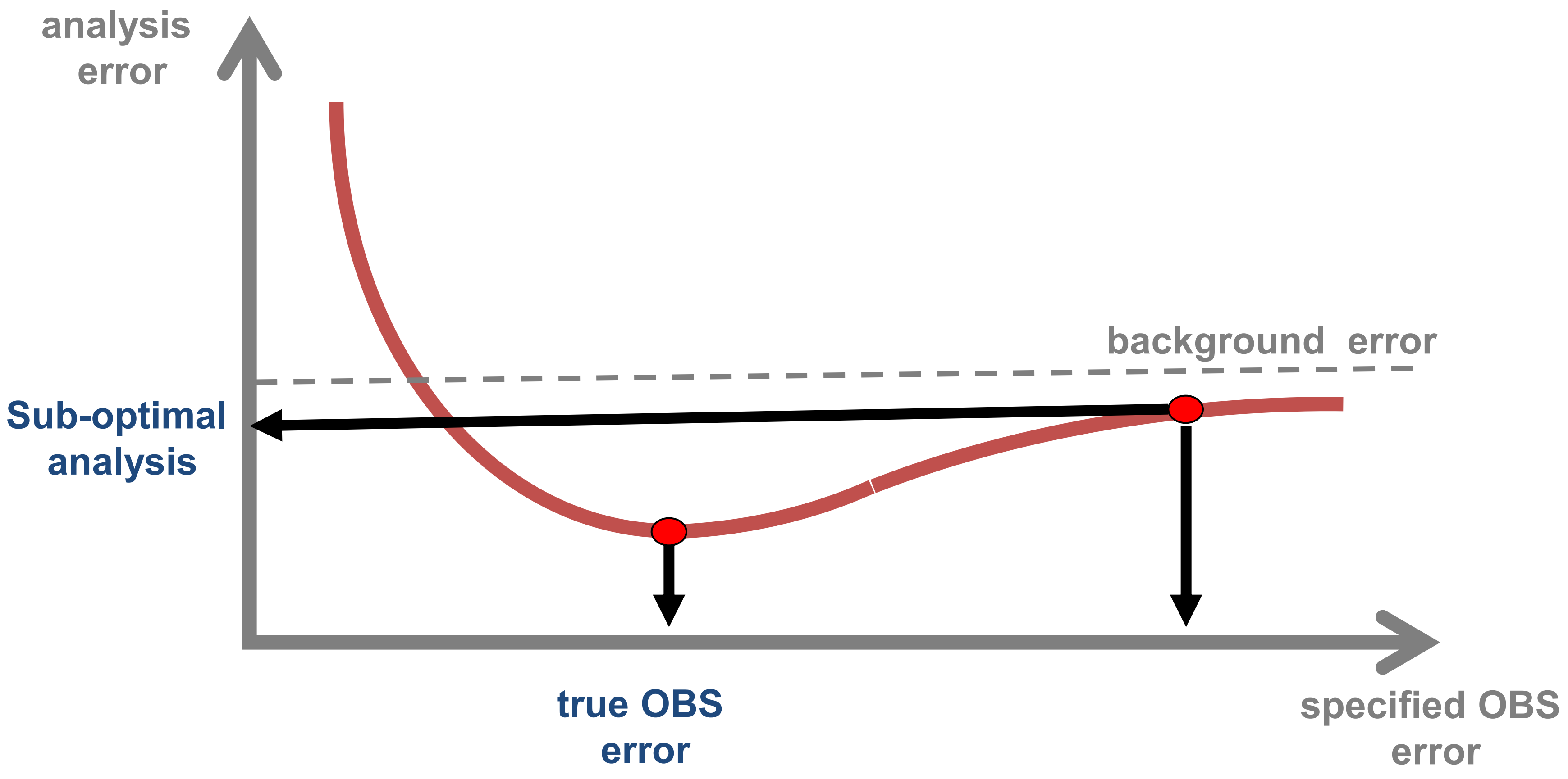
Observation errors:

- Specifying the correct observation error produces an optimal analysis with minimum error.



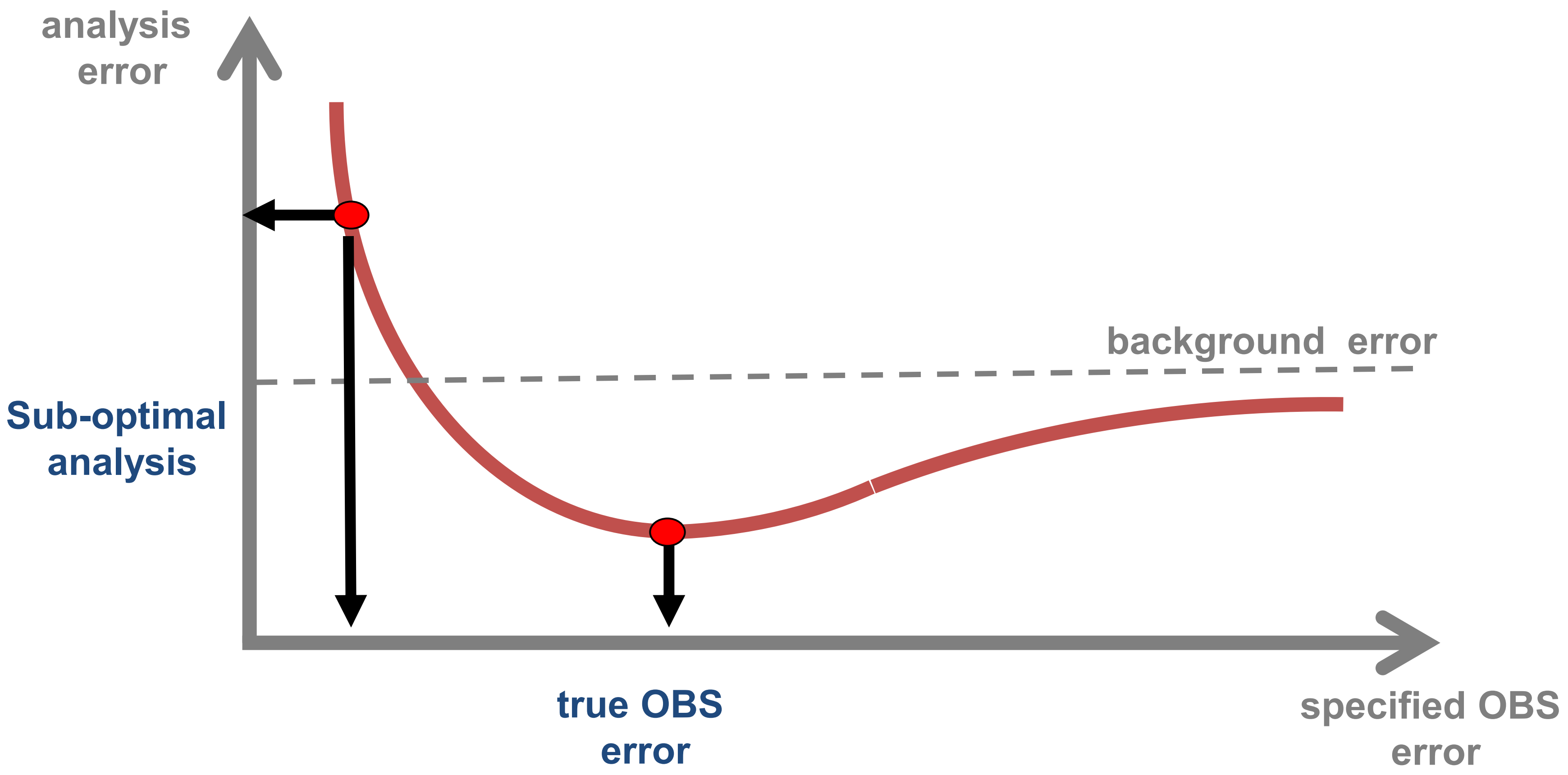
Observation errors:

- Over-estimating the OBS error degrades the analysis, but the result will not be worse than the background.



Observation errors:

- Under-estimating the OBS error degrades the analysis, and **<u>the result can be worse than the background</u>**!



Key elements of a data assimilation system

- observation operator
- background errors
- observation errors
- **bias correction**
- data selection and quality control

Bias correction:

Systematic errors must be removed otherwise biases will propagate in to the analysis (causing **global damage** in the case of satellites!). A bias in the radiances is defined as:

$$\textit{bias} = \textit{mean} \left[Y_{obs} - H(X_{true}) \right]$$

Sources of systematic error in radiance assimilation include:

- instrument error (scanning or calibration)
- radiative transfer error (spectroscopy or RT model)
- cloud / rain / aerosol screening errors

Key elements of a data assimilation system

- observation operator
- background errors
- observation errors
- bias correction
- data selection and quality control

Data selection and quality control (QC):

The primary purpose of this is to ensure that the observations entering the analysis are **consistent with the assumptions** in the observations error covariance (**R**) and the observation operator (**H**).

Primary examples include the following:

- Rejecting bad data with **gross error** (not described by **R**)
- Rejecting data affected by **clouds** if **H** is a clear sky RT
- Thinning data if no **correlation** is assumed (in **R**)
- Always **blacklisting** data where we do not trust our QC!

Data selection and quality control (QC):

Often checks are performed using the forecast background as a reference. That is an observations is rejected if the departure from the background exceeds a threshold T_{QC}:

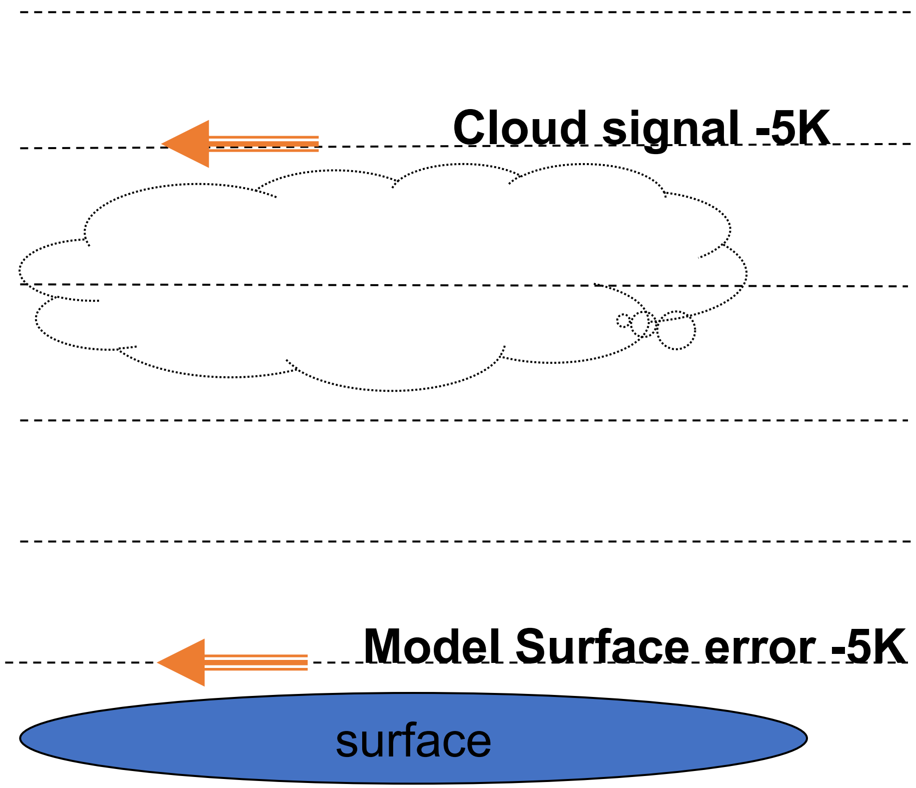
$$Y_{obs} - H(X_{true}) > T_{QC}$$

But sometimes large errors in the background can lead to:

- False rejection of a good observation
- Missed rejection of a bad observation

Data selection and quality control:

- Missed rejection of a **bad** observation



The radiance are contaminated by cloud (**cold 5K**) compared to the clear sky value.

But our computation of the clear sky value from the background is also **cold by 5K** due to an error in the surface skin temperature.

Thus our checking (against the background) sees no reason to reject the observation and is it **passed**!

Summary

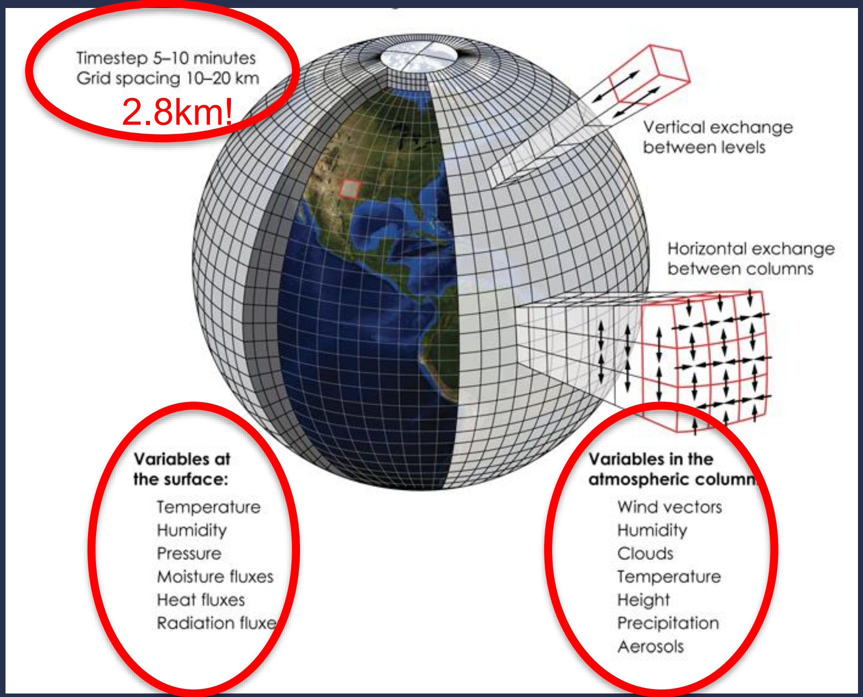
- observation operator
  (complex and expensive for radiances)
- background errors
  (important due to limited vertical resolution)
- observation errors
  (a challenge to specify correctly)
- bias correction
  (small, but global impact of bias)
- data selection and quality control
  (primarily data selection, few bad observations)

Spare slides…

High-resolution and highly complex physics-based models present extreme challenges for DA

Observations are simply **insufficient** and generally of the **wrong variables** to provide initial conditions for NWP models of this resolution and complexity!

…so we are forced to blend observations with a background using DA….

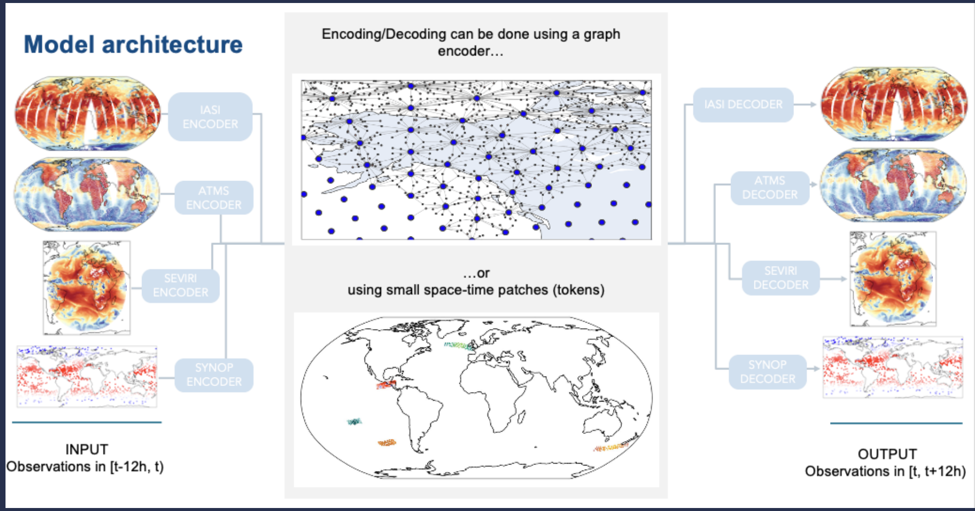


…requiring an exacting specification of poorly known error covariances (all huge multivariate tensors)

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

Accurate observation operators potentially limiting limiting the observations we can exploit…

Direct Observation Prediction

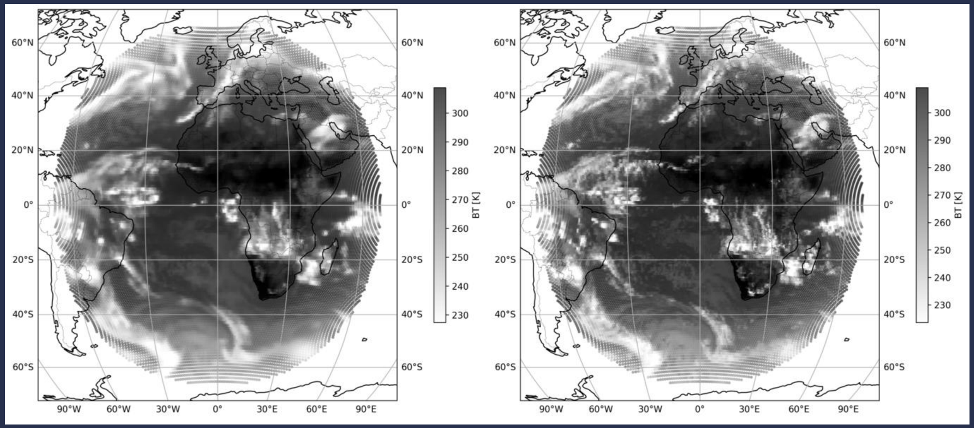


DOP learns a physical model of the entire Earth system directly from decades of historical observations…

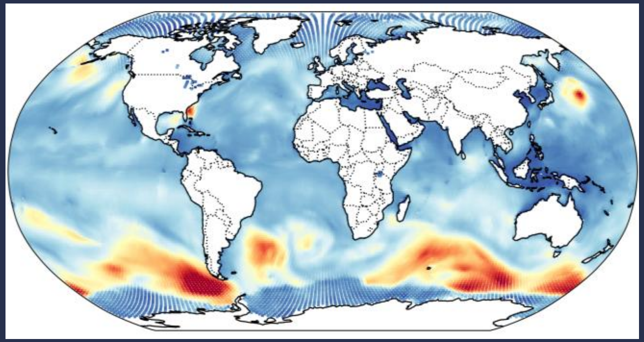
… then initializes this model with the latest daily observations to make forecasts

AI-DOP model

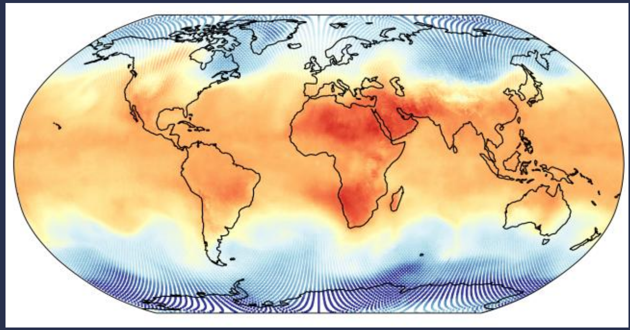
Target real observations



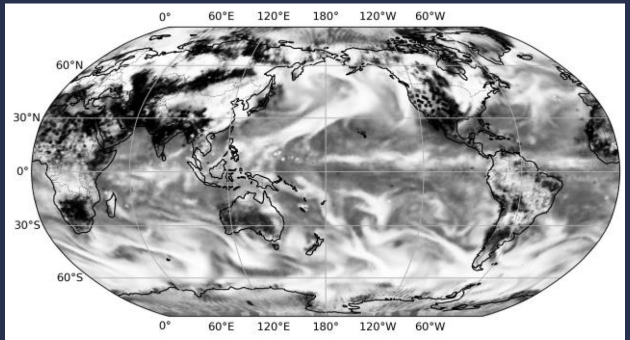
DOP can make predictions for <u>any</u> observed variable…at <u>any</u> location



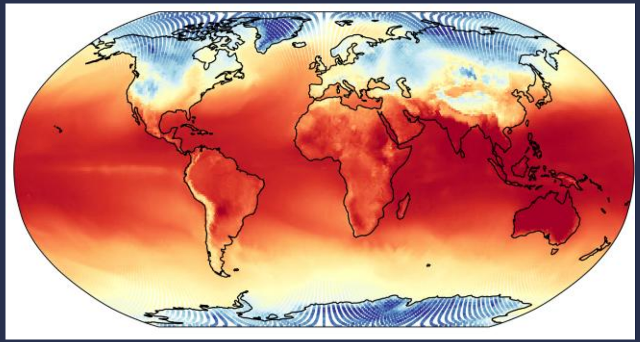
Significant wave height



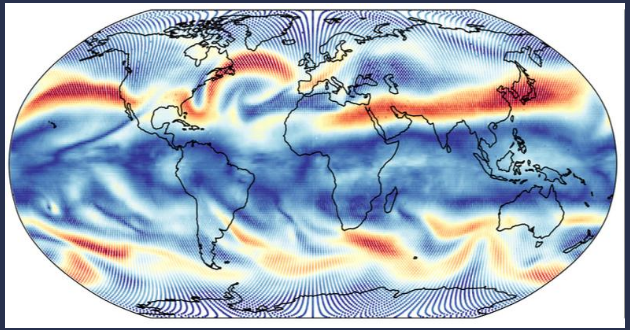
850hPa temperature



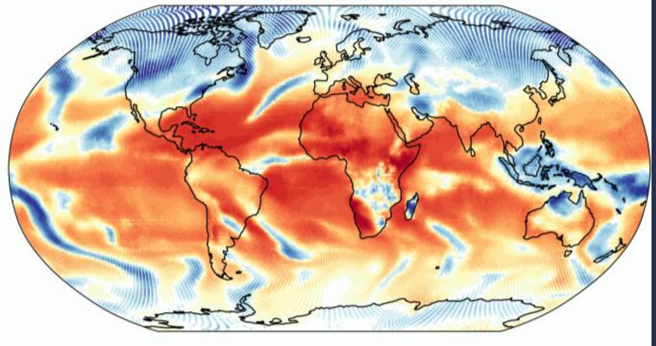
Cloud fraction



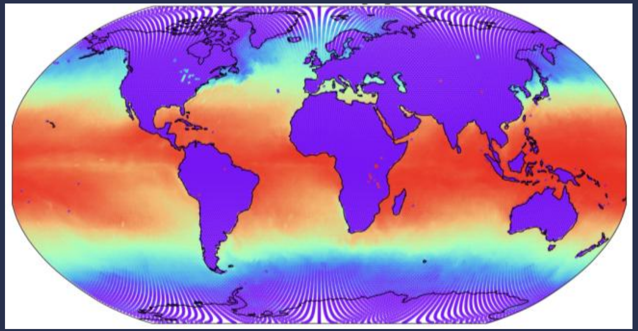
2-meter temperature



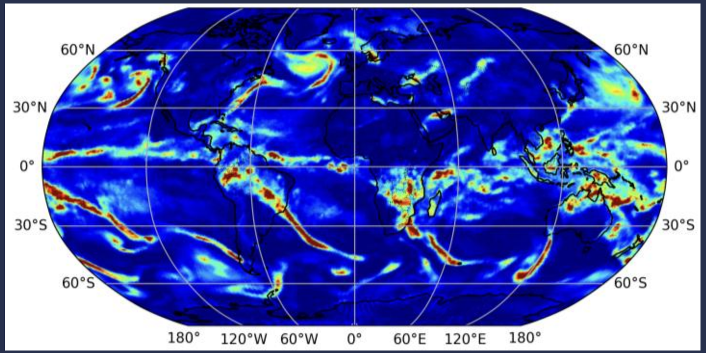
200hPa winds



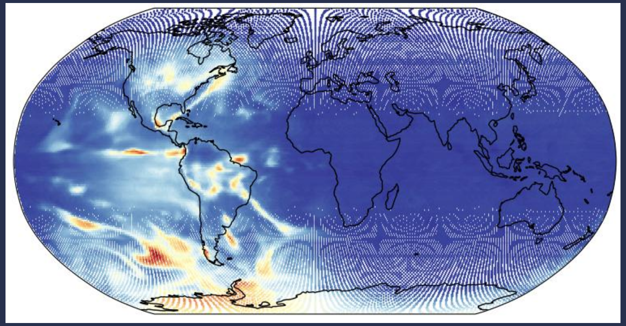
SEVIRI infrared window channel



Sea surface temperature

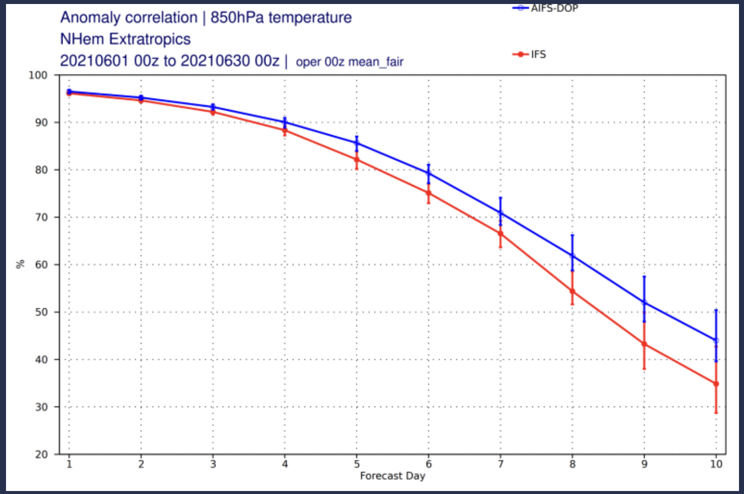


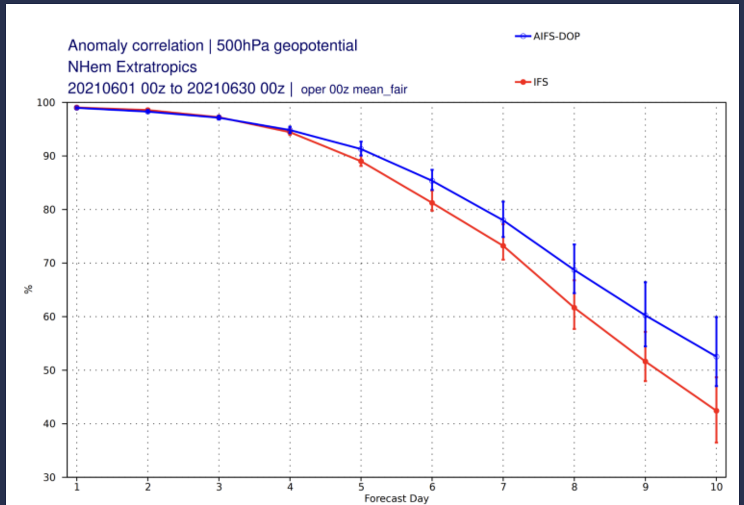
1 hour precipitation accumulation



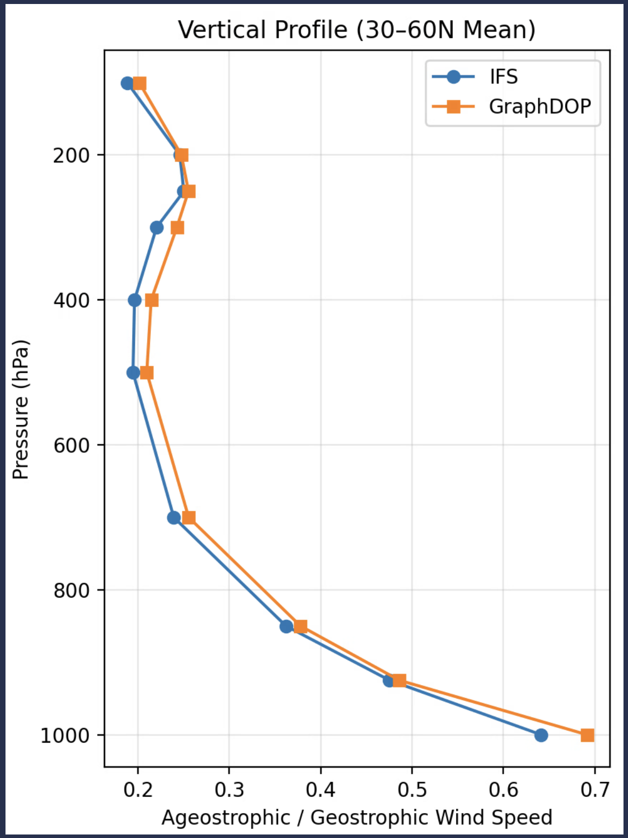
AVHRR visible channel

DOP forecasts now out-perform the IFS for many surface and upper-air parameters…while still demonstrating characteristics of a "physical model"



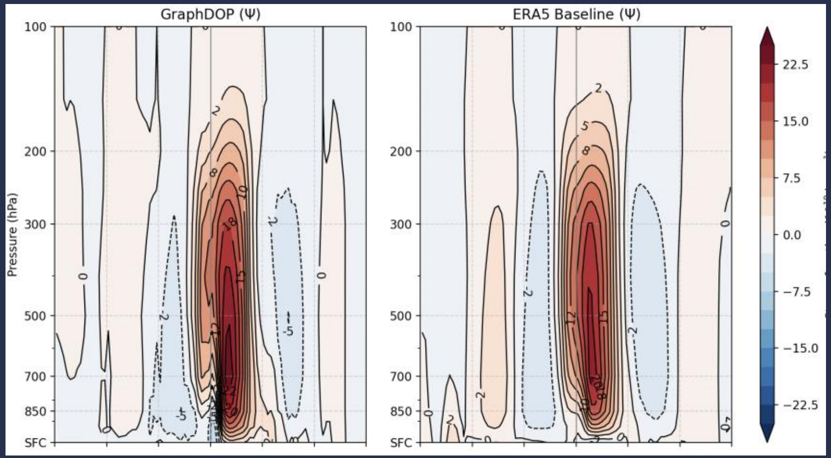


Ratio of G to AG flow in the DOP forecasts compared to the IFS

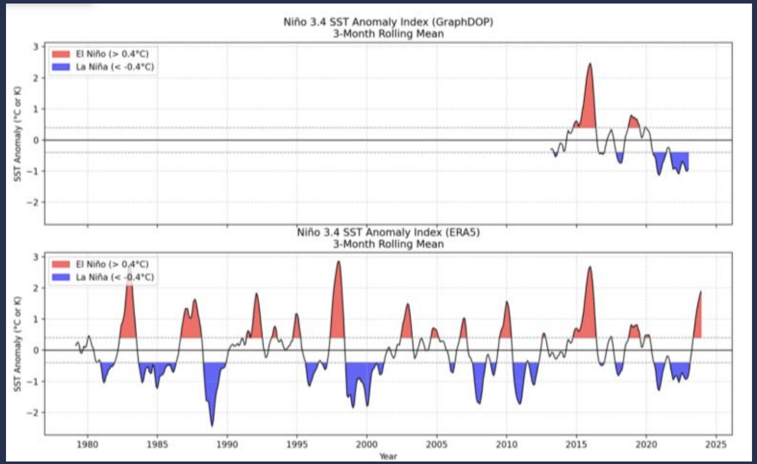


Exploring options for future DOP climate reanalyses:

Hadley Circulation (stream function)

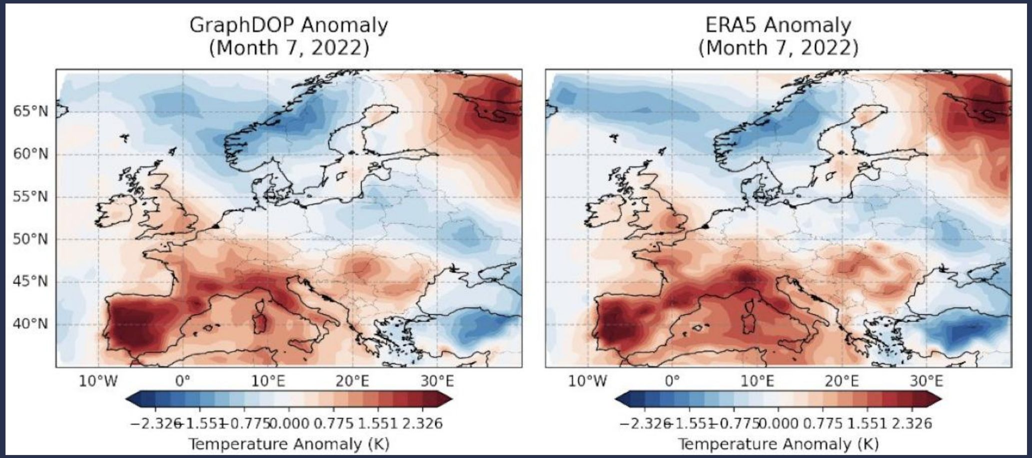


ENSO SST (Nino 3.4)



Reanalysis of the decade took just a few hours on 4 GPUs. But DOP is non-serial, and could be parallelized over many GPUs to run in minutes

2022 European severe heatwave



Large-scale teleconnections