TRAINING COURSE

The assimilation of satellite radiance observations

Tony McNally

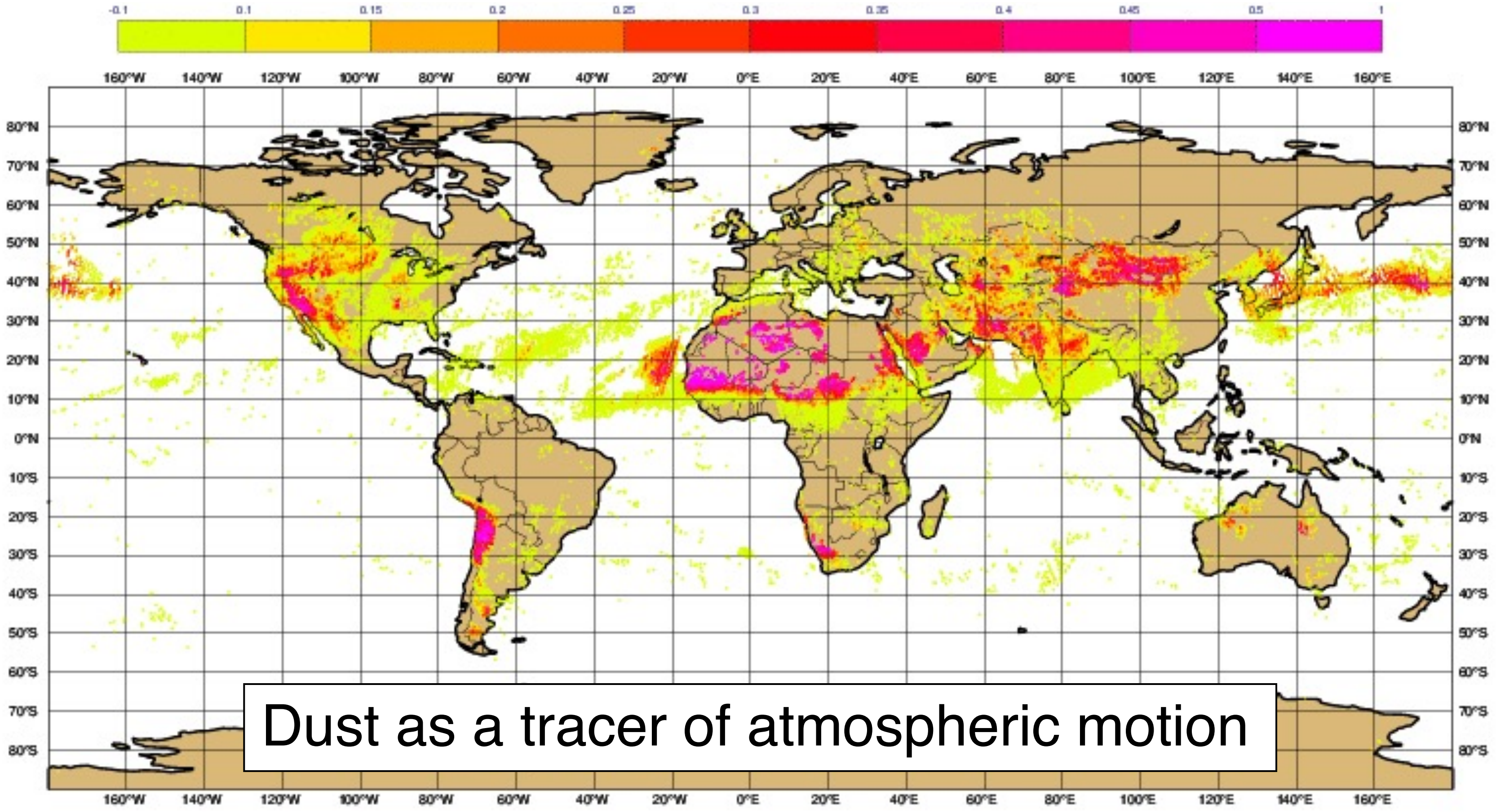
Overview:

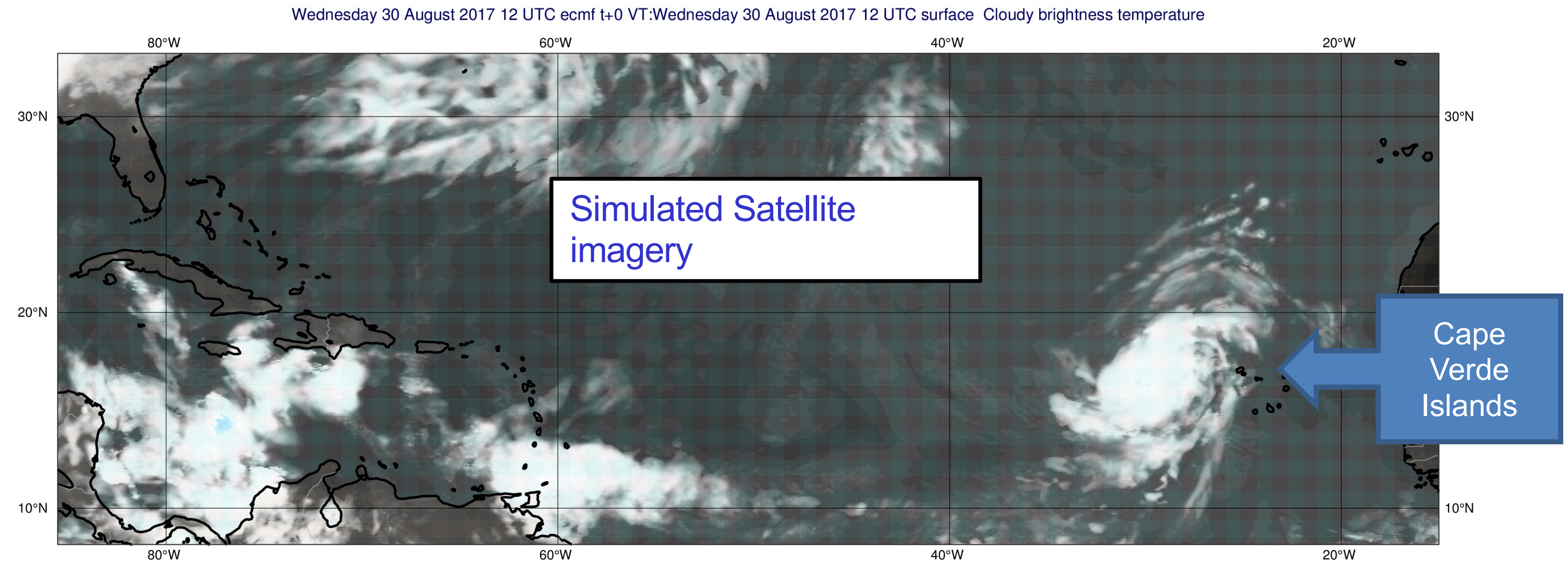
- Why do we need satellites ?
- What do we have and which are most important ?
- What is actually measured ?
- Key elements of satellite data assimilation

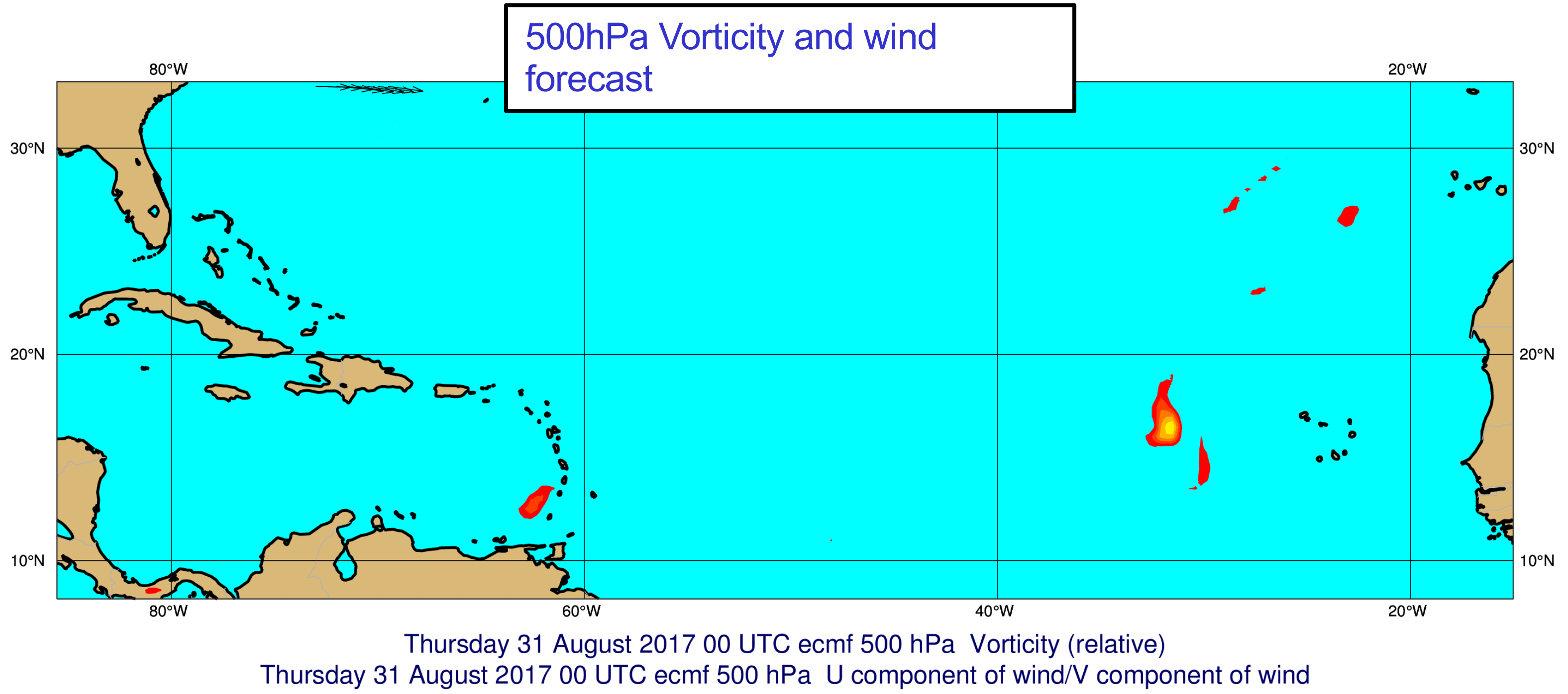
ECMWF

Why do we need satellites ?

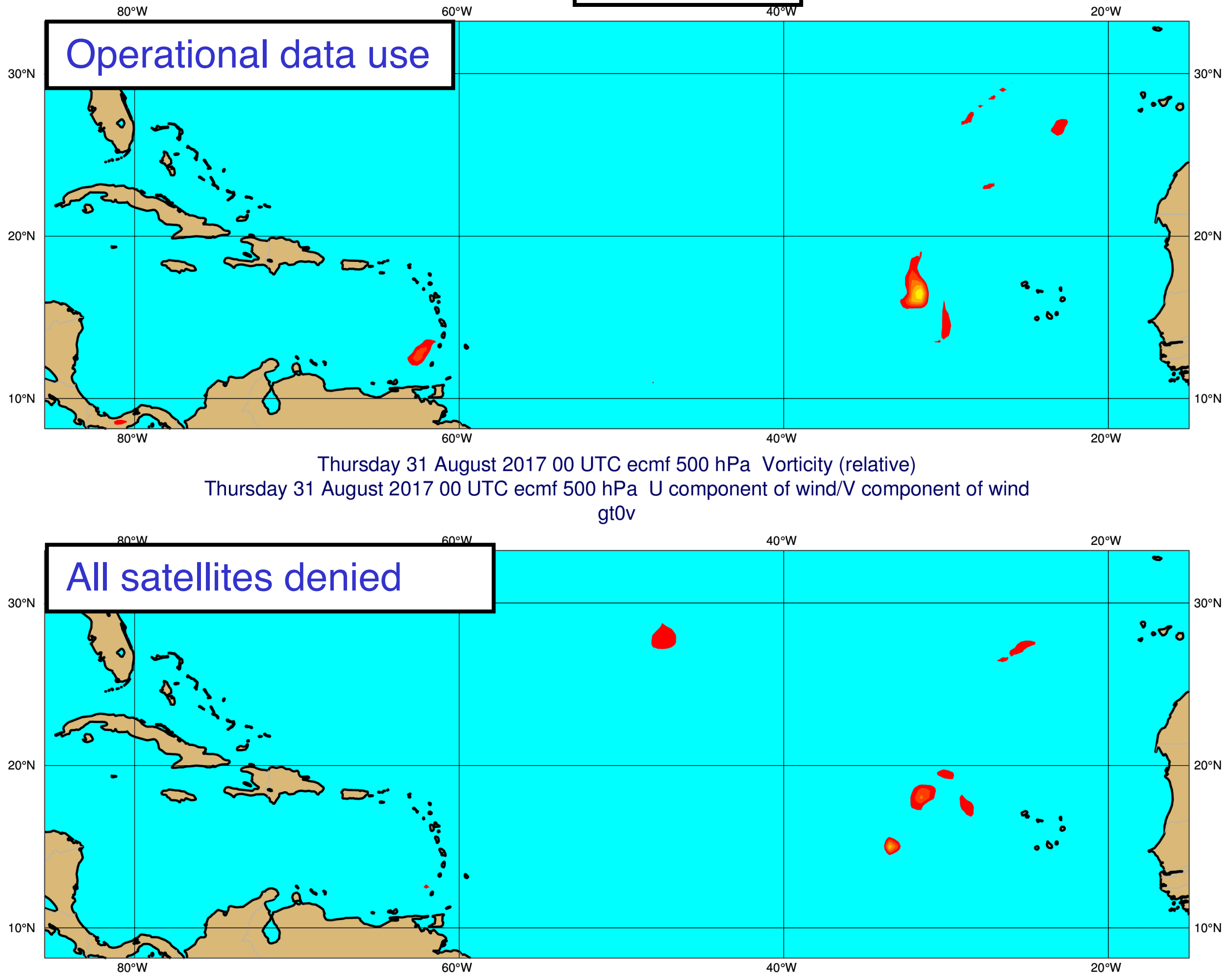
To forecast many days in to the future we need a global picture of the current atmospheric state…



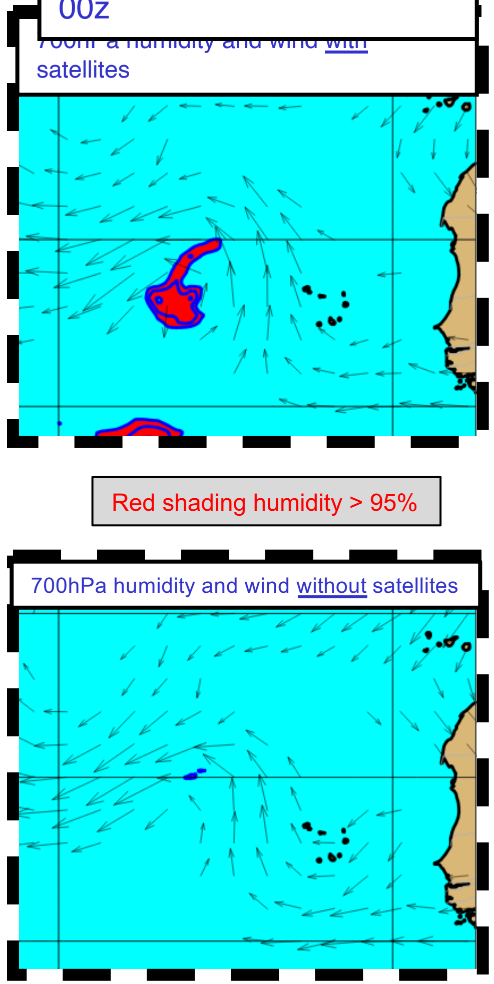

Wednesday 30 August 2017 12 UTC ecmf t+0 VT:Wednesday 30 August 2017 12 UTC surface Cloudy brightness temperature
80°W
60°W
40°W
20°W
30°N
20°N
10°N
Simulated Satellite imagery
Cape Verde Islands


500hPa Vorticity and wind forecast
80°W
60°W
40°W
20°W
30°N
20°N
10°N
Thursday 31 August 2017 00 UTC ecmf 500 hPa Vorticity (relative)
Thursday 31 August 2017 00 UTC ecmf 500 hPa U component of wind/V component of wind

FORECAST



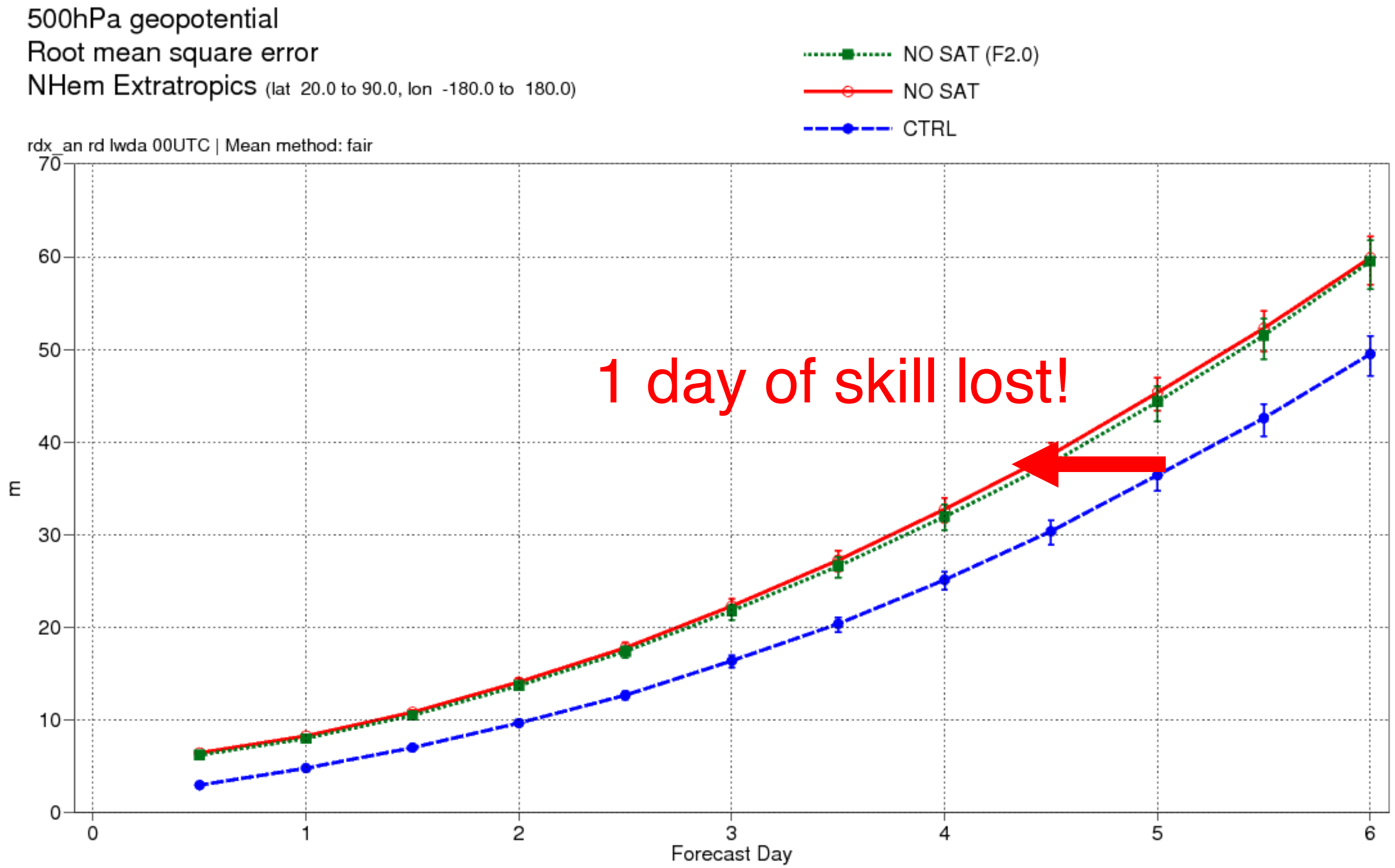
INITIAL CONDITIONS 31/8 00z



Can we quantify how important are satellites for NWP ?

…denial experiments…

Can we quantify how important are satellites for NWP ?



Can we quantify how important are satellites are for NWP ?

Satellites used for NWP at ECMWF

OB TYPE	Satellite / sensors	EUROPE	USA	ASIA
Atmospheric Motion Vectors	METOP A,B,C,DUAL (AVHRR) METEOSAT 8,11 (SEVIRI) HIMAWARI 8 (AHI) NPP, NOAA 20 (VIIRS) NOAA 15,18,19 (AVHRR) GOES 15,16 (I/ABI) AQUA (MODIS)	METOP A,B,C + DUAL (AVHRR) METEOSAT 8,11 (SEVIRI)	NPP, NOAA 20 (VIIRS) NOAA 15,18,19 (AVHRR) AQUA (MODIS) GOES 15,16, 17, 18 (ABI)	HIMAWARI 8, 9 (AHI)
Atmospheric Sounding Radiances	METOP A,B,C (AMSU/MHS/IASI) NPP, NOAA 20 (ATMS/CrIS) NOAA 15,18,19 (AMSU/MHS) AQUA (AMSUA/AIRS) FY3-B,C,D (MWHS/MWHS2) METEOSAT 9,11 (SEVIRI) HIMAWARI 8 (AHI) GOES 15,16, 17,18 (I/ABI) GCOM-W (AMSR-2) GPM (GMI) DMSP 17,18 (SSM/IS)	METOP B,C (AMSU/MHS/IASI) METEOSAT 8,11 (SEVIRI)	NPP, NOAA 20 (ATMS/CrIS) NOAA 15,18,19 (AMSU/MHS) AQUA (AMSUA/AIRS) GOES 15,16, 17, 18 (I/ABI) DMSP 17,18 (SSM/IS)	FY3-C,D,E (MWHS/MWHS2/MWRI) HIMAWARI 8, 9 (AHI) GCOM-W (AMSR-2)
GNSS-RO	METOP B,C (GRAS) COSMIC2 Spire (2020) TERRASAR / TANDEM FY3 (GNOS) KOMPSAT5 (GNOS)	METOP A,B,C (GRAS) TERRASAR / TANDEM SPIRE (commercial)	COSMIC2	FY3 (GNOS) KOMPSAT5
SCAT / ALT	METOP B,C(ASCAT) / JASON3 / AltiKA / S3A/B / Cry2	METOP A,B,C (ASCAT) /JASON3 / JASON3 / AltiKA / S3A/B / CRY2		
Doppler Wind Lidar	Aeolus	Aeolus		

Plus many others used for COPERNICUS Atmospheric composition and climate services

Split by sensor technology…

OB TYPE	Satellite / sensors
Atmospheric Motion Vectors	METOP A,B,C,DUAL (**AVHRR**) METEOSAT 8,11 (**SEVIRI**) HIMAWARI 8 (**AHI**) NPP, NOAA 20 (**VIIRS**) NOAA 15,18,19 (**AVHRR**) GOES 15,16 (**I/ABI**) AQUA (**MODIS**)
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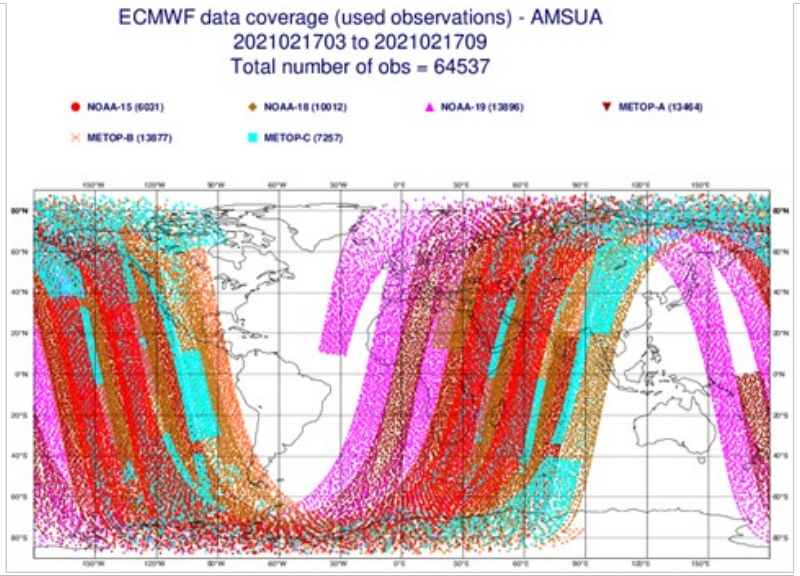
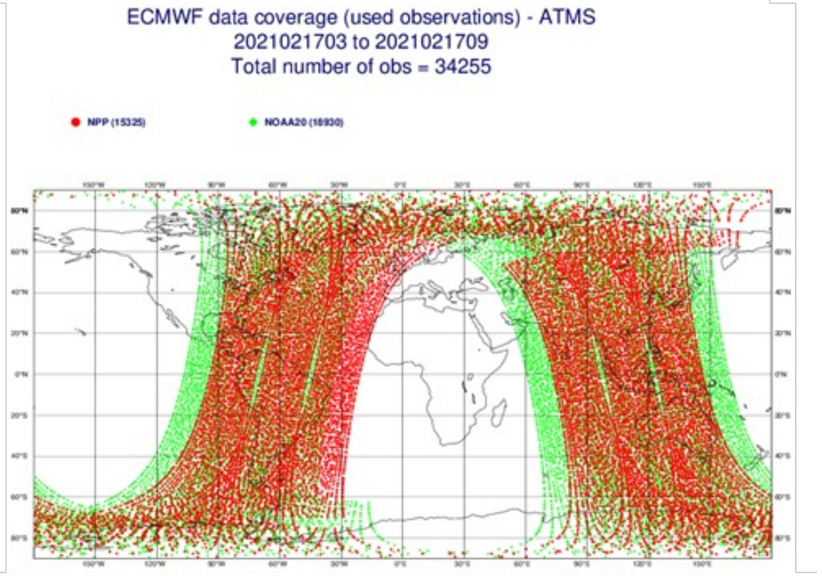
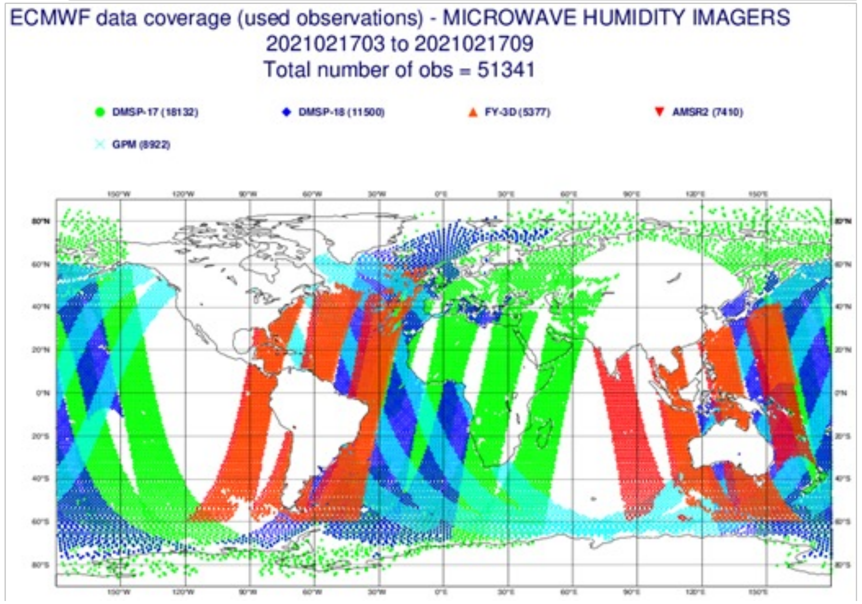
GNSS-RO	METOP A,B,C (**GRAS**) **COSMIC2 Spire** (2020) **TERRASAR / TANDEM** **FY3 (GNOS)** **KOMPSAT5 (GNOS)**
SCAT / ALT	**METOPA,B,C(ASCAT) / Saral JASON3 / AltiKA / S3A/B / Cry2**
Doppler Wind Lidar	**Aeolus**

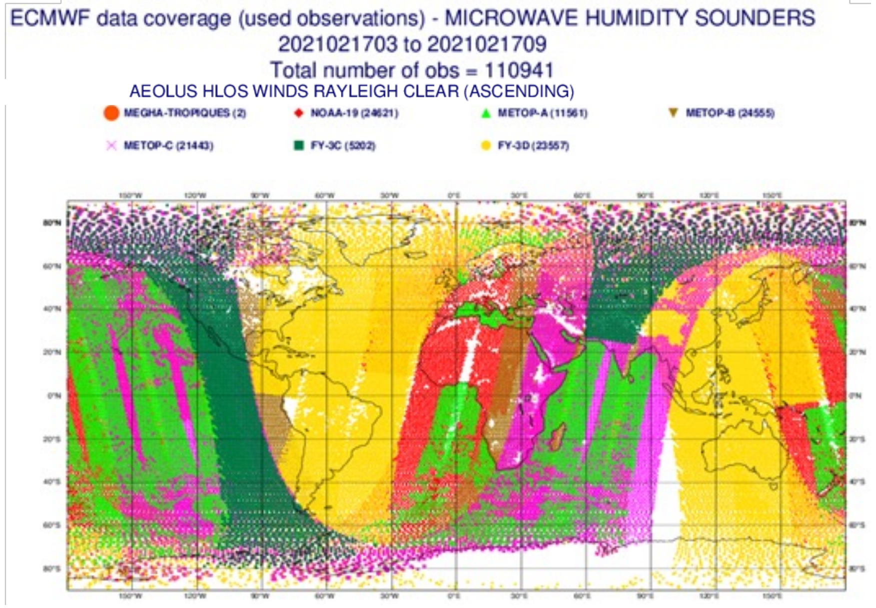
Sensor technology	Processing route
Passive microwave	L1 Radiances
Passive infrared	L1 Radiances / AMV
Radio occultation	Bending angles
SCAT / Altimeter	L2 wind / SLA / SWH
Doppler wind lidar	L2 LOS wind

Passive microwave (LEO)

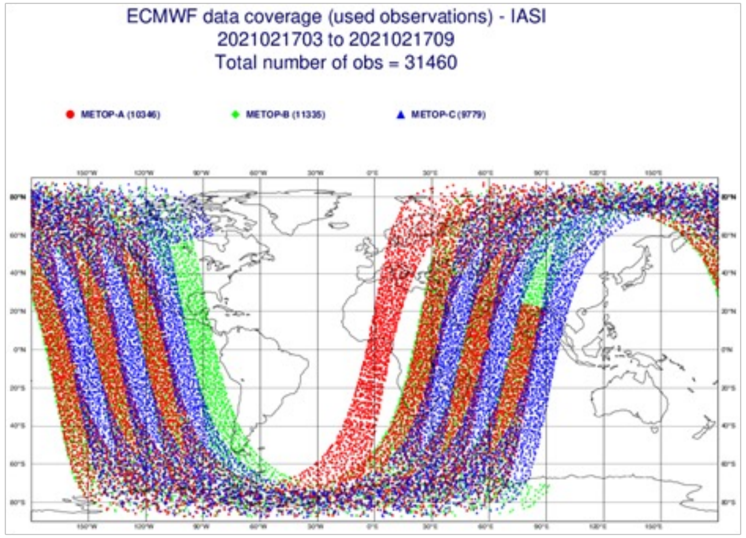


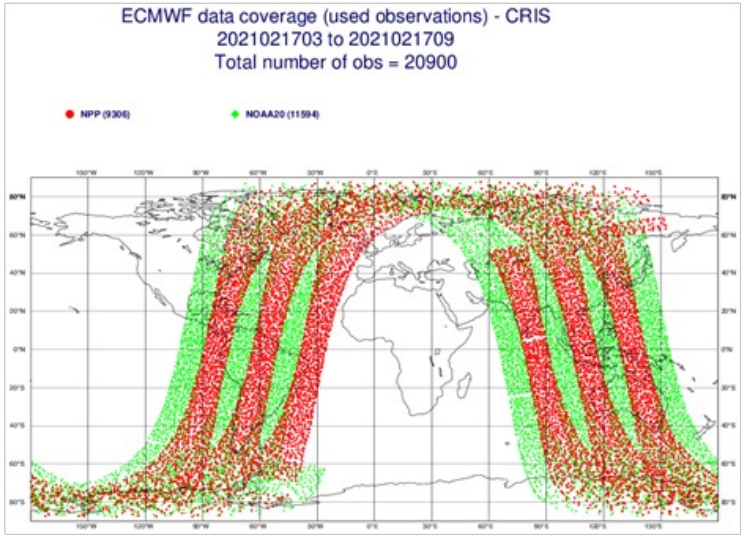


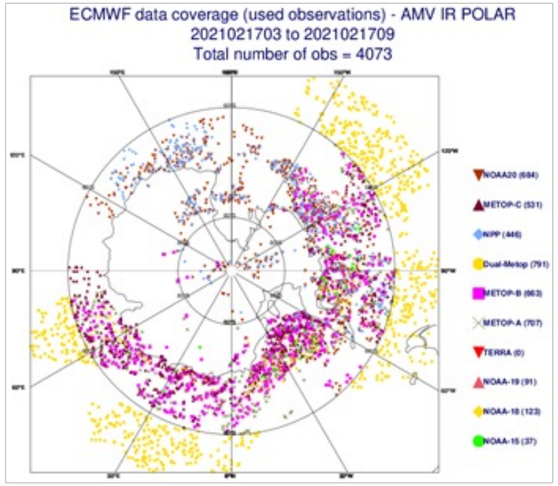


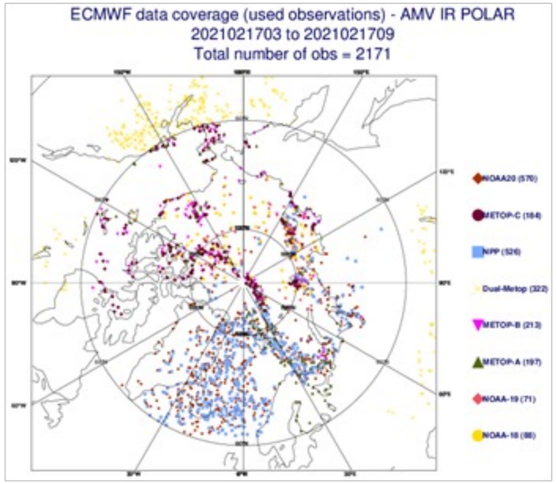


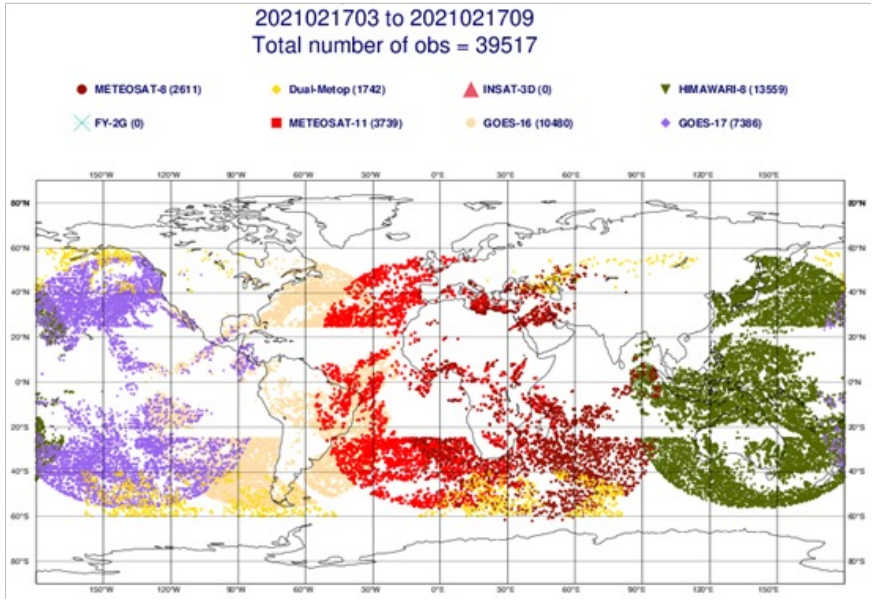
Passive infrared (LEO and GEO)



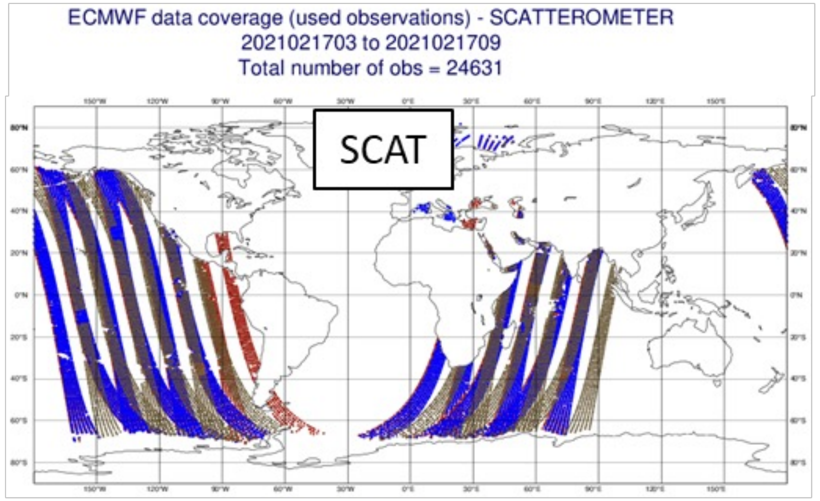


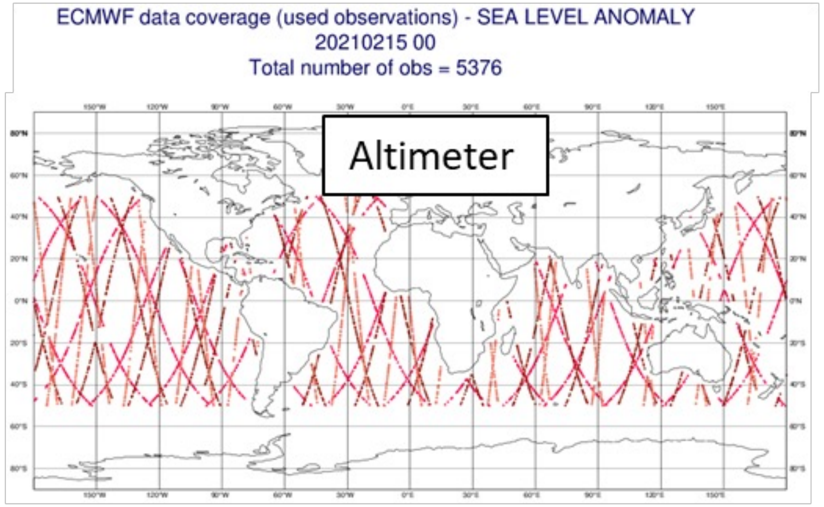


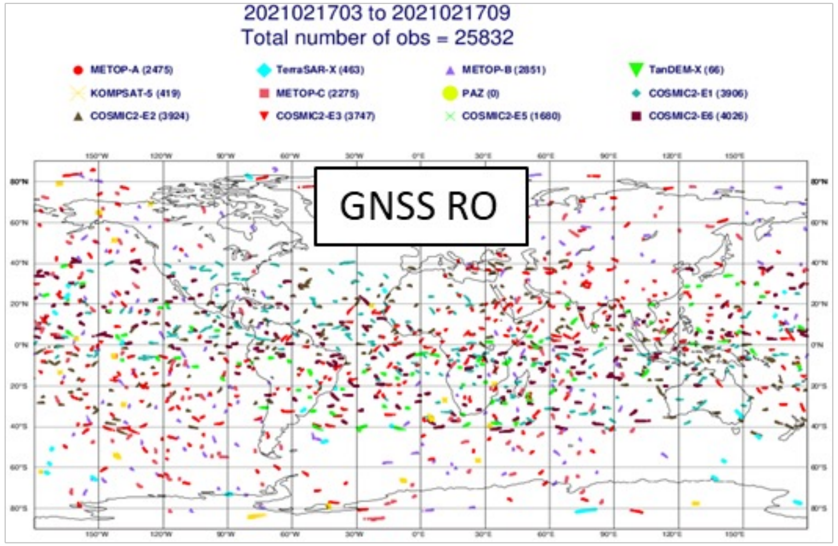


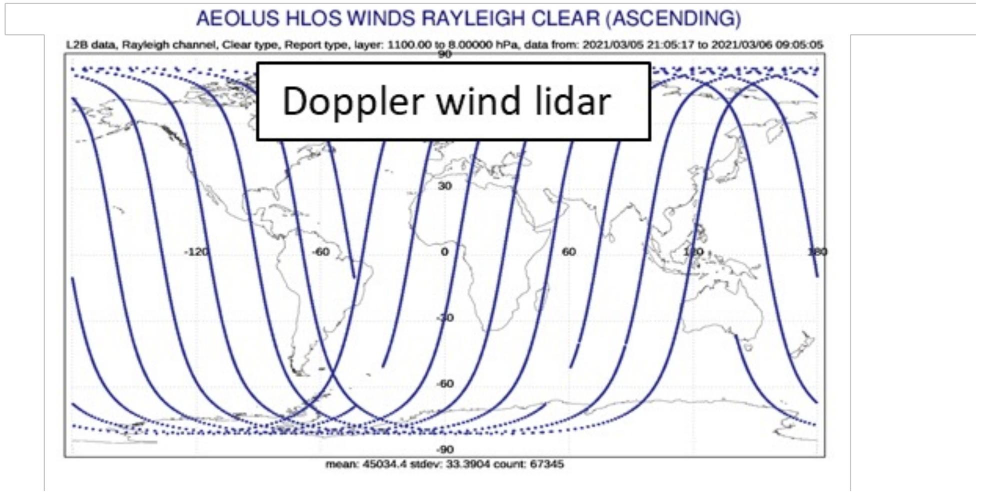


Active sensors



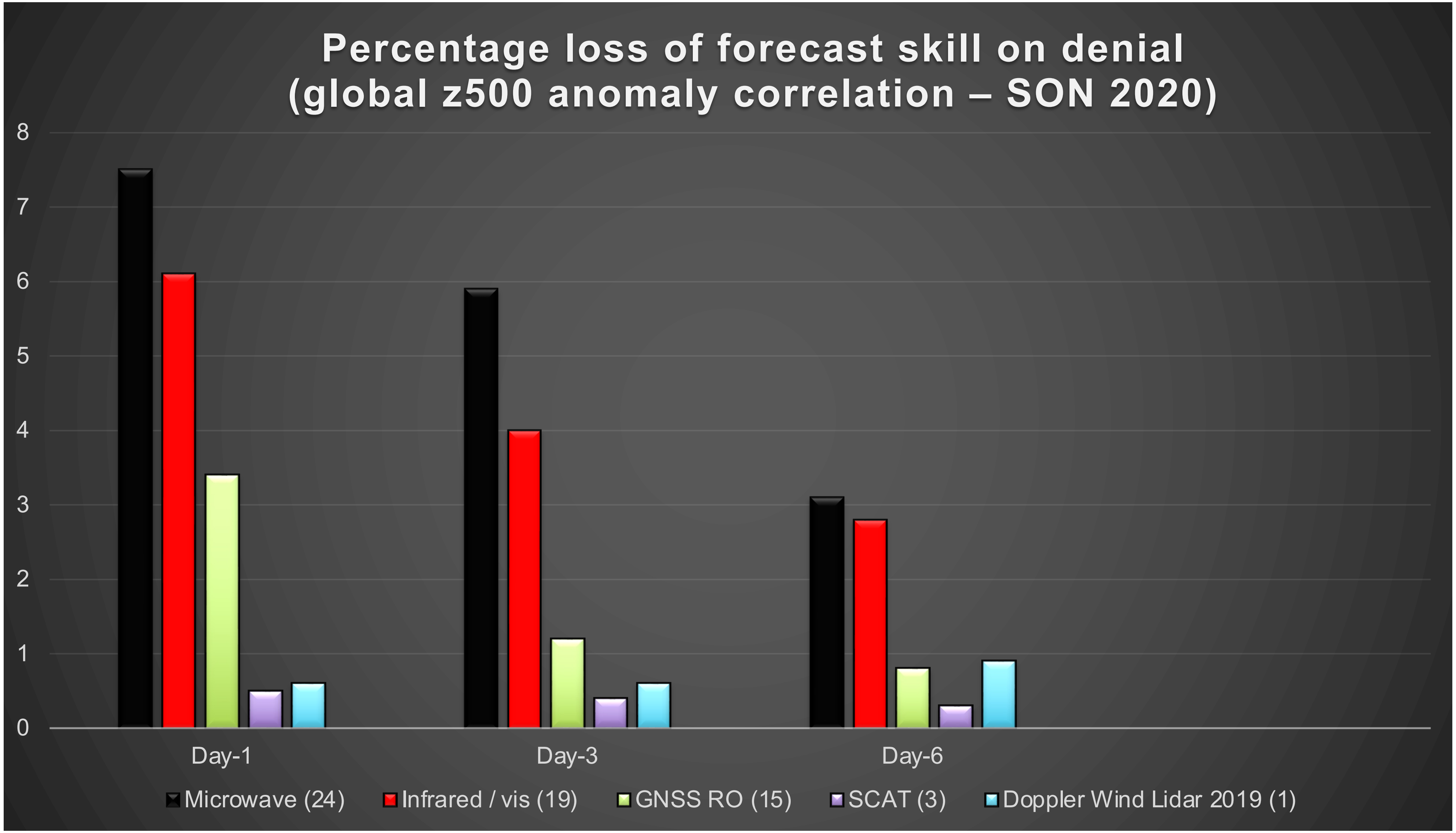






Which satellite observations are most important for NWP ?

Impact of different sensor technologies



Which satellite observations are most important for NWP ?

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

What do passive microwave and infrared satellite instruments measure …?

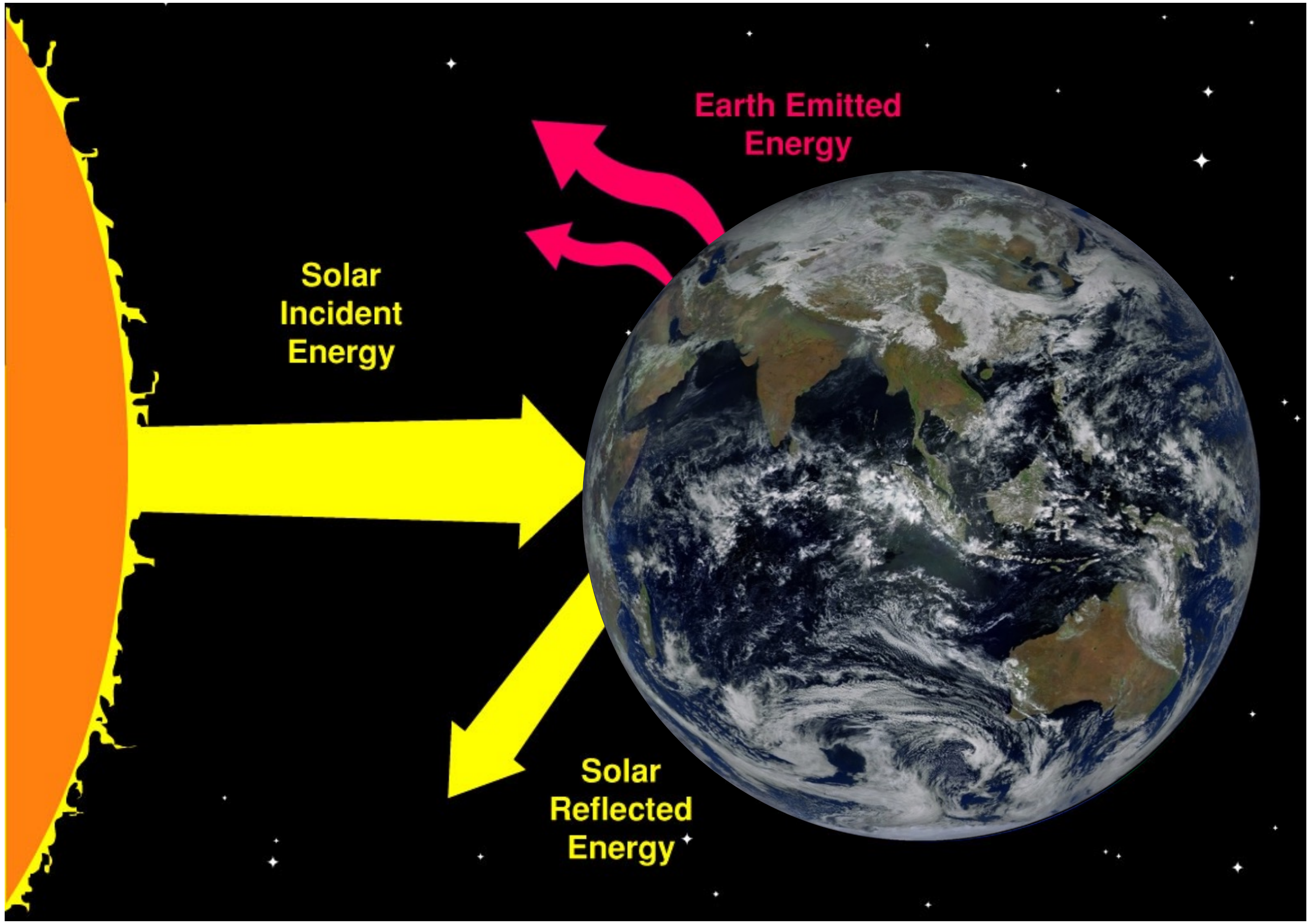
What do passive microwave and infrared satellite instruments measure ...?

They DO NOT measure TEMPERATURE

They DO NOT measure HUMIDITY or OZONE

They DO NOT measure WIND

SATELLITES CAN <u>ONLY</u> MEASURE OUTGOING THERMAL RADIATION FROM THE ATMOSPHERE



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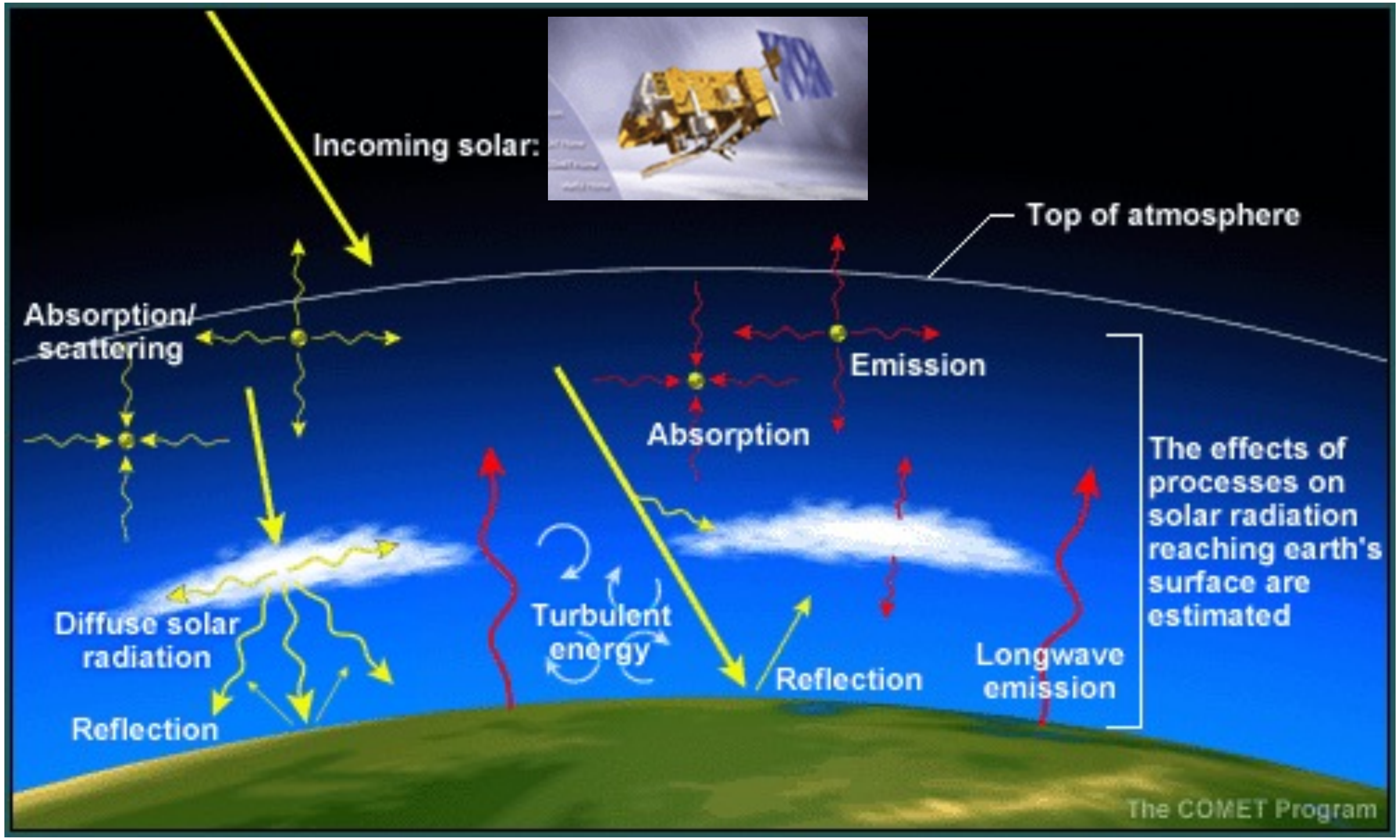
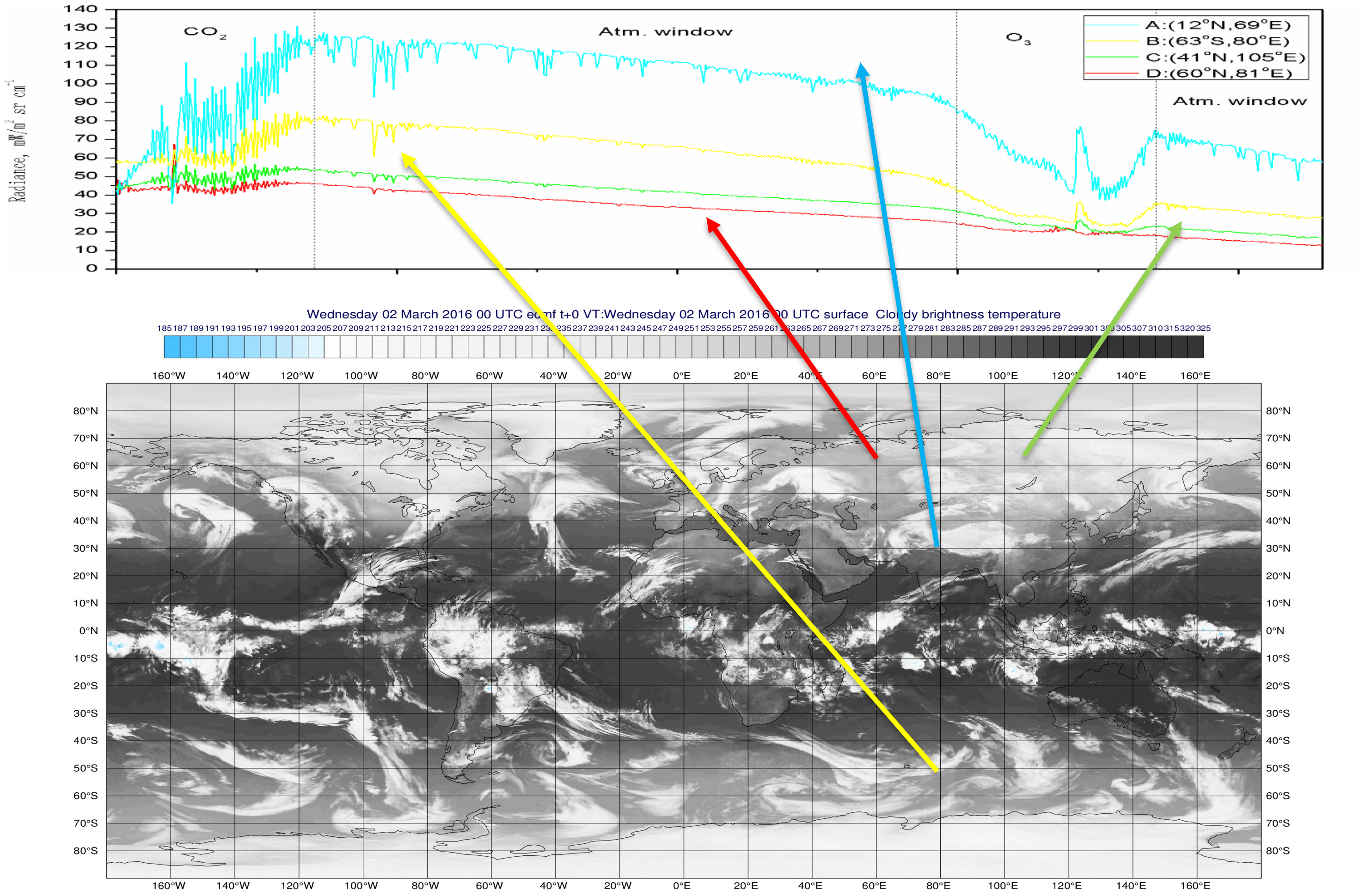


Every atmosphere has its own complex spectral radiance fingerprint …



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

<u>Radiative Transfer Equation</u>

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

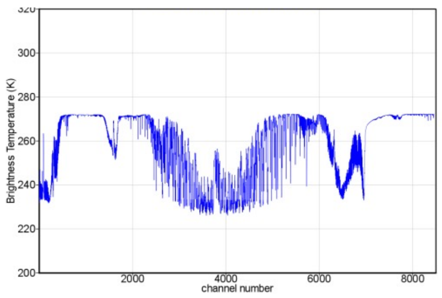
Other contributions to the measured radiances

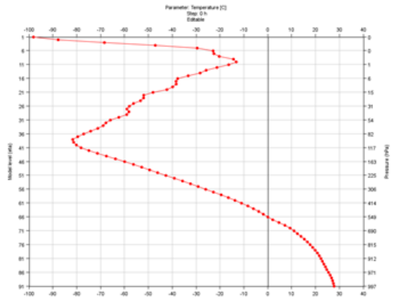
The Radiative Transfer (RT) equation

measured by the satellite

depends on the state of the atmosphere

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





The Radiative Transfer (RT) equation

“Forward problem”

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

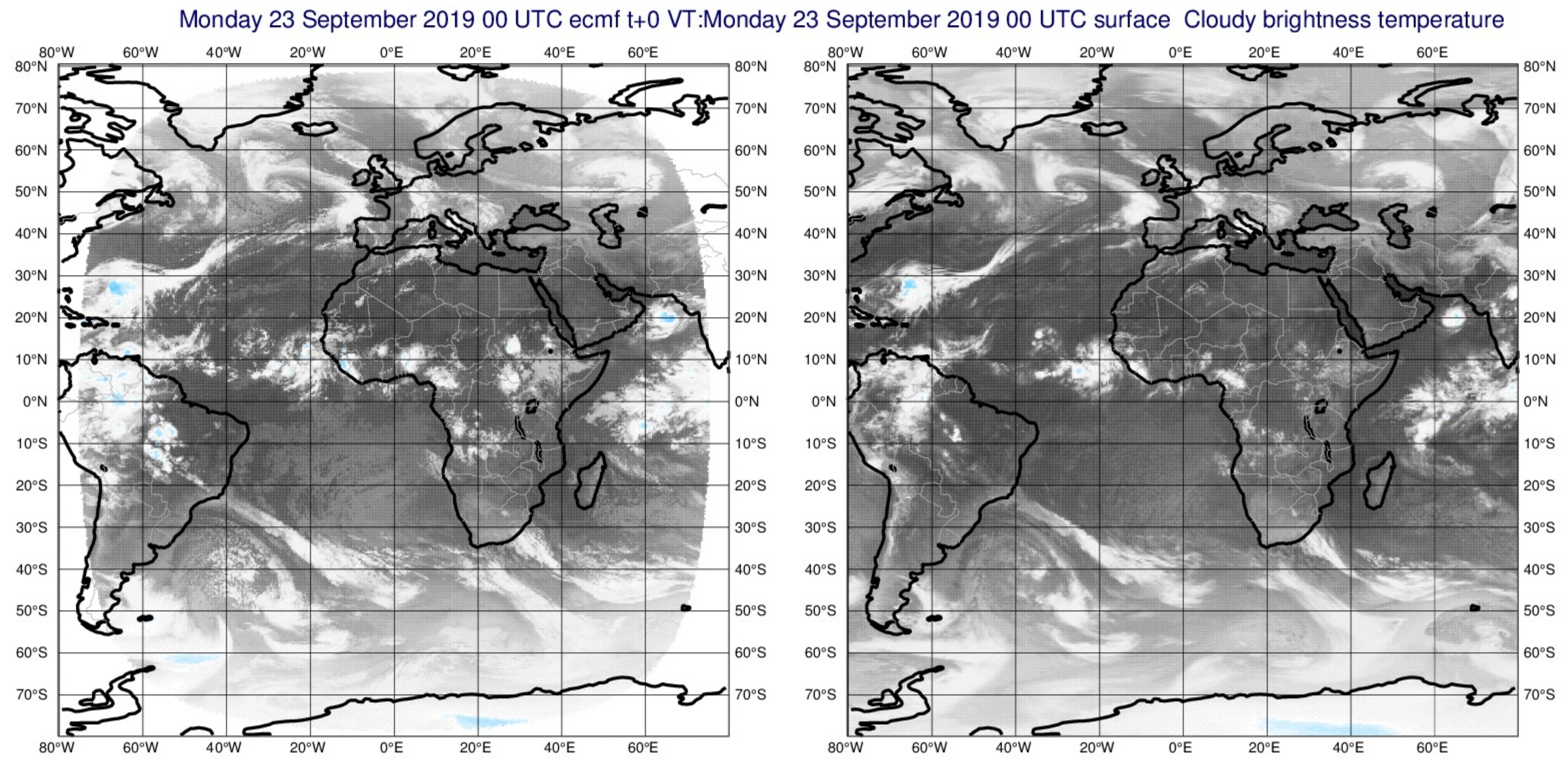
$$\underbrace{L(\nu)}_{\text{measured by the satellite}} = \underbrace{\int_0^\infty B(\nu, T(z)) \left[\frac{d\tau(\nu)}{dz}\right] dz + \text{Surface emission} + \text{Surface reflection/scattering} + \text{Cloud/rain contribution} + \ldots}_{\text{depends on the state of the atmosphere}}$$

…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

Observations from Meteosat-11 Simulated from the forecast model

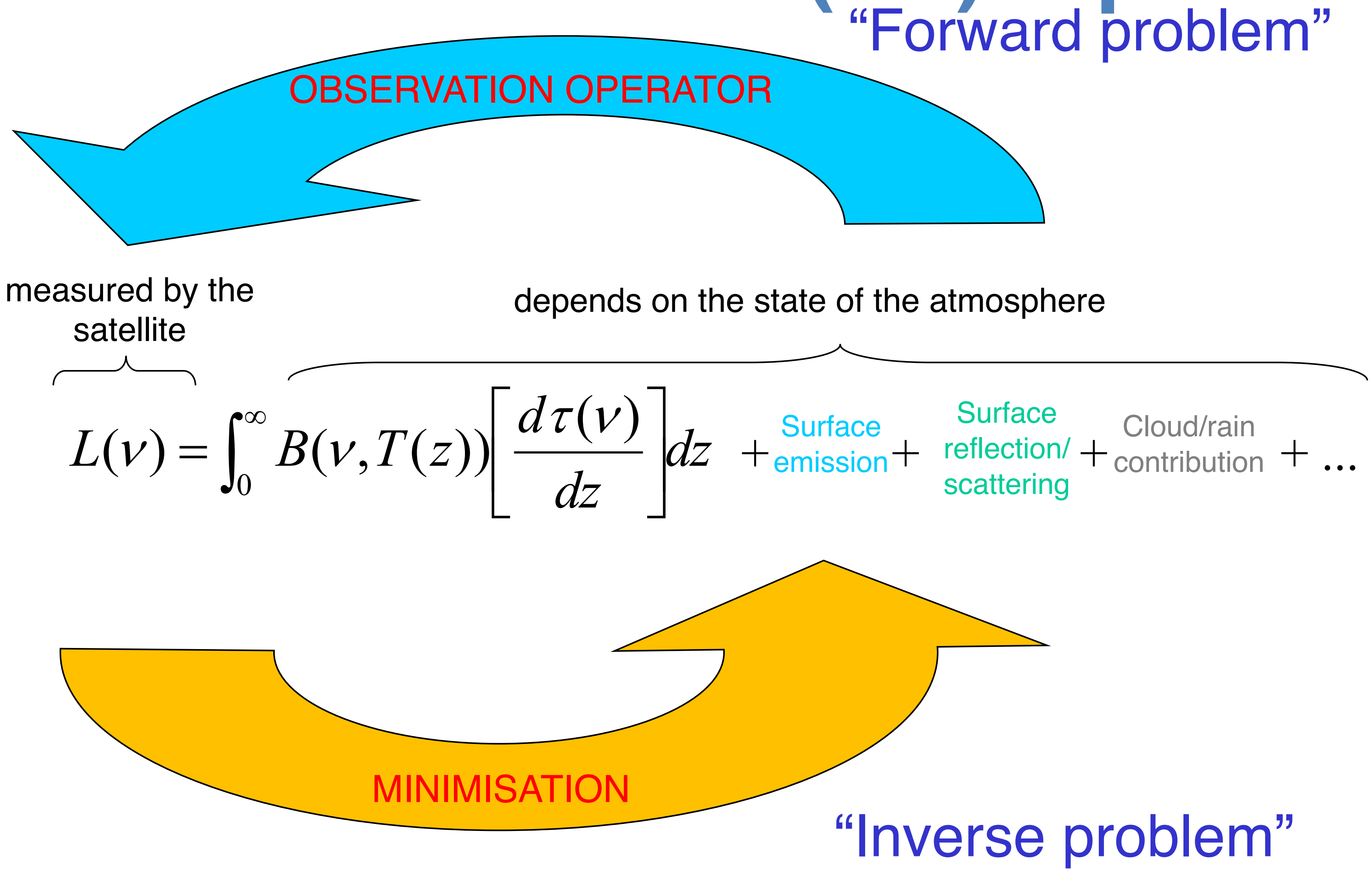


Modern radiative transfer can simulate atmospheric radiation very accurately …so why do these two radiation images diverge ?

So by comparing simulated radiation to real satellite observations we can tell if the assumed state of the atmosphere is right or wrong…..

…..this is the basis for satellite radiance data assimilation…

The Radiative Transfer (RT) equation



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

…but first we have to simplify things a bit…

"Channel selection" …

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

Measuring radiances in different frequencies (channels)

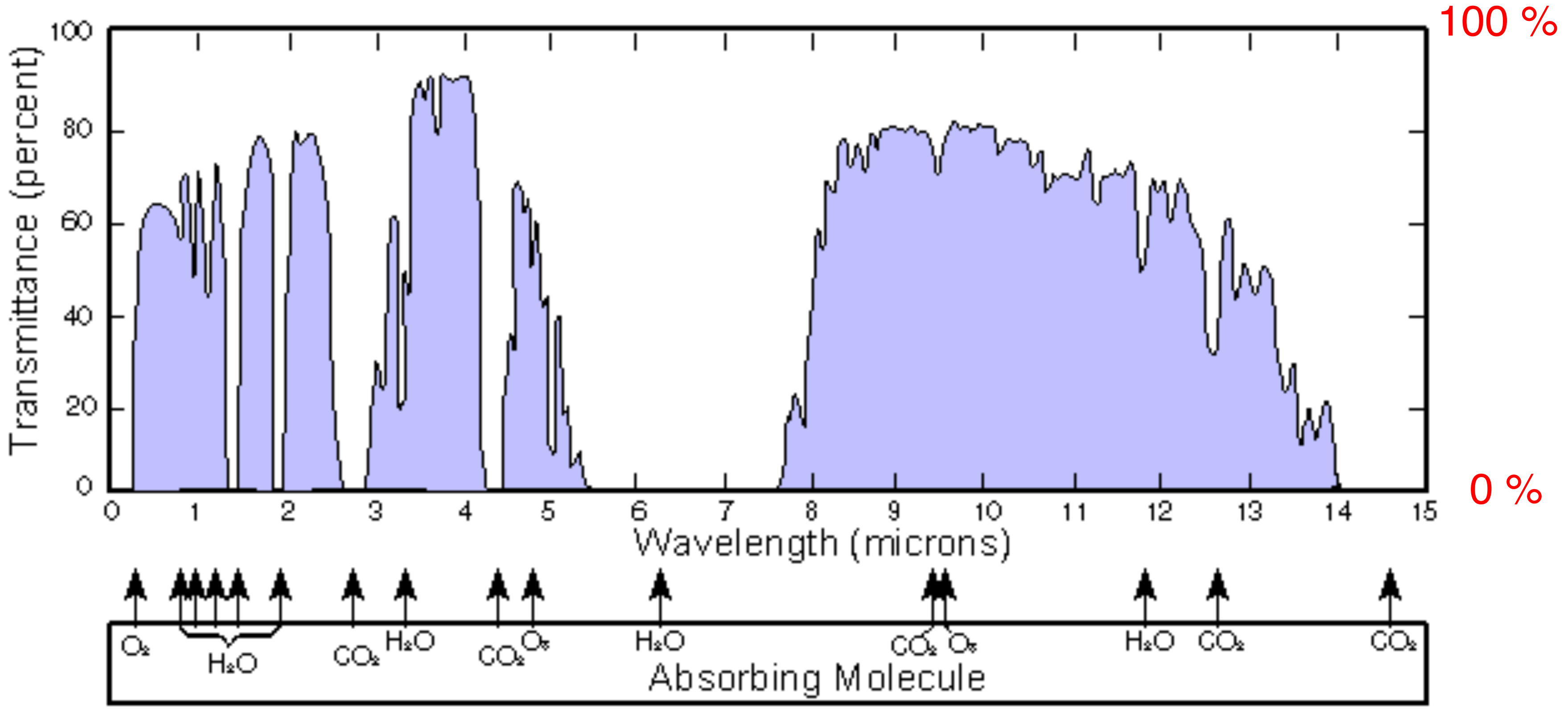
By deliberately selecting radiation at different frequencies or CHANNELS satellite instruments can provide information on specific geophysical variables for different regions of the atmosphere.

In general, the frequencies / channels used within NWP may be categorized as one of 2 different types …

1. atmospheric sounding channels
2. surface sensing channels

Note:
In practice (and often despite their name!) real satellite instruments have channels which are a combination of atmospheric sounding and surface sensing channels

Atmospheric transmission at different wavelengths



Atmospheric sounding channels…

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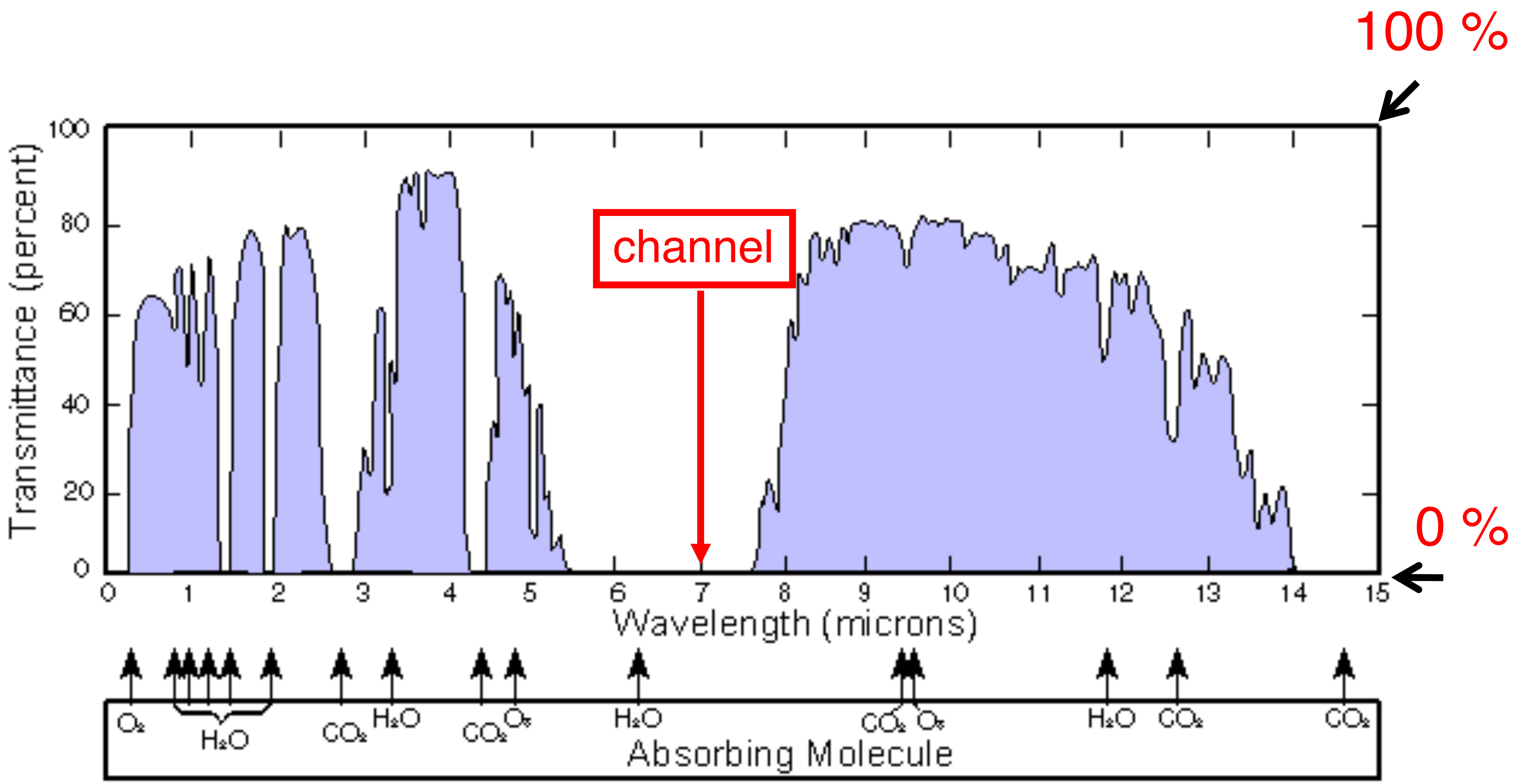
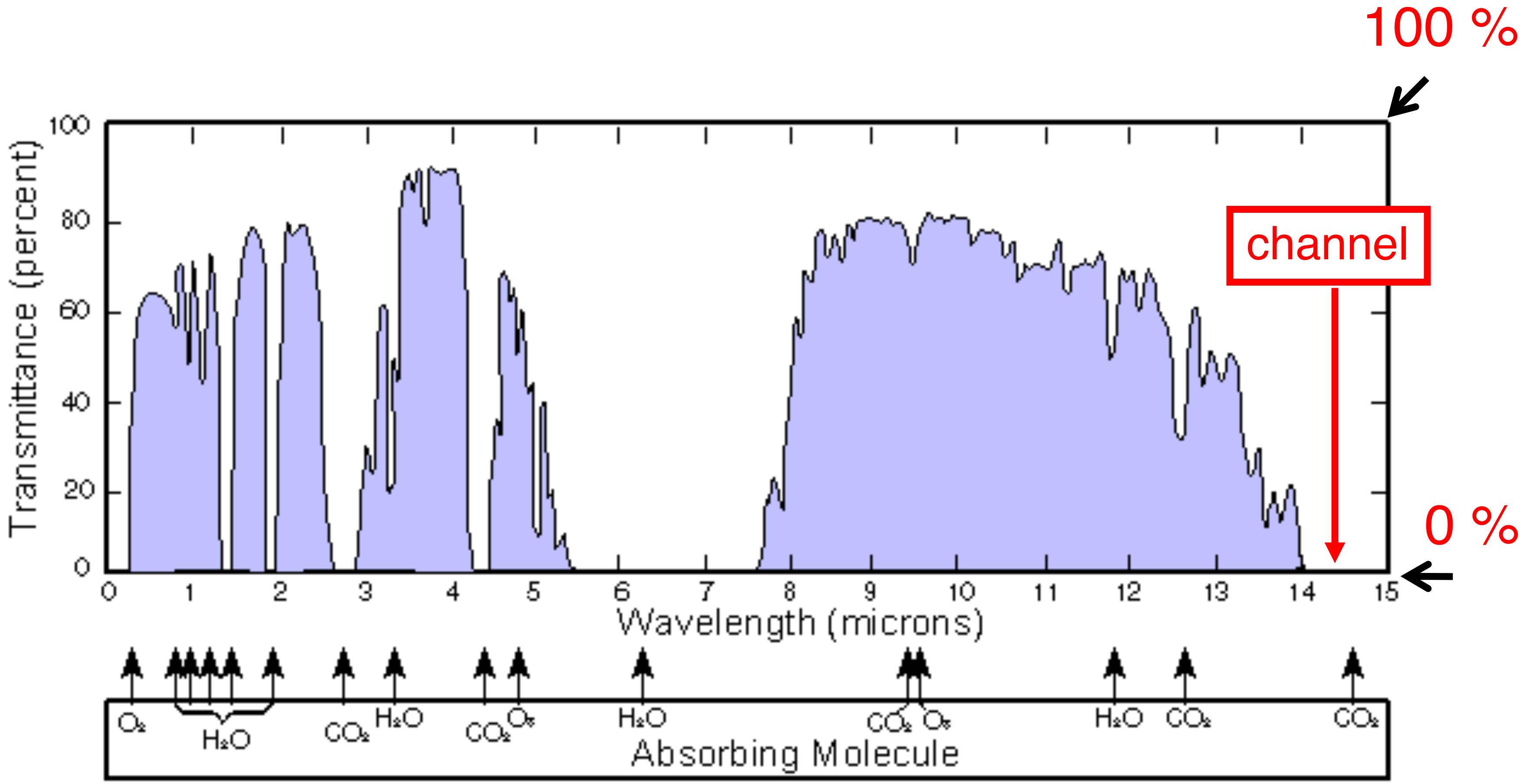


Atmospheric sounding channels…



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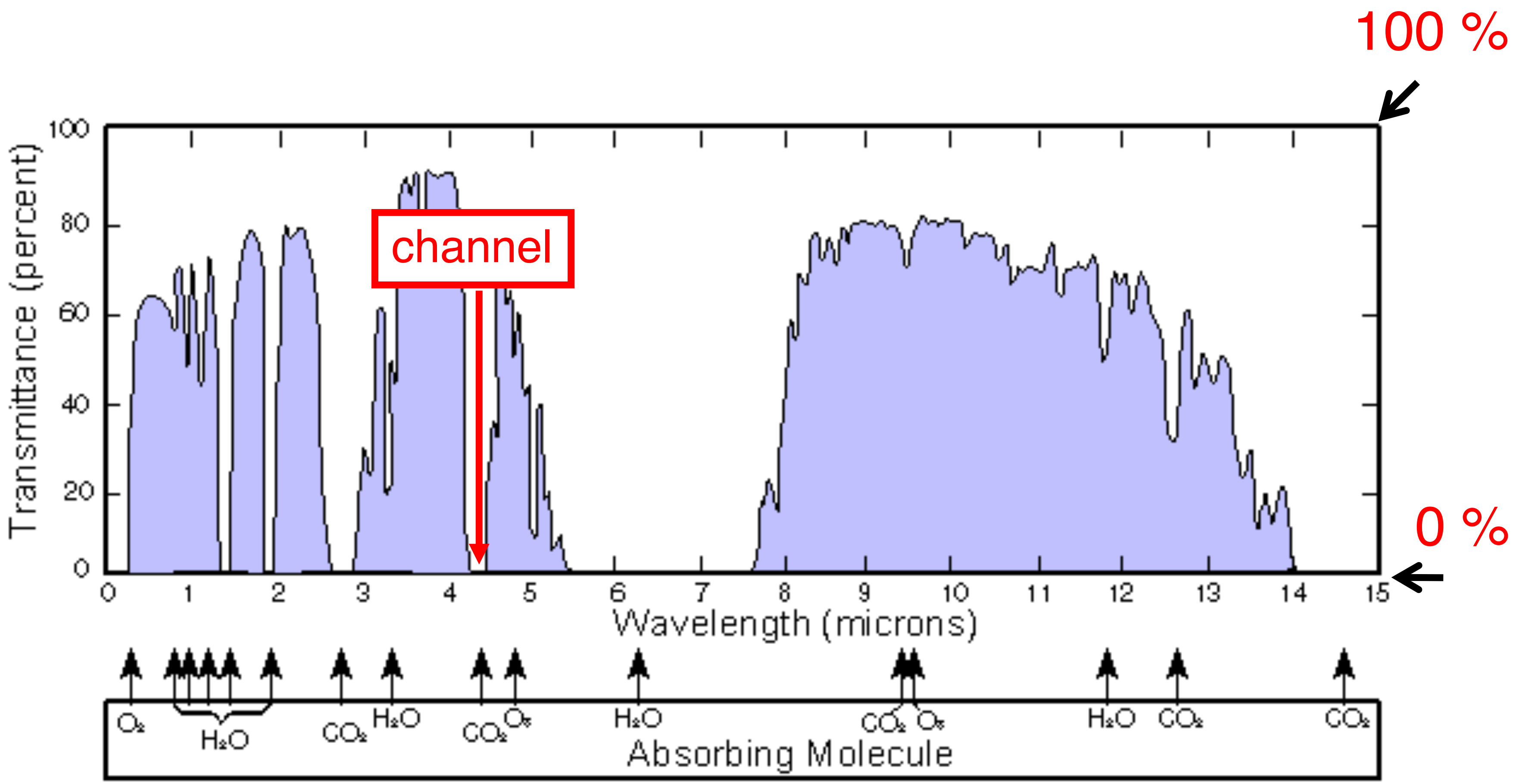

Atmospheric sounding channels…

…selecting channels where there is no contribution from the surface….

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

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Atmospheric sounding channels…

…if we additionally screen observations to remove measurements in cloudy or rain locations…

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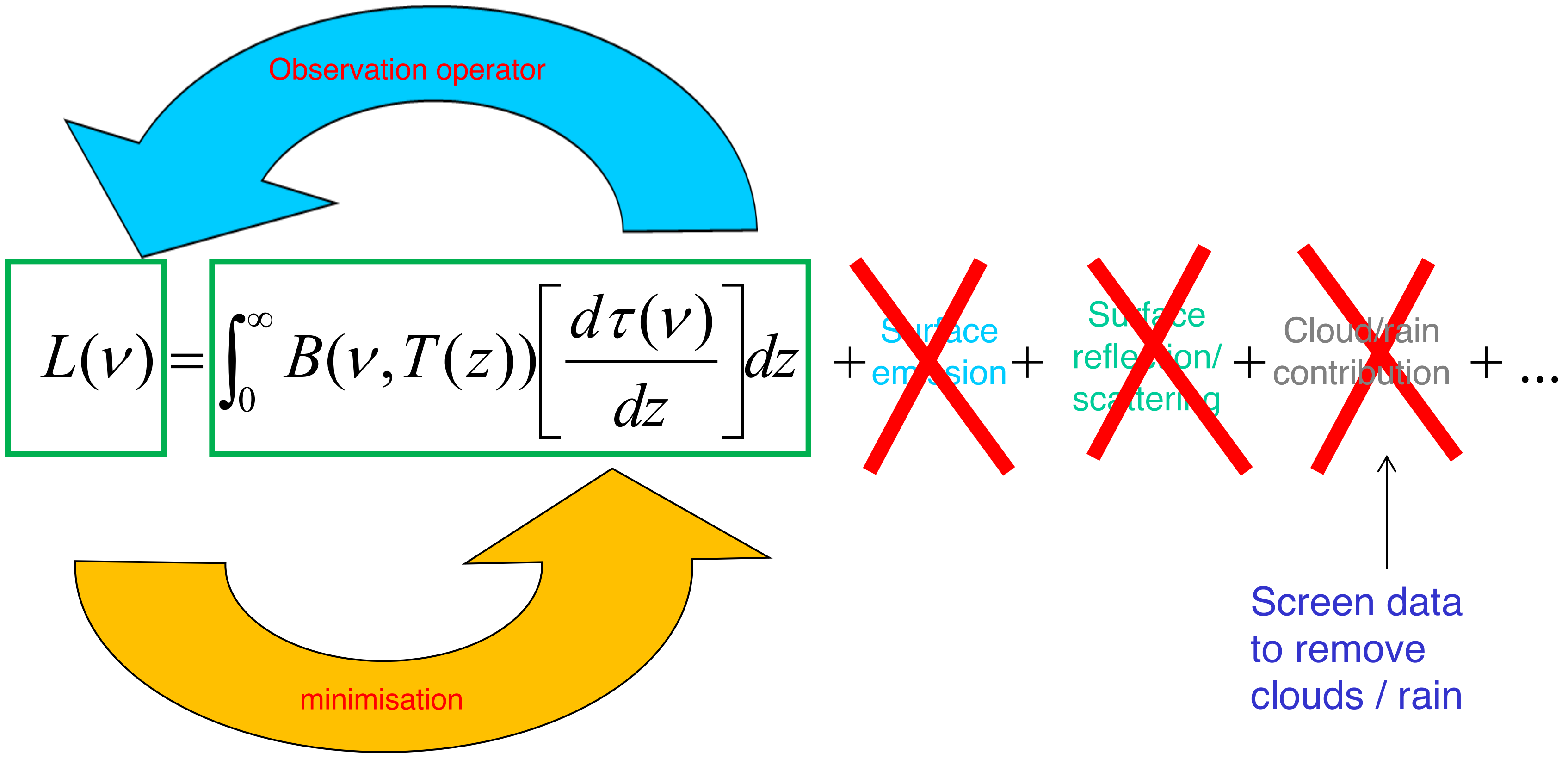
We now have a much simpler forward …and inverse problem for the DA



Atmospheric sounding channels…

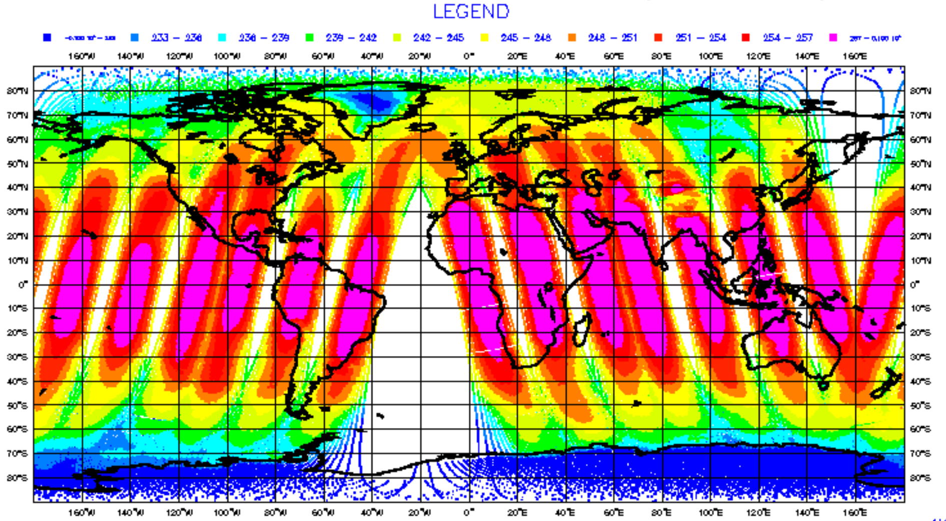
These channels are located in parts of the infra-red and microwave spectrum for which the main contribution to the measured radiance is from the atmosphere and can be written:

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

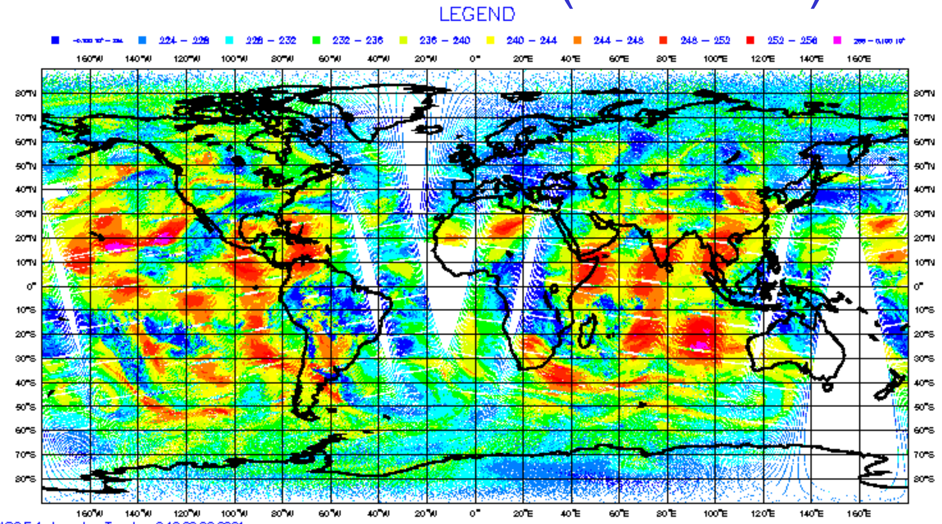
Where B=Planck function
t = transmittance
T(z) is the temperature
z is a height coordinate

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)

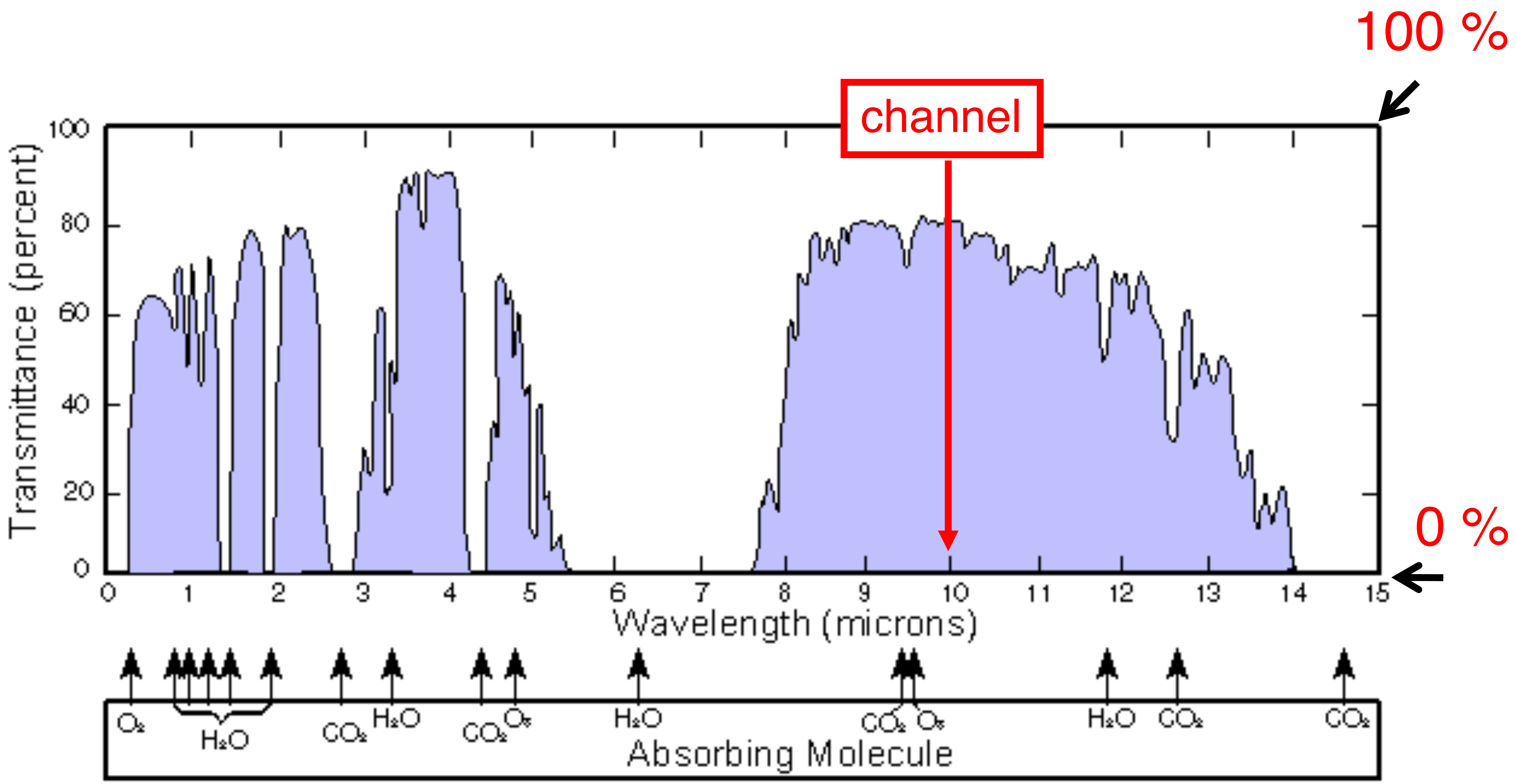


HIRS-channel 12 (6.7micron)

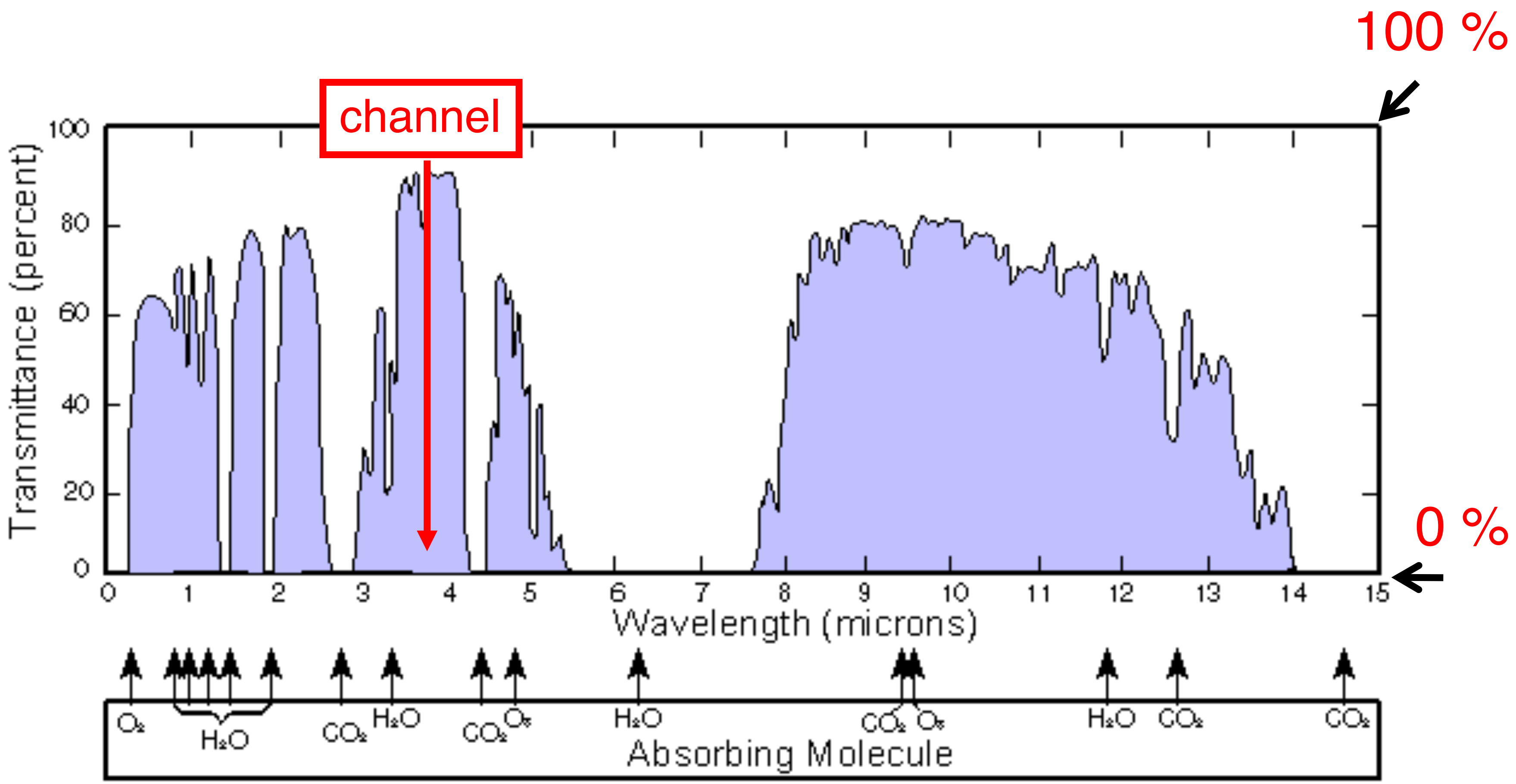


Surface sensing Channels…

Surface sensing Channels



Surface sensing Channels



Surface sensing Channels

…selecting channels where there is no interaction in the atmosphere….

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

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IR ~ zero

Surface sensing Channels

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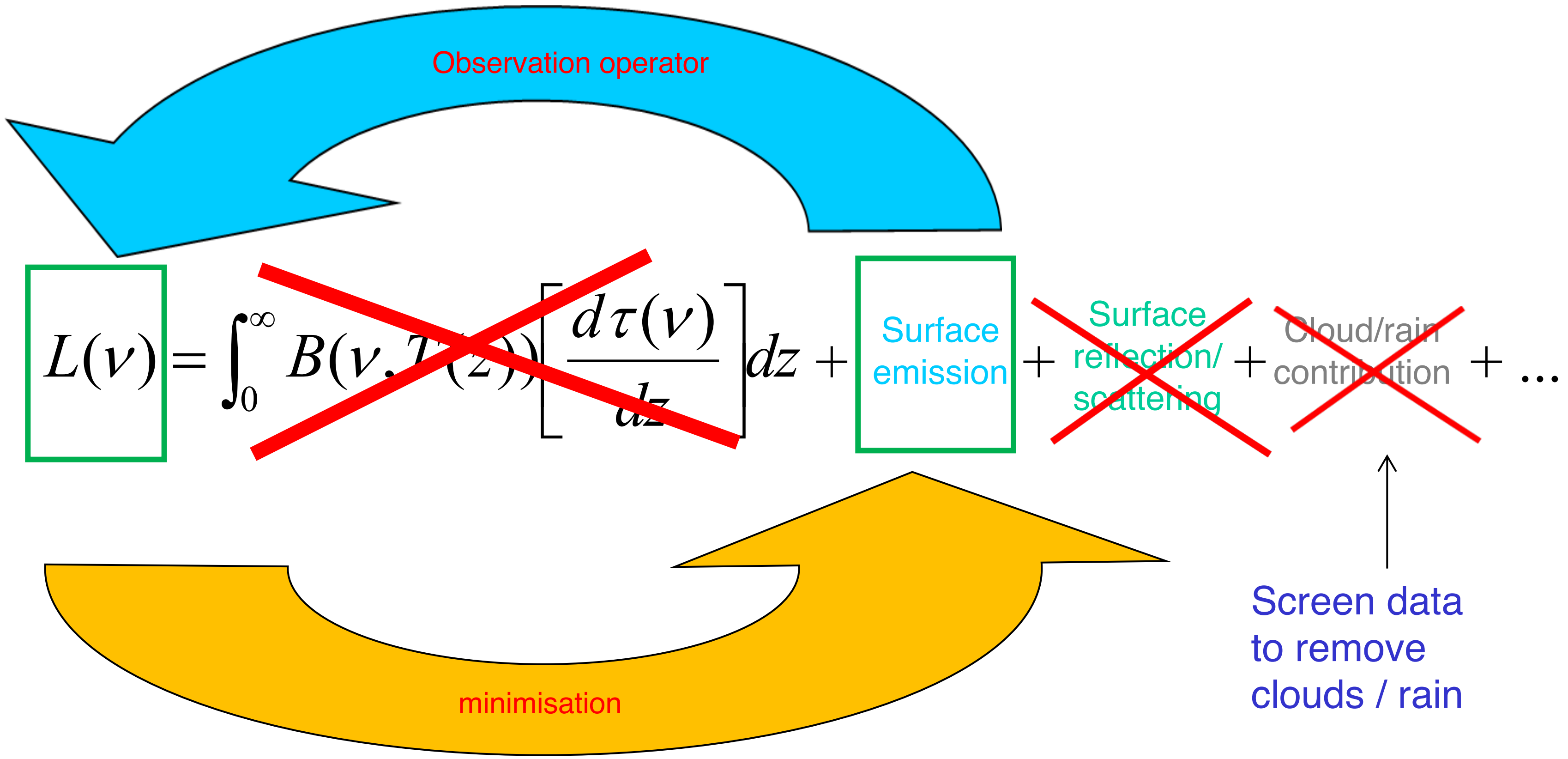
Screen data to remove clouds / rain

We now have a much simpler forward …and inverse problem for the DA



Surface sensing Channels

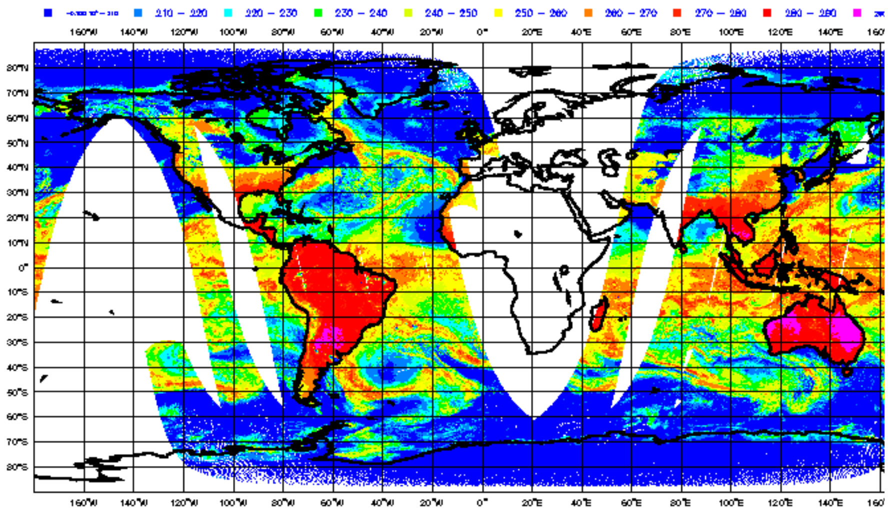
These are located in window regions of the infra-red and microwave spectrum at frequencies where there is very little interaction with the atmosphere and the primary contribution to the measured radiance is:

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

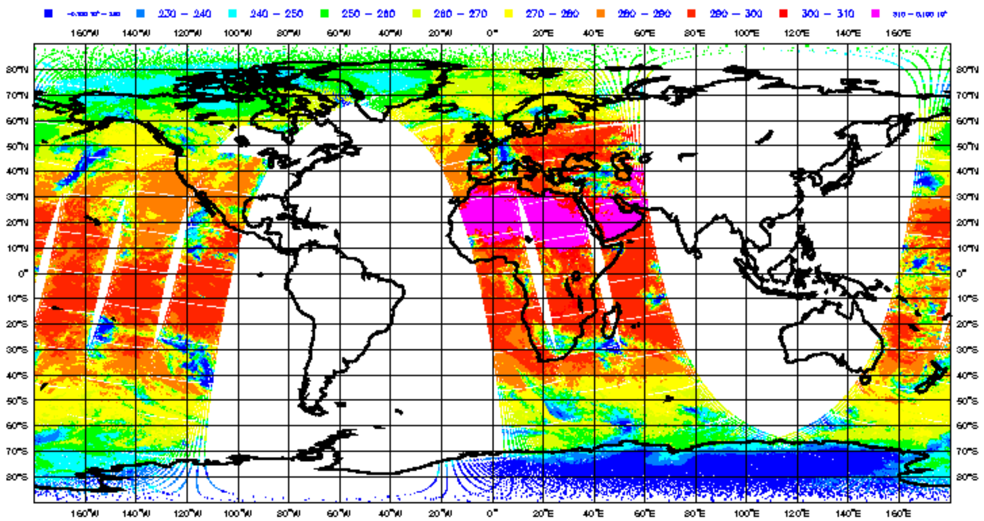
Where T_{surf} is the surface skin temperature and E the surface emissivity

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

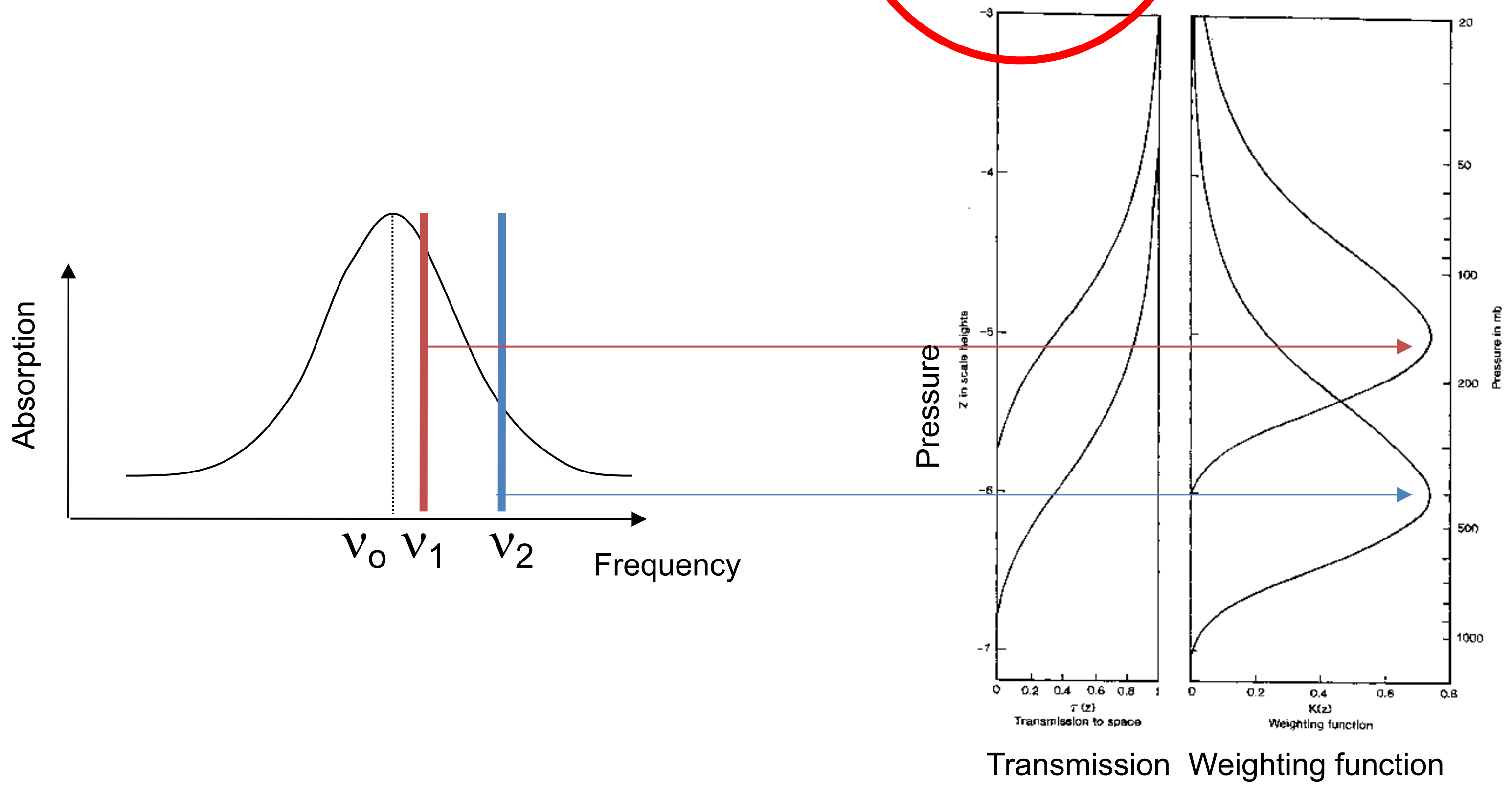
$$L(\nu) = \int_0^{\infty} B(\nu, T(z)) \, H(z) dz$$

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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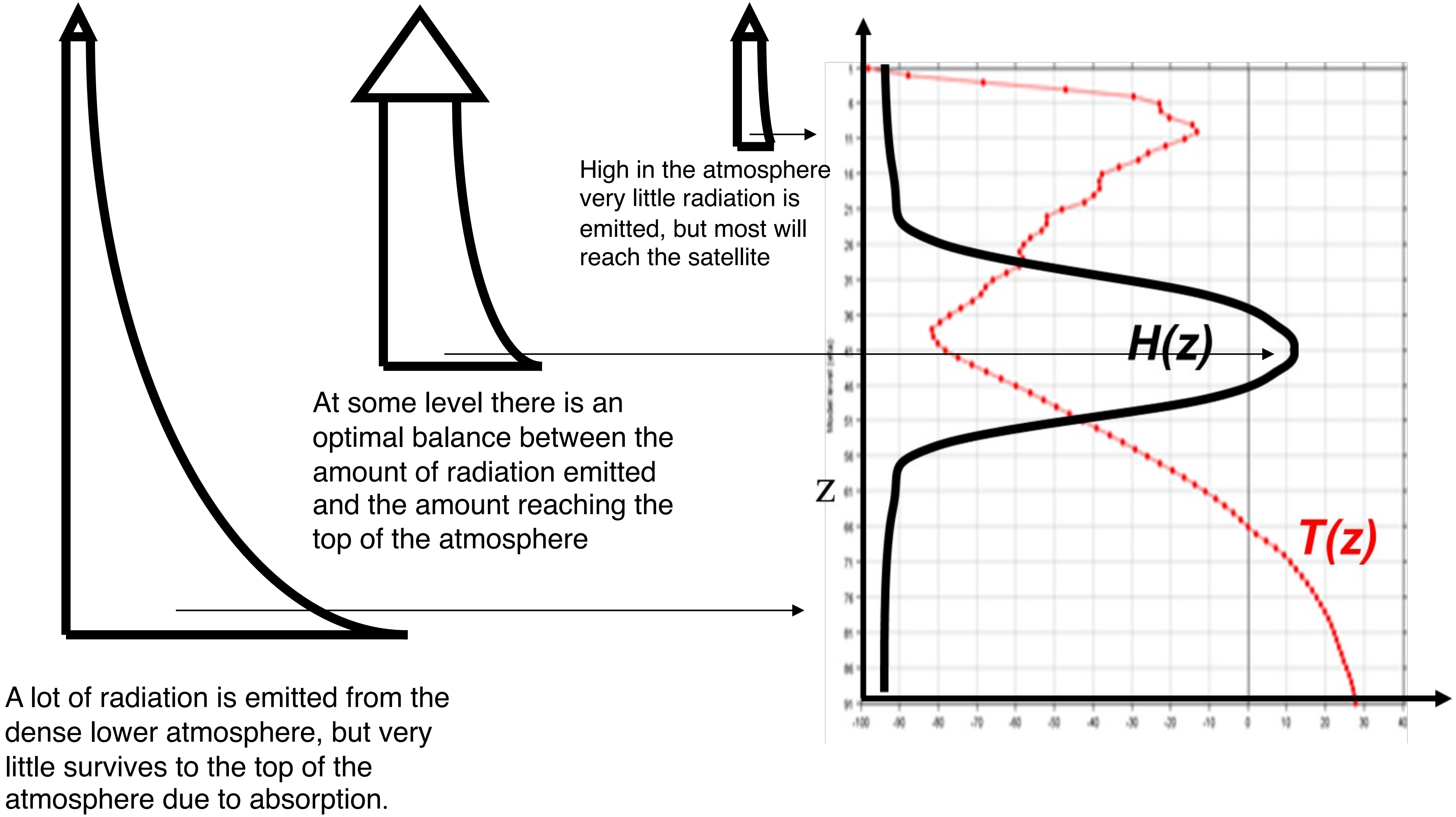
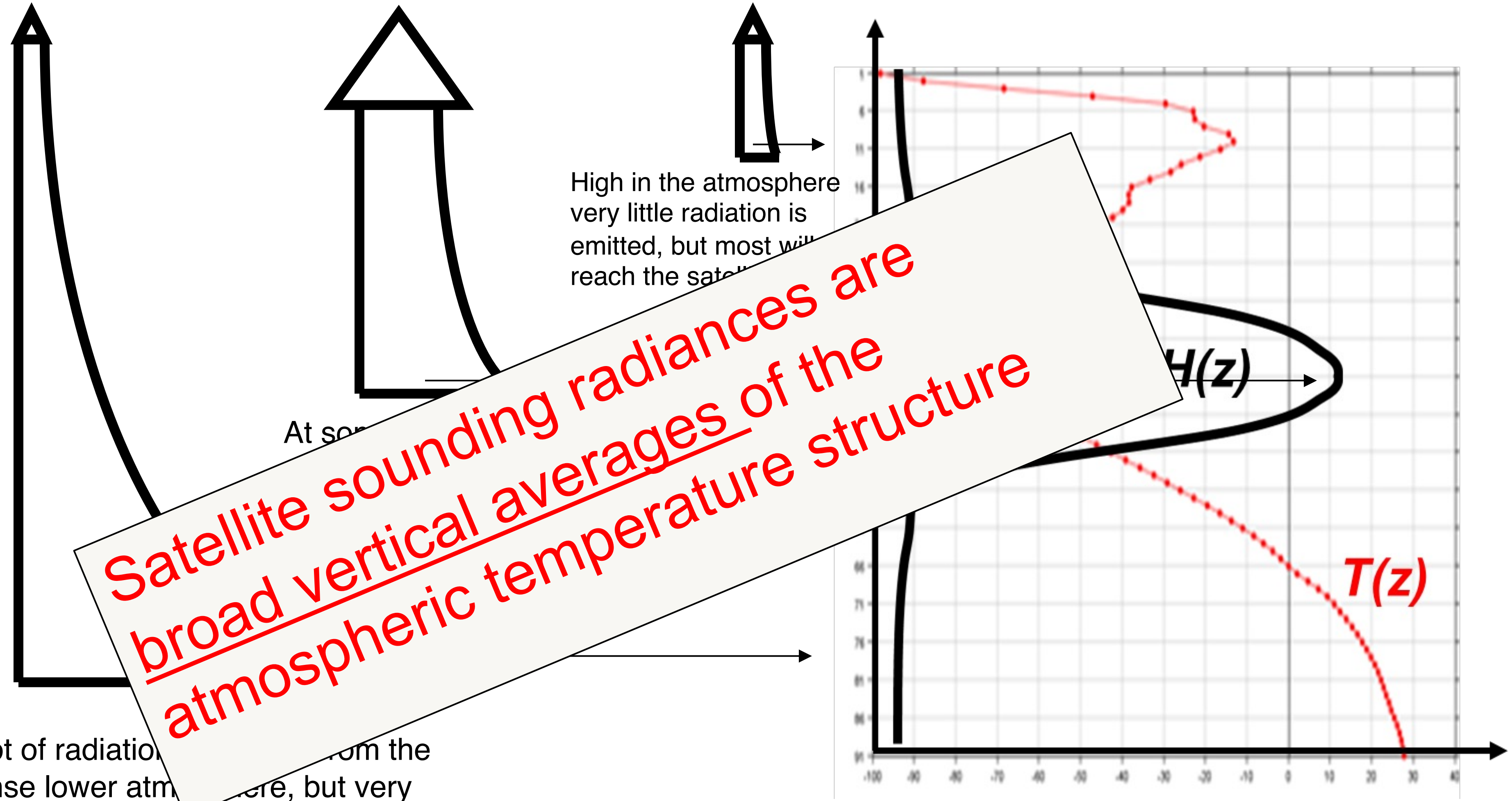


What do weighting functions look like ?



Satellite sounding radiances are broad vertical averages of the atmospheric temperature structure

A lot of radiatio ... om the dense lower atm ... ere, but very little survives to the top of the atmosphere due to absorption.

What do weighting functions look like ?

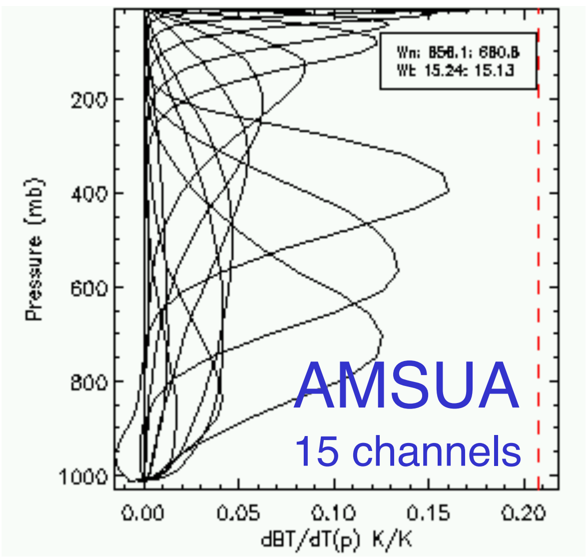
For any given channel the altitude at which the peak of the weighting function occurs depends on the strength of atmospheric absorption :

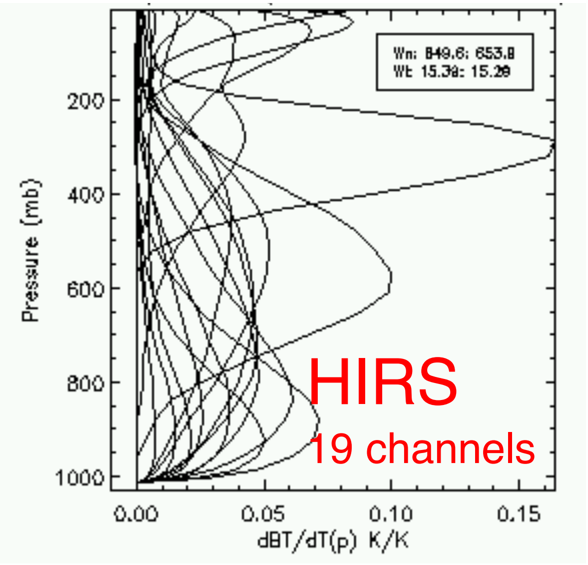
•Channels in parts of the spectrum where the absorption is strong (e.g. near the centre of CO2 or O2 lines) peak high in the atmosphere

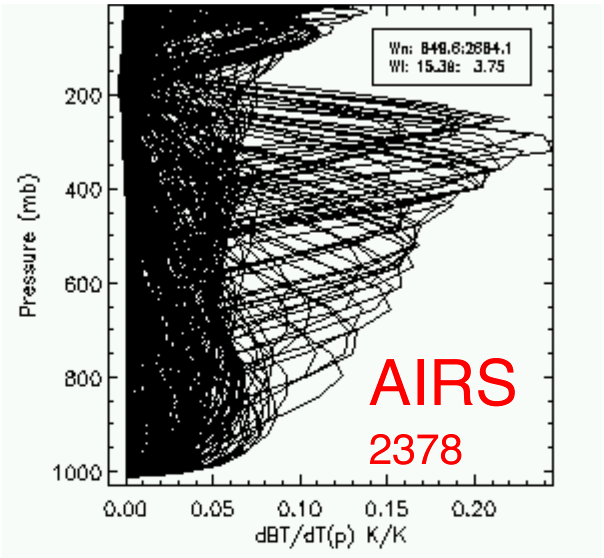
•Channels in parts of the spectrum where the absorption is weak (e.g. in the wings of CO_2 O_2 lines) peak low in the atmosphere

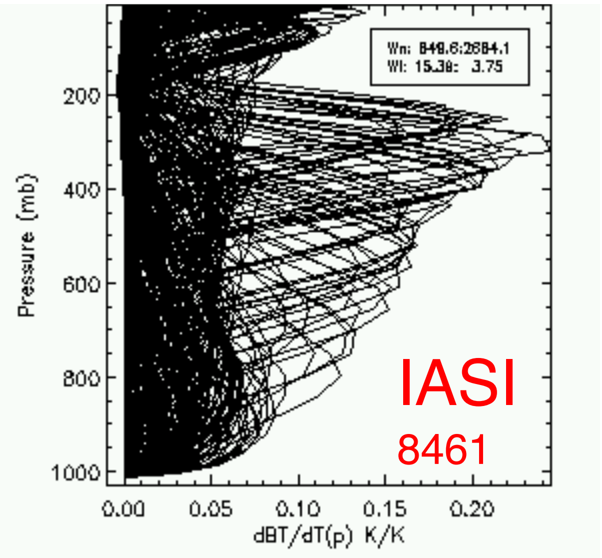
By building a satellite instrument that measures radiation in many different channels, all with varying absorption strengths we sample the atmospheric temperature profile at different altitudes (but of course not independently!)

What do real weighting functions look like ?



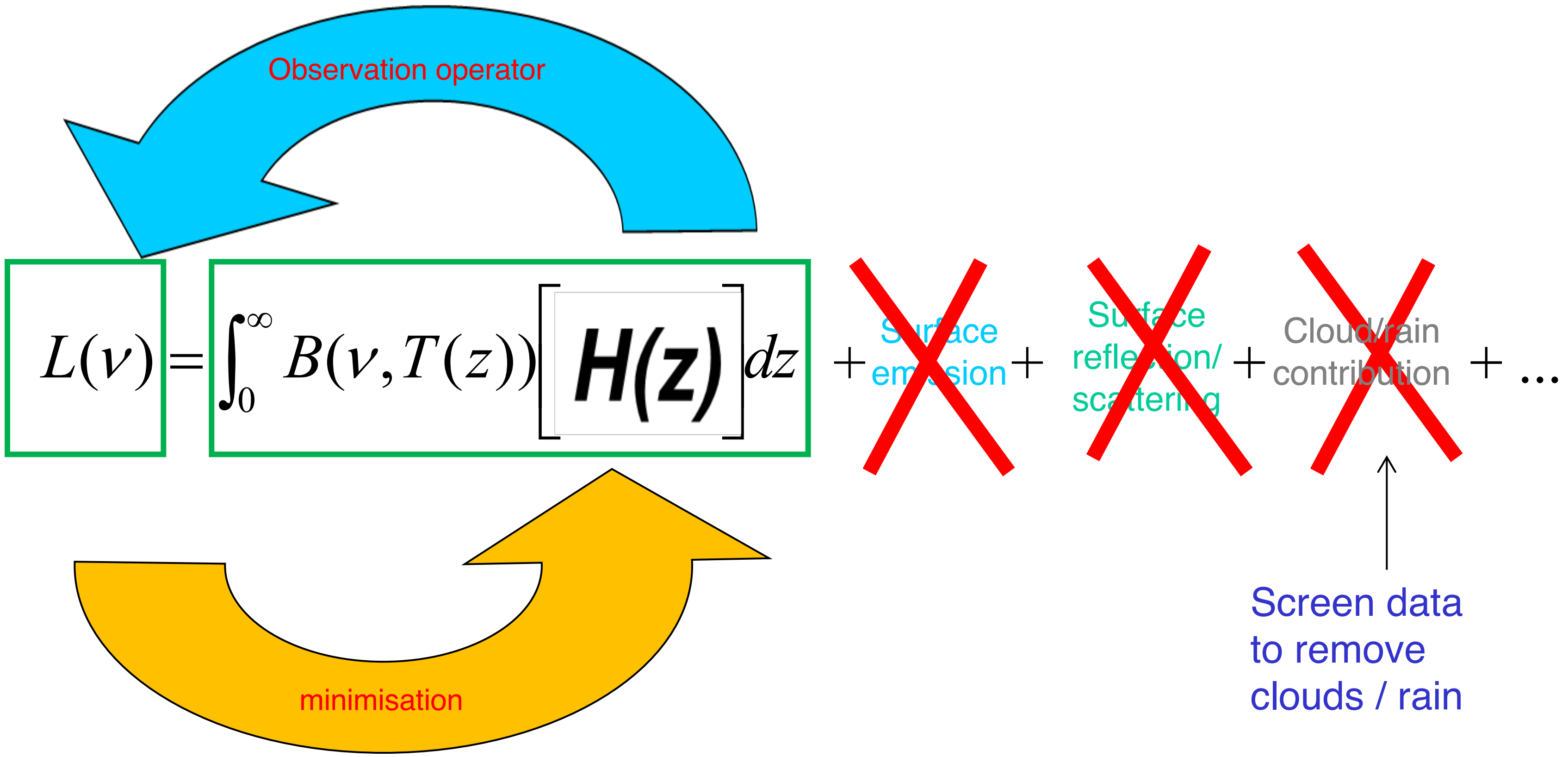




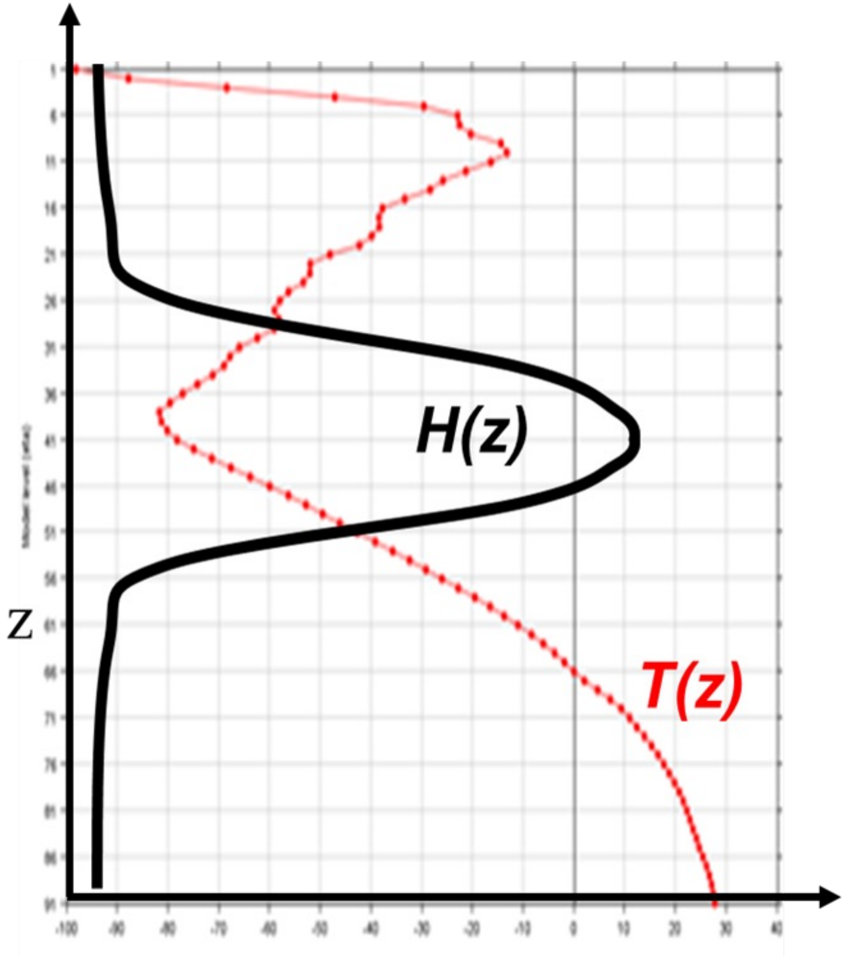


What are the implications of these broad weighting functions for Data Assimilation ?

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



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

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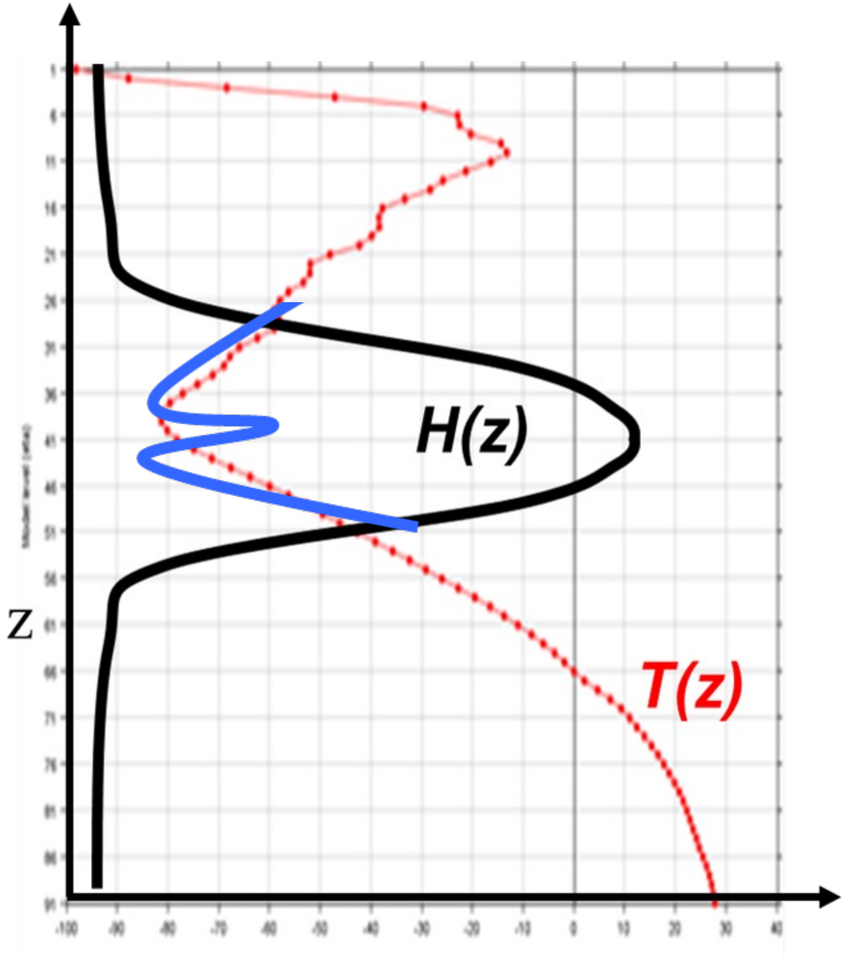

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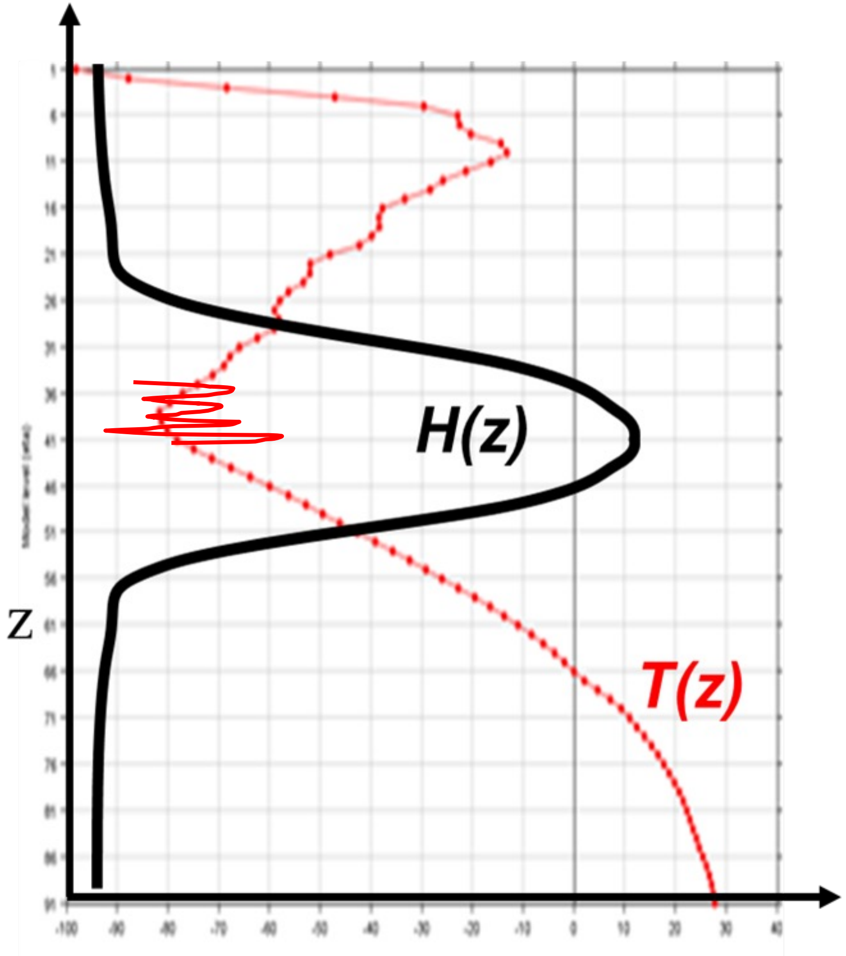


In principle for a single channel an infinite number of different temperature profiles could produce exactly the same measured radiance…

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

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 …

A QUICK REVIEW OF KEY CONCEPTS

•Satellite instruments measure radiance (not T,Q or wind)

• Downward looking satellite radiances are broad vertical averages of the temperature /humidity profile (defined by the weighting functions)

•The estimation of atmospheric temperature (or humidity) from the radiances is mathematically ill- posed and all L2 retrieval / DA algorithms rely heavily on background prior information

Questions ?

Planck's law

From Wikipedia, the free encyclopedia

(Redirected from Planck's law of black body radiation)

For a general introduction, see black body.

In physics, **Planck's law** describes the spectral radiance of electromagnetic radiation at all wavelengths from a black body at temperature T. As a function of frequency ν, Planck's law is written as:[1]

$$I(\nu,T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}}-1}.$$

This function peaks for $h\nu = 2.82kT$.[2]

As a function of wavelength λ it is written (for unit solid angle) as:[3]

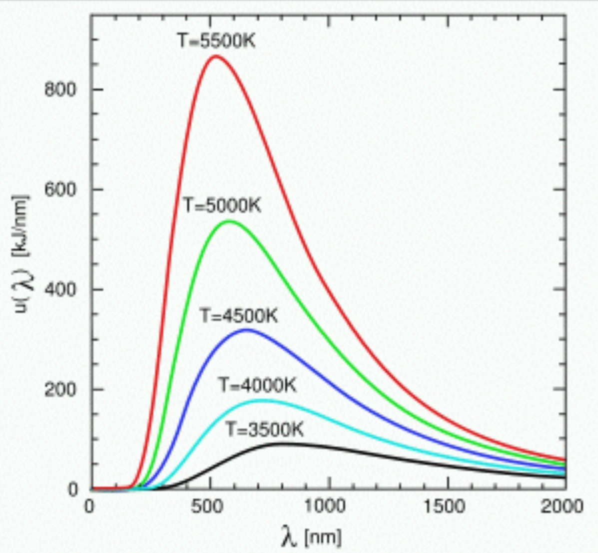
$$I(\lambda,T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda kT}}-1}.$$

Note also that the two functions have different units — the first is radiance per unit frequency interval while the second is radiance per unit wavelength interval. Hence, the quantities $I(\nu,T)$ and $I(\lambda,T)$ are not equivalent to each other. To derive one from the other, they cannot simply be set equal to each other (ie: the expression for λ in terms of ν cannot just be substituted into the first equation to get the second). However, the two equations are related through:

$$I(\nu,T)\,d\nu = -I(\lambda,T)\,d\lambda.$$

One can easily step from the first formula into the latter by using:

$$d\nu = d\left(\frac{c}{\lambda}\right) = c\,d\left(\frac{1}{\lambda}\right) = -\frac{c}{\lambda^2}\,d\lambda.$$



Black body spectrum

The key elements of a satellite data assimilation system

Key elements of a data assimilation system

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

Key elements of a data assimilation system

- **observation operator**
- background errors
- observation errors
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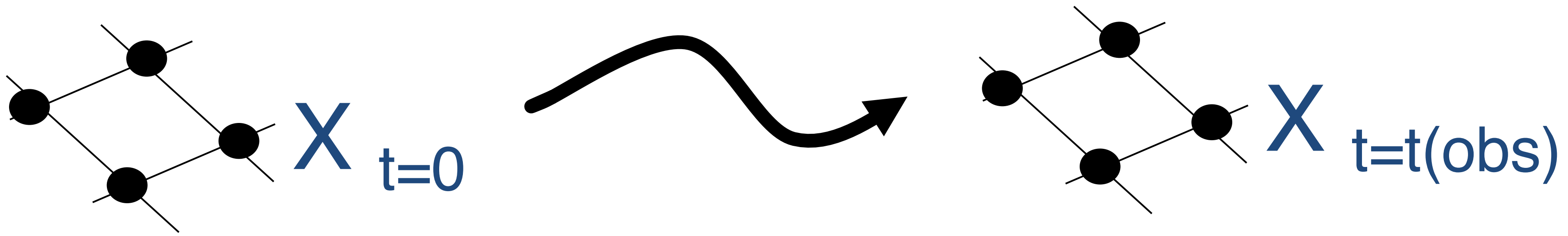
Observation operator

- 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)

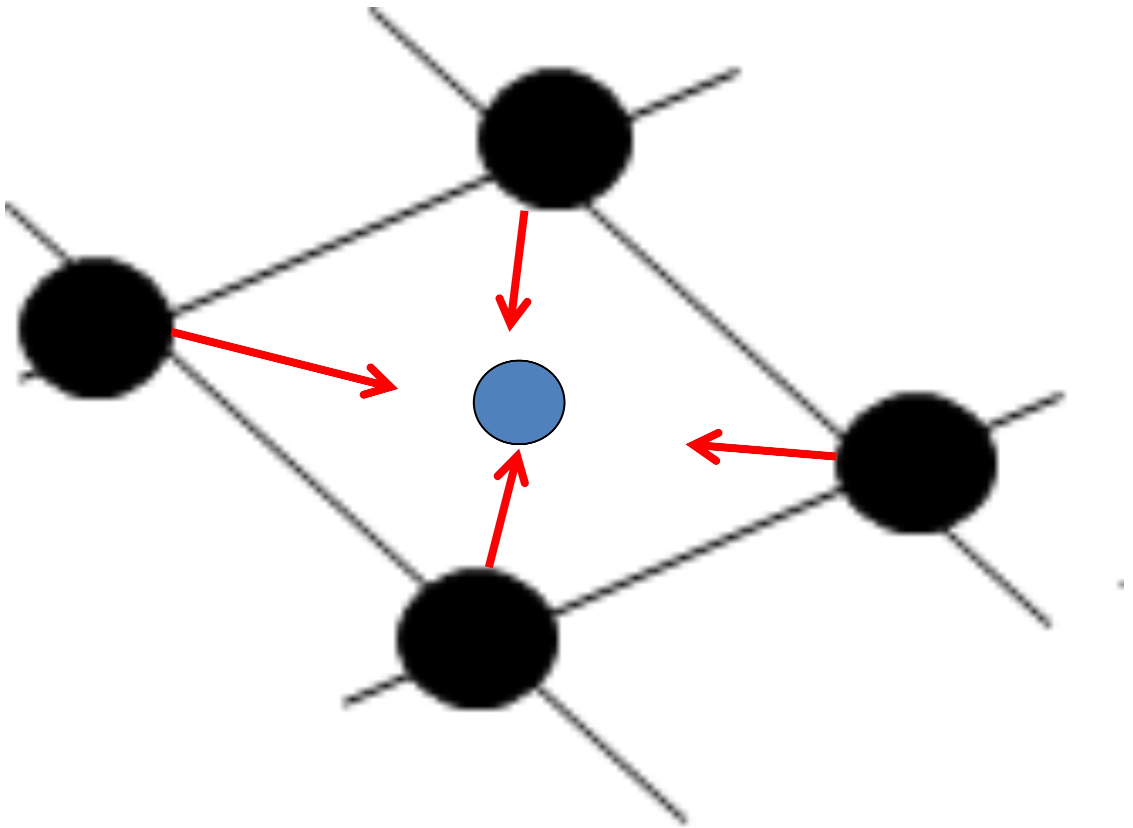
Observation operator

1) Time evolution of forecast model field to OBS time



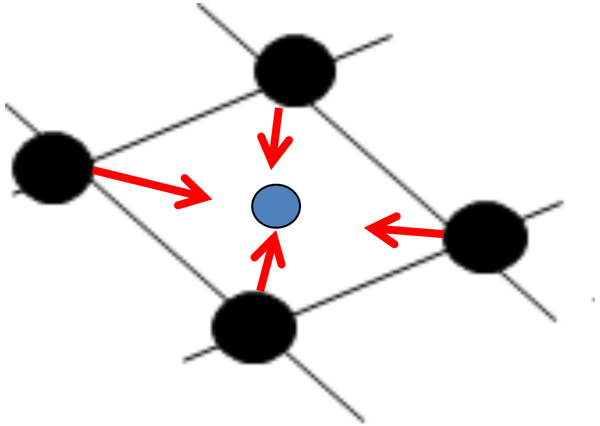
Observation operator

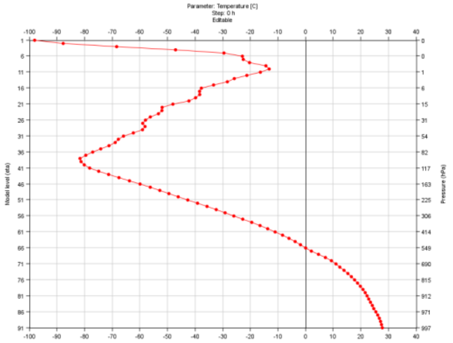
2) Spatial interpolation of model grid to OBS location



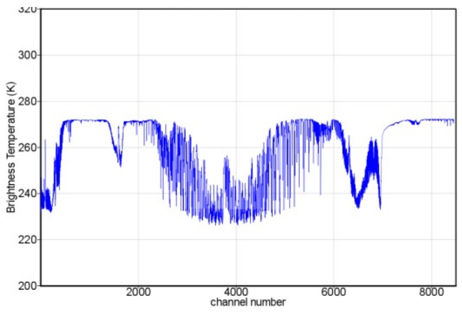
Observation operator

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





RTTOV



Key elements of a data assimilation system

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

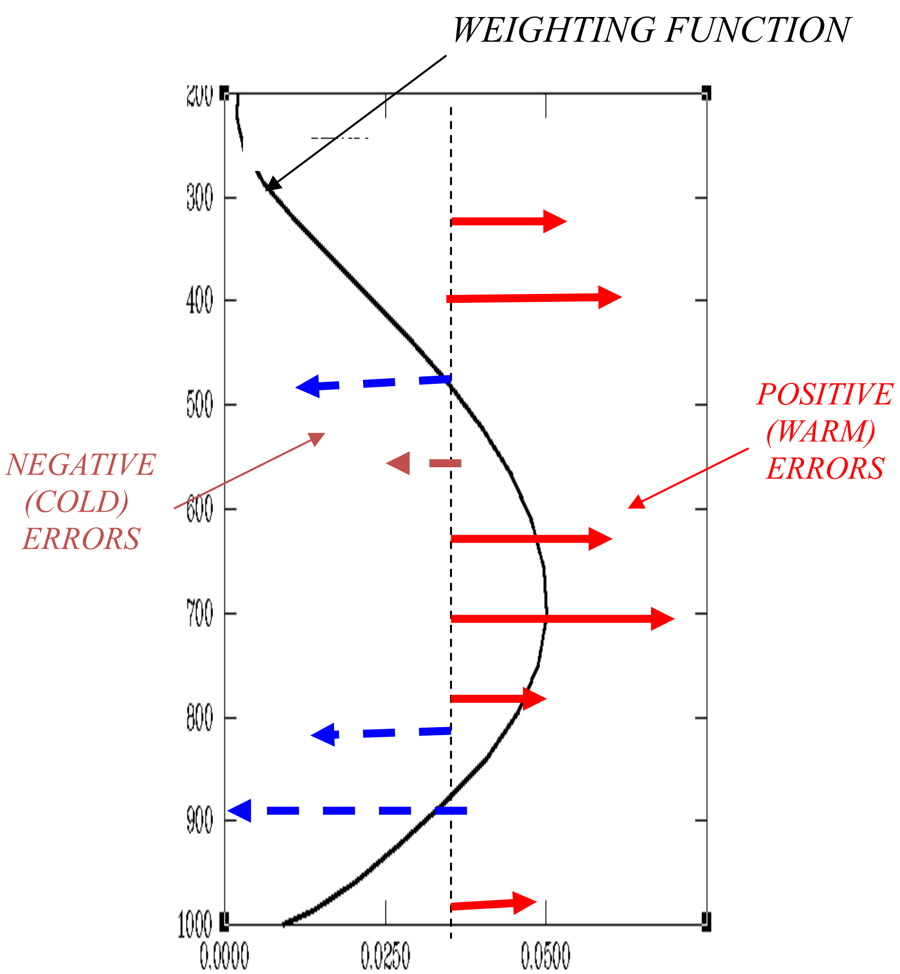
Background errors (and vertical resolution)

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

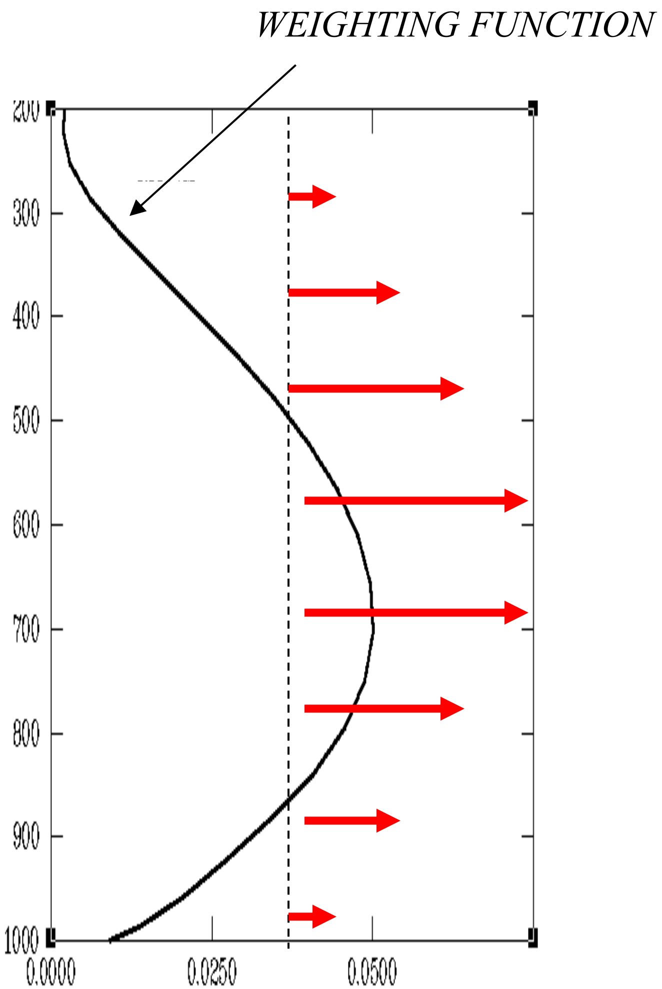
- A very important aspect for the assimilation of near-nadir viewing satellite radiances are the **vertical correlations** that describe how background errors are distributed in the vertical (sometimes called structure functions)

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

Background errors (and vertical resolution)



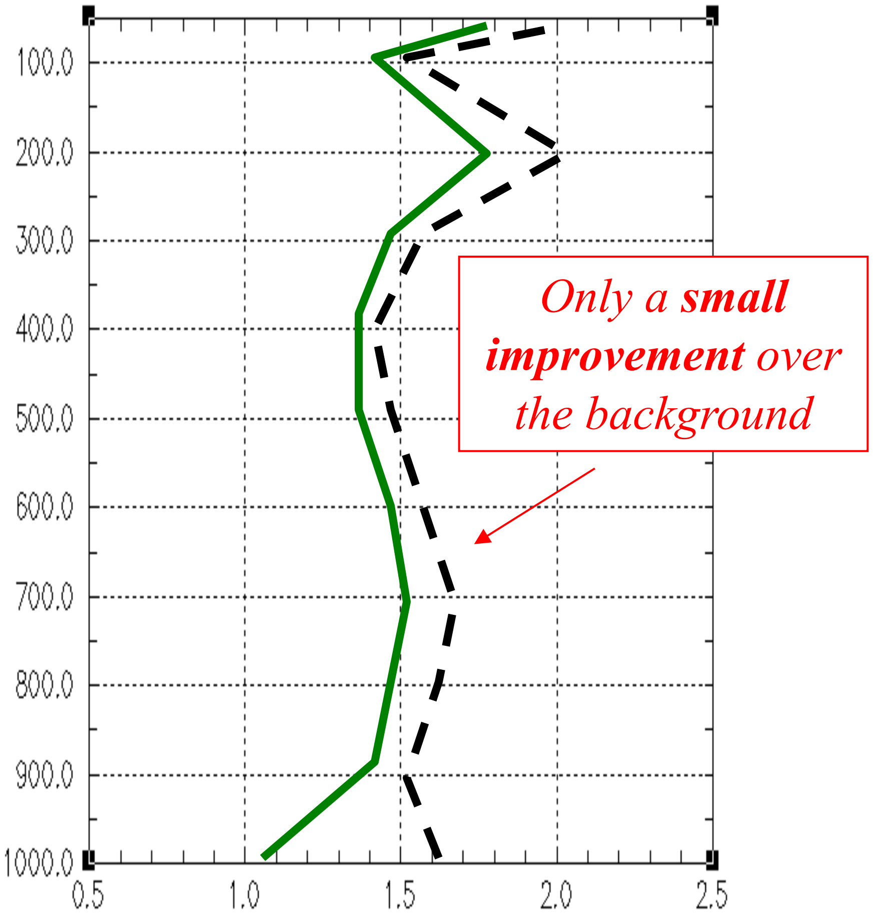
"*Difficult*" to correct



"*Easy*" to correct

Background errors (and vertical resolution)

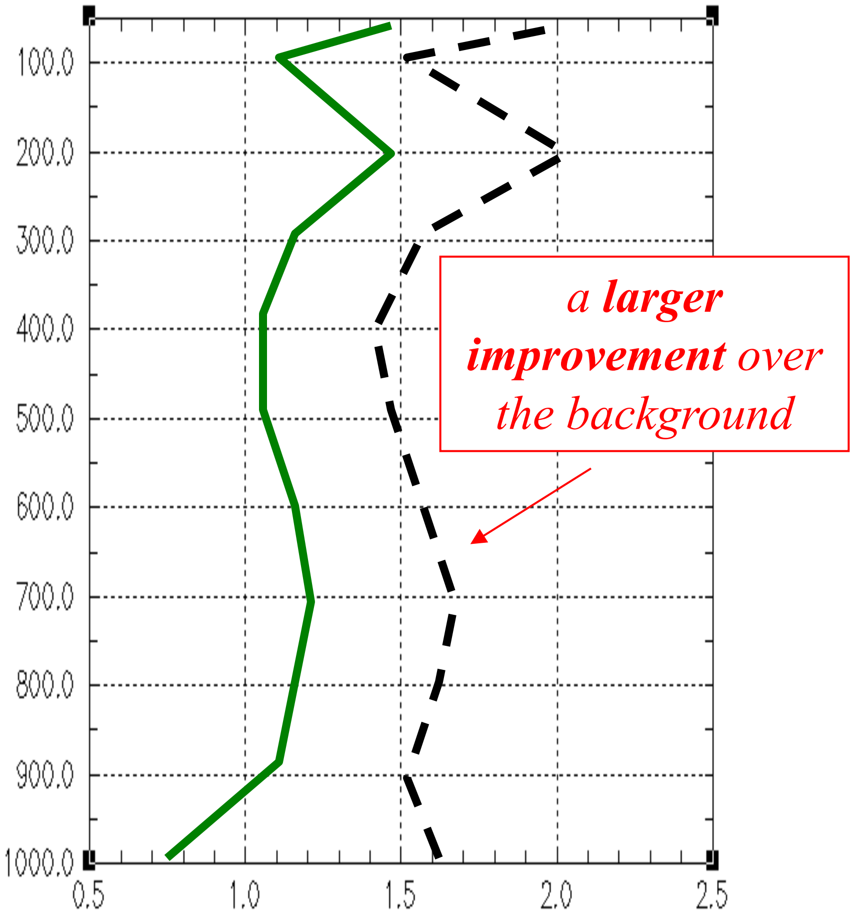
Sharp / anti-correlated background errors



Error standard deviation (K)

S_a

Broad / deep correlated background error

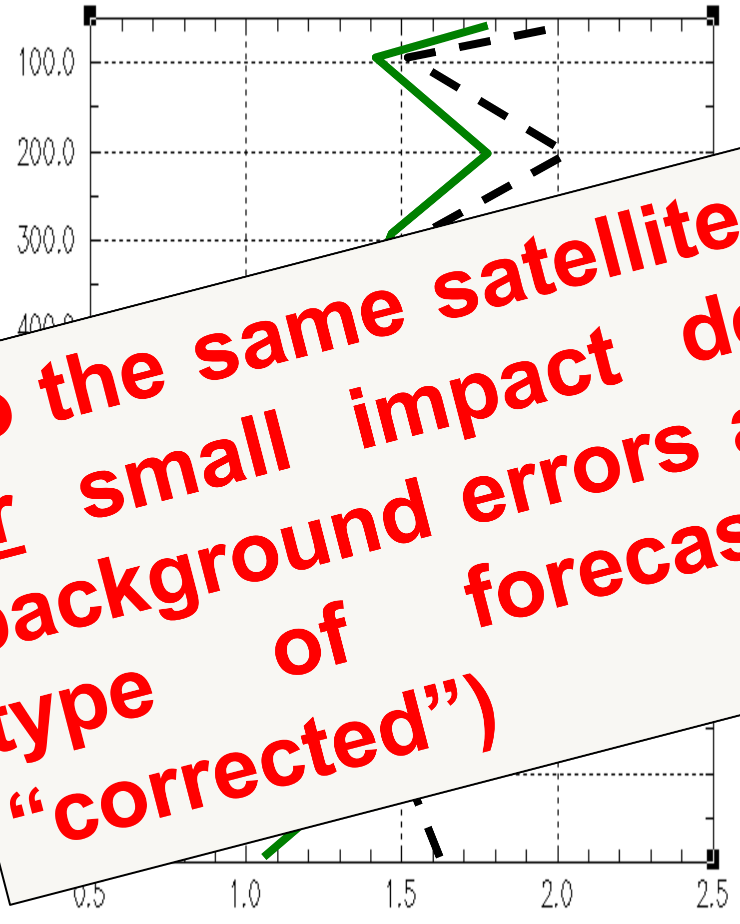


Error standard deviation (K)

S_a

Background errors (and vertical resolution)

Sharp / anti-correlated background errors



Error standard deviation (K)

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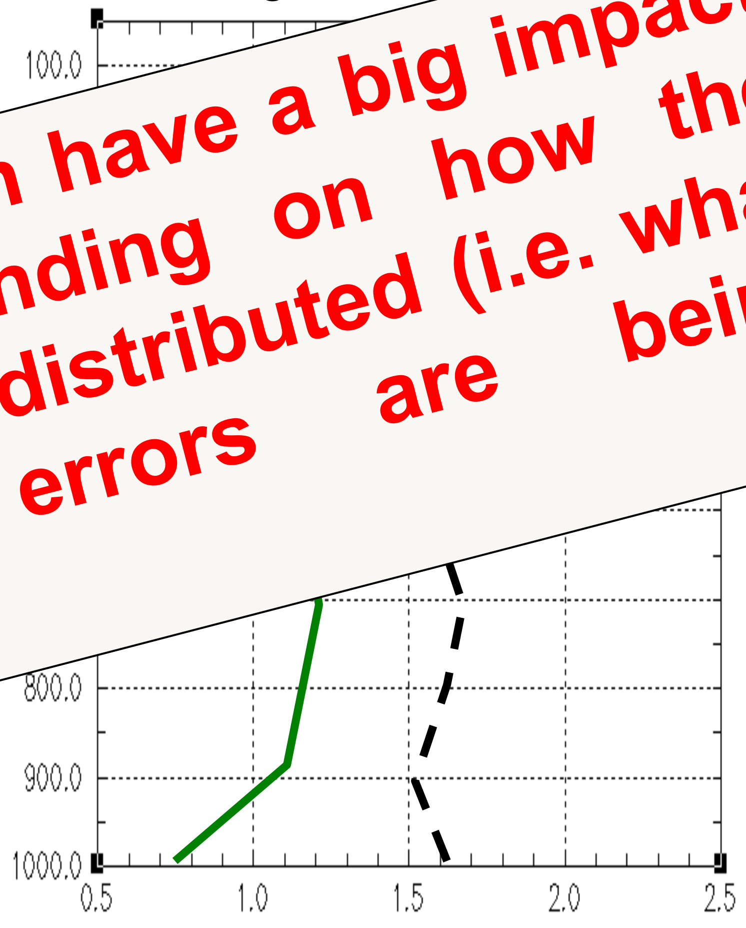
Broad / deep correlated background errors



Error standard deviation (K)

S_a

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:

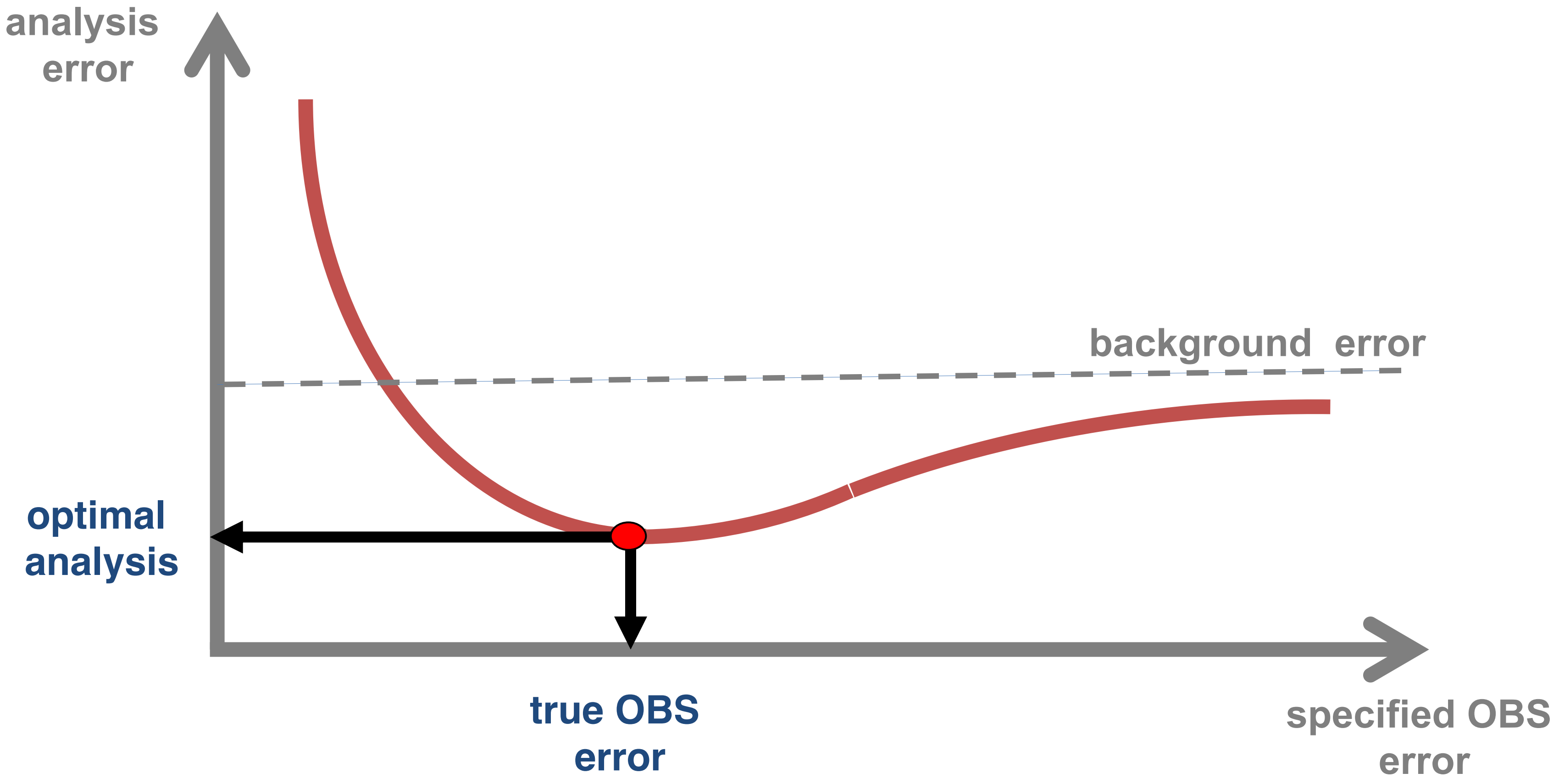
- These determine the weight we give to the radiance observations. The observation error must account for **instrument noise**, random uncertainties in the **observation operator** (e.g. RT model), errors in data **screening** (e.g. residual clouds) and errors of representativeness (e.g. scale mismatch).

- 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**!

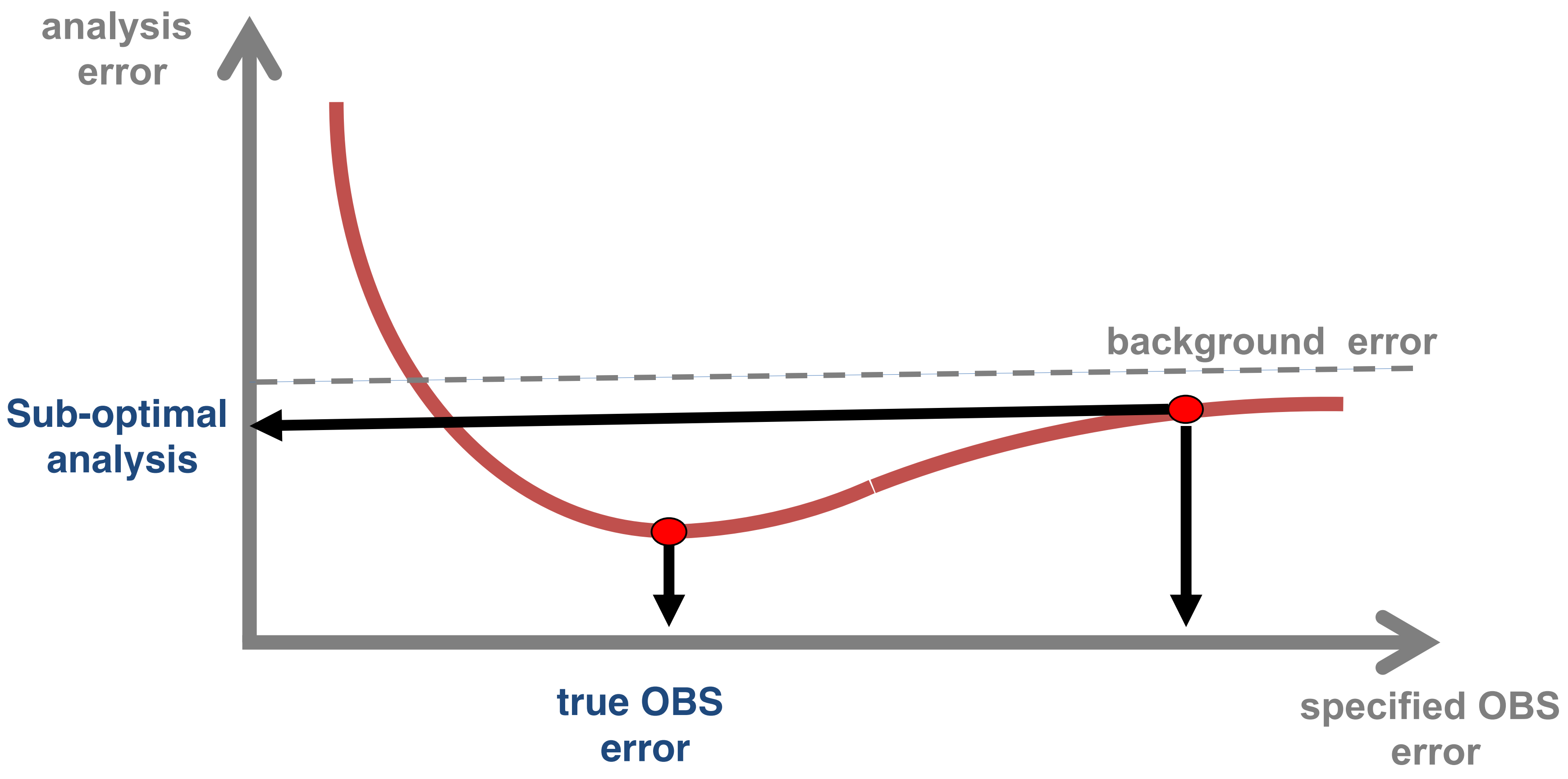
Observation errors:

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



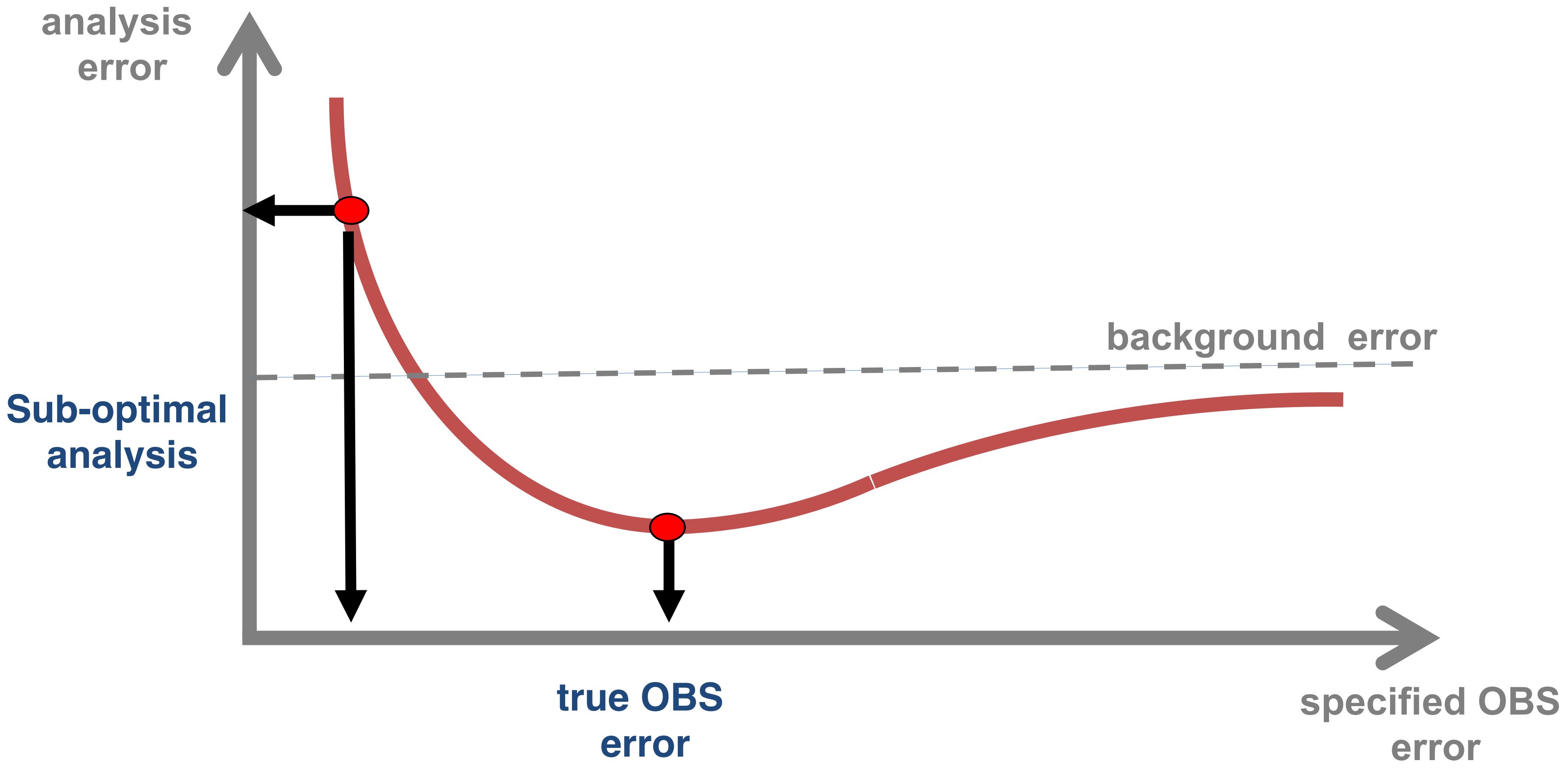
Observation errors:

- 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:

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

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):

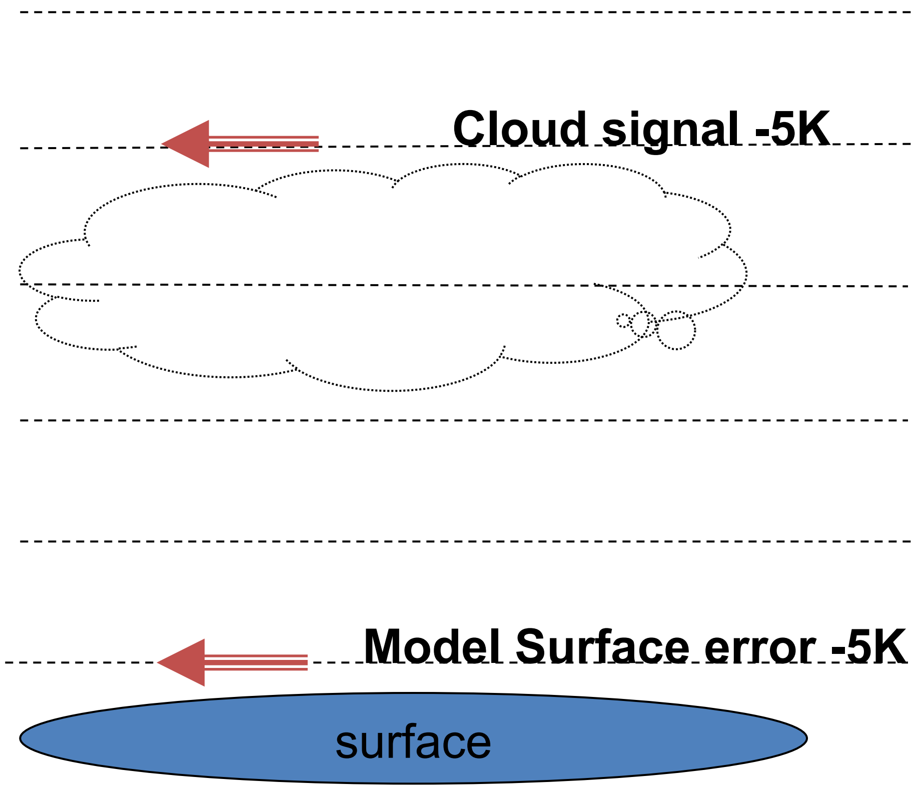
The primary purpose of this is to ensure that the observations entering the analysis are **consistent with the assumptions** in the observations error covariance (**R**) and the observation operator (**H**).

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:

- 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)