The Assimilation of Satellite Data for Numerical Weather Prediction

lecture 1

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1. INTRODUCTION

…is satellite data important for NWP ?
…what does a satellite instrument measure
…different types of satellite instrument

2. ATMOSPHERIC TEMPERATURE SOUNDING

…weighting functions
…definition of the forward and inverse problem

3. RETRIEVAL (inverse) ALGORITHMS

…solutions to reduced (simplified) problems
…statistical regression methods
…forecast background (1DVAR) methods

4. DIRECT RADIANCE ASSIMILATION

…the use of pre-processed (corrected) radiance observations
…the use of raw radiance observations

5. SUMMARY

First…

some key terms

Key elements of the NWP system

- The **forecast model** time evolves fields of geophysical parameters (e.g. $T/Q/U/V/Ps/O_3$) following the laws of thermodynamics and chemistry

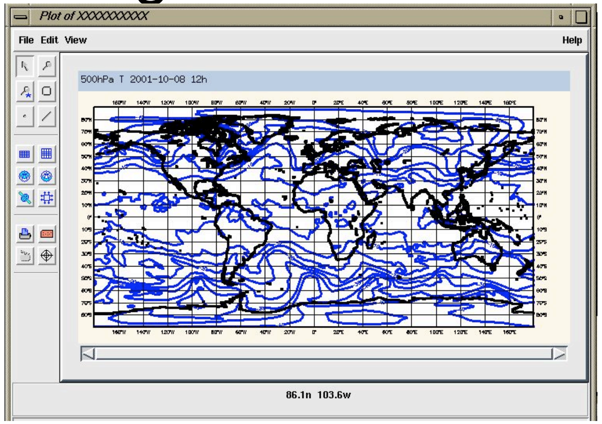
- The initial conditions used to start the **forecast model** are provided by the **analysis**

- The **analysis** is generated from **observations** relating to the geophysical parameters combined with *a priori* **background information** (usually a short-range forecast from the previous analysis).

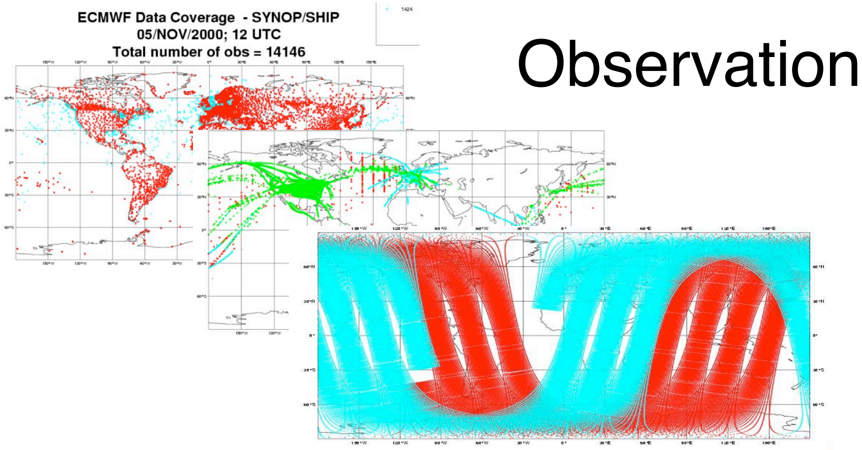
- This combination process is known as **data assimilation**

The data assimilation process

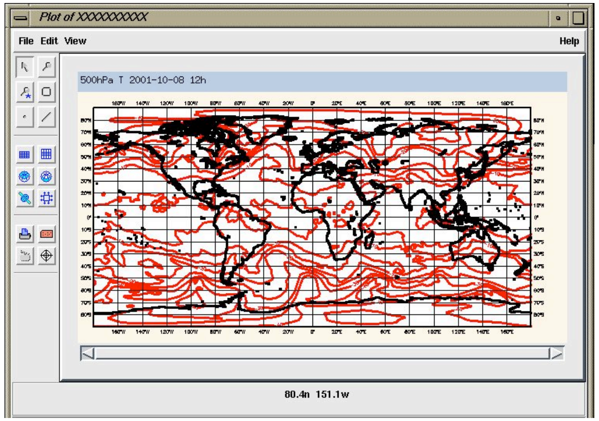
Background information



Observations

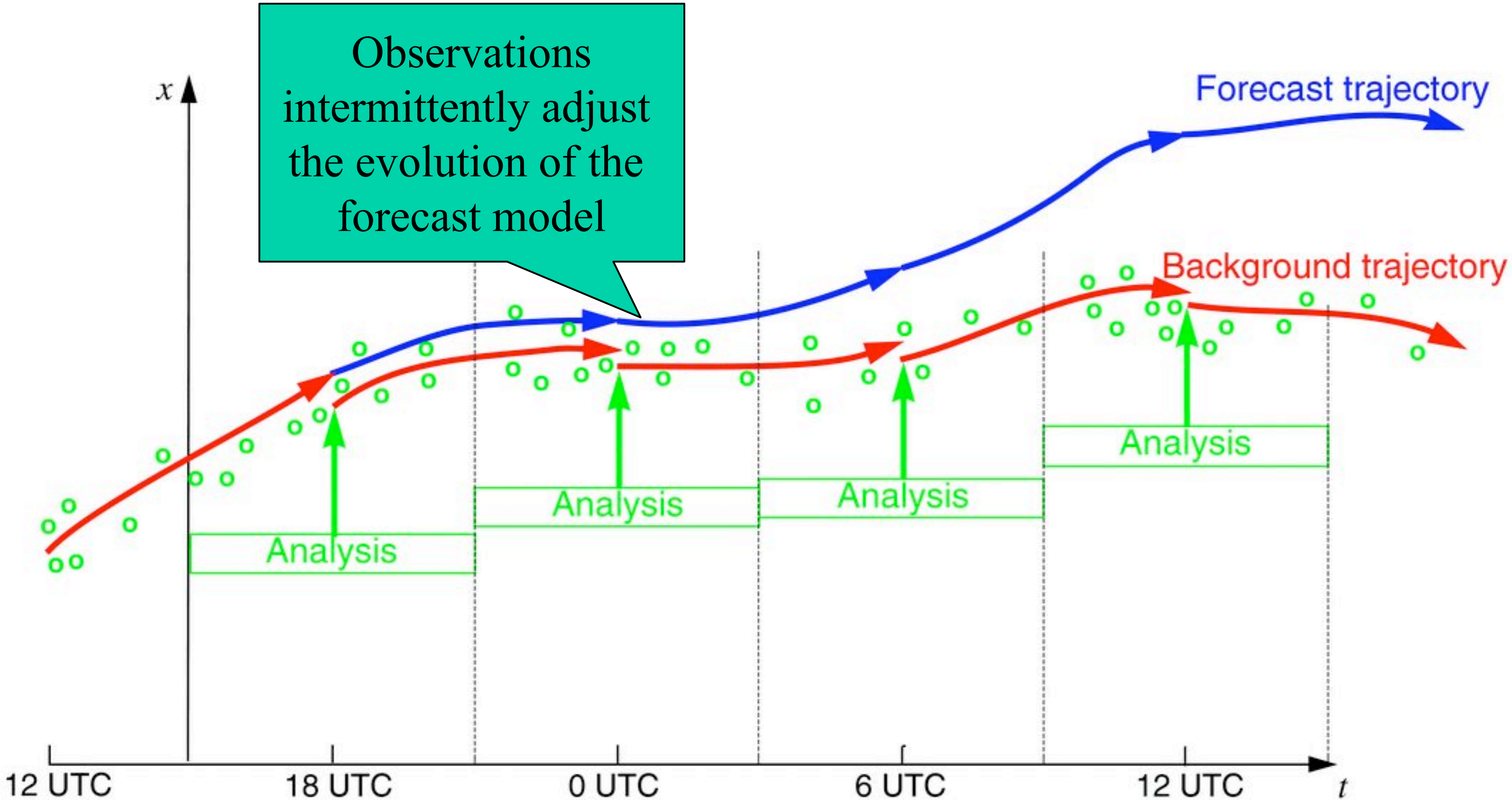

ECMWF Data Coverage - SYNOP/SHIP
05/NOV/2000; 12 UTC
Total number of obs = 14146

Analysis



Initial conditions
for next forecast

The 4DVAR Data Assimilation Process



Observations intermittently adjust the evolution of the forecast model

Some of the main Satellite instruments currently used at ECMWF

On NOAA / NASA / EUMETSAT polar orbiting spacecraft

High resolution IR Sounder (HIRS), Advanced Microwave Sounding Unit (AMSU), Atmospheric IR Sounder (AIRS), Infrared Atmospheric Sounding Interferometer (IASI), Advanced Microwave Scanning Radiometer (AMSR), TRMM (TMI)

On DMSP polar orbiting spacecraft

Special Sensor Microwave Imager (SSMI,SSMI/S)

Geostationary spacecraft

METEOSAT , GOES , GMS / MTSAT

Scatterometer spacecraft

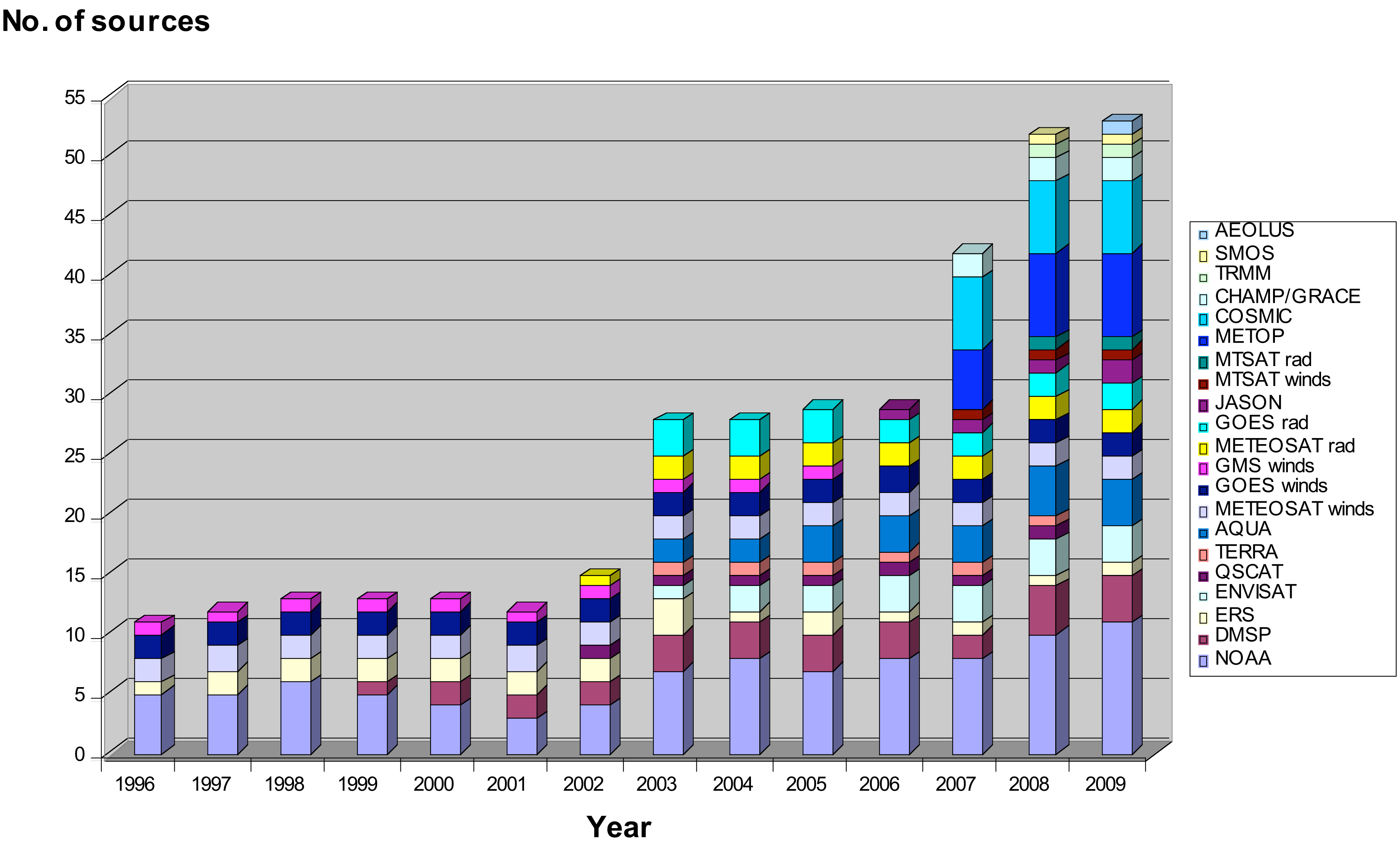
ERS / Quickscat / ASCAT

GPS spacecraft

METOP-GRAS / COSMIC

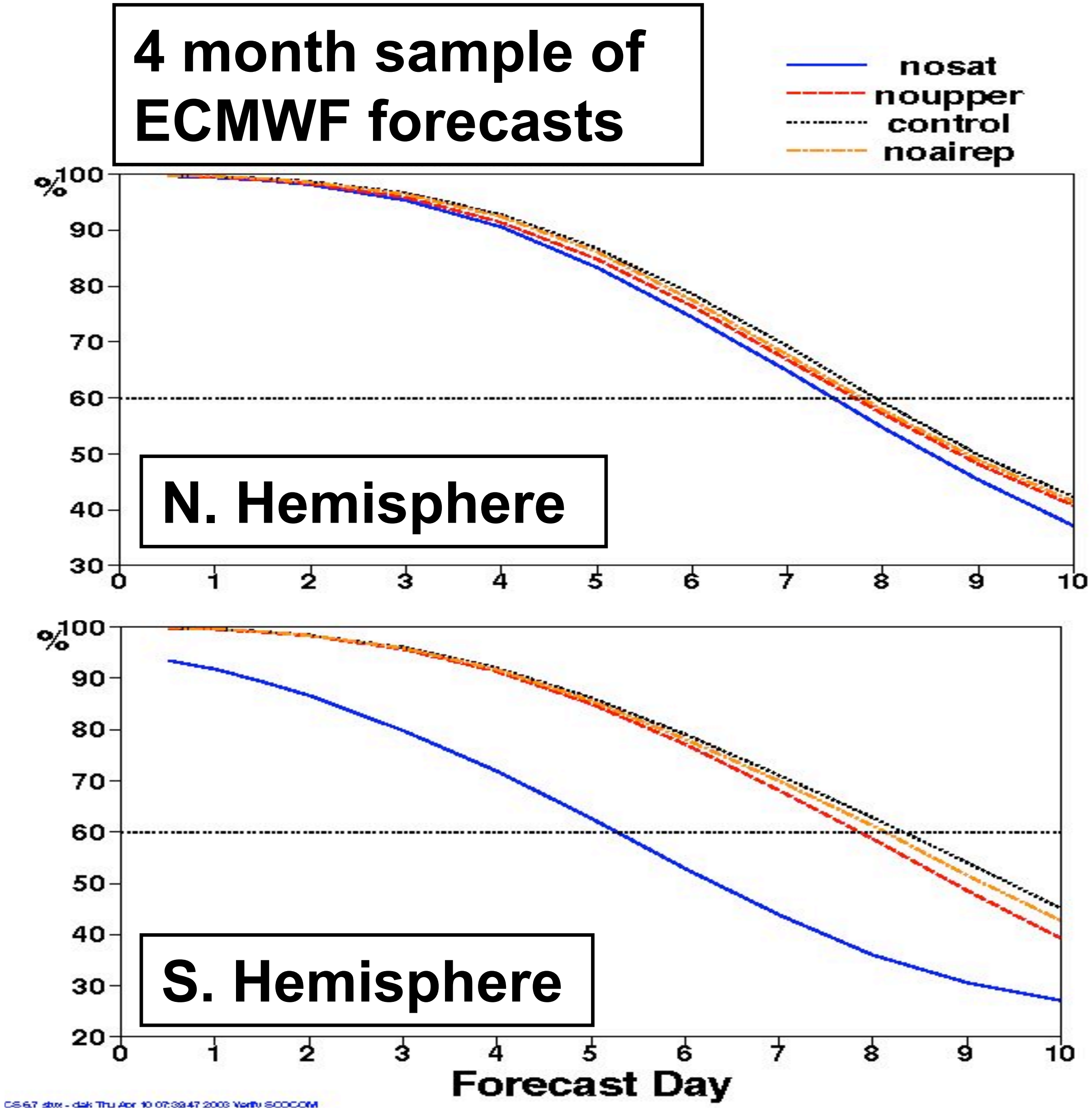
Covered in other lectures

The satellite observing system



IS SATELLITE DATA IMPORTANT FOR NWP ?

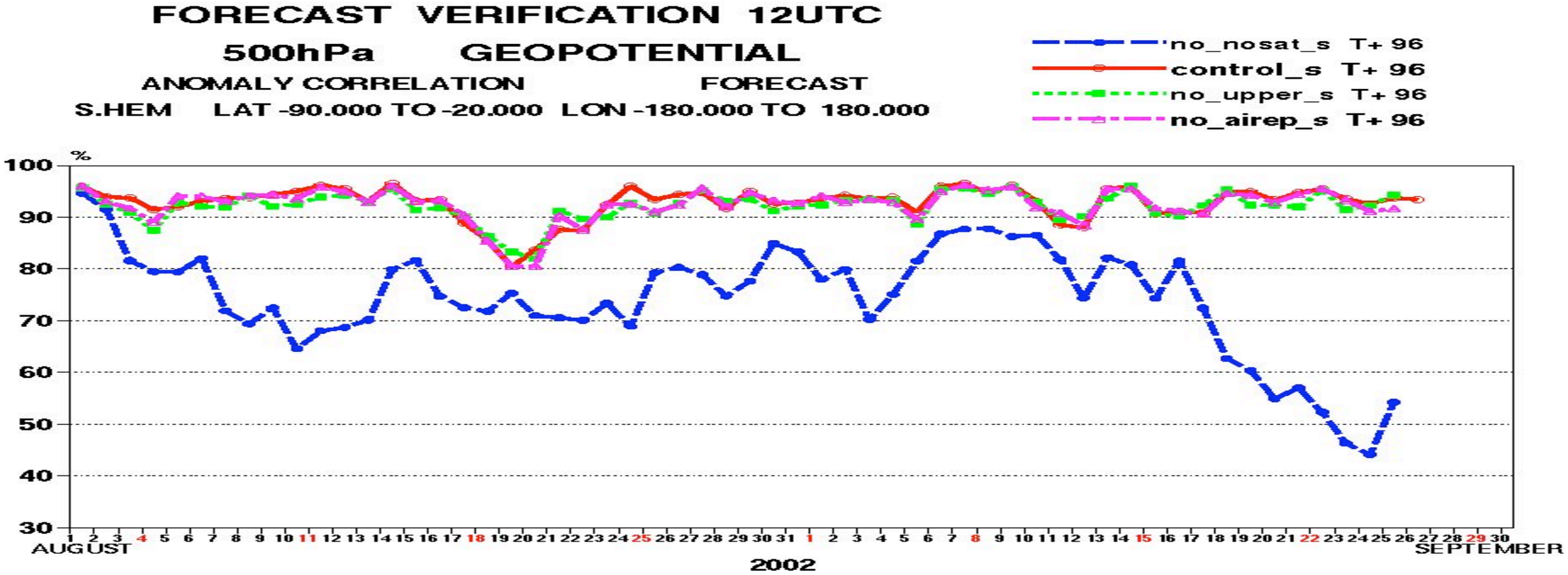
Observing system experiments (OSEs) aimed at measuring the impact of different types of observation routinely confirm that **satellite data is now the single most important component** of the global observing network for NWP.



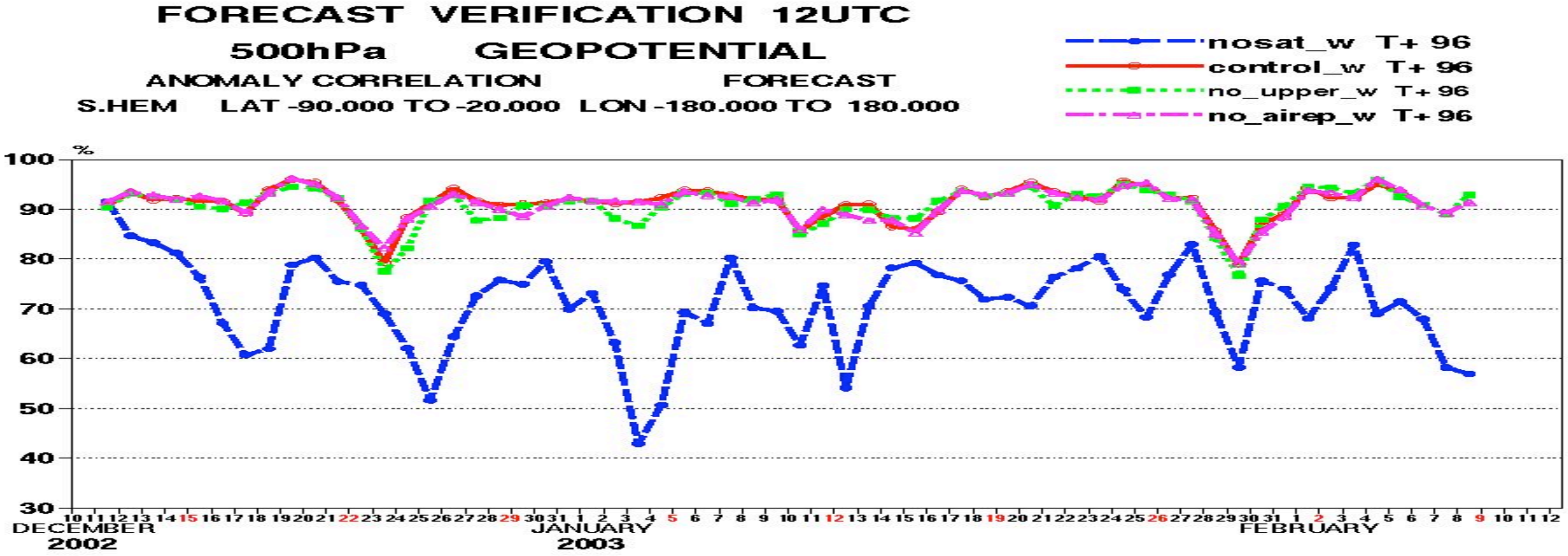
4 month sample of ECMWF forecasts

N. Hemisphere

S. Hemisphere



Satellite data provide robustness to the global numerical forecasts



What do satellite instruments measure

?

What do satellite instruments measure?

They **DO NOT** measure TEMPERATURE
They **DO NOT** measure HUMIDITY or OZONE
They **DO NOT** measure WIND

Satellite instruments simply measure the radiance L that reaches the top of the atmosphere at given frequency ν. The measured radiance is related to geophysical atmospheric variables (T,Q,O_3, clouds etc…) by the radiative transfer equation

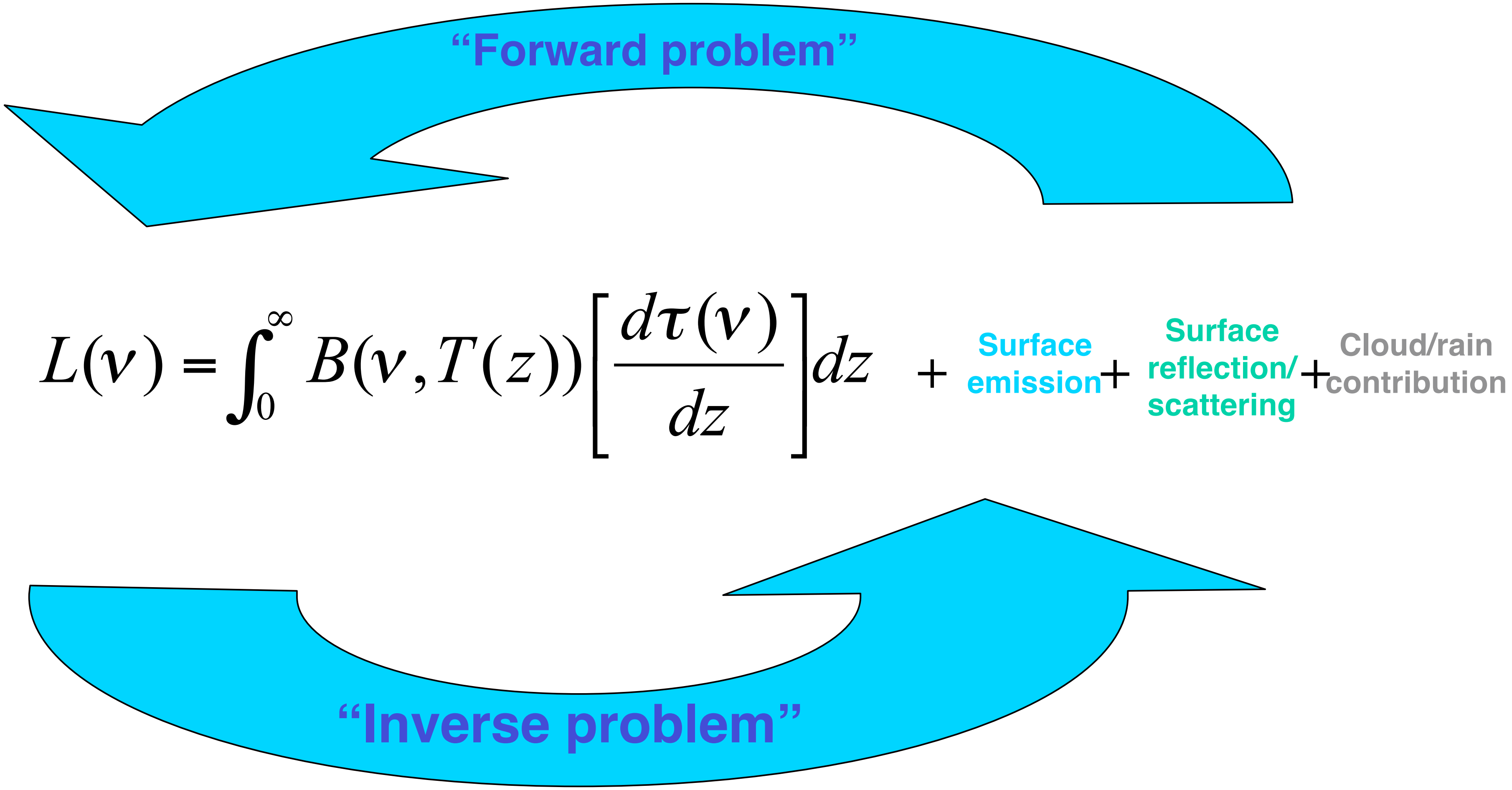
$$\overbrace{L(\nu)}^{\text{measured by the satellite}} = \overbrace{\int_0^\infty B(\nu,T(z))\left[\frac{d\tau(\nu)}{dz}\right]dz + \text{Surface emission} + \text{Surface reflection/scattering} + \text{Cloud/rain contribution} + \dots}^{\text{Our description of the atmosphere}}$$

Planck source term* depending on temperature of the atmosphere

Absorption in the atmosphere

Other contributions to the measured radiances

The Radiative Transfer (RT) equation



“Forward problem”

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

“Inverse problem”

(Details of the RT equation are covered more in other lectures…Bell + Matricardi).

Measuring radiance in different frequencies (channels)

By **selecting** radiation at different frequencies or **CHANNELS** a satellite instrument can provide information on specific geophysical variables.

In general, the frequencies / channels used within NWP
may be categorized as one of 3 different types …

1. **atmospheric sounding** channels (**passive** instruments)
2. **surface sensing** channels (**passive** instruments)
3. **surface sensing** channels (**active** instruments)

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

1. ATMOSPHERIC SOUNDING CHANNELS

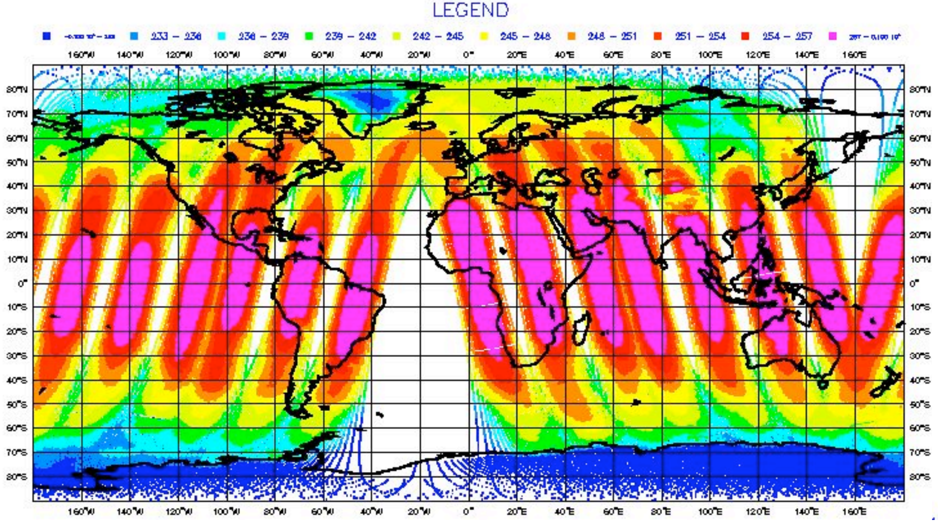
These channels are located in parts of the infra-red and microwave spectrum for which the main contribution to the measured radiance is from the **atmosphere** and can be written:

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

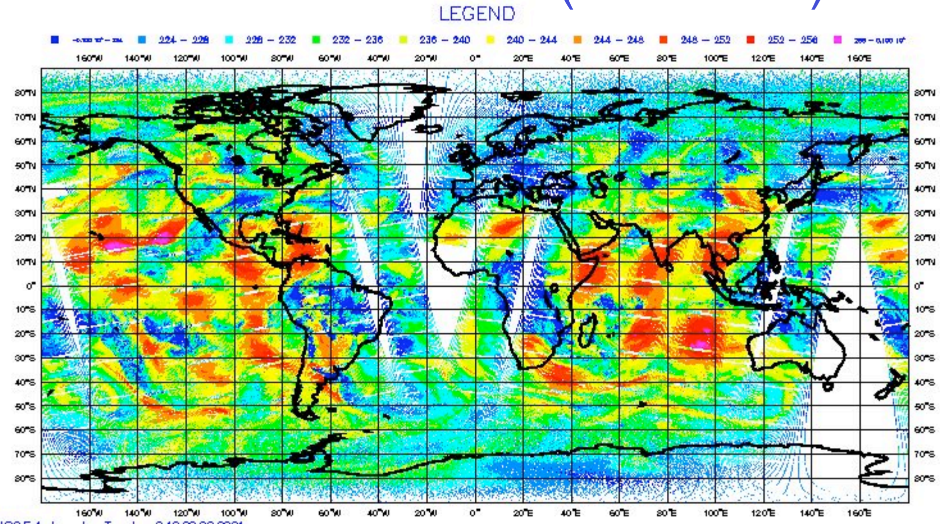
Where B=Planck function
t = transmittance
T(z) is the temperature
z is a height coordinate

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)



2. SURFACE SENSING CHANNELS (PASSIVE)

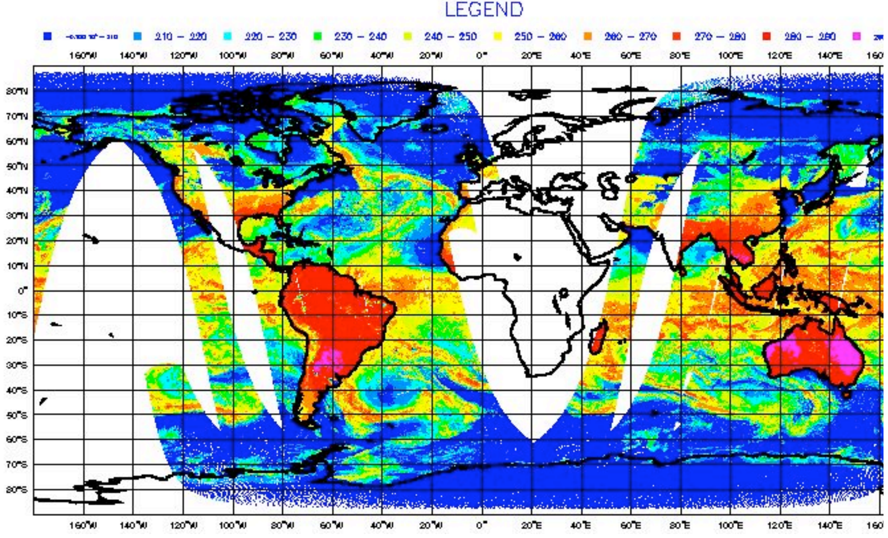
These are located in **window regions** of the infra-red and microwave spectrum at frequencies where there is very little interaction with the atmosphere and the primary contribution to the measured radiance is:

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

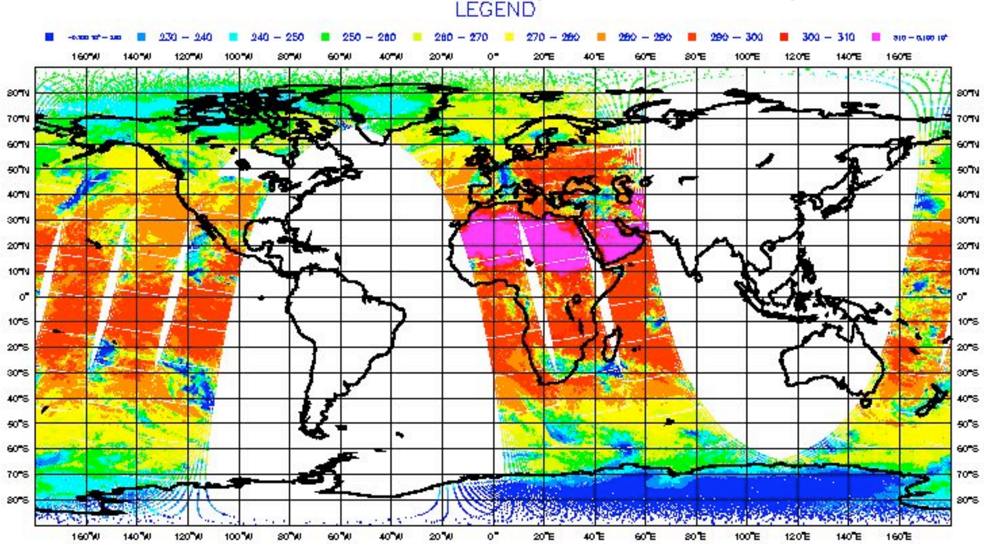
Where T_{surf} is the surface skin temperature and E the surface emissivity

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)

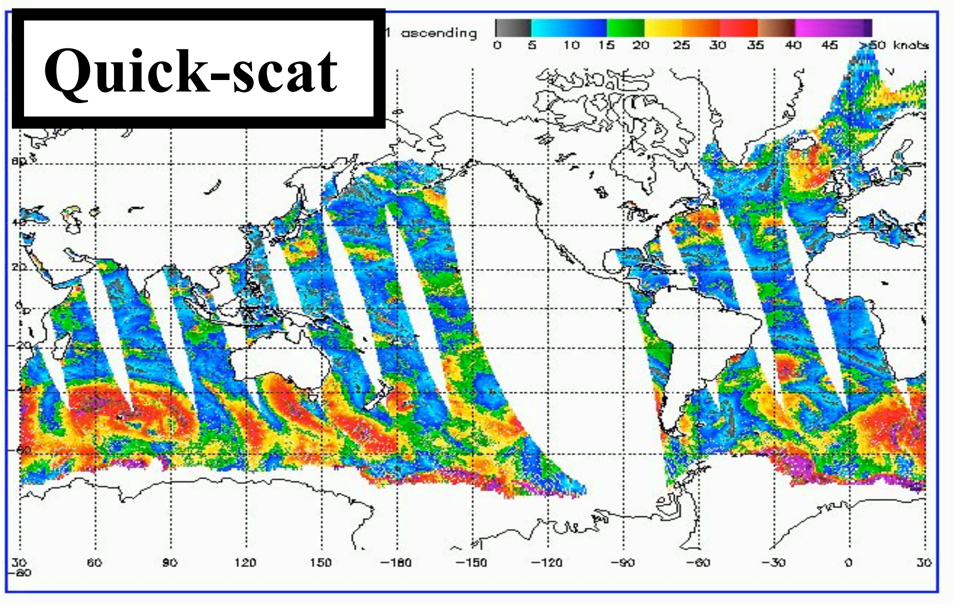


3. SURFACE SENSING CHANNELS (ACTIVE)

These (e.g. scatterometers) **actively illuminate the surface** in window parts of the spectrum such that

$$L(\nu) = \text{surface scattering } [\ \varepsilon(u,v)\ ]$$

These primarily provide information on **ocean winds** (via the relationship with sea-surface emissivity) **without** the strong surface temperature ambiguity .



ATMOSPHERIC TEMPERATURE SOUNDING

If radiation is selected in a sounding channel for which

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

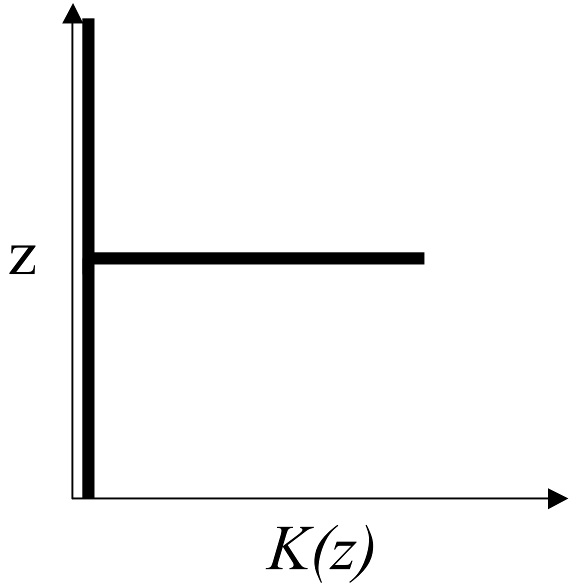
and we define a function $K(z) = \left[\frac{d\tau}{dz}\right]$

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

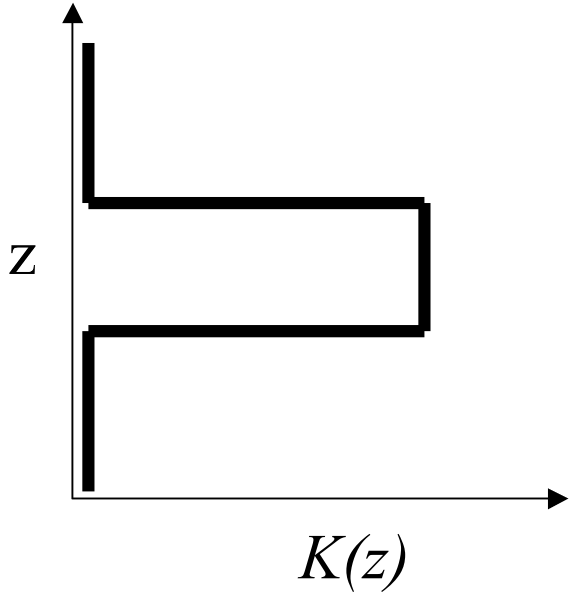
$$\boxed{L(\nu) = \int_0^\infty B(\nu, T(z)) K(z) dz}$$

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

IDEAL WEIGHTING FUNCTIONS

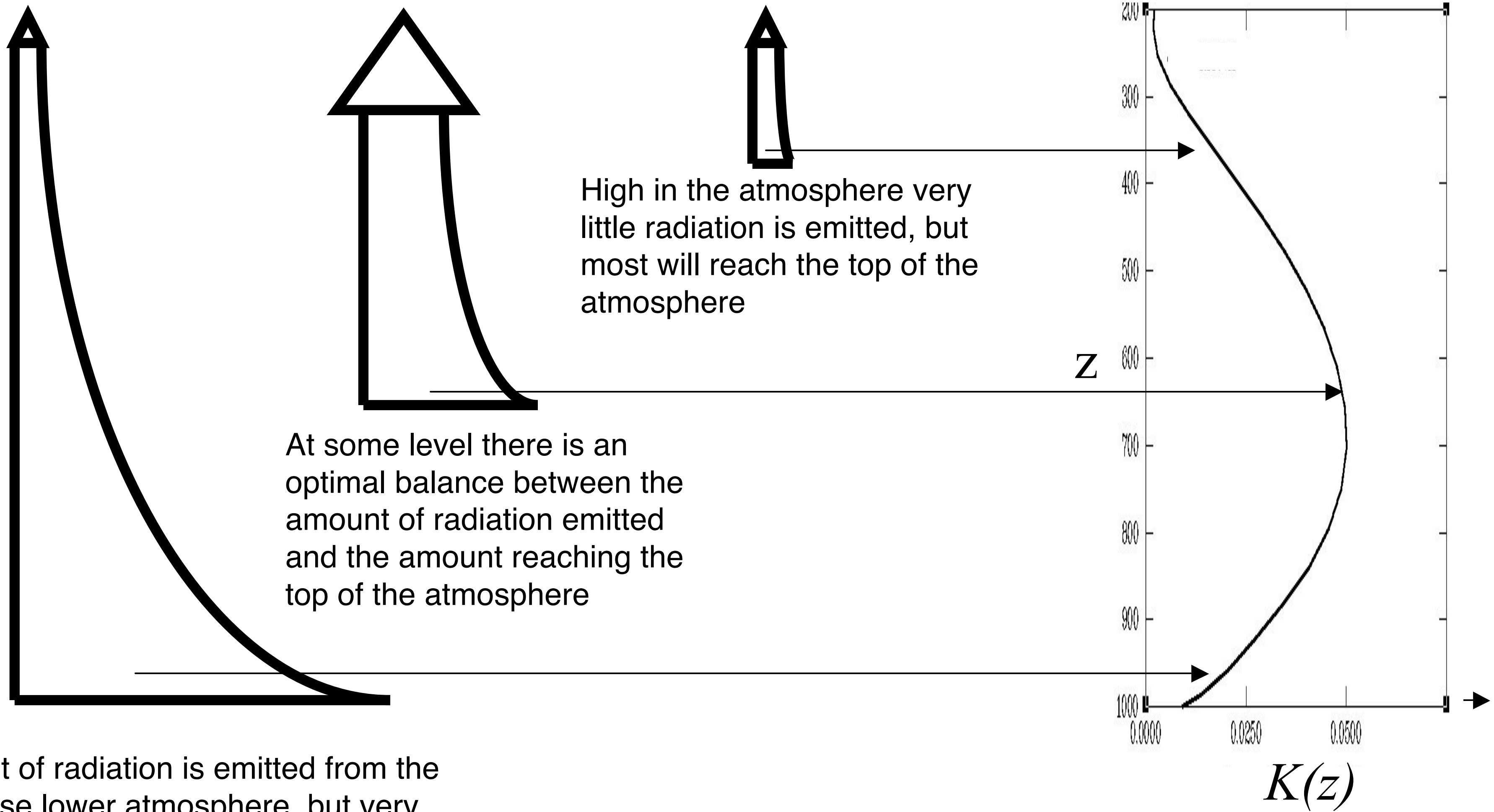


If the weighting function was a delta-function, this would mean that the measured radiance is sensitive to the temperature at a single level in the atmosphere.



If the weighting function was a box-car function, this would mean that the measured radiance was only sensitive to the temperature between two discrete atmospheric levels

REAL ATMOSPHERIC WEIGHTING FUNCTIONS



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

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

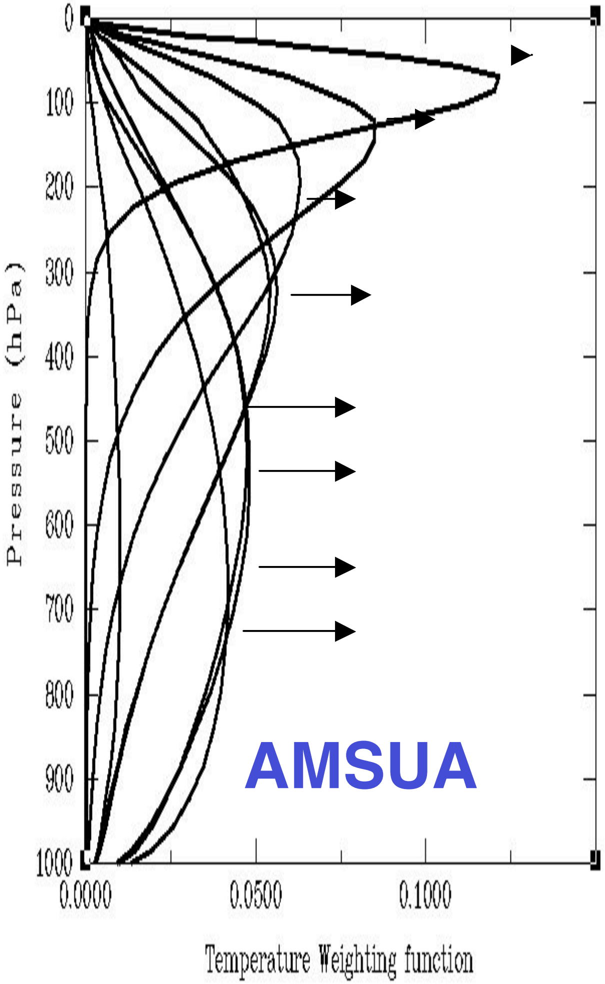
A lot of radiation is emitted from the dense lower atmosphere, but very little survives to the top of the atmosphere due to absorption.

REAL WEIGHTING FUNCTIONS continued...

- The altitude at which the **peak** of the weighting function occurs depends on the **strength** of absorption for a given channel

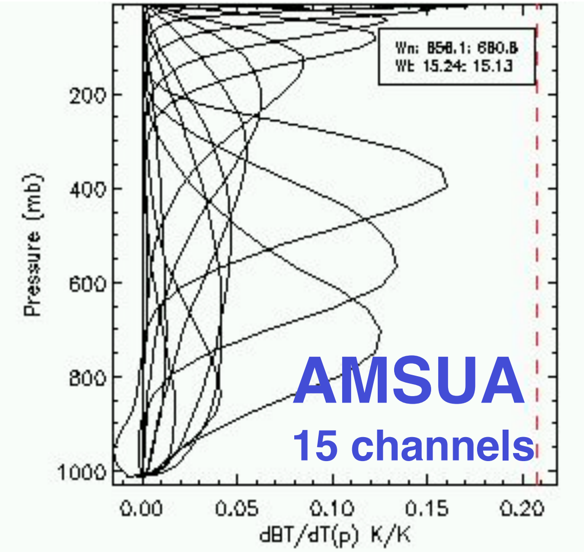
- Channels in parts of the spectrum where the absorption is **strong** (e.g. near the centre of CO2 or O2 lines) peak **high** in the atmosphere

- 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



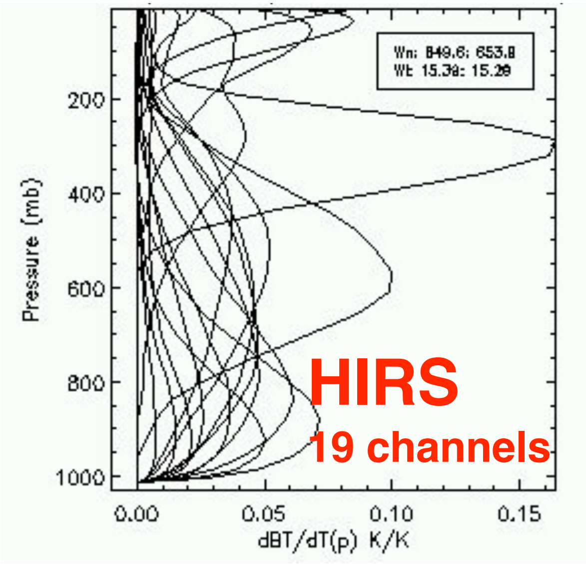
By selecting a **number of channels** with varying absorption strengths we **sample** the atmospheric temperature at **different altitudes**

MORE REAL WEIGHTING FUNCTIONS ...



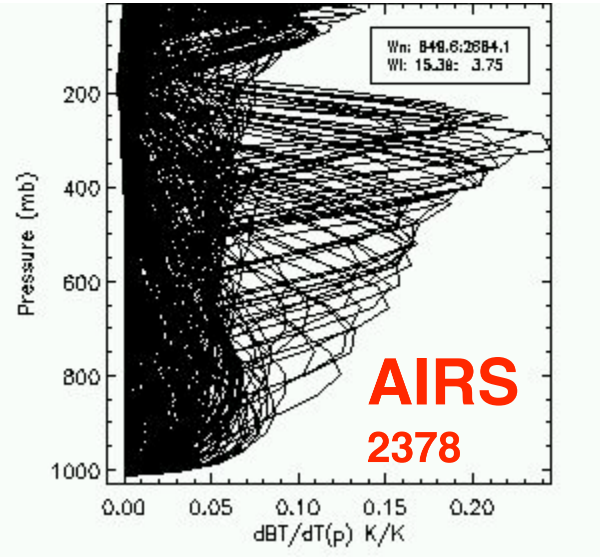
AMSUA

15 channels



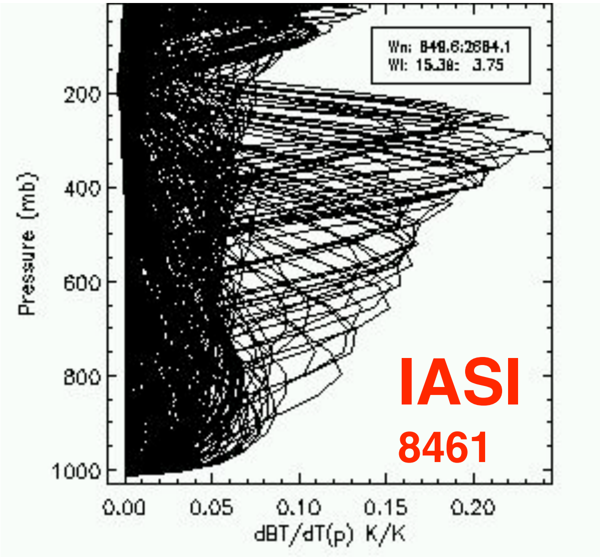
HIRS

19 channels



AIRS

2378



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How do we extract atmospheric information (e.g. temperature) from satellite radiances

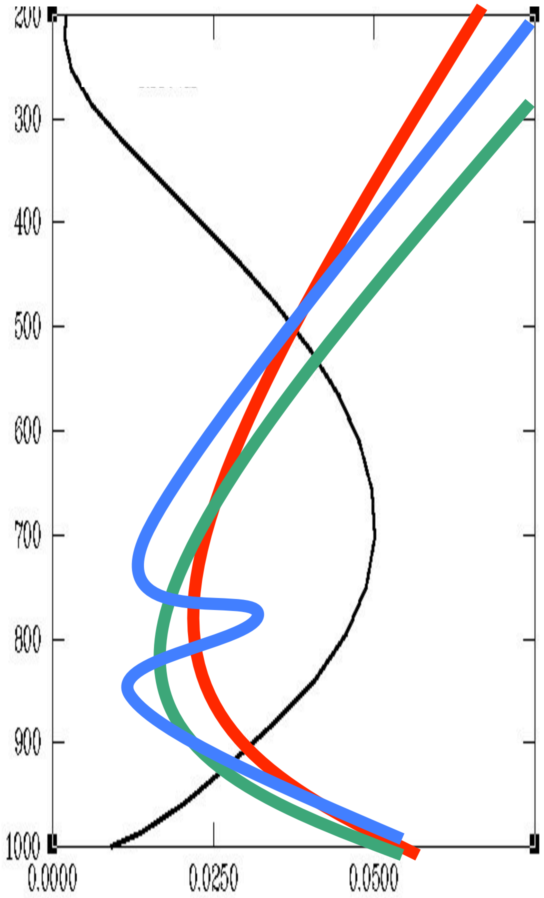
?

EXTRACTING ATMOSPHERIC TEMPERATURE FROM RADIANCE MEASUREMENTS

If we know the entire atmospheric temperature profile T(z) then we can compute (uniquely) the radiances a sounding instrument would measure using the *radiative transfer equation*. This is sometimes known as the **forward problem**

In order to extract or **retrieve** the atmospheric temperature profile from a set of measured radiances we must solve what is known as the **inverse problem**

Unfortunately as the weighting functions are generally broad and we have a finite number of channels, the inverse problem is **formally ill-posed** because **an infinite number of different temperature profiles could give the same measured radiances !!!**



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

SATELLITE RETRIEVAL ALGORITHMS for NWP

The **linear data assimilation schemes** used in the past at ECMWF such as **Optimal Interpolation (OI)** were unable to assimilate radiance observations directly (as they were nonlinearly related to the analysis variables) and the radiances had to be **explicitly converted to temperature products** before the analysis.

This conversion was achieved using a variety of **retrieval algorithms** that differed in the way they used **prior information**

All retrieval schemes use some (either explicit of implicit) form of **prior information** to supplement the information of the measured radiances and solve the inverse problem !

Three different types of retrieval have been used in NWP:

1. Solutions to reduced inverse problems
2. Regression / Neural Net (statistical) methods
3. Forecast background (1DVAR) methods ←

1. Solutions to reduced inverse problems

We acknowledge that there is a limited amount of information in the measured radiances and re-formulate the ill-posed inverse problem in terms of a **reduced number of unknown variables** that can be better estimated by the data e.g. Deep mean layer temperatures, Total Column Water / Ozone or EOF's (eigenfunctions)

Unfortunately it is **difficult to objectively quantify the error in these quantities** (which is very important to use the retrieval in NWP) due to the sometimes subjective choice of reduced representation.

2. Regression and Library search methods

Using a sample of temperature profiles matched (collocated) with a sample of radiance observations/simulations, a **statistical relationship** is derived that predicts e.g atmospheric temperature from the measured radiance. e.g. NESDIS operational retrievals or the 3I approach

These tend to be **limited by the statistical characteristics of the training sample / profile library** and will not produce physically important features if they are statistically rare in the training sample. Furthermore, their assimilation can destroy sharp physical features in the analysis!

3. Forecast Background or 1D-Var Methods

These use an **explicit background** or *first-guess* profile from a short range forecast and perform **optimal adjustments using the measured radiances**. The adjustments minimize a **cost function**

1D-Var RETRIEVALS AND THE COST FUNCTION

It can be shown that **maximum likelihood** approach to solving the inverse problem (which is a particular case of the generalized analysis problem covered in previous lectures replacing T(z) with a vector *x* and L with *y*) requires the **minimization of a cost function** *J* which is a combination of 2 distinct terms.

$$J(x) = \boxed{(x \overset{\text{1D state or profile}}{\overset{\downarrow}{-}} x_b)^T \mathbf{B}^{-1}(x - x_b)} + \boxed{(\overset{\text{Radiance vector}}{\overset{\downarrow}{y}} - \mathrm{H}[x])^T \mathbf{R}^{-1}(y - \overset{\text{RT equation}}{\overset{\downarrow}{\mathrm{H}}}[x])}$$

Fit of the solution to the background estimate of the atmospheric state weighted inversely by the background error covariance ***B***

Fit of the solution to the measured radiances (y) weighted inversely by the measurement error covariance ***R*** *(observation error + error in observation operator* ***H****)*

The solution obtained is **optimal** in that it fits the prior (or background) information and and measured radiances **respecting the uncertainty in both**.

CHARACTERISTICS OF 1D-Var RETRIEVALS

These have a number of advantages that make them **more suitable for NWP assimilation** than other retrieval methods

- The prior information (short-range forecast) is **very accurate** (more than statistical climatology) which improves retrieval accuracy.

- The prior information contains information about **physically important features** such as fronts, inversions and the tropopause.

- The **error covariance** of the prior information and resulting retrieval is better known (crucial for the subsequent assimilation process).

- The 1DVAR may be considered an intermediate step towards the **direct assimilation of radiances**

BUT the error characteristics of the 1DVAR retrieval may still be very complicated due to its correlation with the forecast background …

Direct radiance assimilation

… But do we still really need to do explicit retrievals for NWP

?

DIRECT ASSIMILATION OF RADIANCE DATA

Variational analysis methods such as 3DVAR and 4DVAR allow the direct assimilation of radiance observations (without the need for and explicit retrieval step).

This is because such methods do **NOT** require a linear relationship between the observed quantity and the analysis variables)

The retrieval is essentially incorporated within the main analysis by finding the 3D or 4D state of the atmosphere that minimizes

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

3/4D atmospheric
state vector

Vector of all
observed data

“Observation operator”
H = radiative transfer equation

In direct radiance assimilation the forecast background still provides the prior information to supplement the radiances, **but it is not used twice** (as would be the case if 1D-Var retrievals were assimilated).

DIRECT ASSIMILATION OF RADIANCE DATA

By the direct assimilation of radiances we avoid the problem of assimilating retrievals with complicated error structures.

BUT

There are still a number of significant problems that must be handled

- specifying the covariance **(B)** of **background errors**
- specifying the covariance **(R)** of **radiance error**
- removing **biases** and **ambiguities** in the radiances / RT model

→ **Some of these issues are simplified by the direct assimilation of raw (unprocessed) radiance observations**

DIRECT ASSIMILATION OF RAW RADIANCE DATA

Further to the move away from retrievals to radiance data, many NWP centres are starting to assimilate **raw radiances** (level-1b/1c)

•Avoid **complicated errors** (random and systematic) introduced by (unnecessary) pre-processing such as cloud clearing, angle (limb) adjustment and surface corrections.

•Avoid having to change (retune) our assimilation system when the **data provider changes the pre-processing**

•Faster **access to data** from new platforms (e.g. AMSU data from NOAA-16 assimilated 6 weeks after launch)

•Allows **consistent treatment of historical data** for re-analysis projects (ERA-40) and other climate studies

A QUICK REVIEW OF KEY CONCEPTS

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

Ø Sounding radiances are **broad vertical averages** of the temperature profile (defined by the weighting functions)

Ø The retrieval of atmospheric temperature from the radiances is **ill- posed** and all retrieval algorithms use some sort of **prior information**

Ø There has been an evolution in NWP away from the use of **retrievals** to the **direct assimilation of radiances** with simpler error characteristics

Ø To further simplify the assimilation process, NWP centres have moved towards the direct assimilation of **raw radiances**

Topics covered in Lecture 2:

1. BACKGROUND ERROR STRUCTURES

Why are they important ?
How do we estimate them ?

2. AMBIGUITY BETWEEN VARIABLES

Temperature and humidity
Surface and the atmosphere
Clouds / precipitation and the atmosphere

3. SYSTEMATIC ERRORS

Why are they important ?
How do we estimate them ?

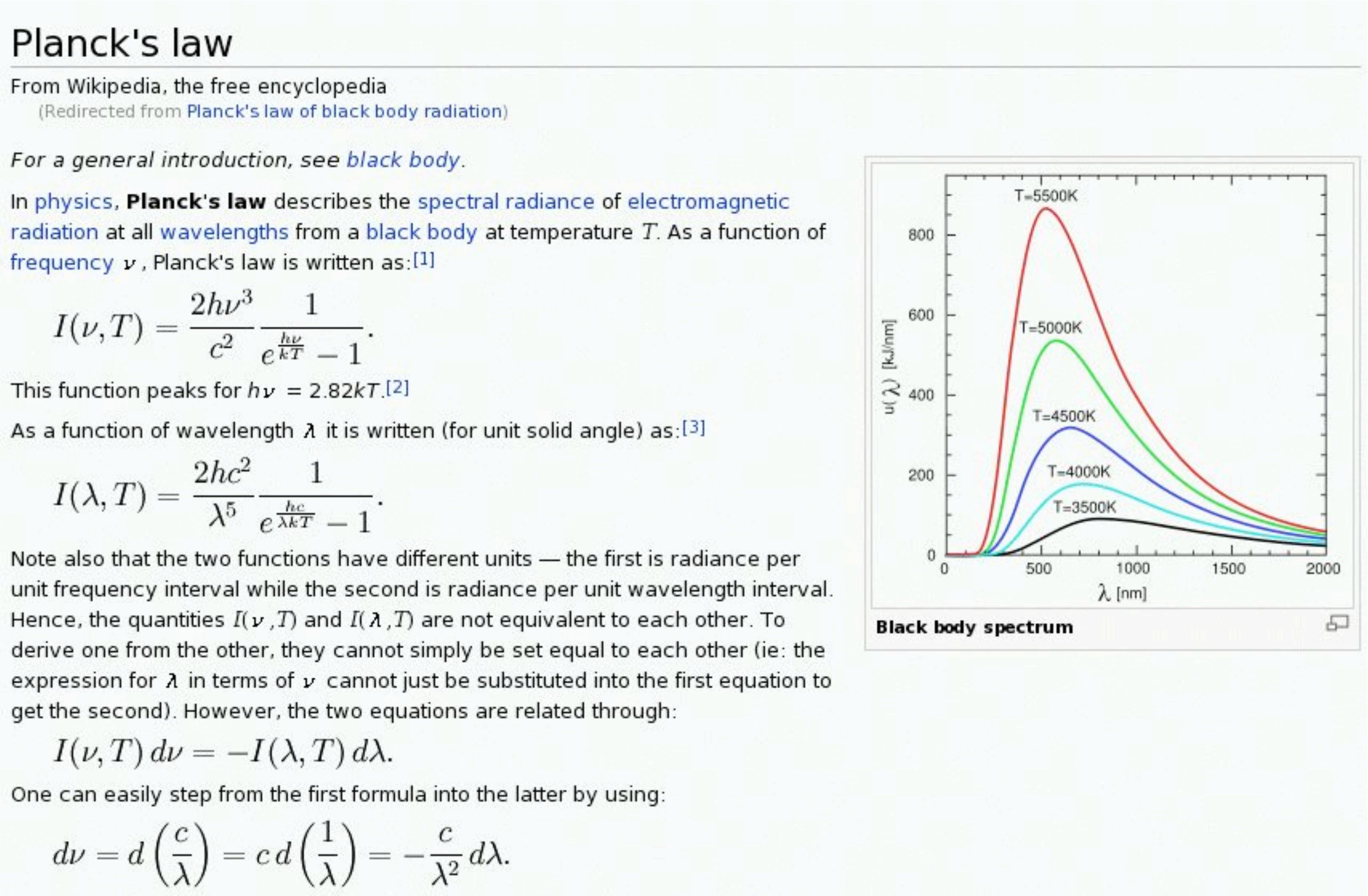
4. WIND ADJUSTMENTS FROM RADIANCES

Direct and indirect wind adjustments

End…

Questions ?

Planck Source Term
(or B from the RT equation)



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