Use of satellite observations

Elisabeth Gérard
on behalf of CNRM/GMAP/OBS

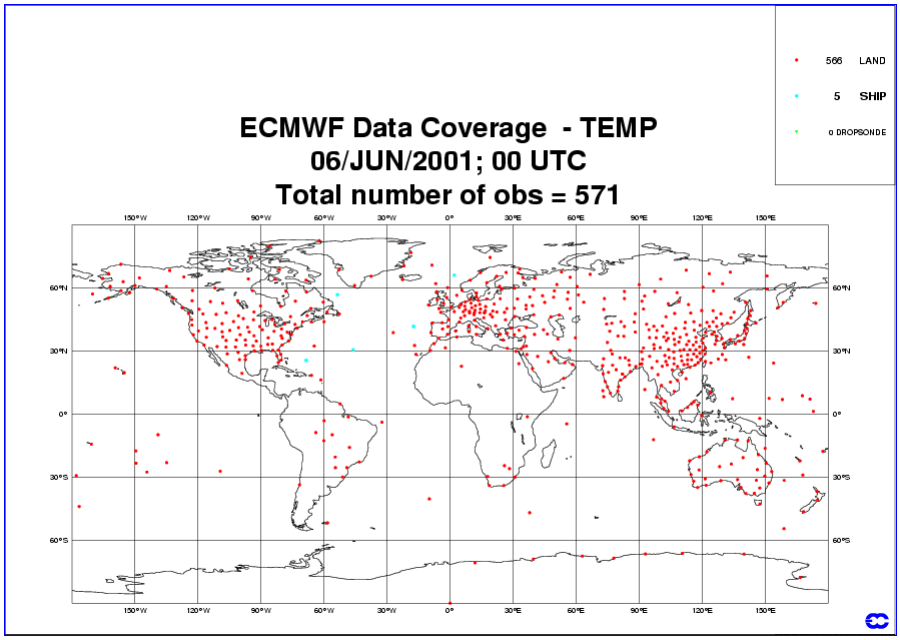
ALATNET Seminar on Data Assimilation,
Gourdon, France, 11-22 June 2001

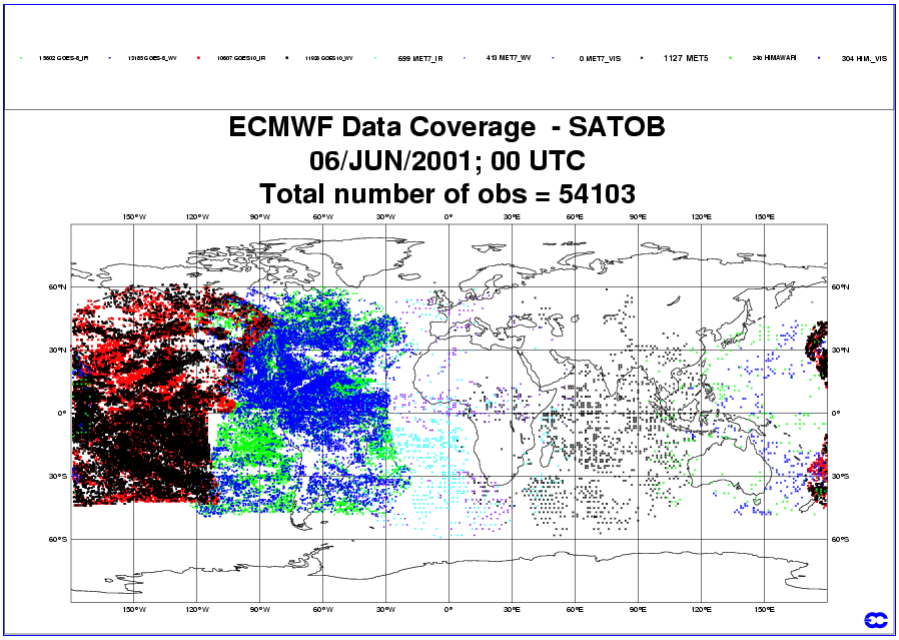
Overview

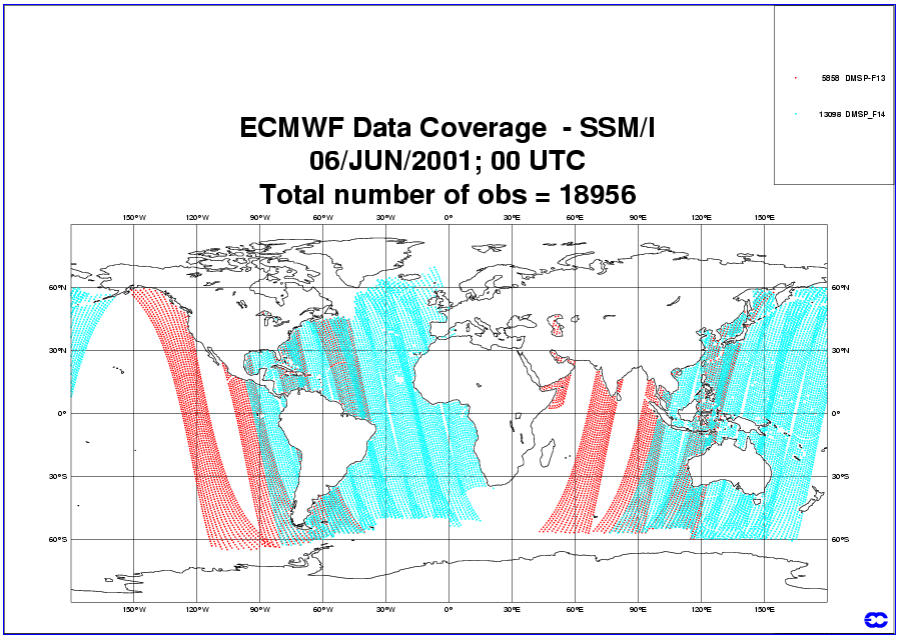
1. Influence of satellite data in NWP
2. Principle of remote sensing
3. Information content
4. Problems due to complex observation operator
5. Data compression with future instruments

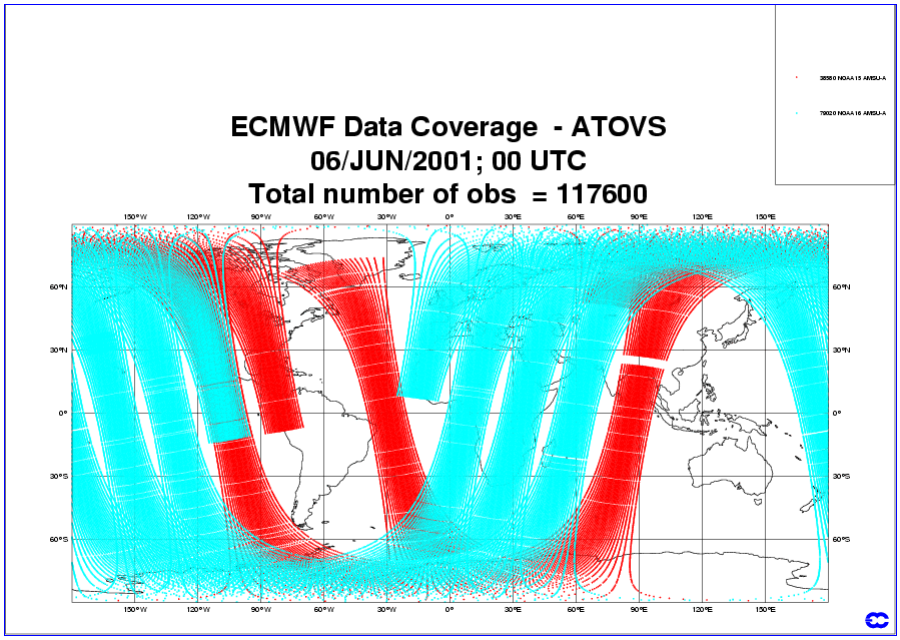
1. Influence of satellite data in NWP

- Lack of conventional observations over the oceans
- Relative importance of the different sources of data




15602 GOES-8_IR
13183 GOES-8_WV
10697 GOES10_IR
11028 GOES10_WV
699 METZ_IR
413 METZ_WV
0 METZ_VIS
1127 METS
249 HIMAWARI
304 HIM_VIS
ECMWF Data Coverage - SATOB
06/JUN/2001; 00 UTC
Total number of obs = 54103
150°W
120°W
90°W
60°W
30°W
0°
30°E
60°E
90°E
120°E
150°E
60°N
30°N
0°
30°S
60°S

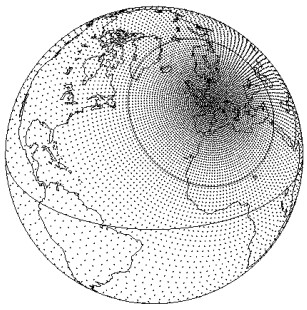

5858 DMSP-F13
13098 DMSP_F14
ECMWF Data Coverage - SSM/I
06/JUN/2001; 00 UTC
Total number of obs = 18956
150°W
120°W
90°W
60°W
30°W
0°
30°E
60°E
90°E
120°E
150°E
60°N
30°N
0°
30°S
60°S



ARPEGE grid

ARPEGE T199 C3.5 operational grid

1 grid-point over 16 plotted



ARPEGE T199 C3.5 operational grid

1 grid-point over 16 plotted

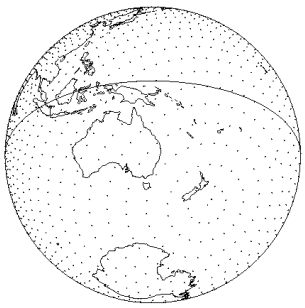


Illustration of the OSEs

- OSE=Observing System Experiment
- Results obtained at ECMWF in 2000 with 4D-Var (T319L60) over 6 weeks (summer + winter)
- One type of observation is not used in operational analyses/forecasts
- Scores computed with respect to radiosonde data (continent) or with respect to operational analyses

Short range in Northern Hemisphere

- The impact of radiosonde data dominates.
  The impacts of aircraft and satellite data are of the same order
- In Europe: aircraft data have more impact than satellite data thanks to an excellent coverage upstream the flow
- In Northern America: domination of satellite data over the Pacific Ocean
- In Asia: the impact of radiosonde data over Europe predominates

Medium range

- In Northern Hemisphere: equivalent impact of satellite and radiosonde data
- In Southern Hemisphere: satellite data predominate
- In Tropics: satellite data dominate
- In Europe: radiosonde data dominate

Conclusions

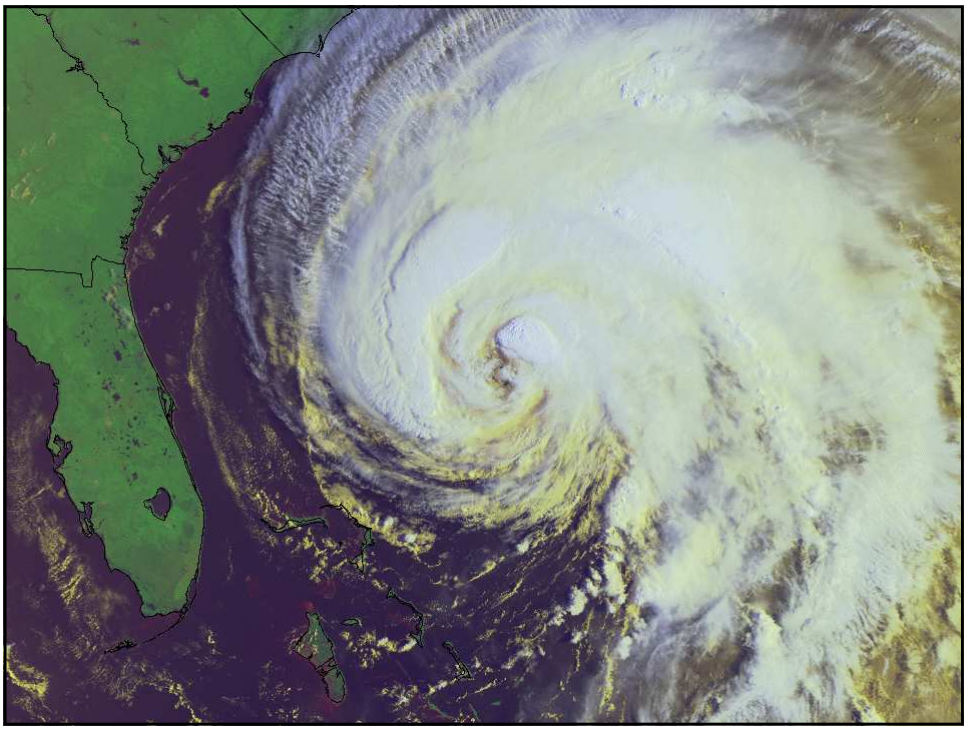
- New: increasing importance of the satellite data in NWP
- Reasons: better instrument (ATOVS), better use of data (4D-Var, raw radiances), erosion of the radiosonde network
- Motivation: optimal use of satellite data for improving the NWP as well as the reanalyses for climate studies

2. Principle of remote sensing

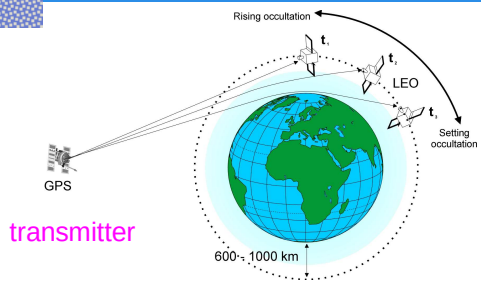
- **Measurement of the electromagnetic radiation**
- **Most of the methods are passive**
  - **Measurement of the natural radiation**
- **Other ones are active**
  - **Use of artificial sources**

Active remote sensing

- Scatterometer: provides wind at the surface of the oceans
- Wind lidar: Doppler measurement of the wind along the laser beam. Molecule and aerosol scattering.
- GPS=Global Positioning System. The signals used are sensitive to the atmosphere. The radio occultation technique provides soundings. The information is converted in terms of refractivity, and thus can be related to temperature and humidity



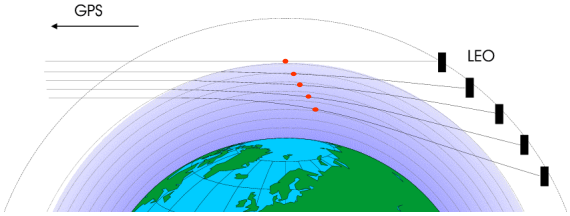
Radio occultation geometry



receiver

transmitter

- = the path of the ray perigee through the atmosphere



Passive remote sensing

- Scattered solar radiation:

Avantage= relatively intense radiation

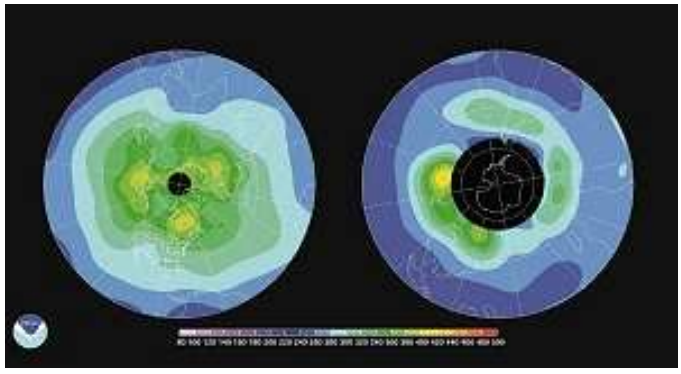
Disadvantage= only during daytime!

Absorption used to estimate the quantity of absorption factors (ozone for example). Examples: SBUV, TOMS.

- Absorbed solar radiation:

The radiation absorption is measured during an occultation when the instrument looks through the atmosphere. Examples: HALOE, GOMOS.

SBUV - The Solar Backscatter Ultraviolet Spectral Radiometer



Maps of total atmospheric ozone for the northern hemisphere (left) and southern hemisphere (right) obtained from the SBUV/2 instrument on NOAA-14 for 8 July 1998. The black circles at the centres of these images are a data void over areas not seen by the instrument.

Passive remote sensing

- Thermal emission:

The infrared and microwave emission is the most useful measurement, as details of the emission spectrum strongly depend upon the molecules. Examples HIRS, AMSU, SSM/I

Nadir Sounders: downwards,
good horizontal resolution

Limb sounders: good vertical resolution

3. Information content

- Radiative transfer equation
- Introduction of useful concepts:
  - Number of degrees of freedom for signal
  - Entropy reduction
  - Vertical resolution

Radiative transfer equation

- Radiance: quantity of energy per time unit, going through a surface in a solid angle and for a wave number interval. Unit: $W/m^2Sr.cm^{-1}$
- Planck function: $B_\upsilon(T)$= radiance emitted by a black body at temperature T for a wave numver υ
- Intensity of the radiation emitted by the atmosphere at wave number υ:

$$R_\upsilon = (I_0)_\upsilon \tau_\upsilon(z_0) + \int_{z_0} B_\upsilon(T(z)) (d\tau_\upsilon(z)/dz)\, dz$$

Radiative transfer equation

- $(I_0)_\upsilon$ is the surface emission at altitude z_0
- $\tau_\upsilon(z)$ is the transmittance from z to the top of the atmosphere, accounts for absorption and scattering
- $B_\upsilon(T(z))$ is the corresponding Planck function

- Intensity of the radiation emitted by the atmosphere at wave number υ:

$$R_\upsilon = (I_0)_\upsilon \tau_\upsilon(z_0) + \int_{z_0} B_\upsilon(T(z)) (d\tau_\upsilon(z)/dz)\, dz$$

Radiative transfer equation

- Integration on frequency:

The instruments actually measure the radiation over a frequency range. It is necessary to integrate the equation taking into account the response function of the instrument

Weighting function:

$R_\upsilon = (I_0)_\upsilon \tau_\upsilon(z_0) + \int_{z_0} B_\upsilon(T(z))\, K_\upsilon(z)dz$

$K_\upsilon(z) = d\tau_\upsilon(z)/dz$ is called weighting function. It weights the Planck function and determines the region of the atmosphere that is sounded at this frequency

Radiative transfer equation

Interpretation of the weighting functions

- The emission depends on three factors:
  - Temperature
  - Number of molecules of the emitting gas
  - Transmittance towards the top of the atmosphere
- Low atmosphere: high density therefore intense radiation, but most of the radiation is absorbed above
- High atmosphere: low radiation but high transmittance

Radiative transfer equation

- Combination of these opposite effects so that the contribution of a parcel is maximum at an intermediate height
- The position of the peak depends on the atmosphere composition and on the spectroscopy; its intensity depends on temperature
- Use of many frequencies to reconstitute a temperature profile
- The weighting functions are wide and intersect

Information content: degrees of freedom for signal

- The number of degrees of freedom can be smaller than the number of measurements
- Notations: $y=Hx+\varepsilon$, $x_a= x_b + K(y-Hx_b)$, $K= A\, H^T R^{-1}$

Analysis error covariance matrix: $A^{-1}=B^{-1}+H^T R^{-1} H$

Normalisation $x'=B^{-1/2}x$ $y'= R^{-1/2}y$ $\varepsilon'= R^{-1/2}\varepsilon$

Normalised Jacobian matrix: $H'=R^{-1/2}H\, B^{1/2}$

Thus: $y'=H'x'+\varepsilon'$ and $Cov(y')=H'H'^T + I$

1st term (variability of the atmosphere); 2nd term (noise)

Information content: degrees of freedom for signal

SVD (singular vector decomposition) for H':
$H'=U\Lambda V^T$ with $U^TU=I$, $V^TV=I$
$y''= U^Ty =U^T(U\Lambda V^T x'+ \varepsilon')=\Lambda V^Tx''+\varepsilon''$
With $x''= V^Tx'$, $\varepsilon''= U^T\varepsilon'$
$Cov(x'')=V^TV=I$, $Cov(\varepsilon'')= U^TU=I$
$Cov(y'')= \Lambda^2+ I$ where Λ^2 is due to variability, I to noise

The elements of y'' which varie more than the noise are the ones for which λ_i^2 is greater than 1

The number of effective independent measurements is the number of singular values of $R^{-1/2}H\,B^{1/2}$ that are greater than 1

Information content: degrees of freedom for signal

Formalisation of the concept of « degrees of freedom for signal » (DFS):

$x_a= x_b + K(y-Hx_b)$,

$K= A\,H^TR^{-1}=(B^{-1}+H^TR^{-1}H)^{-1}H^TR^{-1} =BH^T(HBH^T+R)^{-1}$

$x_a-x_b = K(y-Hx_b)$,

DFS= $E((x_a-x_b)^T B^{-1}(x_a-x_b))$

The DFS quantifies what is brought in by the analysis

$DFS=E(tr((x_a-x_b)(x_a-x_b)^T B^{-1}))=tr(E((x_a-x_b)(x_a-x_b)^T)\,B^{-1})$

Information content: degrees of freedom for signal

$E((x_a - x_b)(x_a - x_b)^T) = E(K(y - Hx_b)(y - Hx_b)^T K^T)$

$= K(R + HBH^T)K^T = BH^T(HBH^T + R)^{-1}HB$

$DFS = tr(BH^T(HBH^T + R)^{-1}H) = tr(KH) = tr(HK)$

Knowing that $AB^{-1} + KH = A(B^{-1} + H^T R^{-1}H) = I$

Thus $DFS = tr(KH) = tr(I - AB^{-1})$

- DFS=tr(KH)=tr(G) with G the « Model Resolution Matrix »: $x_a - x_b = G(x_t - x_b)$ if $\varepsilon = 0$

G shows to which extent the analysis represents the reality

- $DFS = tr(I - AB^{-1})$

The more information you put into the system, the more A is different from B

Information content: entropy reduction

- The entropy is the gaussian distribution of the covariance C: $E(C) = cst + 1/2 \log_2 |C|$

E measures the volume of the space occupied by the probability law that describes the knowledge of the system

- When a measurement is performed, this « incertainty volume » decreases and the entropy reduction is:

  $ER = 1/2 \log_2 |B| - 1/2 \log_2 |A| = -1/2 \log_2 |AB^{-1}|$

Information content: vertical resolution

The inversion can be characterised by:

- The matrix $A=Cov(x_a-x_t)$
- The matrix G: $x_a-x_b=G(x_t-x_b)$ if $\varepsilon=0$

G indicates to which extent the analysis represents the reality. In particular, the vertical resolution of G indicates how the analysis smoothes the reality.

Vertical resolution$=dz_i/G_{ii}$

where dz_i is the depth of layer i

G_{ii} is the corresponding diagonal element of G

4. Problems due to complex H

Particularity of the satellite data:
the observation operator H is complex,
which can cause problems in the analysis

Problems due to complex H

- Bias correction: H is often inaccurate and introduces a bias most of the time greater than the signal. The optimal estimation assumes unbiased errors. Thus it is necessary to bias correct the data before using them in the assimilation
- Contamination: the measurements can be affected by clouds (infrared) and precipitations (microwave). A good quality control is necessary to eliminate the erroneous data

Problems due to complex H: Bias correction

- Objective: correction of systematic biases between observed and simulated radiances:
  - Measurement errors
  - Radiative transfer model imperfections
- Correction with respect to scanning angle
  the two central scans being taken as references
- Correction with respect to air mass
  with a linear regression over a wide dataset
  - observed data and model data (called predictors)

Problems due to complex H: Bias correction (ATOVS)

- Data selection
  - land / ocean ; clear / cloudy; altitude < 2000m
- Quality control
  - 150 K < Tb < 250 K
  - | obs-mod | < 20 K
  - Control on particular channels

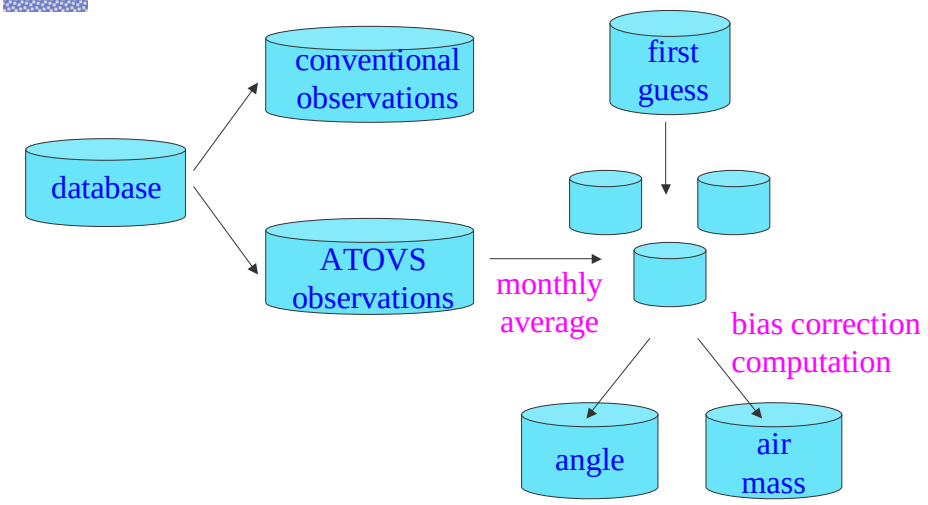
Problems due to complex H: Bias correction (ATOVS)

- For air mass bias correction computation
  - Linear regression for each channel
- Predictors
  - Model thickness 1000hPa – 300 hPa
  - Model thickness 200 hPa – 50 hPa
  - Model surface temperature
  - Model total column water vapour

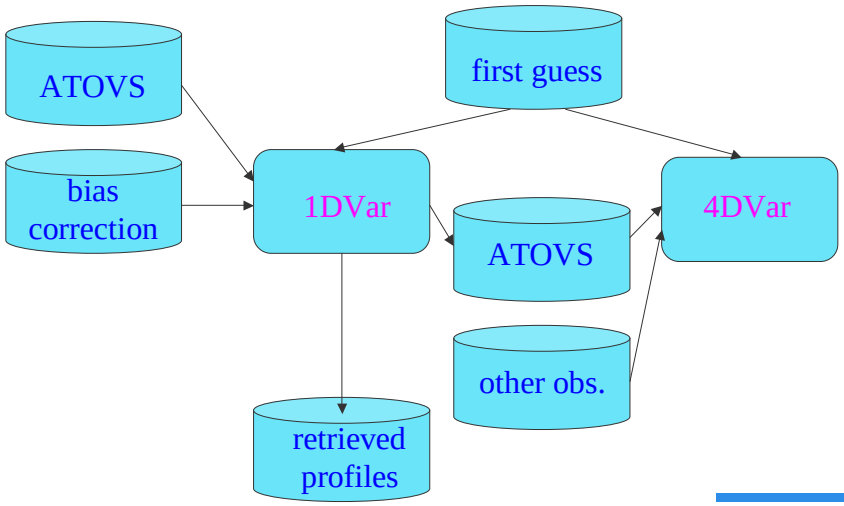
Problems due to complex H: Bias correction – alternative ?

- This methods assumes the model to be unbiased, which is not proven…
- Another alternative is to bias correct first the model fields to build up « true » fields and bias correct the observations with respect to these « unbiased » fields
- Example: SSM/I at ECMWF before the unified satellite radiance bias correction
  - rescaling of the model humidity profile so that TCWV model = TCWV Alishouse derived from SSM/I

Use of preprocessed ATOVS data at Météo-France



Use of preprocessed ATOVS data at Météo-France



Problems due to complex H

Direct assimilation of radiances in 3/4D-Var or assimilation of derived products?

- The assimilation of derived products is cheaper: a few iterations with costly H are sufficient
- However:
  - « Incest » problem if inversion uses the same x_b as in the analysis
  - Difficulty of characterising the error covariance matrices

5. Compression of the data with future instruments

How to choose a subset of channels to perform an inversion when thousands of channels are available?

DRM method

(Menke)

- « Data Resolution Matrix »: DRM=HK
- As y_a-y_b=DRM (y-y_b), the diagonal elements of DRM indicate how much weight an observation has in its own analysis
- These diagonal elements measure the « importance » of the different channels
- The method implies the computation of matrix A

SVD method: singular vector decomposition

(Prunet)

- SVD of H
- $G= R^{-1/2}HB^{1/2} =U\Lambda V^T$
- Truncation in Λ^2 so that the eigenvalues of $G^TG= B^{1/2}H^T R^{-1}HB^{1/2}$, equivalent to σ_b^2/ σ_o^2, represent 10% of the contribution of the observations in the analysis
- $G= R^{-1/2}HB^{1/2} =>U_p\Lambda_p V_p^T$
- DRM = $V_p V_p^T$. Its diagonal elements are used in terms of « importance » of the channels

Iterative method

(Rodgers)

- This method enables an iterative selection of the channels. At each step, the most interesting channel is chosen and the matrix $B_i=A_{i-1}$ is updated
- After normalising the Jacobian with R
  - $A_i^{-1}=B_i^{-1}+h^Th$
  - where $B_0=B$ and h is a line of H
- The selection criterion is the DFS or ER:
  - $DFS(h)_i=Tr(I-AB_i^{-1})=h^TB_ih/(1+ h^TB_ih)$
  - $ER (h)_i=-1/2 \log_2 det(AB_i^{-1})=1/2 \log_2(1+ h^TB_ih)$

Jacobian method

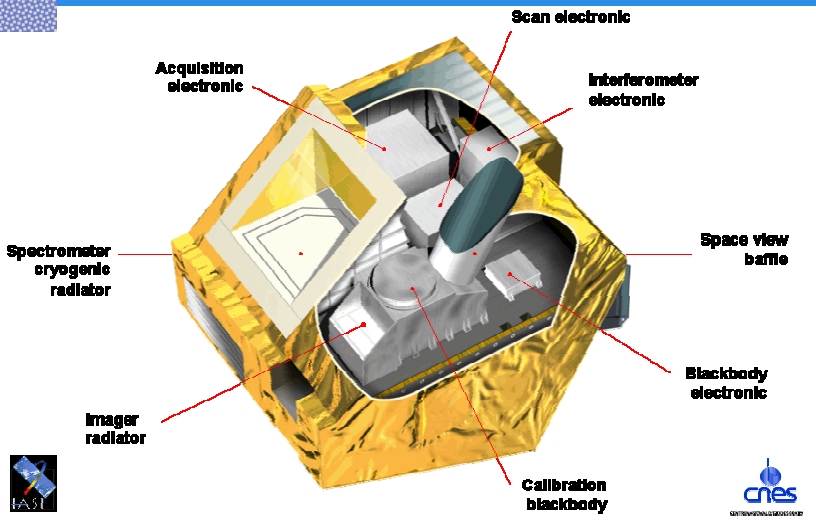
(Goldberg, Aires)

- Method based on weighting functions that describe the channel sensitivity to the atmosphere parameters
- Normalisation of H: $R^{-1/2}HB^{1/2}$
- For each parameter, at each vertical level, one channel is chosen:
  - Amongst the ones which maximum is at this level
  - With the greater ratio:
    Intensity of the max / width of the weighting function

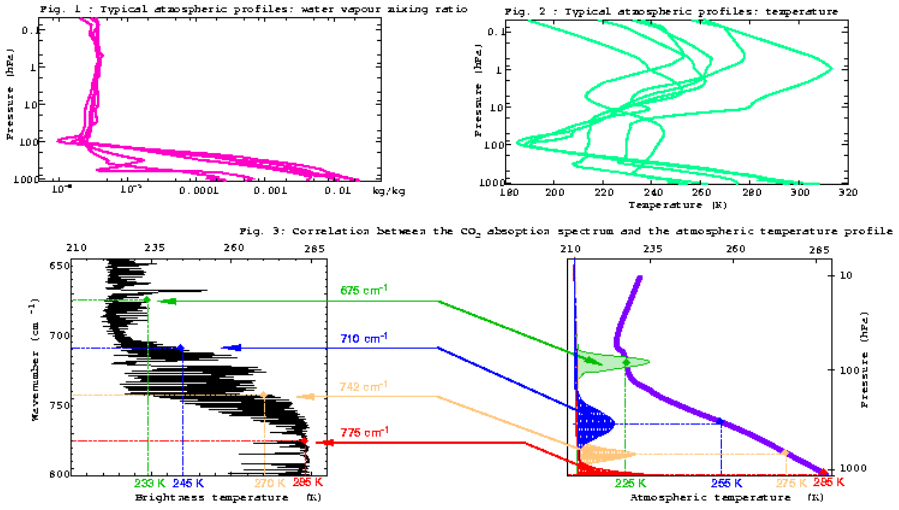
Illustration for IASI

- Infrared Atmospheric Sounding Interferometer (Michelson interferometer)
- IASI= 8461 radiances in each pixel
- The 4 different methods have been compared for 3 stations extracted from the SODA database, representative of the midlatitudes, the Tropics and the polar regions
- For each station, 24 profiles (T,Q,O3) observed in a year

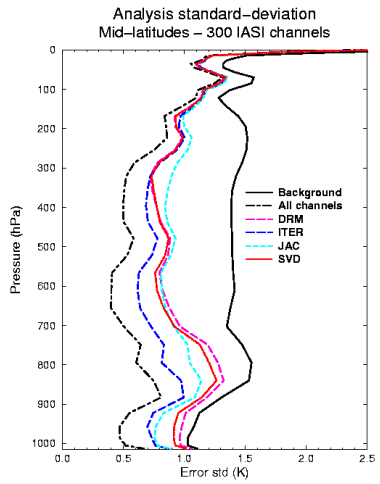
IASI
to be launched in 2005 on Metop

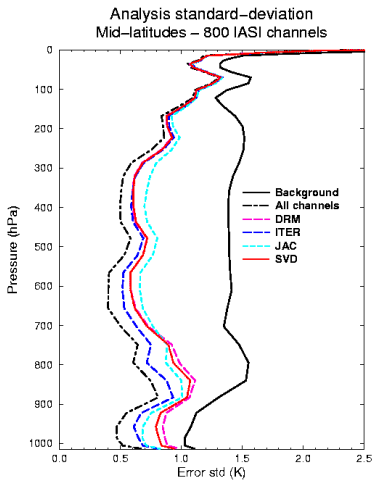


Remote sounding from IASI

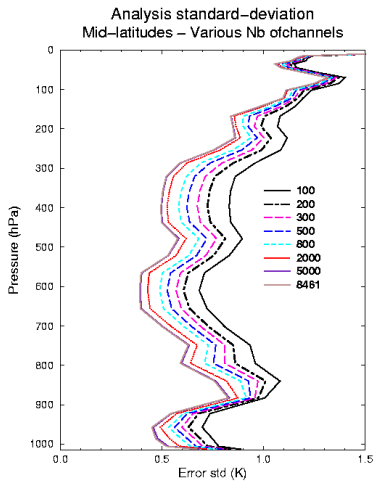


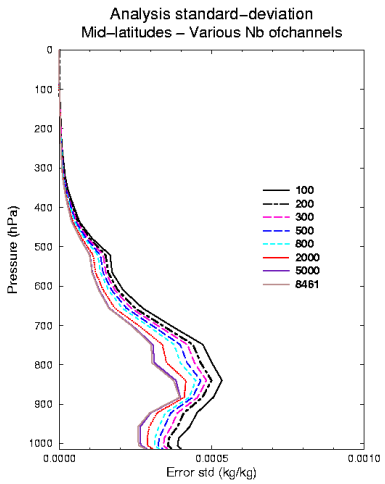
Midlatitudes - T



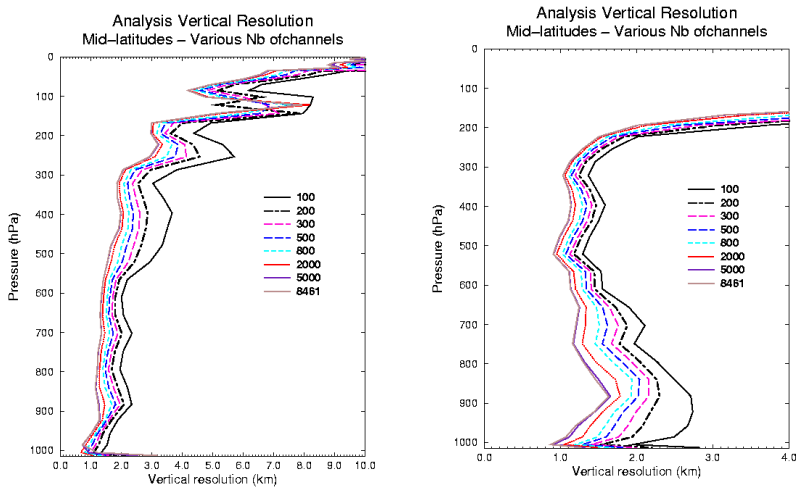


Accuracy / No. of channels

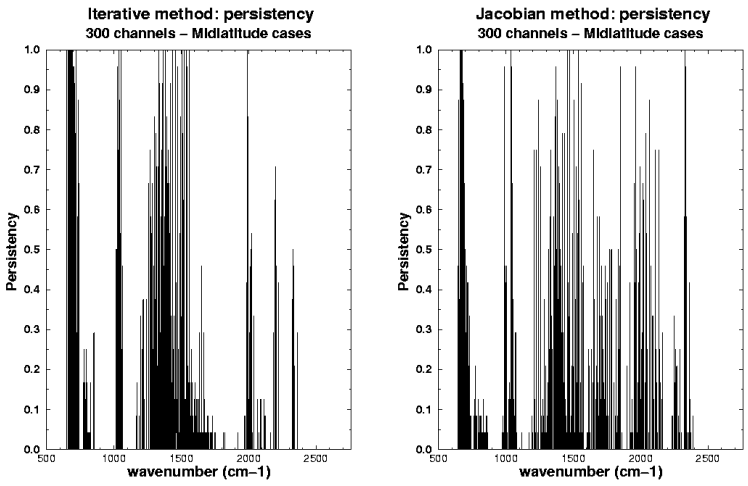




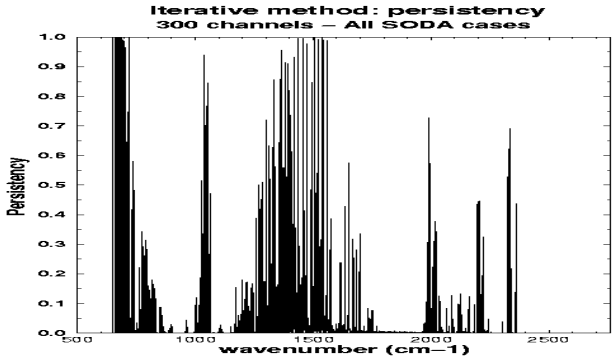
Vert. resolution / No. of channels



Channel selection – Midlatitudes



Statistics on 518 SODA profiles



Amongst 8461 channels, 28 are used for each selection and 5506 are never used

DFS: 10.7 for T, 9.0 for Q et 1.3 pour O3.

Conclusions

- The iterative method for channel selection gives the best results
- A method based on the Jacobians is efficient in the low troposphere and the method based on SVD is efficient in the high troposphere
- Only 1/3 of the channels are common to selections by ITER et JAC
- The channels are chosen amongst ~3000
- Very few channels are systematically chosen