Assimilation of satellite data in operational meteorology

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Overview

A. Influence of satellite data in NWP
   - One type amongst various types of observations
   - Observing System Experiments

B. Principle of remote sensing
   - Active
   - Passive

C. Complexity of the assimilation
   - Radiative transfer equation
   - Observation weighting functions
   - Convolution of H and B
   - Other issues

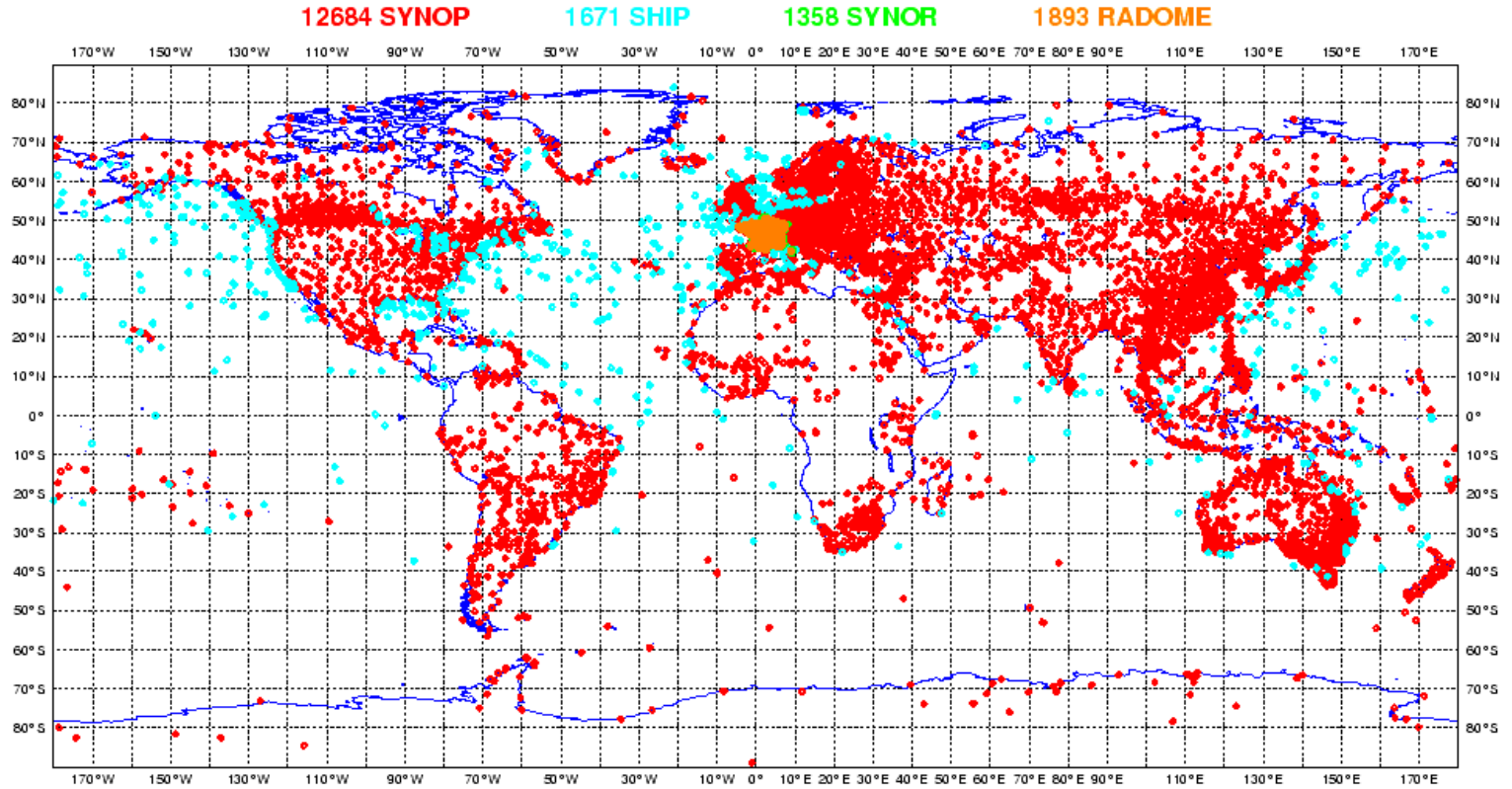
A. Influence of satellite data in NWP

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

METEO-FRANCE couverture de donnees - SYNOP/SHIP

2004/07/06 00H UTC cut-off long

Nombre total d'observations avant screening : 17606



METEO-FRANCE couverture de donnees - BUOY

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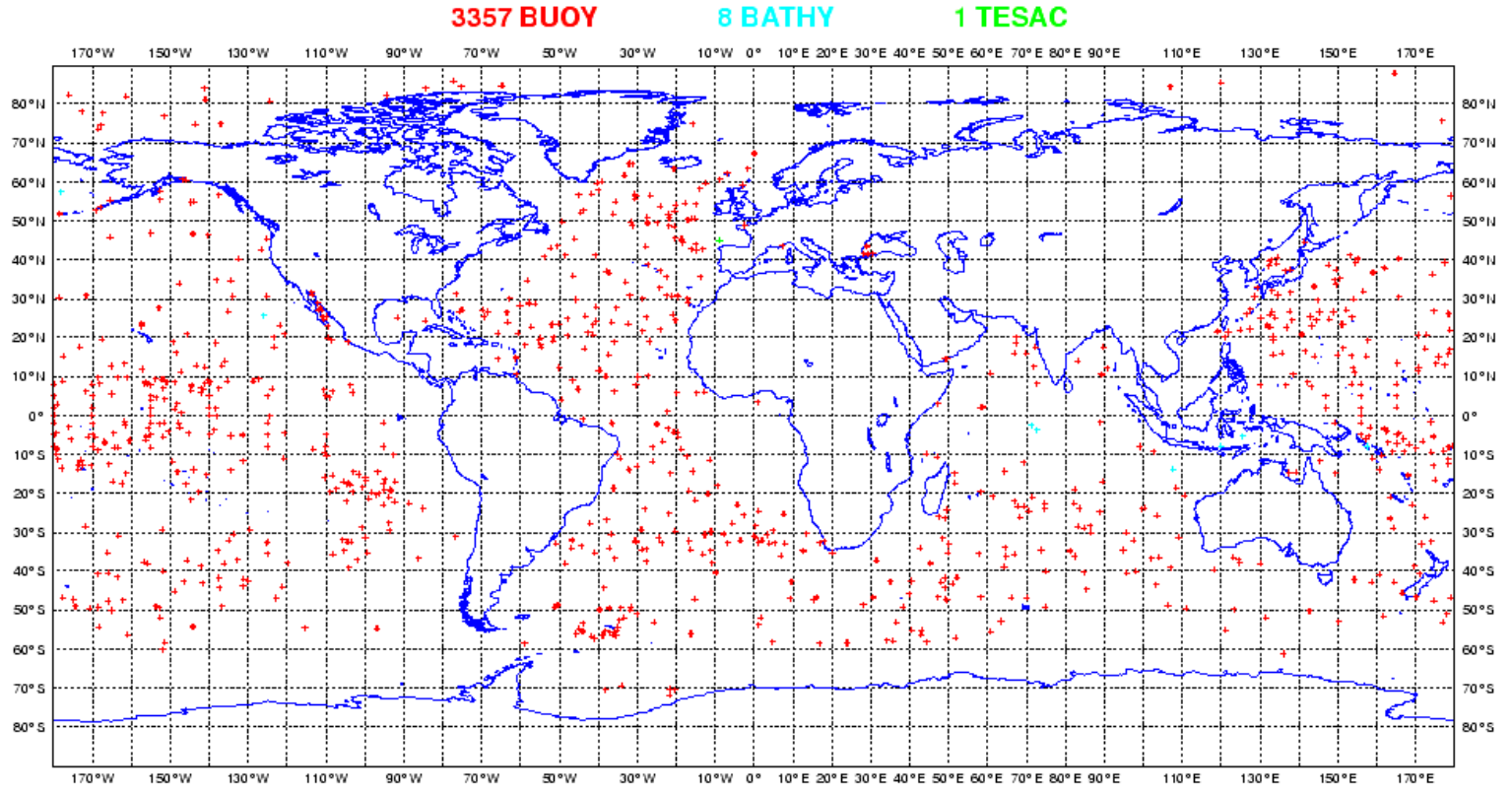

METEO-FRANCE couverture de donnees - TEMP

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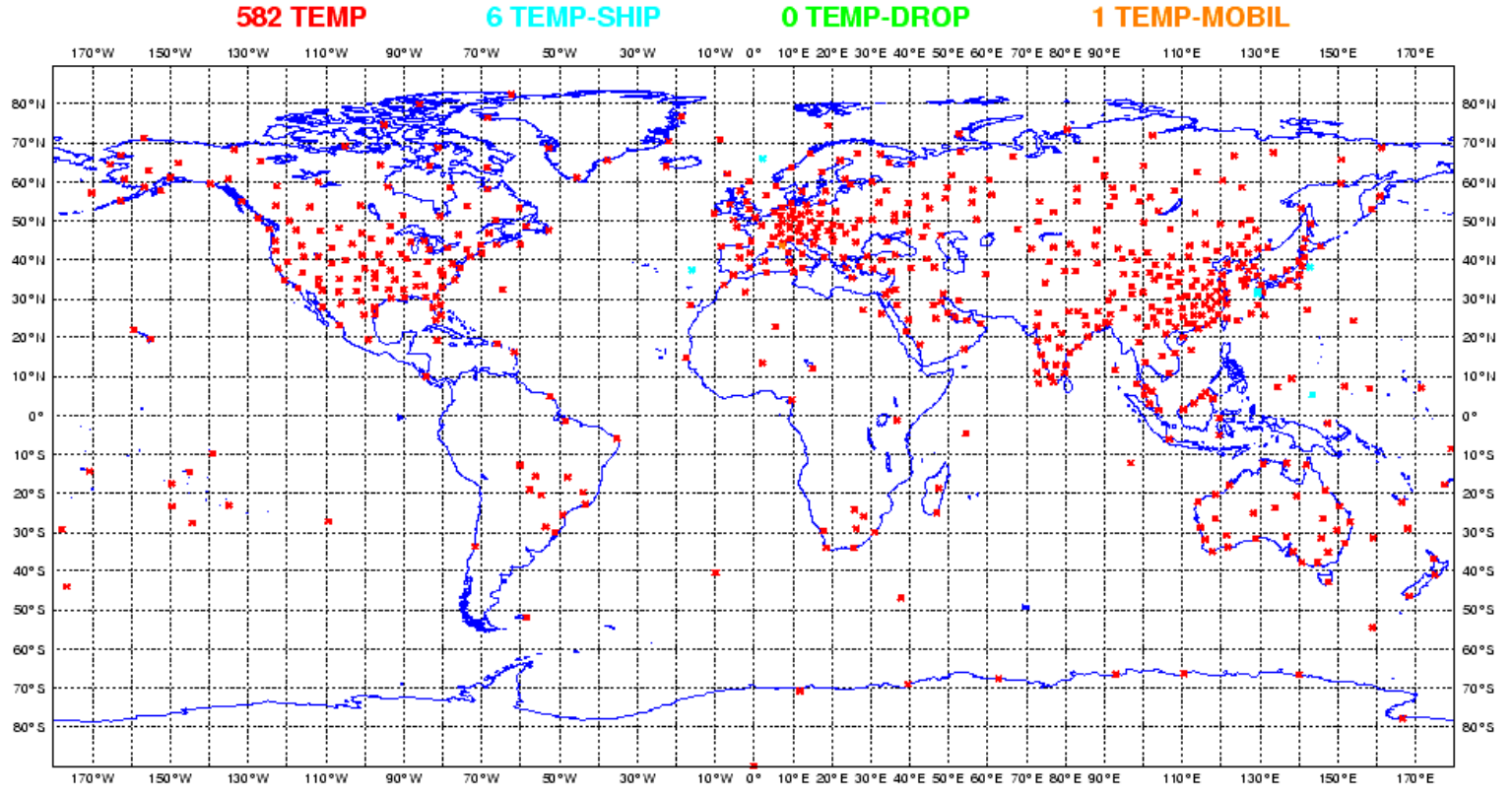

METEO-FRANCE couverture de donnees - PILOT/PROFILEUR

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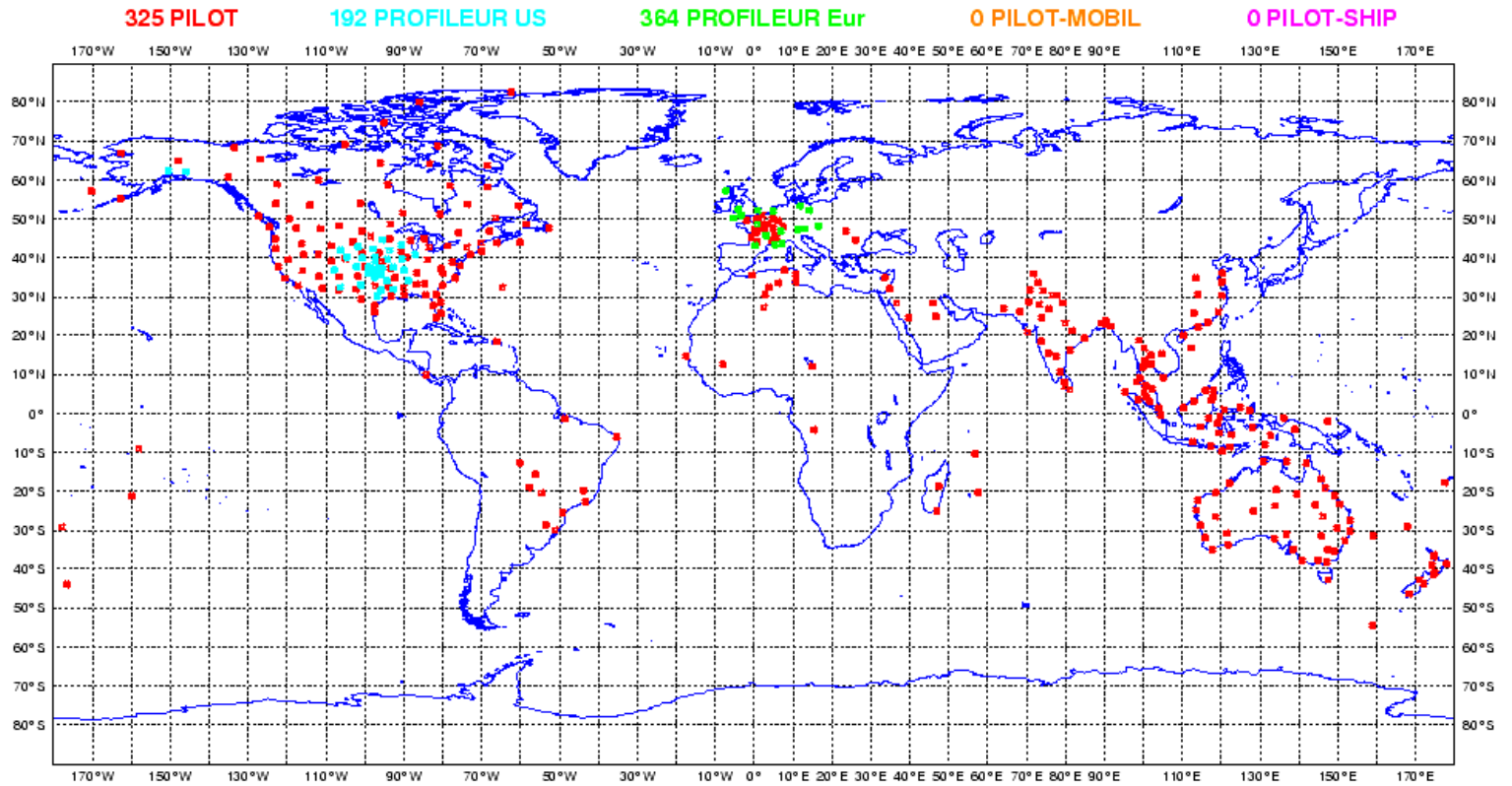

METEO-FRANCE couverture de donnees - AVIONS

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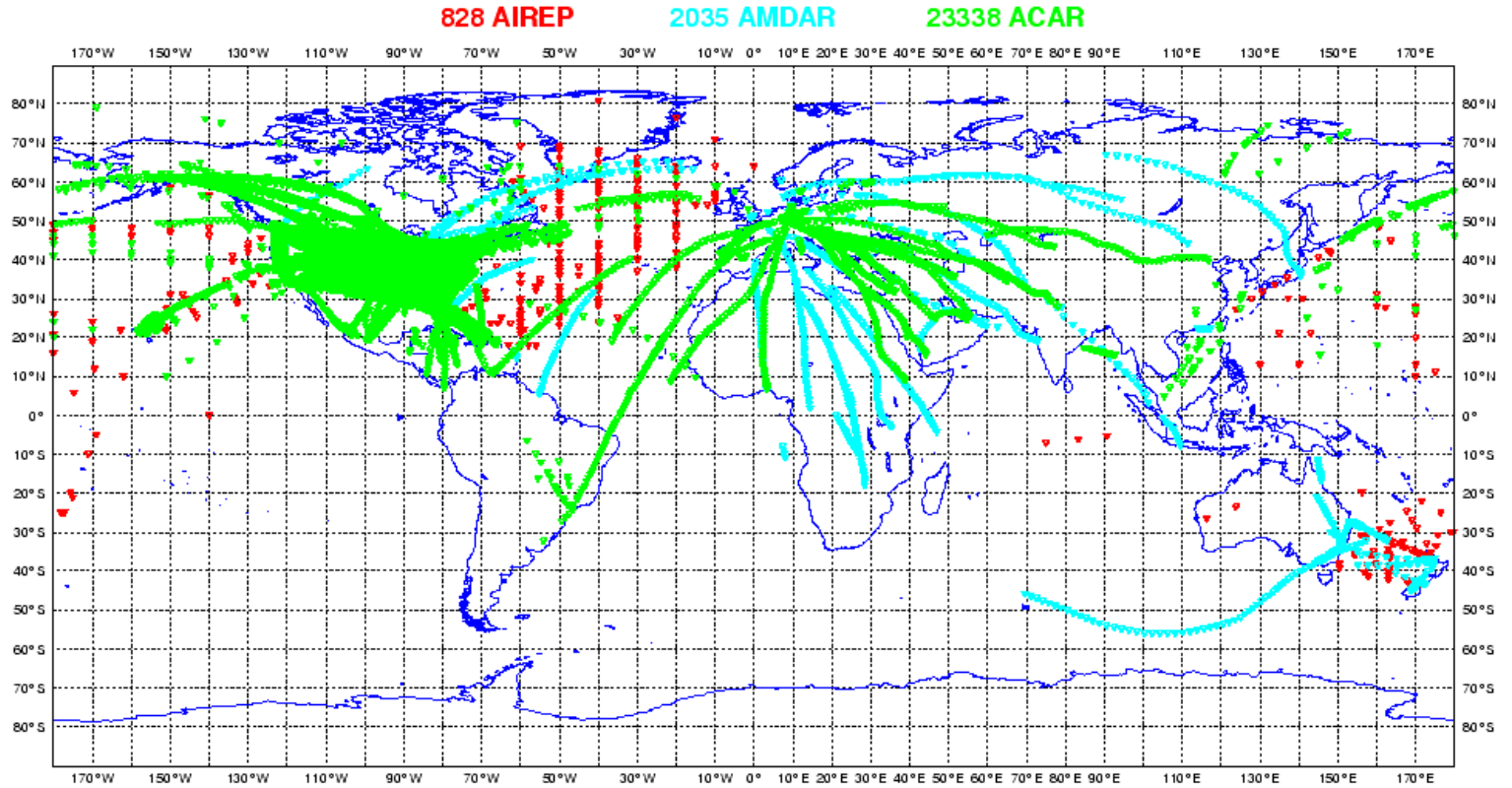

METEO-FRANCE couverture de donnees - SATOB

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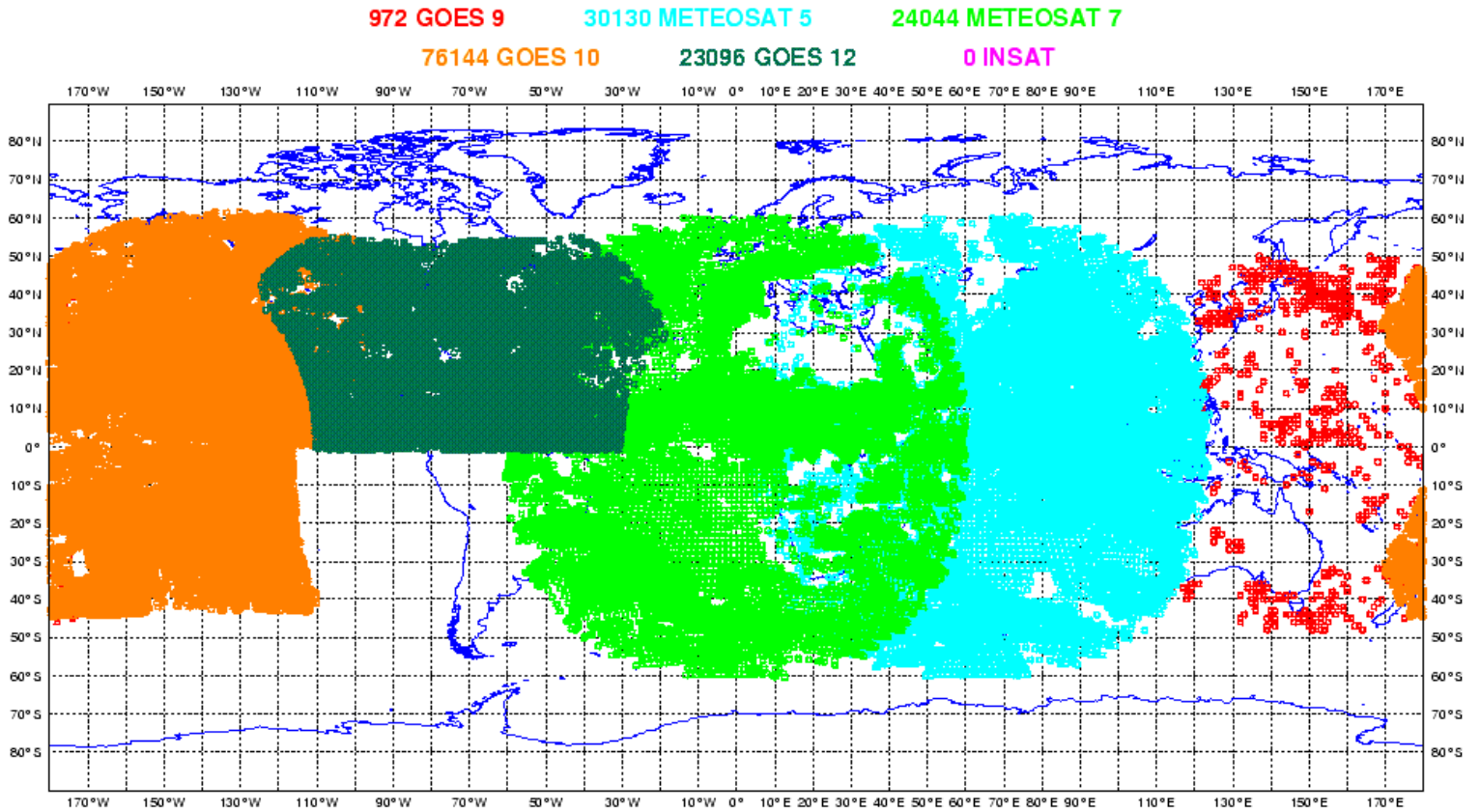

METEO-FRANCE couverture de donnees - ATOVS Bracknell HIRS

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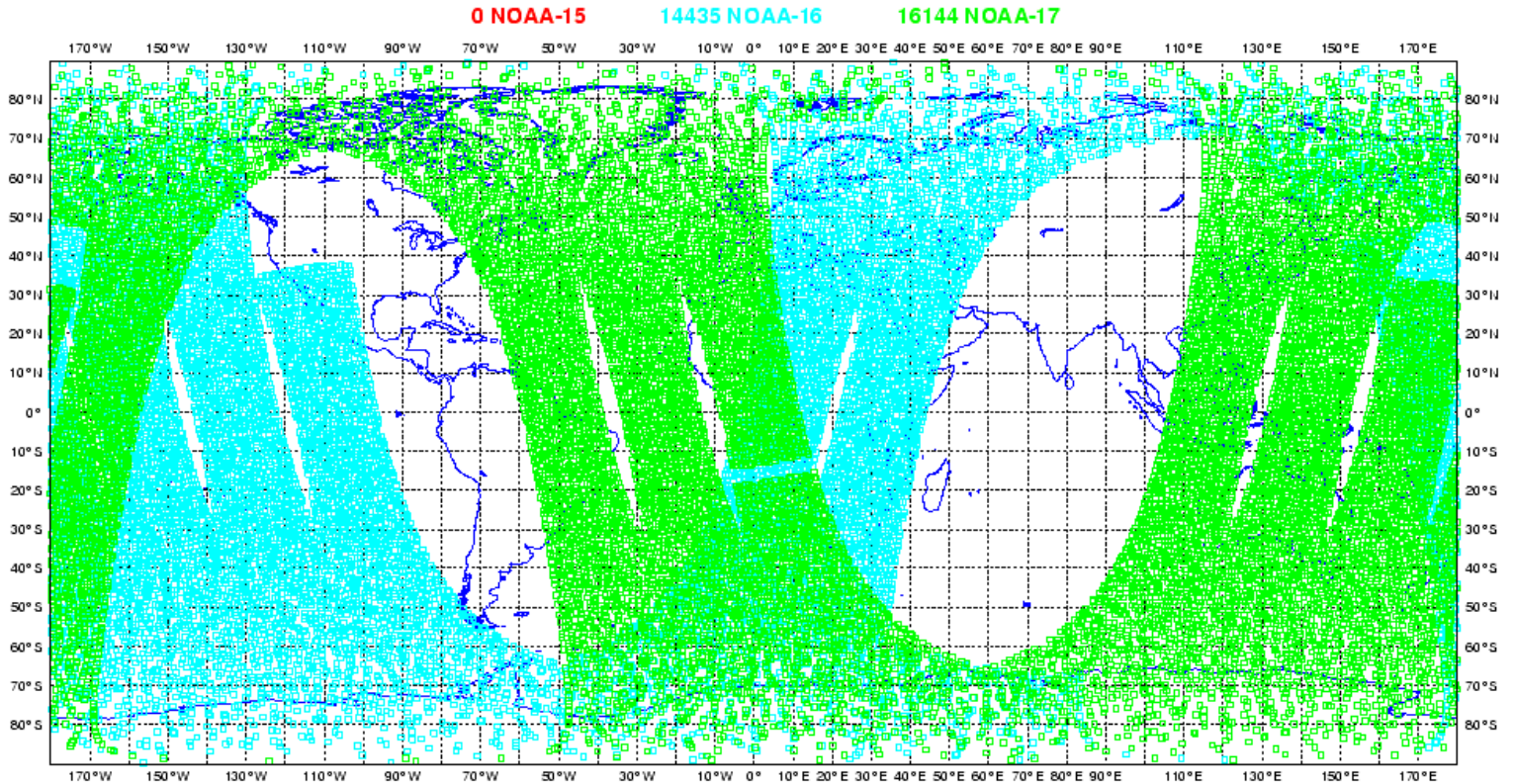

METEO-FRANCE couverture de donnees - ATOVS Bracknell AMSU-A

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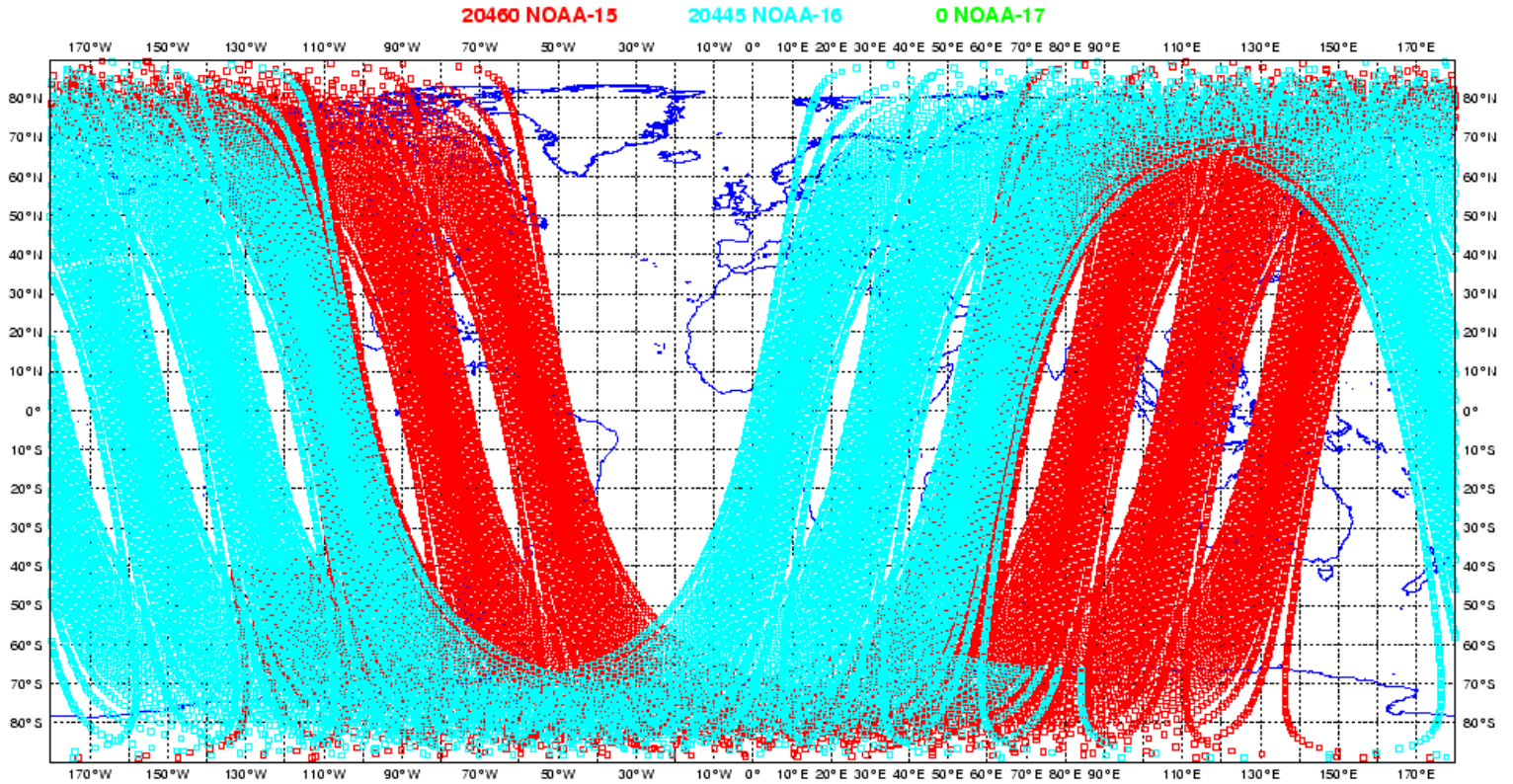


Geostationary satellites (36000 km)

- Advantages
  - Spatial coverage (complete disk)
  - High temporal resolution (a few minutes)
    - Adapted to short range forecast and nowcasting
    - Adapted to structure tracking (wind from imagery)
    - Adapted for applications where diurnal cycle is predominent
- Inconveniences
  - Constellation needed for global coverage
  - Not adapted to polar regions

Low Earth orbit satellites (400-900 km)

- Advantages
  - Global coverage
  - More adapted for sounding the atmosphere in the microwave spectrum
- Inconveniences
  - Temporal resolution (a few hours before sounding the same point)
  - Constellation necessary for an optimal temporal coverage

Space-based
Global Observing System (GOS)

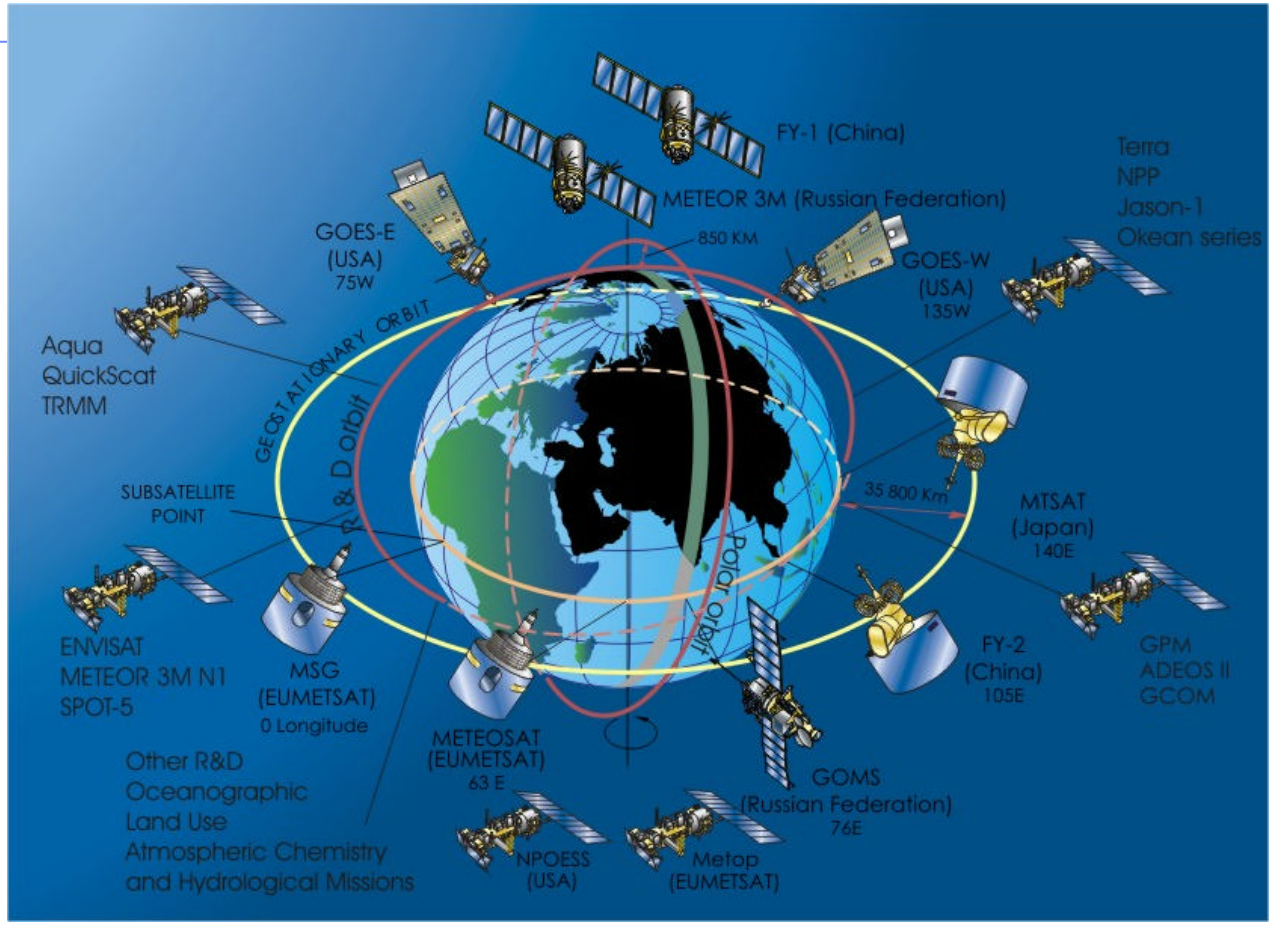
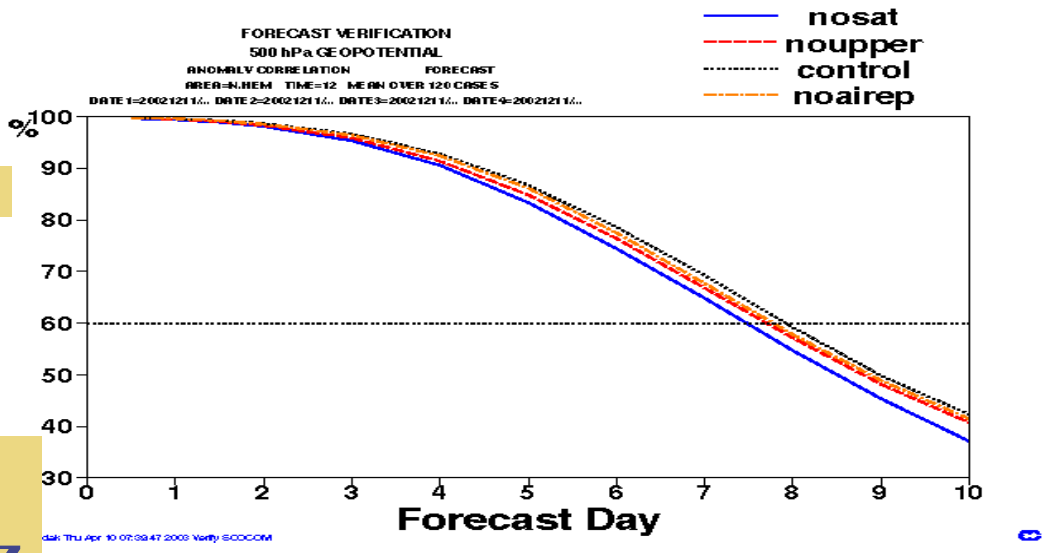


Illustration through OSEs

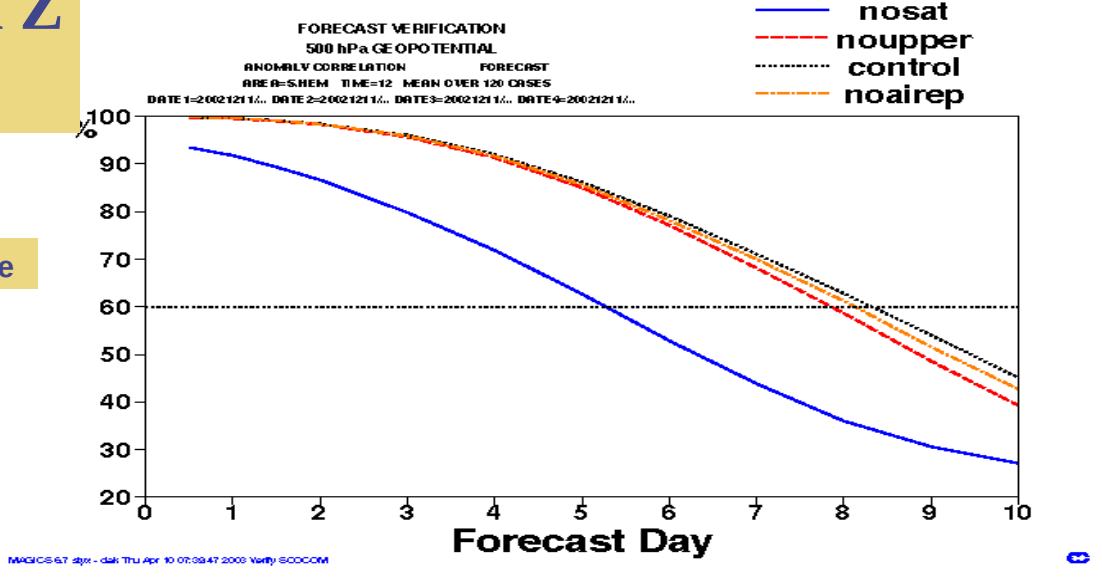
- OSE = Observing System Experiment
- Results obtained at ECMWF in 2003 with 4D-Var over 120 situations
- One type of observation is not used in operational analyses/forecasts
- Scores computed with respect to radiosonde data (continent) or with respect to operational analyses

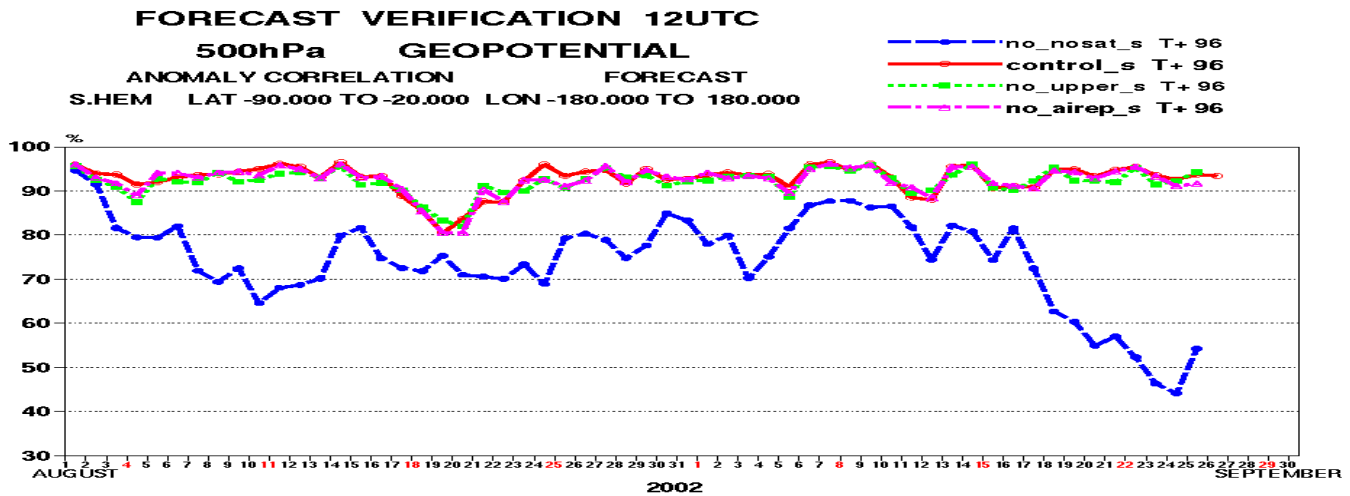
120 days 500 hPa Z scores

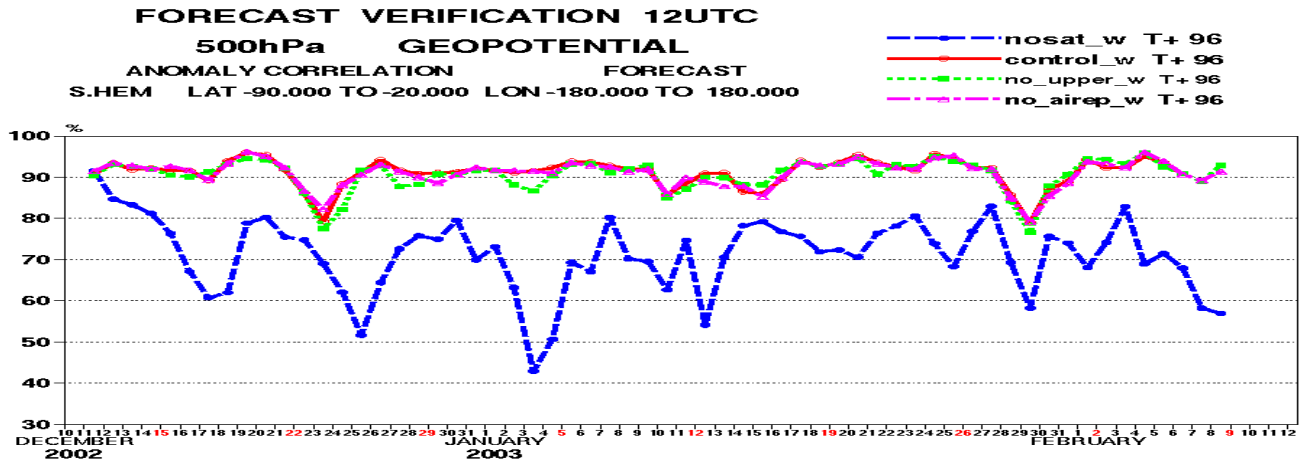
N. Hemisphere



S. Hemisphere




FORECAST VERIFICATION 12UTC
500hPa GEOPOTENTIAL
ANOMALY CORRELATION FORECAST
S.HEM LAT -90.000 TO -20.000 LON -180.000 TO 180.000
no_nosat_s T+ 96
control_s T+ 96
no_upper_s T+ 96
no_airep_s T+ 96
%
AUGUST
SEPTEMBER
2002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S.HEM LAT -90.000 TO -20.000 LON -180.000 TO 180.000
nosat_w T+ 96
control_w T+ 96
no_upper_w T+ 96
no_airep_w T+ 96
%
DECEMBER
2002
JANUARY
2003
FEBRUARY

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

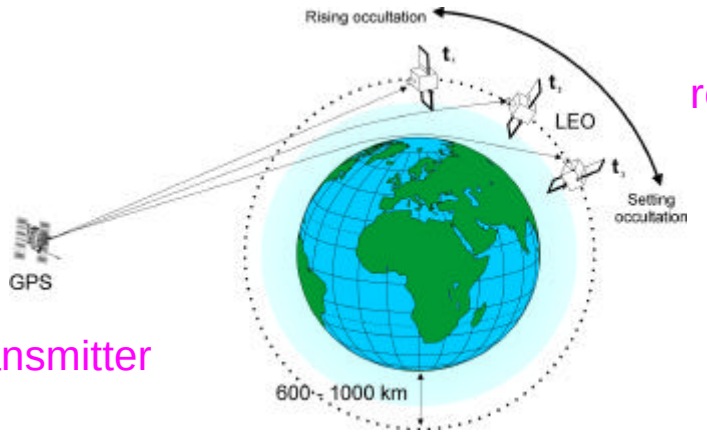
B. Principle of remote sensing

- 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 emitted 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

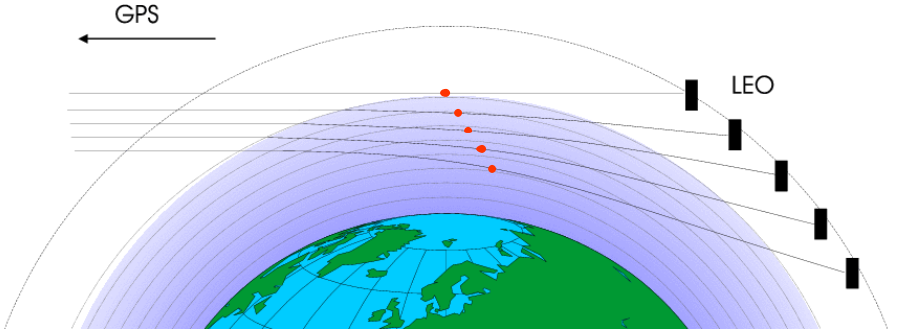
Radio occultation geometry



receiver

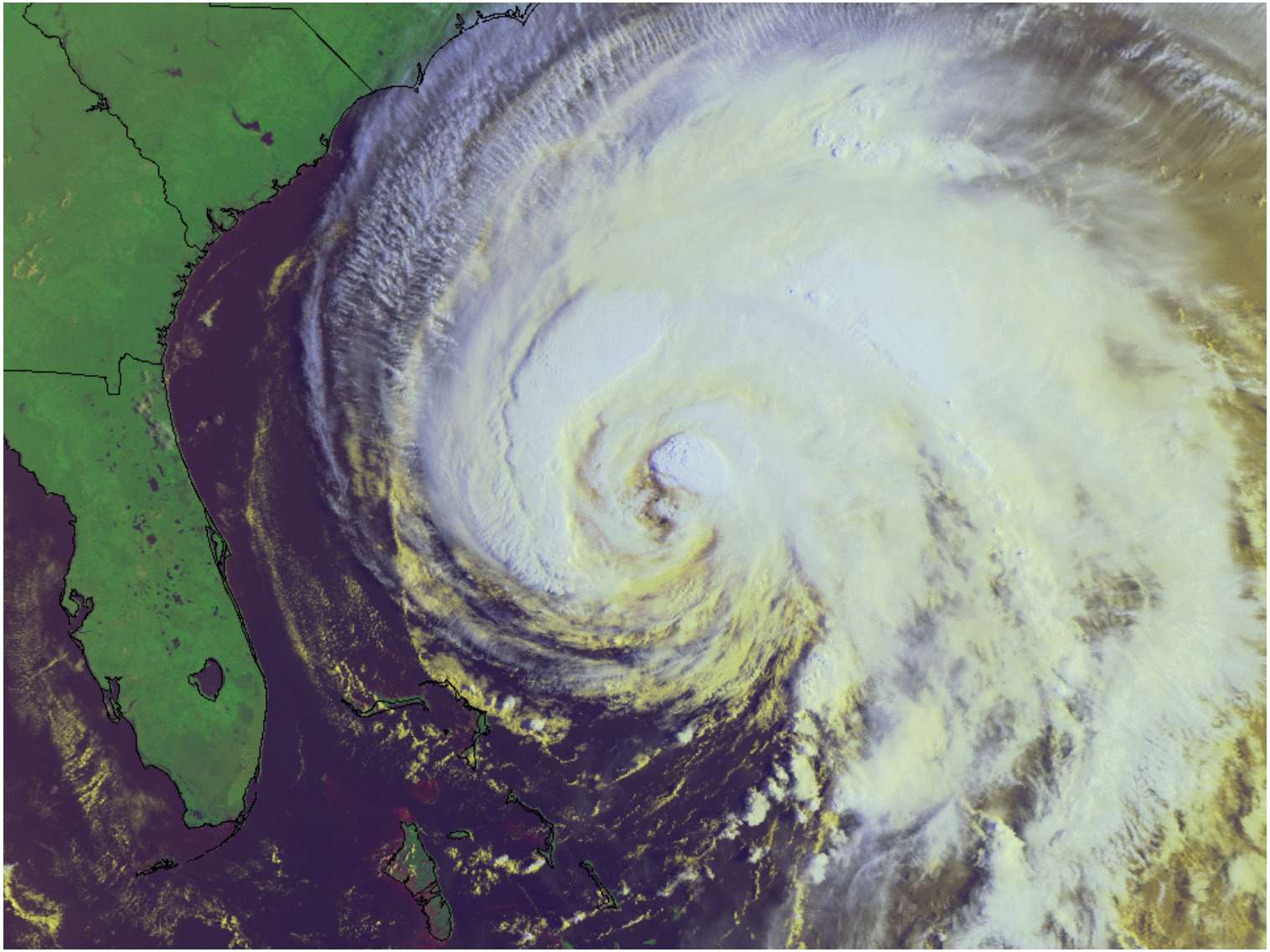
transmitter

- = the path of the ray perigee through the atmosphere



Passive remote sensing

- Thermal emission
- The infrared and microwave emission is the most useful measurement, as details of the emission spectrum strongly depend upon the molecules present in the atmosphere. Examples HIRS, AMSU-A, AMSU-B, SSM/I
- Nadir soundings: high horizontal resolution
- Limb soundings: high vertical resolution



C. Compexity of the assimilation

- Radiative transfer model (H)
- Observation weighting functions
- Convolution of H and B
- Other issues

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: $B_?(T)$= radiance emitted by a black body at temperature T for a wave number ?
- Intensity of the radiation emitted by the atmosphere at wave number ?:

$$R_? = (I_0)_? \, t_?(z_0) + \int_{z_0} B_?(T(z)) \, (dt_?(z)/dz) \, dz$$

Radiative transfer equation

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

$$R_? = (I_0)_? \, t_?(z_0) + \int_{z_0} B_?(T(z)) \, (dt_?(z)/dz) \, dz$$

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

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:

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

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

Observation weighting functions

Interpretation of the weighting functions

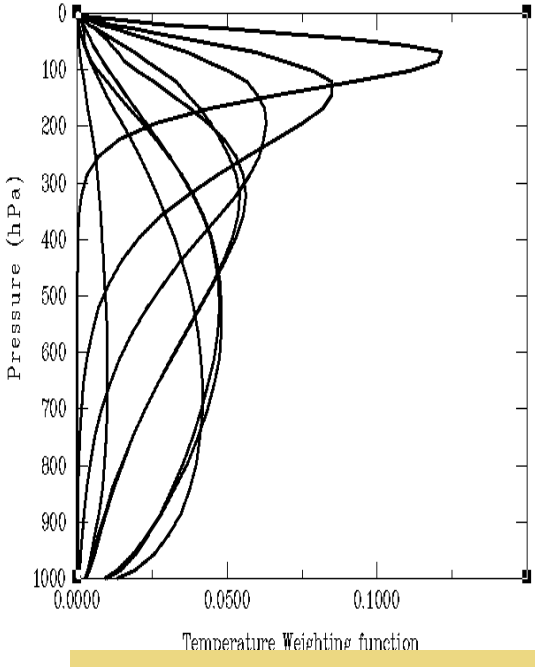
- The emission depends on three factors:
  - Temperature
  - Number of molecules of the emitting gas
  - Transmittance towards the top of the atmosphere
- Low atmosphere: high density therefore intense radiation, but most of the radiation is absorbed above
- High atmosphere: low radiation but high transmittance

Observation weighting functions

- 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

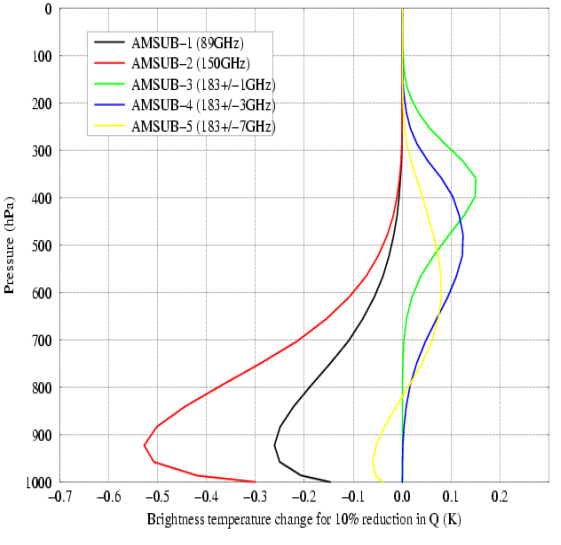
Weighting functions of AMSUA/B

AMSUA



wrt temperature

AMSUB



wrt humidity

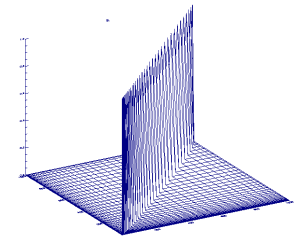
Convolution of H and B

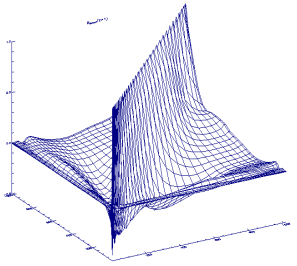
- For a given observation, first guess and associated matrices of covariance, the analysis is given by:

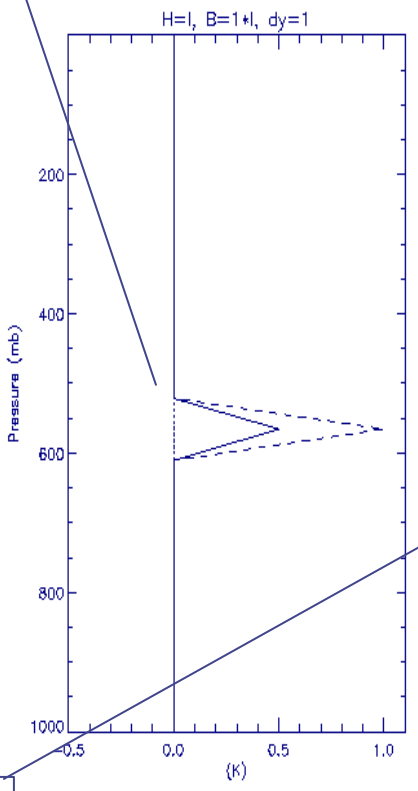
$$x_a = x_b + \frac{BH^T}{HBH^T + R}\left[y - H(x_b)\right]$$

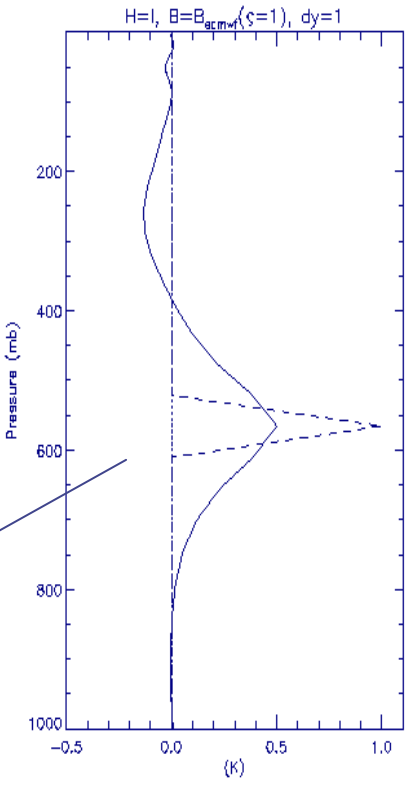
- The convolution of B and H determines how the information is spread in space

Dirac increment if H=B=I



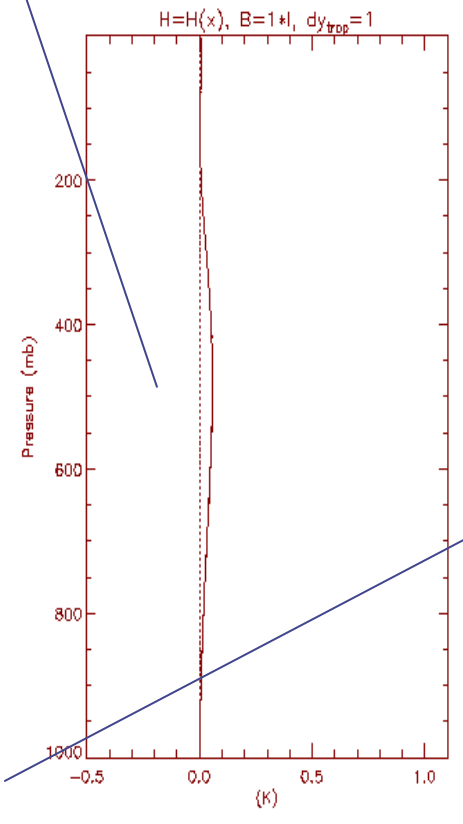


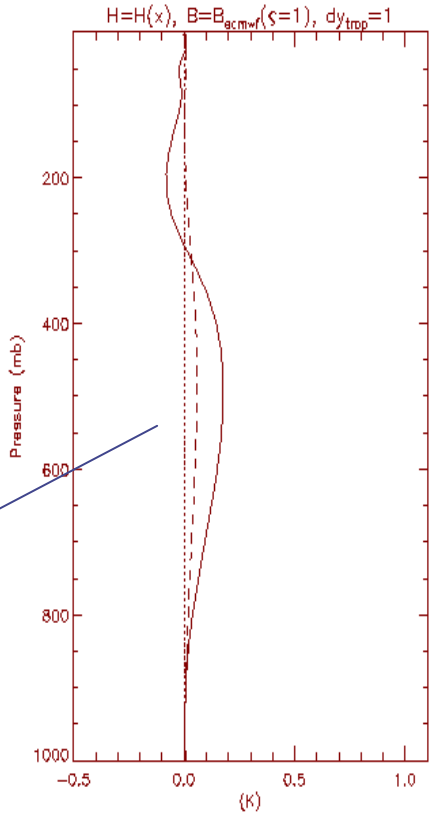




Increment propagated with the B matrix

Increment proportional to H (Jacobian proportionel to the weighting function)





Even more propagation with the B matrix

Convolution of H and B

- B and H propagate the radiance information. The estimation of B is crucial for the assimilation
- Problem even more complicated when
  - Information is temperature and humidity sensitive
  - Information is temperature, humidity, O_3, CO_2, cloud, rain, ... sensitive
  - Information must be distributed in space and time

Other issues due to complex H

- Clouds and rain contaminate infrared and microwave measurements → quality control
- Raw radiances instead of derived products
  - Expensive as RT model is called at each iteration
  - But no “incest” problem and a better error covariance matrix characterization
- Bias correction issue
  - H is often inaccurate and can introduce a bias 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

Bias correction

- Objective: correction of systematic biases between observed and simulated radiances
  - Measurement errors
  - Radiative transfer model imperfections
- Correction with respect to air mass
  - With a linear regression over a wide dataset
  - Observed data and model data (called predictors)
- Correction with respect to scanning angle
  - The two central scans are taken as references
- It is helpful to « lock » the model onto one set of observations (at present radiosondes)
  - Bias correction wrt model often but not always in the vicinity of radiosondes.

Bias correction (ATOVS)

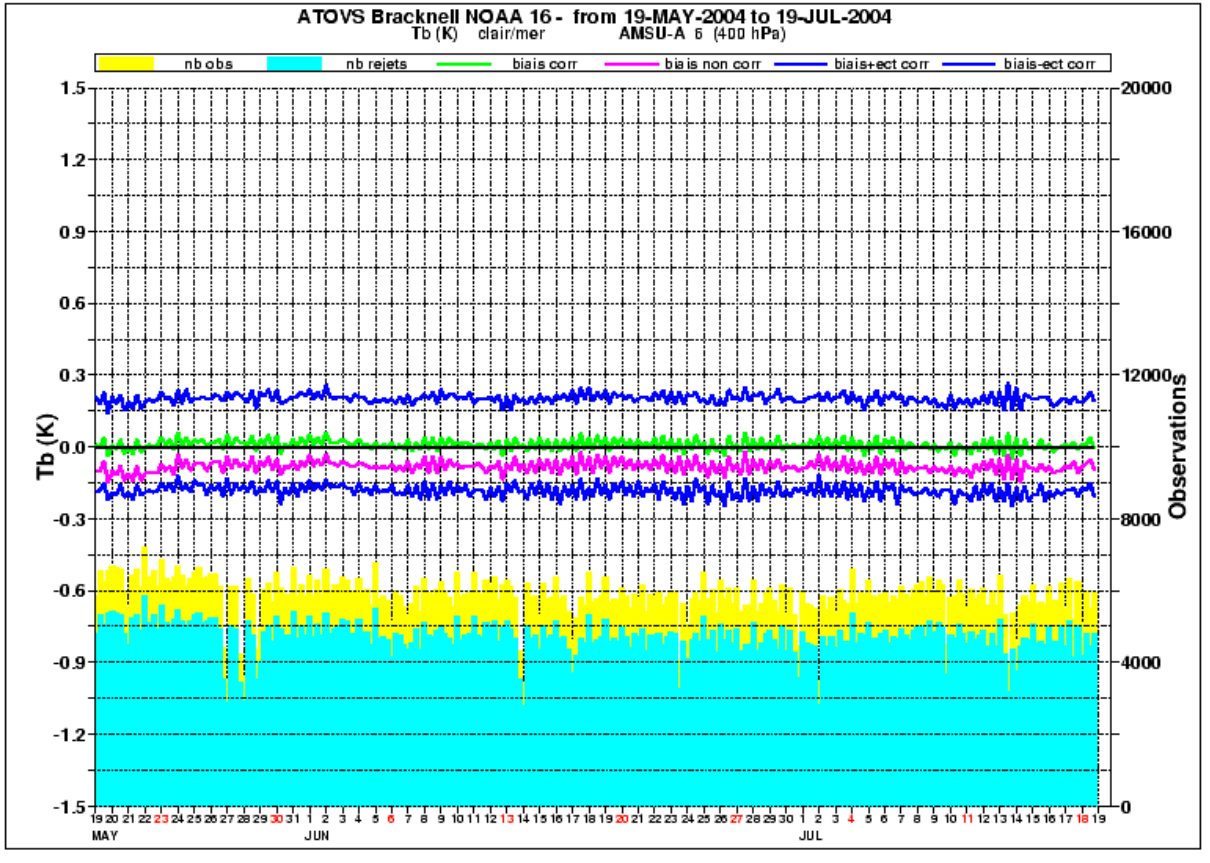
- Data selection
  - land / sea ; clear / cloudy; altitude
- Quality control
  - 150 K < Tb < 250 K; | obs - mod | < 20 K
- Predictors
  - Model thickness 1000hPa – 300 hPa
  - Model thickness 200 hPa – 50 hPa
  - Model surface temperature
  - Model total column water vapour

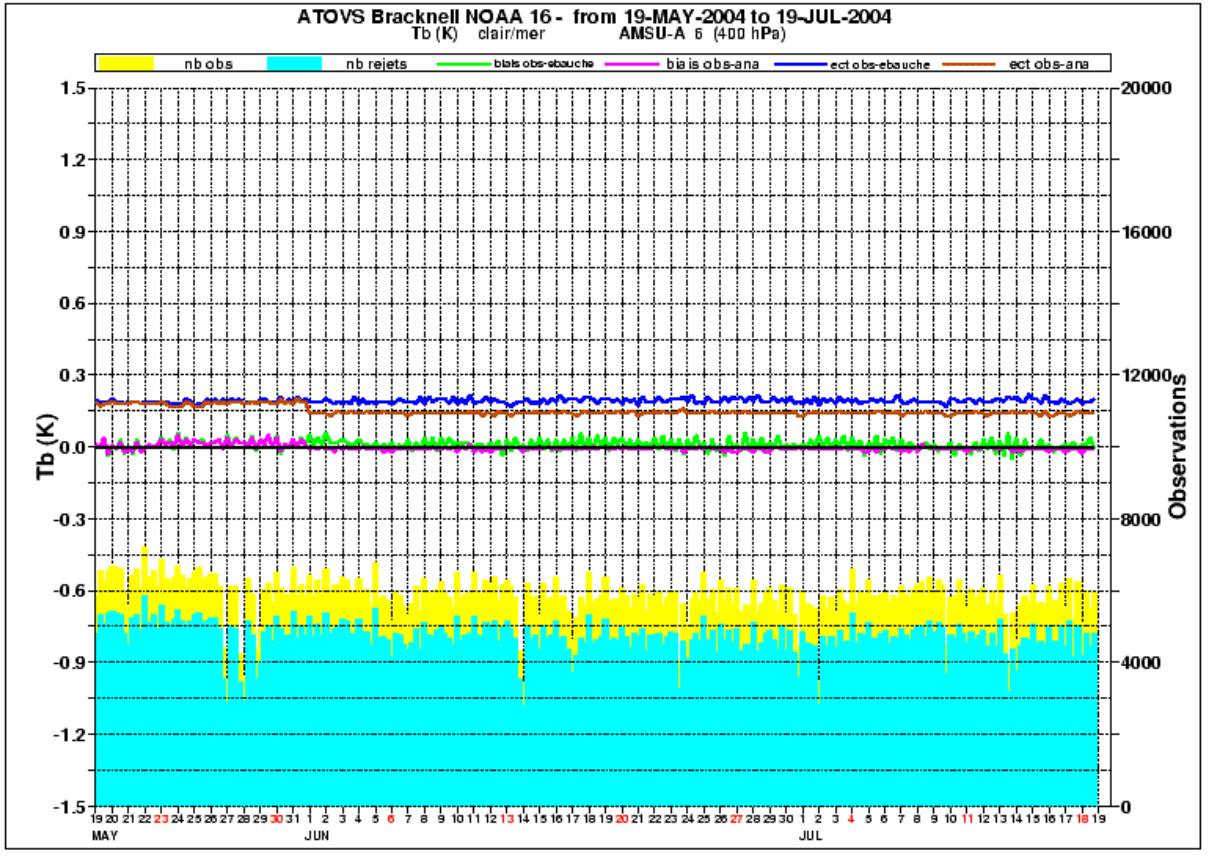
Bias correction comments

- Bias corrections are specific to one model
  - Not transferrable between NWP centres
  - Not transferrable between global and regional models
- If model is biased, do we:
  - Assimilate uncorrected data, or
  - Bias correct and assume there is useful information content in the remaining random component, or
  - Apply a reduced bias correction (e.g. by computing correction coefficients only in the vicinity of radiosondes and against analysis rather than background)?

Radiance monitoring

Before and after bias correction



Radiance monitoring

Before and after assimilation