Satellite Data Assimilation Overview

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with thanks to:
ECMWF Satellite Section
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Outline

- Introduction to the Satellite Observing System
- What do satellite data measure?
  - Observing techniques
  - Inversion techniques
- Importance of satellite data in current NWP data assimilation systems
  - Data volume
  - Information content
  - Impact studies
- Assimilation of satellite data: current issues
- Future evolution and challenges

Introduction to the Satellite Observing System

- **Two different types of space agencies**
  - ➔ Research Agencies
  - ➔ Operational Agencies

- **Two ways of looking at the earth/atmosphere**
  - ➔ GEO (geostationary satellites)
  - ➔ LEO (low earth observing satellites)

RESEARCH AGENCIES

- **NASA: National Aeronautics and Space Administration**
- **NASDA: National Space Development Agency (soon JAXA: Japanese Aerospace eXploration Agency)**
- **ESA: European Space Agency**
- **…(several other national agencies)**

• Research Agencies promote demonstration missions, with innovative technologies

• Research instruments can provide independent information for model and/or other observations validation

• Near Real Time delivery of data is not necessarily a priority

• Research satellites pioneer future operational missions

• In principle, the life time of research missions is short (<10 years)

OPERATIONAL AGENCIES

- **EUMETSAT: EUrope's METeorological SATellite organisation**
- **NOAA: National Oceanic and Atmospheric Administration**

  ➔ NOAA-NESDIS-DMSP
- **JMA: Japan Meteorological Agency**
- **Russia, China,…**

• Operational Systems inherit from Research demonstration missions

• Operational Satellites are committed to Real Time delivery to end-users

• Operational missions ensure a stabilised long-life mission technology (HIRS instrument onboard NOAA satellites has lasted for ~30 years)

Operational versus Research Agencies

- Thanks to a WMO initiative, R&D satellites are now fully considered as part of the Global Observing System
  - Should ease the transition from research to operations
  - Has implications on NRT delivery requirements
- Operational centres use pragmatically R&D instruments:
  - for model validation (POLDER, CERES,…)
  - for data assimilation (ERS, QUIKSCAT, AIRS,…)

GEOSTATIONARY OBSERVING SYSTEMS

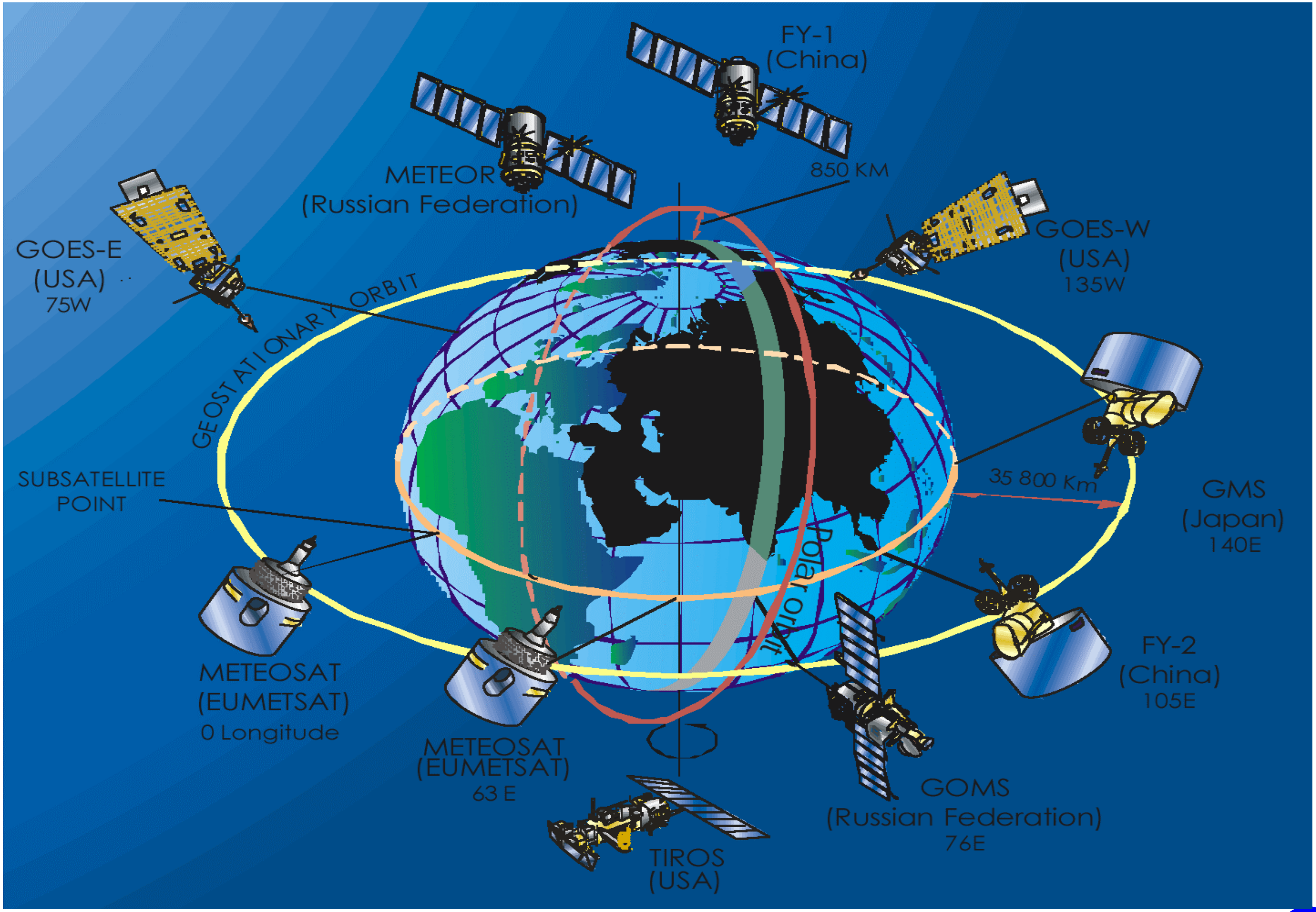
(36 000 km from the earth)

- **Advantages:**
  - **Wide space coverage (whole disk)**
  - **Very high temporal coverage (a few minutes)**
    - Particularly suitable for short-range NWP and Now-casting applications
    - Suitable also for meteorological feature tracking
      - (**Atmospheric Motion winds**)
    - Suitable for applications in which the diurnal cycle representation is crucial
- **Drawbacks:**
  - **Spatial coverage limited to the disk (need for constellation)**
  - **Unsuitable to observe the polar regions**

Low Earth Orbiting OBSERVING SYSTEMS
(400 to 800 km from the Earth)

- Advantages:
  - Cover the whole earth after several cycles (polar orbiting satellites)
  - More suitable to sound the atmosphere in the microwave spectrum.
- Drawbacks:
  - Moderate temporal sampling (several hours to go back to the same point)
  - Requires constellation to ensure a reasonable temporal sampling

Current Space based Observing System



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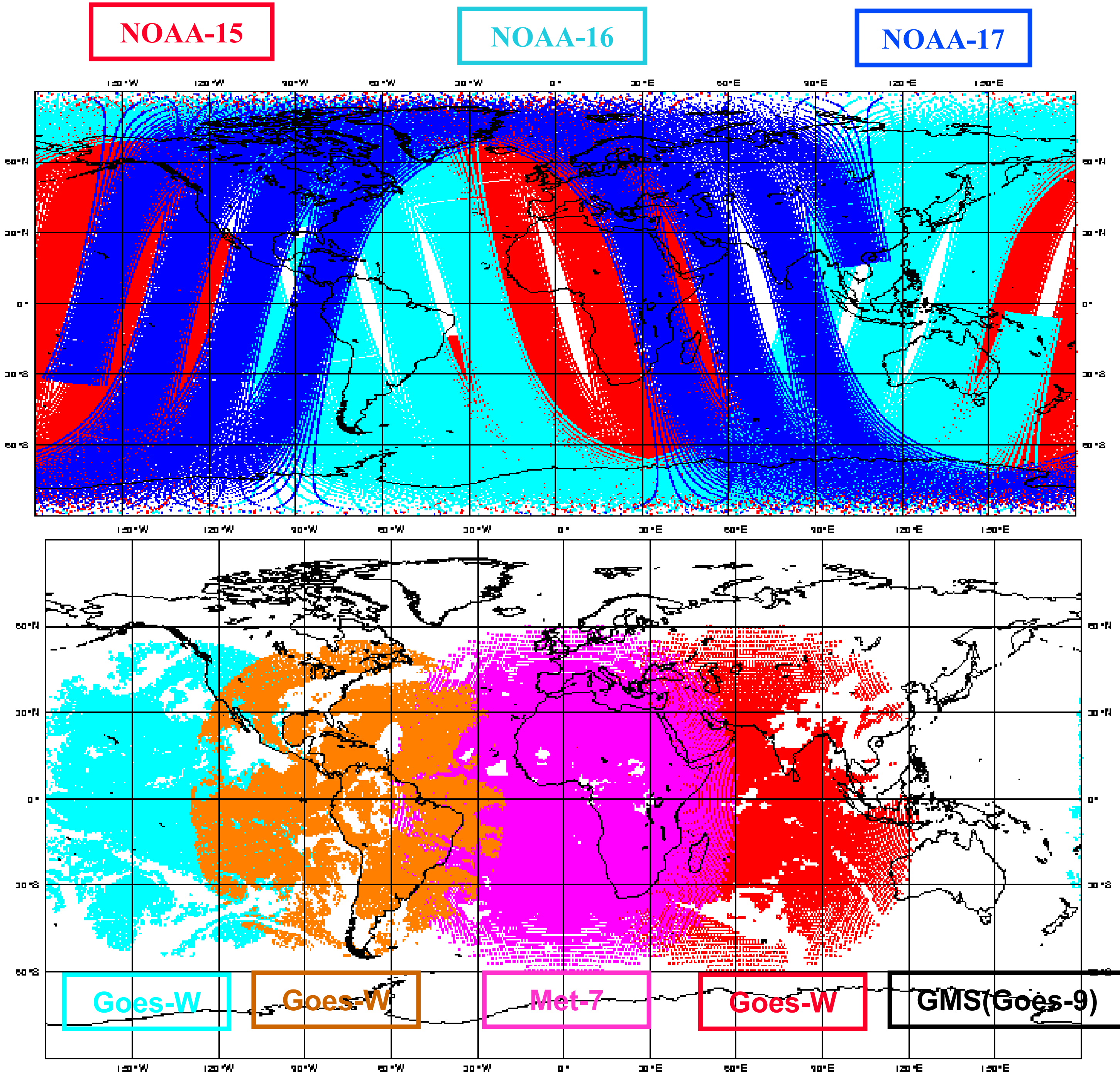

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Outline

- Introduction to the Satellite Observing System
- **What do satellite instruments measure?**
- Importance of satellite data in current NWP data assimilation systems
- Assimilation of satellite data: current issues
- Future evolution and challenges

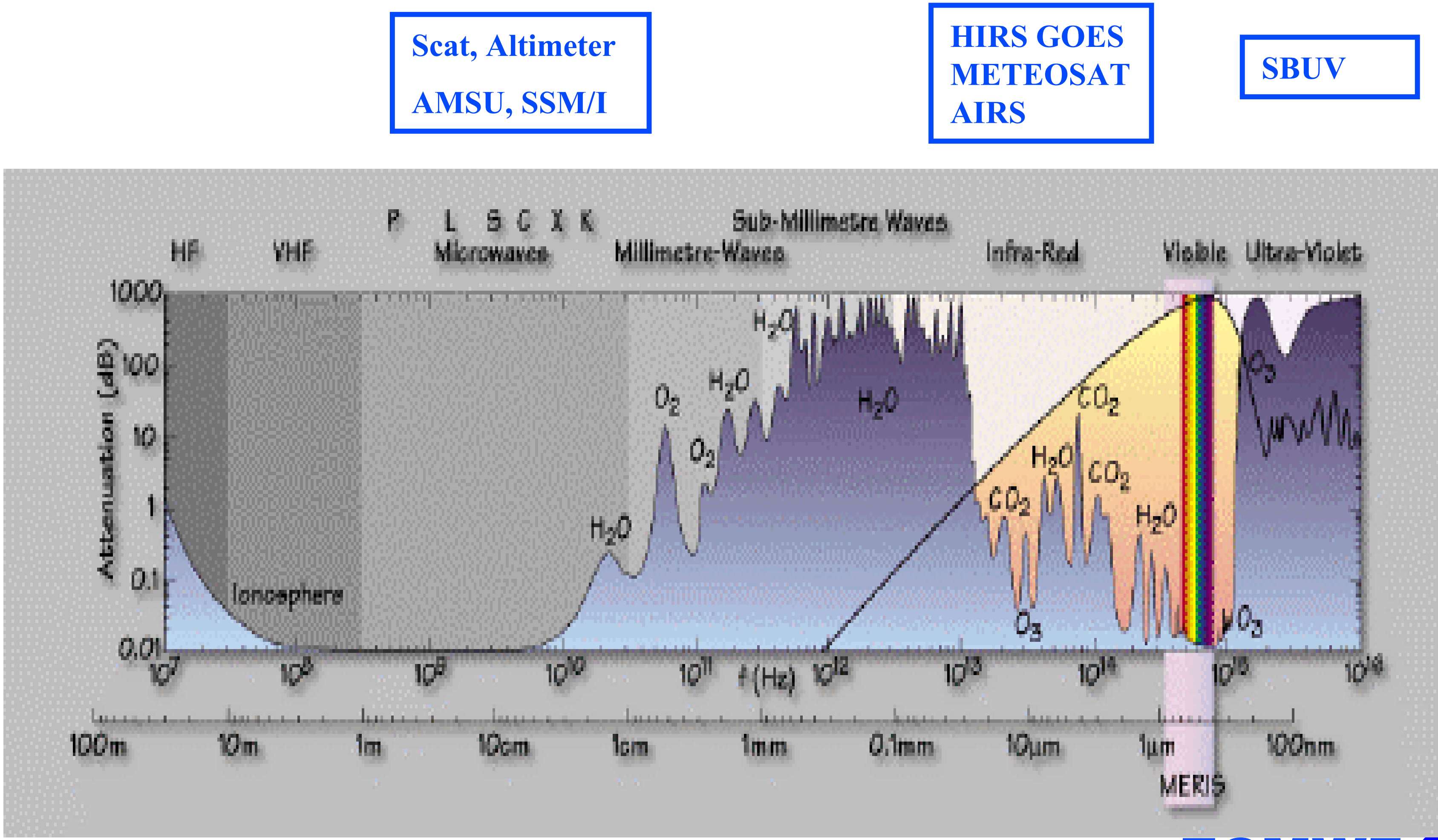
What do satellite instruments measure?

- Satellite instruments are specific in that they do not measure directly geophysical quantities (temperature, moisture, ozone, wind,…)
- Satellite instruments measure the radiation emitted by the Earth/Atmosphere
- The conversion of this measurement into a geophysical information is an inverse problem
- Data assimilation techniques try to solve this inverse problem as "optimally" as possible

$Y_b = H(X_b)$ Forward modelling problem (Radiative Transfer Equation)

$X_a = H^{-1}(Y_{obs})$ Inverse problem (need for prior information)

- **Depending on the wavelength, the radiation at the top of the atmosphere is sensitive to different atmospheric constituents**



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Three ways of sensing the Earth/Atmosphere

- **Passive technologies**
  - **Passive instruments sense the:**
    - natural radiation emitted by the Earth/Atmosphere
    - solar radiation reflected by the Earth/Atmosphere
- **Active technologies**
  - **Active instruments:**
    - Emit radiation towards the Earth/Atmosphere
    - Sense how much is scattered (or reflected) back
- **GPS technologies**
  - **GPS receivers:**
    - Measure the phase delay of a GPS signal when refracted through the atmosphere

Passive technologies

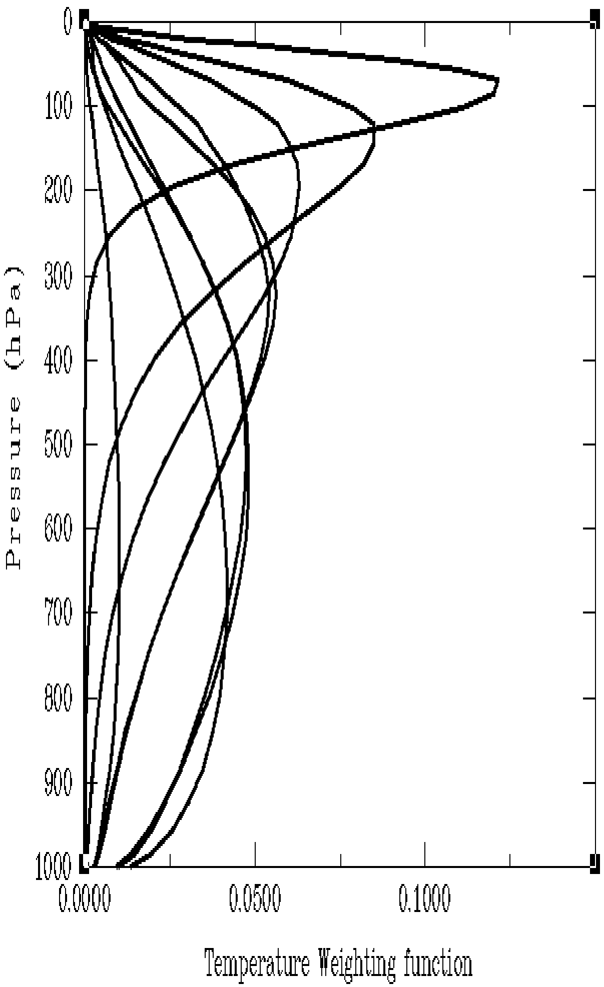
- "Imaging" instruments
  - Sense in spectral "window" regions where the atmosphere is close to transparent, therefore sense essentially the surface emission
  - Provide indirectly information on:
    - VIS/IR: surface temperature, cloud top, wind (through cloud motion), snow/ice, vegetation
    - μW: surface ocean wind speed, sea-ice, total column water vapour, cloud liquid water, rain
  - Vis/IR instruments: AVHRR on NOAA, MODIS on TERRA/AQUA, GOES+METEOSAT/MSG,…
  - Microwave instruments: SSM/I on DMSP, TMI on TRMM, AMSR on AQUA and ADEOS-2,…

Passive technologies

- “sounding” instruments
  - **Sense in spectral regions where the contribution from the surface is negligible (strong atmospheric absorption bands)**
  - **Provide indirectly information on:**
    - IR: profiles of temperature-humidity-ozone, surface temperature (limited to non cloudy areas)
    - µW: temperature and humidity profiles (limited to non rainy areas)
  - **IR instruments: HIRS on NOAA, AIRS on AQUA, GOES,…**
  - **Microwave instruments: AMSU-A, AMSU-B on NOAA,…**

Passive sounding instruments: AMSU-A

- Sense radiation from different atmospheric layers by selecting different absorption bands



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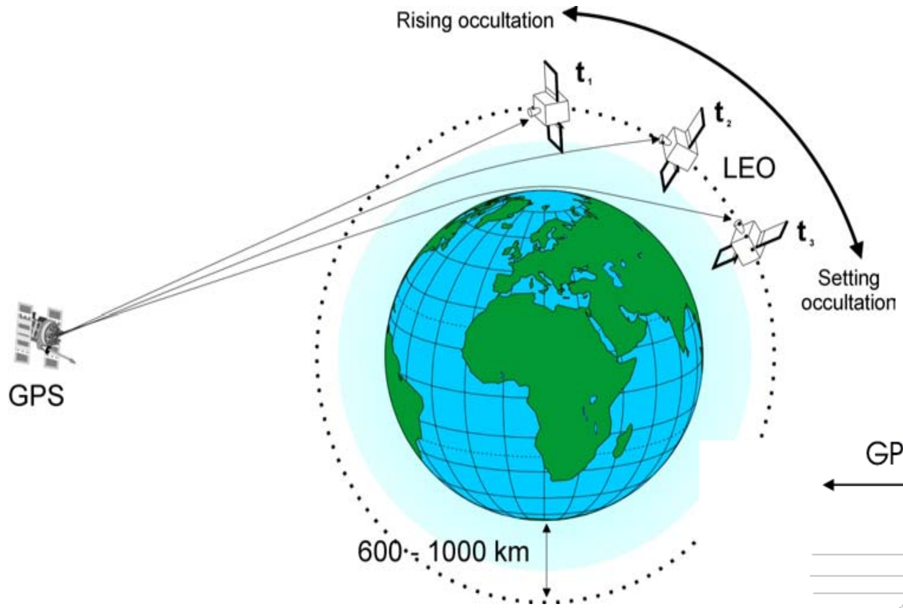
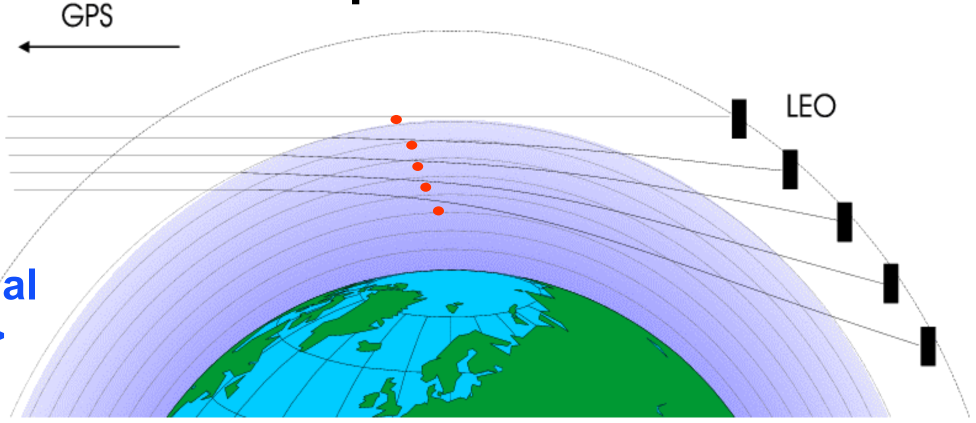
Active technologies

- **Active instruments**
  - **Send radiation to a target (Earth/Atmosphere) and measure what is back reflected/scattered.**
  - **Provide indirectly information on:**
    - Surface wind (scatterometers, radar altimeter)
    - Sea surface height, wave height and spectra (altimeters, SARs)
    - Rain, cloud and aerosol profiles (radars, lidars)
    - Atmospheric wind profiles (Doppler lidars)
    - Moisture profiles (DIALS)
  - **TRMM-PR, ERS-2 (Scat/RA/SAR), SeaWinds on QuikScat and ADEOS-2, ENVISAT (RA-2, ASAR)**

GPS radio occultation technologies



• = the path of the ray perigee through the atmosphere



- GPS-MET, CHAMP
- The impact of the atmosphere on the signal propagation depends on the refractivity => the vertical profile of the refractivity (and further down temperature, humidity and pressure) at the location of the ray perigee can be inverted from the observation

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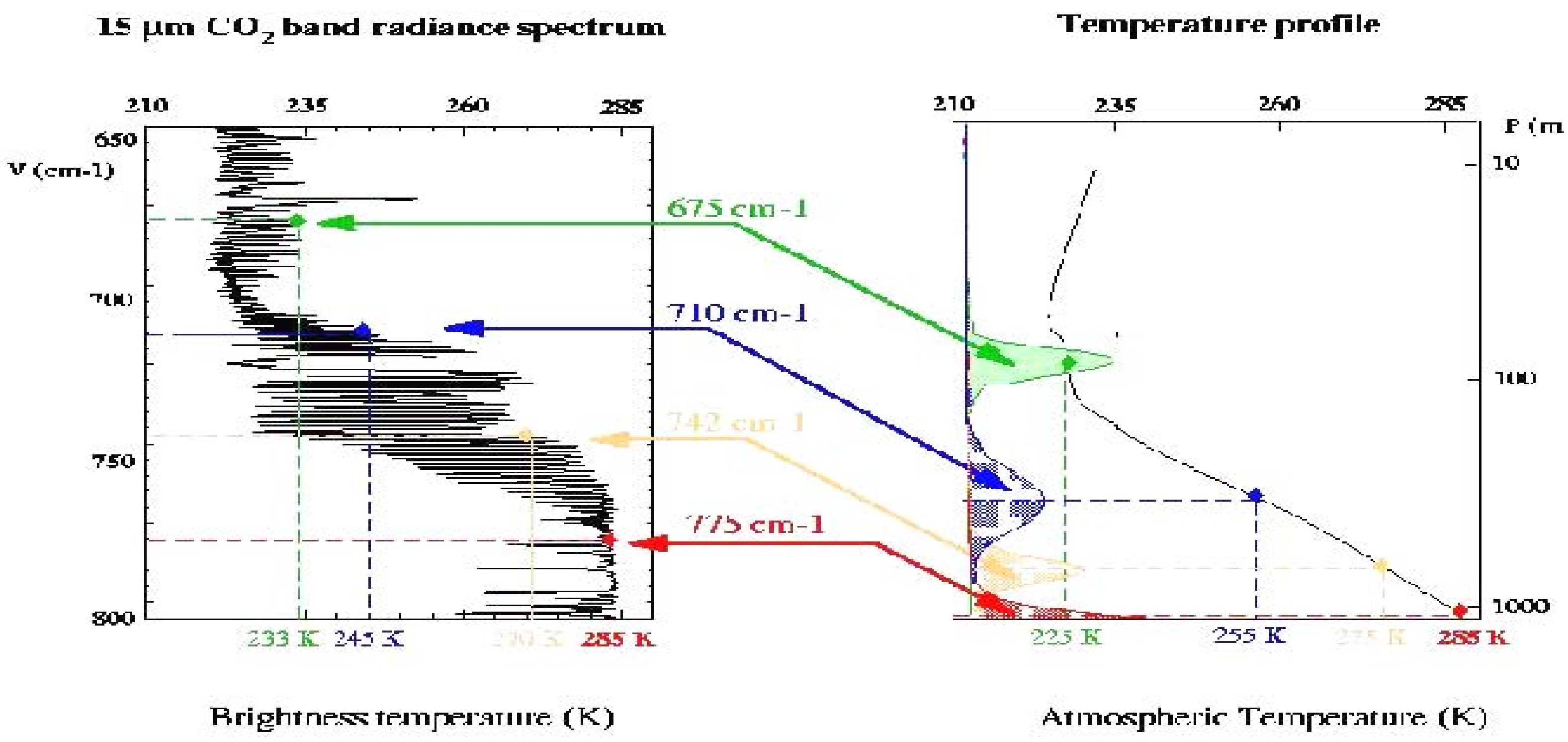
GPS radio occultation technologies

- GPS receivers on LEO work in the following way:
  - Sense the phase delay of a radio signal as its propagation path descents or ascents through the atmosphere and derives the bending angle of the ray propagation path
  - The impact of the atmosphere on the signal propagation depends on the refractivity => the vertical profile of the refractivity (and further down temperature, humidity and pressure) at the location of the ray perigee can be inverted from the observation
  - RO is self calibrating (because the it is based on change rate of the phase delay and not on absolute phase) and provides high vertical resolution
  - GPS-MET, CHAMP,…

Inversion Techniques

- Atmospheric/Oceanic models need initial conditions in terms of geophysical parameters
- Data assimilation solves this inverse problem



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Inversion Problem: Example

Given one observation y (radiance), a background x_b (temperature/moisture/ozone/surface pressure/…) , R and B the associated error covariances,

The analysis equation reads:

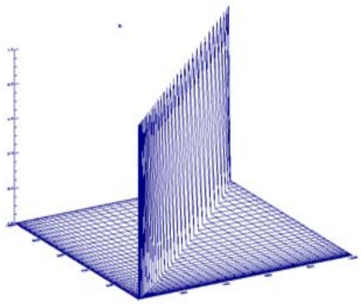
$$x_a = x_b + \frac{BH^T}{HBH^T + R}\left[y - H(x_b)\right]$$

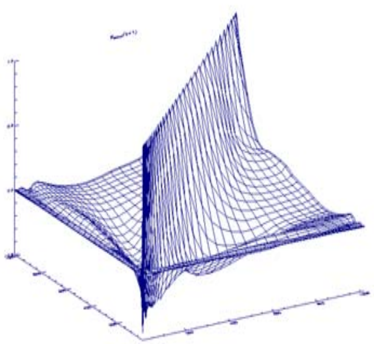
The convolution of B and H will determine how a given measurement information will be distributed in space and among different geophysical quantities

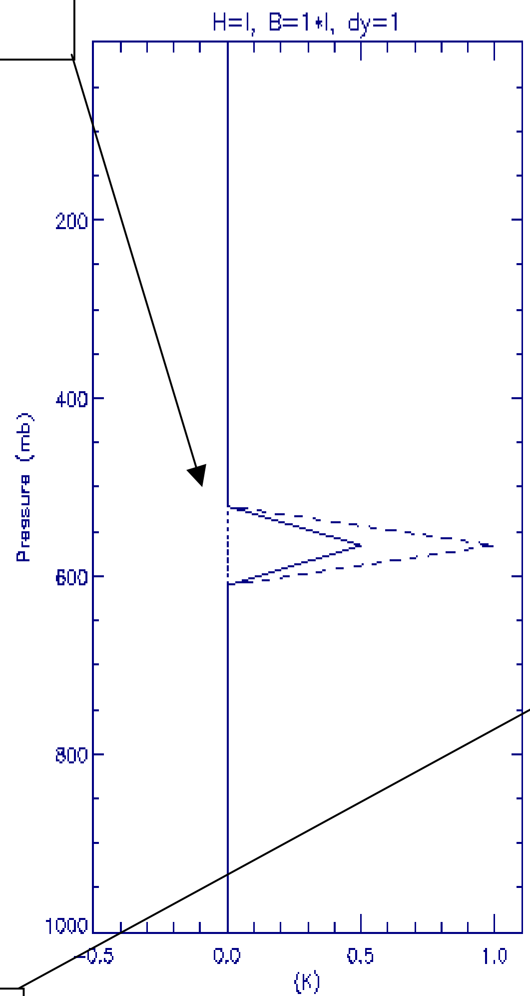
Inversion Problem: Example

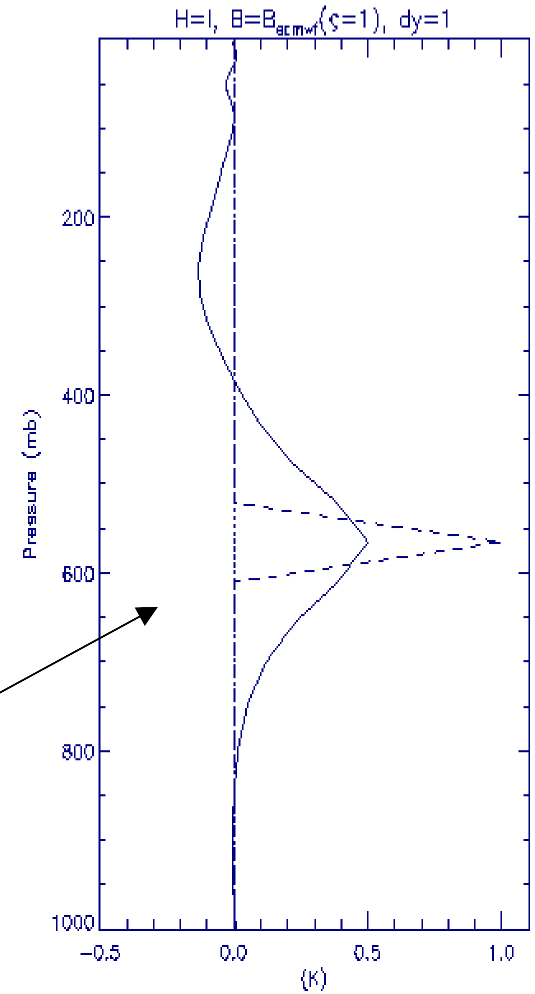
Straight Dirac increment

If H=B=I









Increment propagated with ECMWF B

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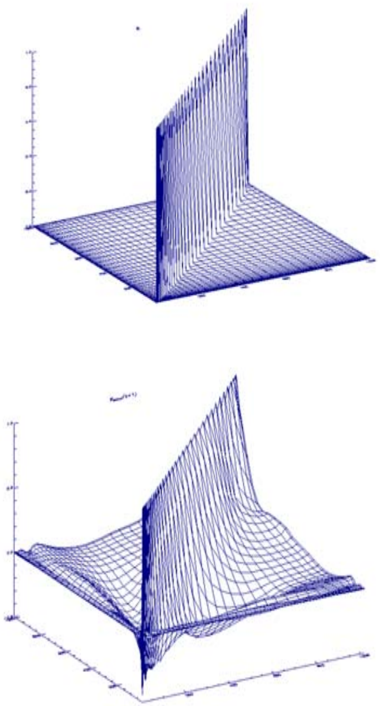
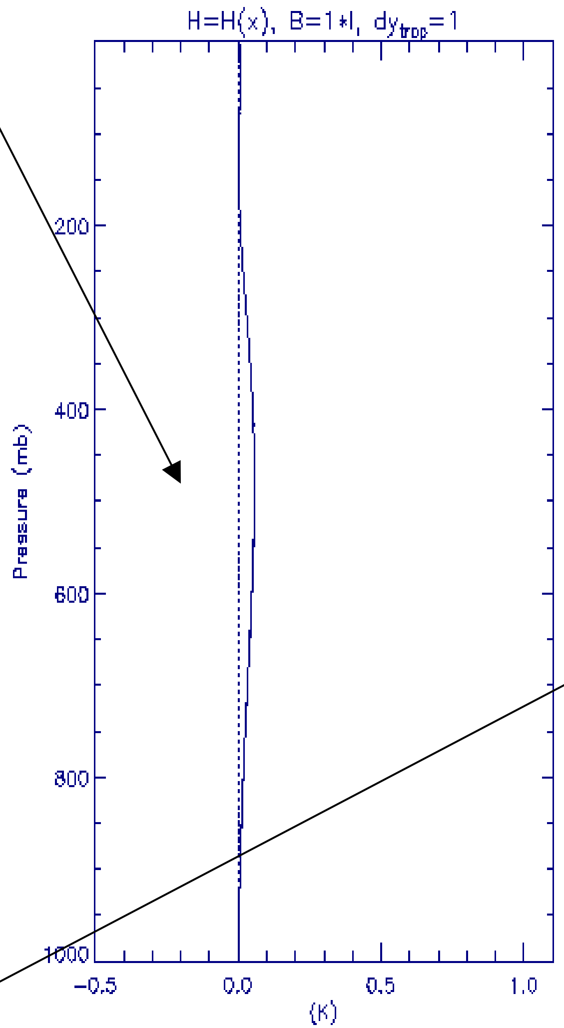
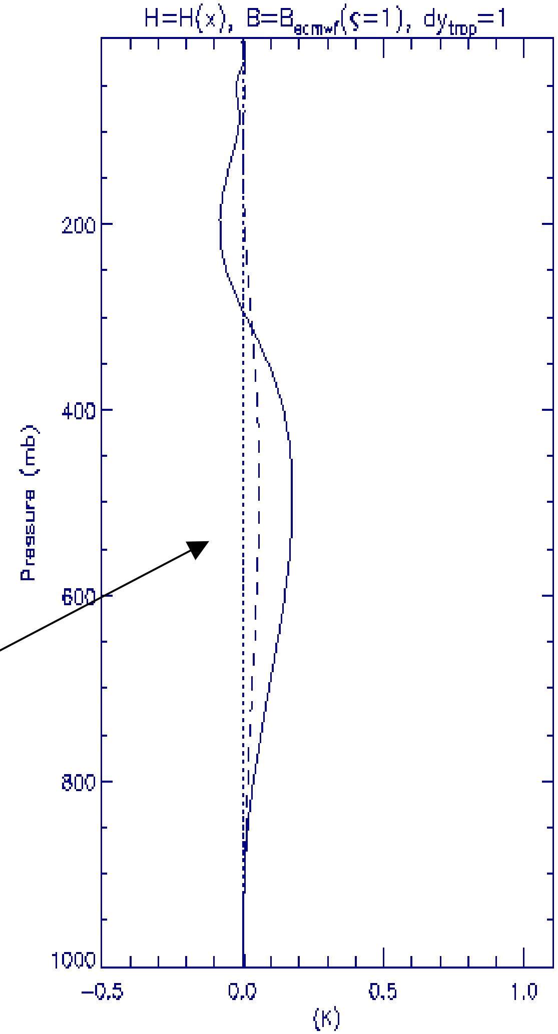
Inversion Problem: Example

Broad increment proportional to H (Jacobian proportional to weighting function)







Further spread of increment propagated with ECMWF B

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Inversion problem: Importance of *B*

- ***B*** **together with H will propagate the information coming from the satellite radiances that can sense very broad atmospheric layer. Modelling of *B* is therefore crucial for a proper assimilation of satellite radiances**
- **Problem even more complicated when:**
  - ➔ radiance information has to be distributed in temperature and moisture
- **Problem even even more complicated when:**
  - ➔ Radiance information has to be distributed in temperature, moisture, ozone, CO2, cloud, rain,…
- **Problem even even even more complicated when:**
  - ➔ Radiance information has to be distributed in space and time

Inversion Techniques

- Data assimilation in some way or another converts radiance measurements in temperature/moiture/winds,…
- Different possibilities
  - Use of externally generated retrievals
  - Use of interactive retrievals (e. g. 1D-Var retrievals)
  - Direct use of radiances (e.g. 3D-Var or 4D-Var)
- In NWP at least, the direct assimilation of satellite raw radiances has progressively replaced the assimilation of retrievals

Inversion Techniques

- **The direct assimilation of radiances has several advantages over that of retrievals:**
  - ➔ avoid the contamination by external background information for which error characteristics are poorly known
  - ➔ Avoid further complicated errors entailed by the processing of the data provider
  - ➔ Avoid vulnerability to changes in the processing of the data provider
  - ➔ Allow a faster implementation of new data (no delay due to readiness of pre-processing)
  - ➔ 3D and 4D-Var allow for some (weak) non linearities in the observation operator
  - ➔ Increments further constrained by many other observations/information

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Inversion Techniques

- **Exceptions exist:**
  - **Atmospheric Motion Vectors from geostationary satellites**
    - Poor ability to represent clouds in observation operators
    - Very easy to implement in the system (e.g. MODIS polar winds)
  - **Surface Winds from Scatterometers**
    - Observation operator highly nonlinear
    - Validation easier with ancillary data
  - **Ozone information from UV instruments**
    - Poor modelling of the Radiative Transfer in the UV
- **The approach has to be based on pragmatism**

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ECMWF operations September 2003 (26R3)

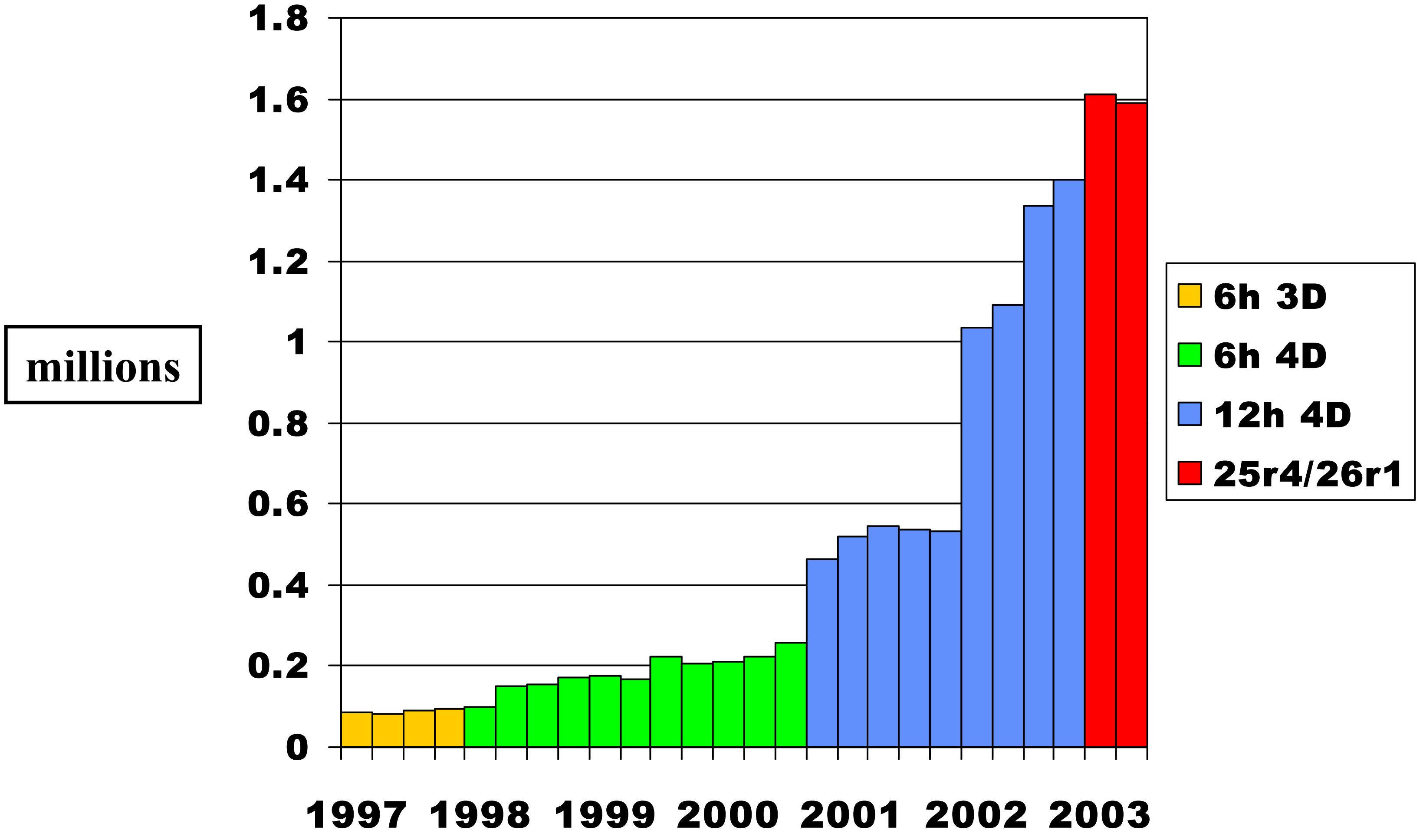
- AQUA AIRS
- **3xAMSUA (NOAA-15/16/17) +** AQUA AMSUA
- **3 SSMI (F-13/14/15)**
- **2xHIRS (NOAA-16/17)**
- 2xAMSU-B (NOAA-16/17)
- **Radiances from 5xGEOS (Met-5/7 GOES-9/10/12)**
- **Winds from 4xGEOS (Met-5/7 GOES-10/12)and MODIS/TERRA**
- **SeaWinds from QuiKSCAT**
- **ERS-2 Altimeter / SAR (limited coverage)**
- **SBUV (NOAA 16)**
- ENVISAT OZONE (MIPAS)

27 satellite data sources!

Observations used at ECMWF

Boundary & Initial Field	Conventional Observations	Current Satellites Or Instruments	Future Satellites Or Instruments
Orography Surface Type/Veg. Snow Cover Soil Moisture Albedo	SYNOP (T_{2m},RH_{2m}) Manual OBS	GPS AVHRR, MODIS, AIRS AVHRR, SSM/I METEOSAT, GOES, GMS	IASI,CrIS,GIFTS,polder SMOS SEVIRI
SST/salinity Sea Ice Cover Waves / Roughness	Ship, Buoy	AVHRR, ATSR, AATSR SSM/I, AVHRR, AMSR Alt, SAR, RA2, ASAR	SMOS,Jason-2… SSM/IS
Wind	RS, Aircraft, Pilot Profiler, SYNOP, Ship, Buoy	AMVs (GEO/MODIS), SSM/I, ERS, QuikScat Adeos-2, Windsat	ADM-AEOLUS, ASCAT
Temperature	RS, Aircraft, SYNOP	AMSU-A, HIRS, AIRS MODIS	IASI, CrIS, GIFTS, SSM/IS, GRAS, ACE+,…
Humidity	RS, SYNOP	HIRS, AMSU-B, METEOSAT SSM/I, GOES,AIRS, MODIS	IASI, MHS, SSM/IS, SEVIRI, GRAS, ACE+,…
Clouds/aerosols	SYNOP	AVHRR, HIRS, GEO Sat. MODIS, AIRS	IASI, CrIS, GIFTS,Earthcare SEVIRI, CLOUDSAT,polder Calipso,…
Rain	Rain gauges	TRMM/TMI, SSM/I	SSM/IS, AMSR, (E)GPM
Ozone / Chemical Species	Ozone sondes	SBUV, SCIA, AIRS HIRS-9, MIPAS, GOMOS	IASI, OMI, OMPS, GOME-2 ...

Number of observational data used in the ECMWF assimilation system (prior AIRS)



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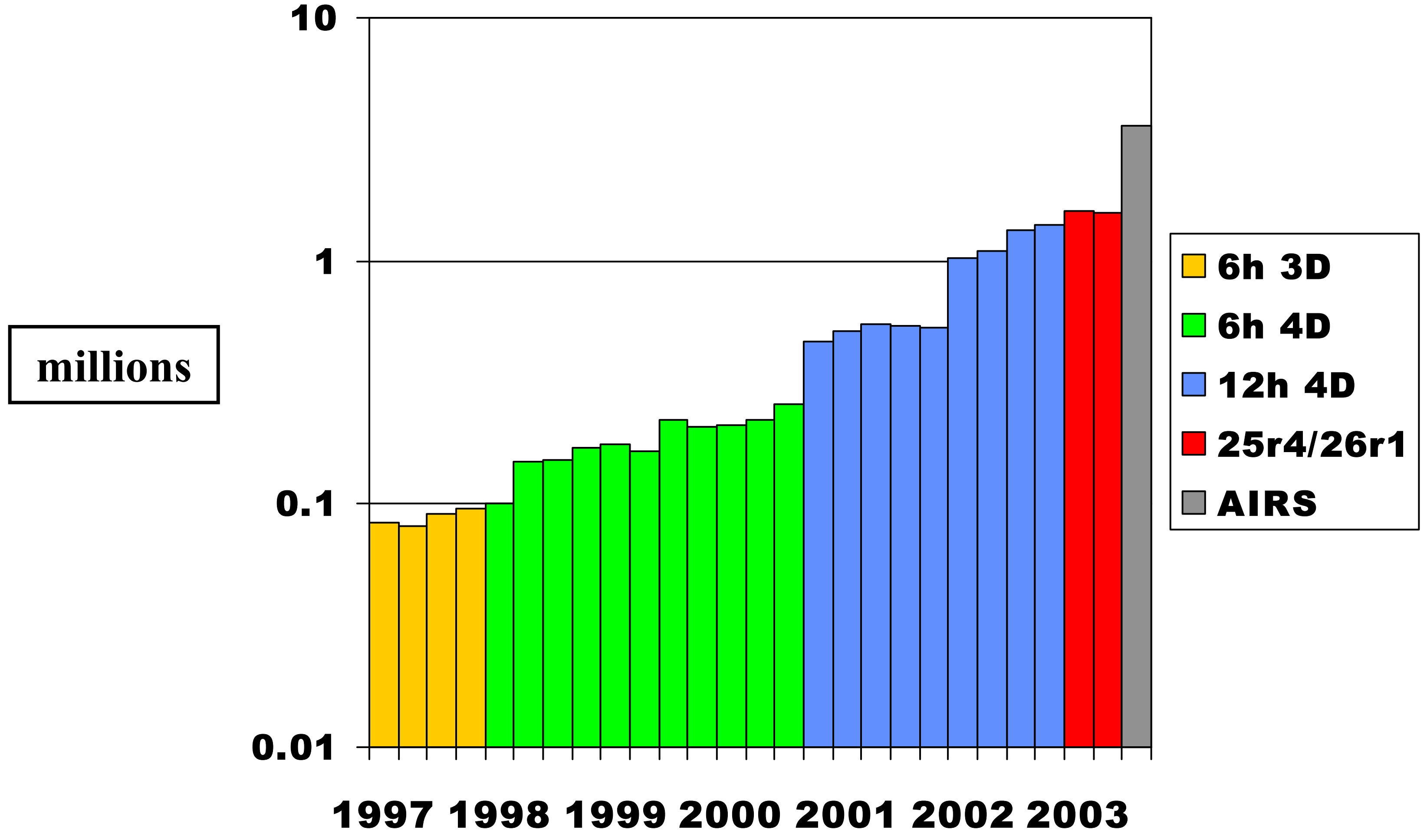
Number of observational data used in the ECMWF assimilation system (with AIRS)



Current data count 26R3 (18/06/03 00Z)

Screened		
Synop:	190370	(0.27%)
Aircraft:	233306	(0.33%)
Satob:	543340	(0.78%)
Dribu:	15081	(0.02%)
Temp:	110998	(0.16%)
Pilot:	98364	(0.14%)
UpperSat :	68358565	(97.97%)
PAOB:	530	(0.00%)
Scat:	222410	(.32%)
TOTAL:	69 772 964	

assimilated		
Synop:	38112	(1.06%)
Aircraft:	146749	(4.07%)
Satob:	71220	(1.97%)
Dribu:	4381	(0.12%)
Temp:	63763	(1.77%)
Pilot:	56324	(1.56%)
UpperSat :	3107200	(86.19%)
PAOB:	185	(0.00%)
Scat:	117196	(3.25%)
TOTAL:	3 605 130	

99.07% of screened data are Satellite Data

91.41% of assimilated data are Satellite Data

Information content

- A pure data count can be misleading (although these absolute figures have direct cost/disk space implications)
- There are various ways of estimating the information content of data types (*see Cardinali's lecture*)
  - Exemple: *DFS* =Degrees of Freedom for Signal

$$DFS = tr(\mathbf{I} - \mathbf{A}\mathbf{B}^{-1})$$

or

$$DFS = n - \sum_{\lambda \in \sigma(\mathbf{A}\mathbf{B}^{-1})} \lambda$$

where

$$\mathbf{A} = \left(\mathbf{B}^{-1} + \mathbf{H}^{\mathrm{T}}\mathbf{R}^{-1}\mathbf{H}\right)^{-1}$$

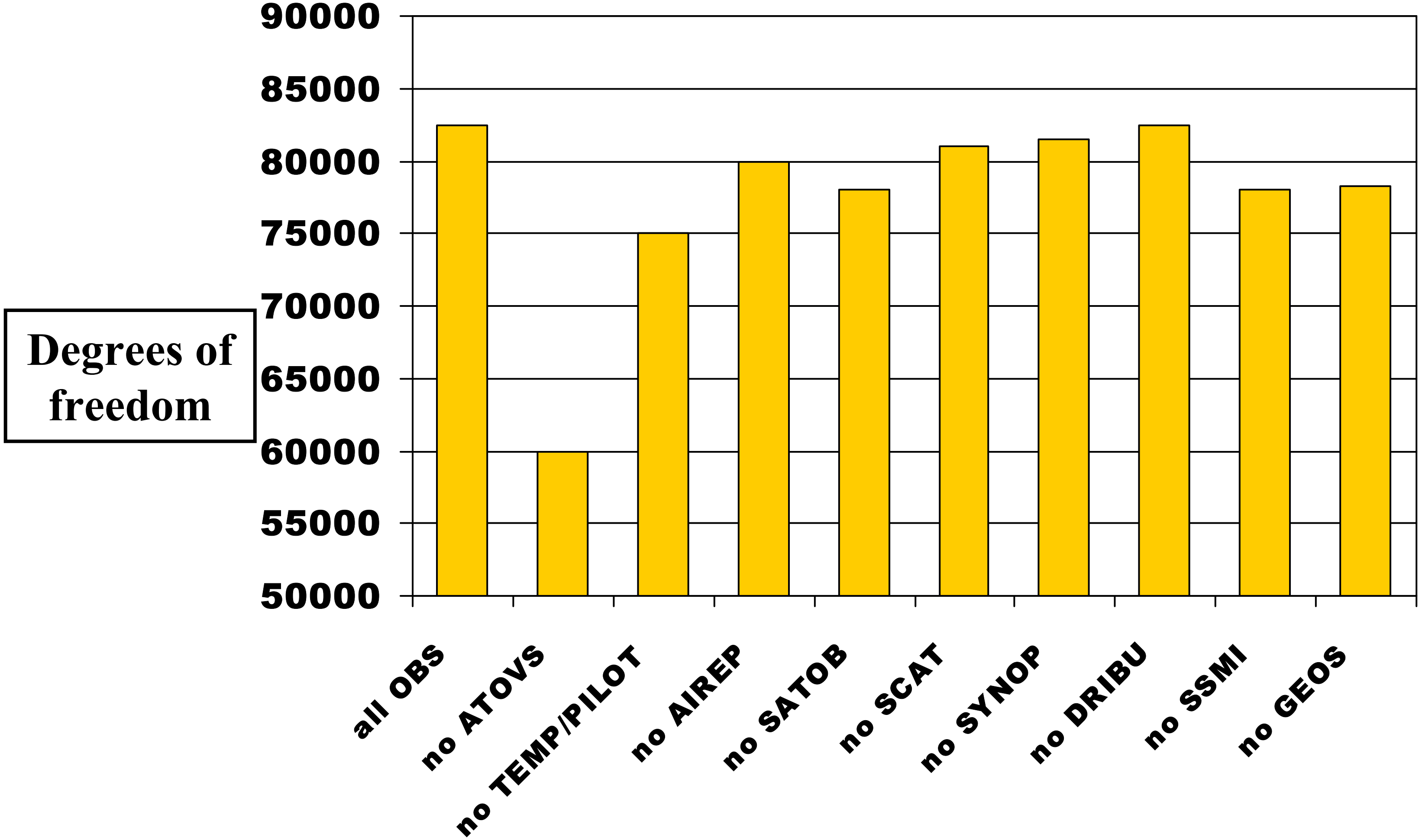
$\mathbf{B}$ Background error covariance matrix

H Observation operator

$\mathbf{R}$ Observation error covariance matrix

$\mathbf{A}$ Analysis error covariance matrix

Information content of the ECMWF analysis (Fisher, 2003)

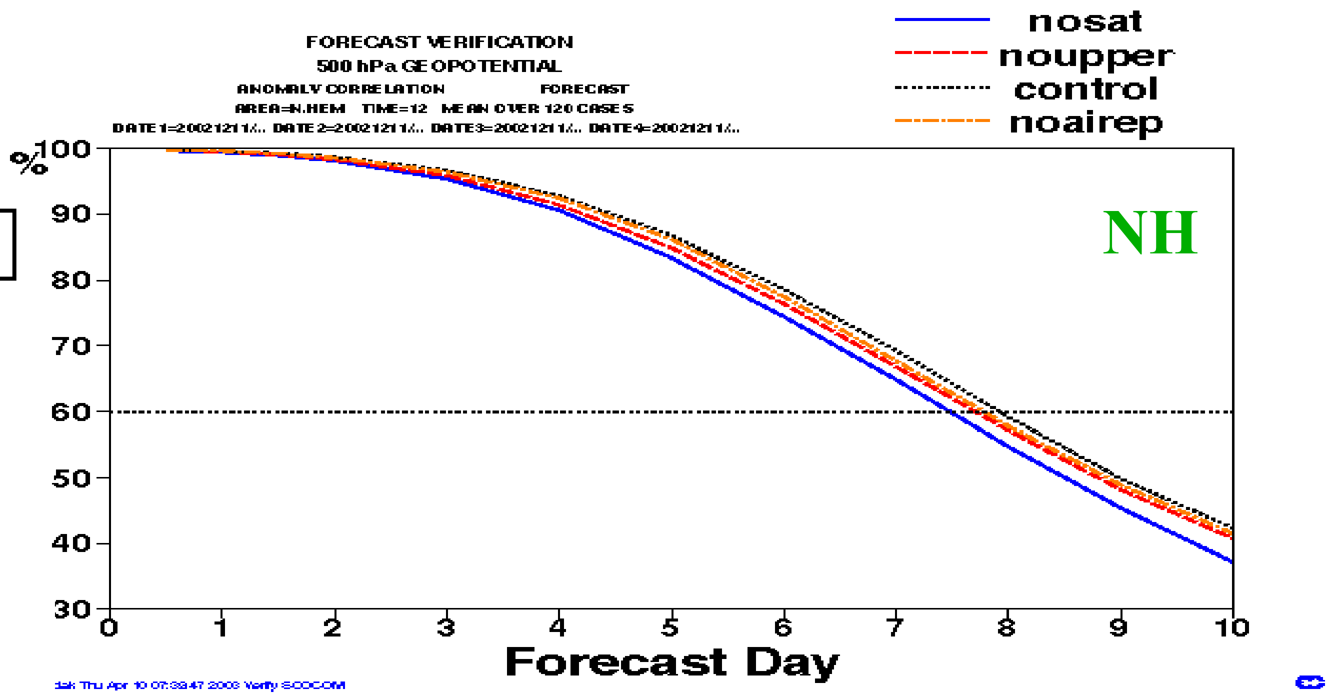


Impact studies

- Observing System Experiments (OSEs) are a very useful sanity check for both the data assimilation and the observing system (*see Dumelow's lecture*)

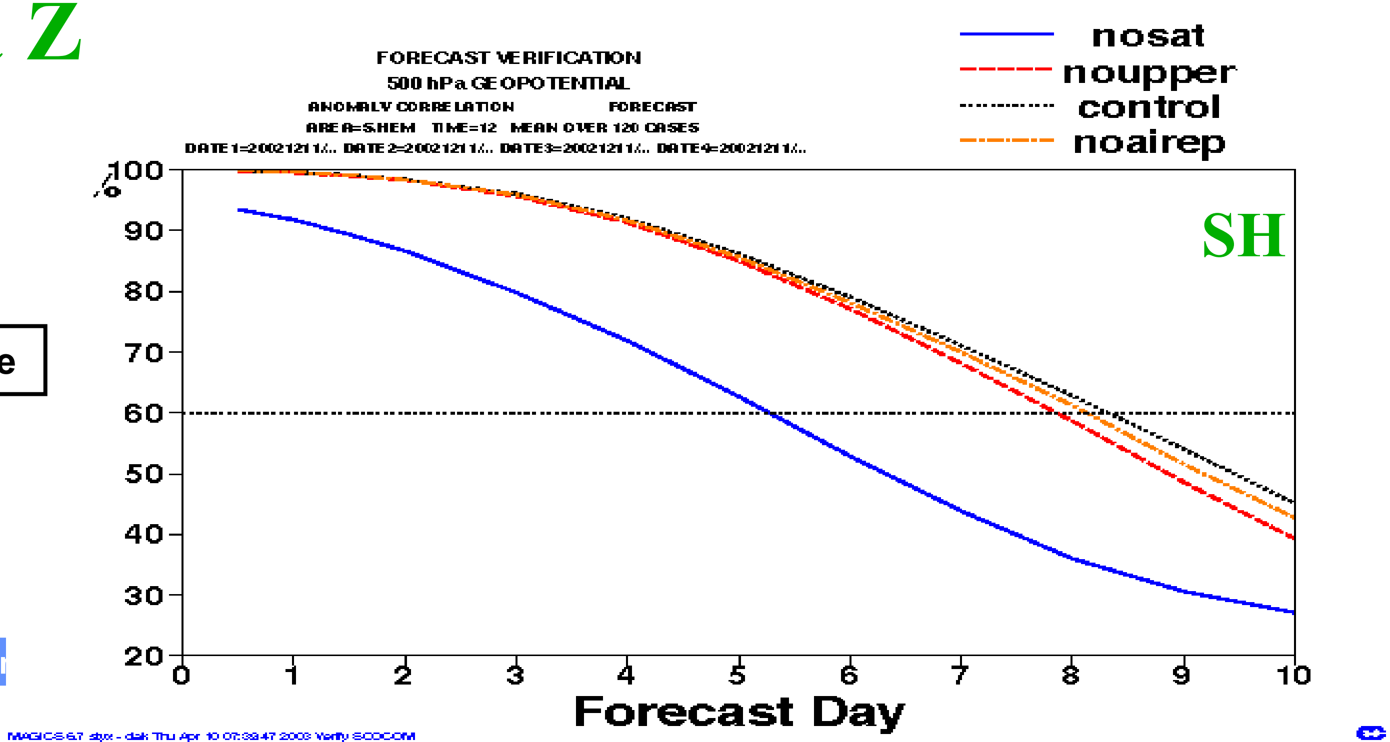
- A 120 case OSE has been undertaken at ECMWF (Kelly, 2003) to evaluate the quality of the different major Observing Systems

N. Hemisphere

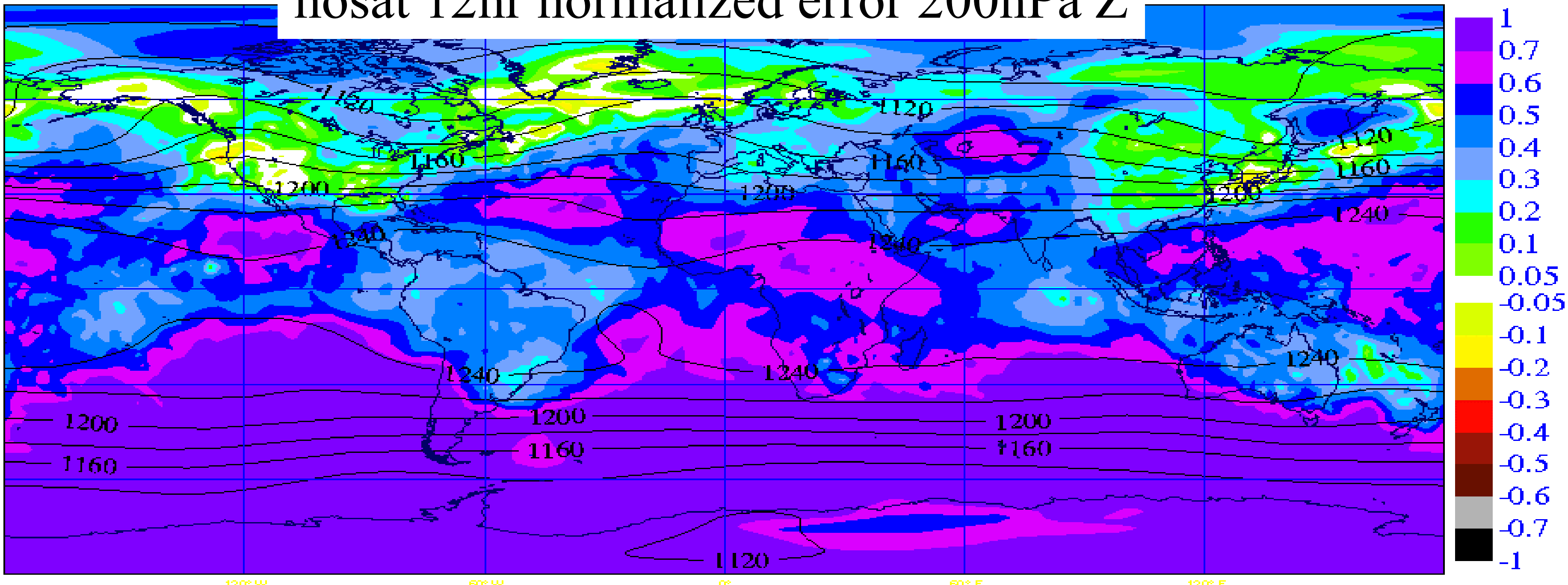


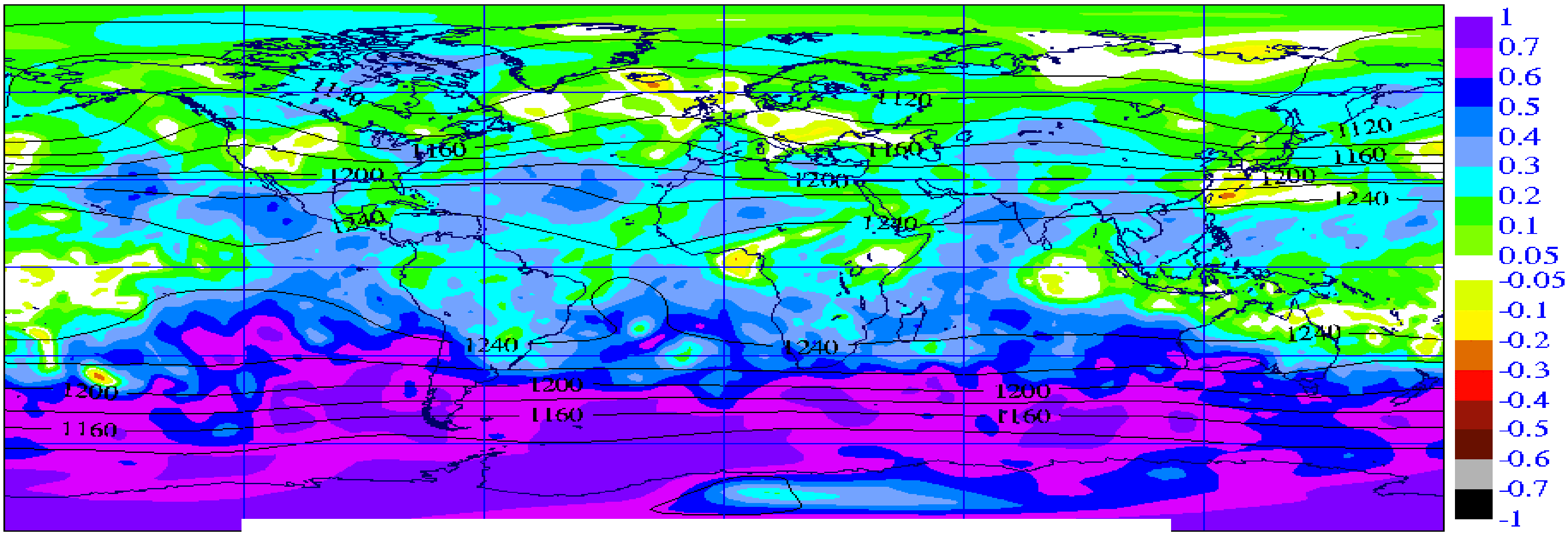
120 days 500 hPa Z scores

S. Hemisphere

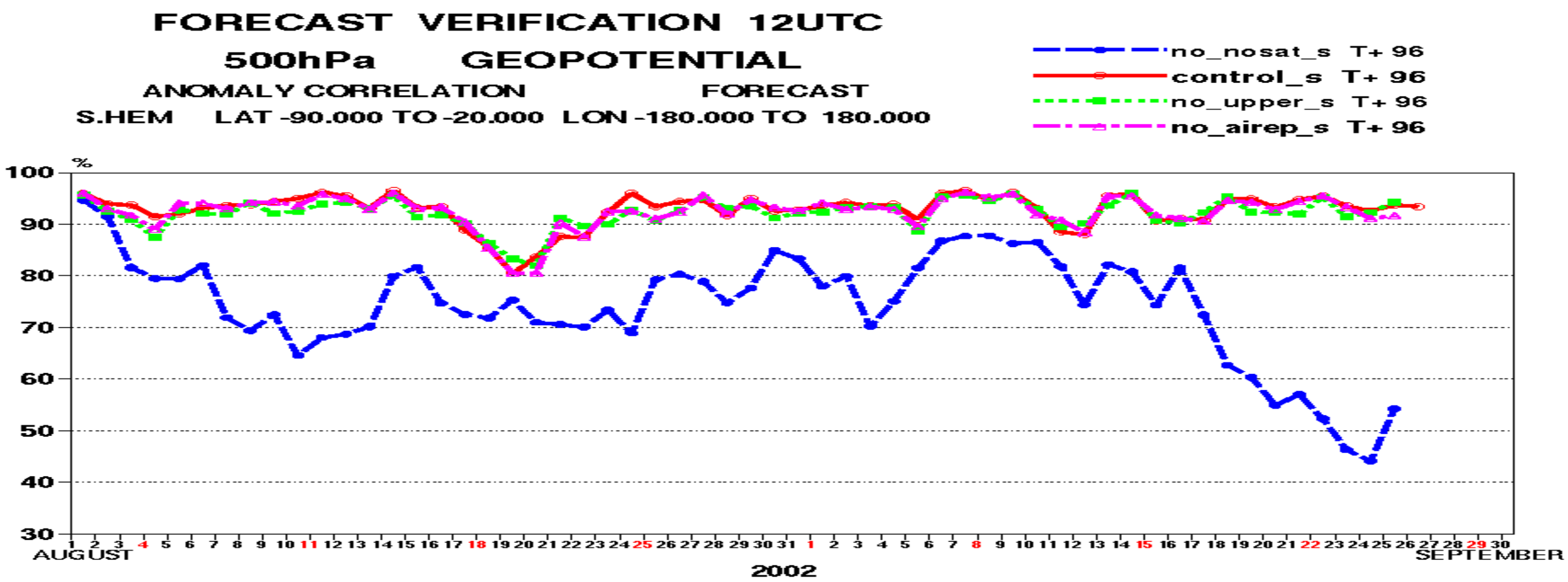


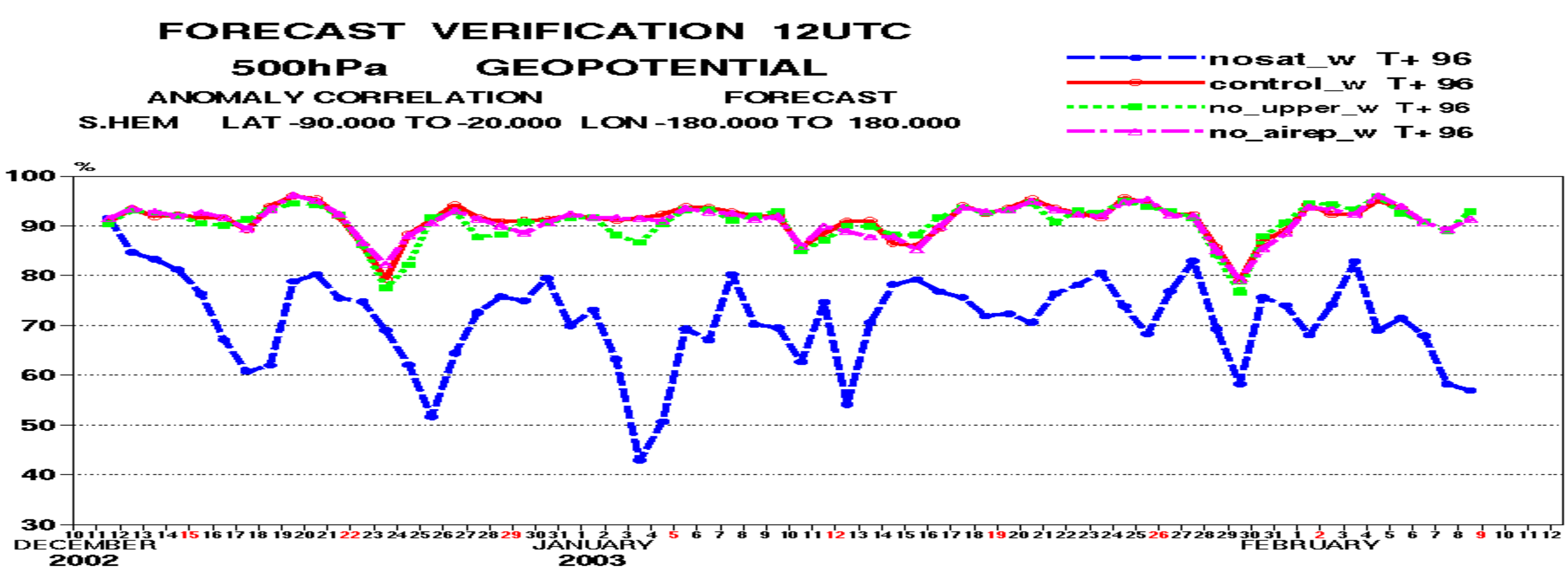
nosat 12hr normalized error 200hPa Z





nosat 48hr normalized error 200hPa Z


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
%
100
90
80
70
60
50
40
30
AUGUST
SEPTEMBER
2002

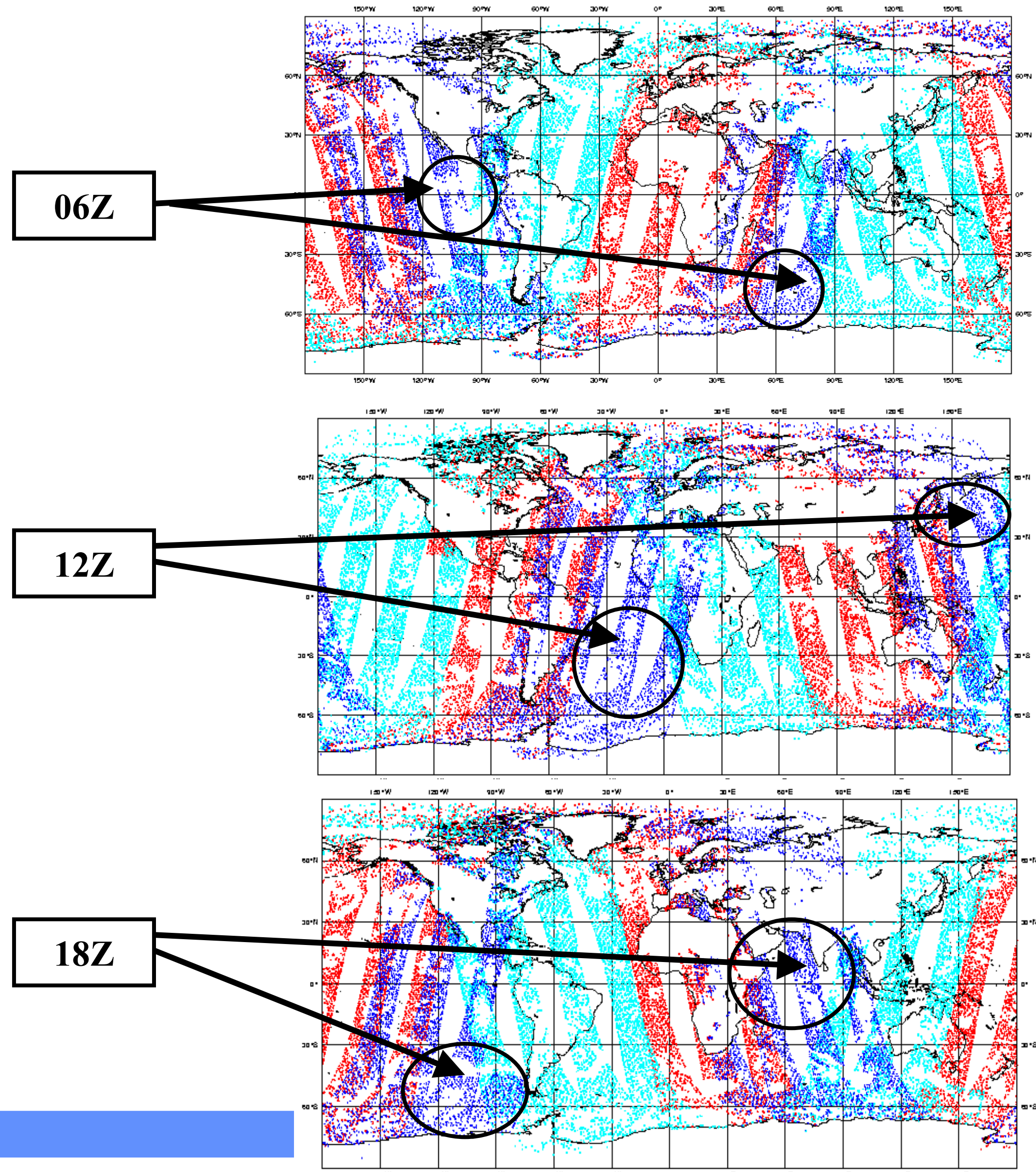

FORECAST VERIFICATION 12UTC
500hPa GEOPOTENTIAL
ANOMALY CORRELATION FORECAST
S.HEM LAT -90.000 TO -20.000 LON -180.000 TO 180.000
nosat_w T+ 96
control_w T+ 96
no_upper_w T+ 96
no_airep_w T+ 96
%
100
90
80
70
60
50
40
30
DECEMBER
2002
JANUARY
2003
FEBRUARY

Impact of 3 sounding (AMSU-A) instruments

NOAA-15 (07:30 am)

NOAA-16 (13:30 pm)

NOAA-17 (10:00 am)

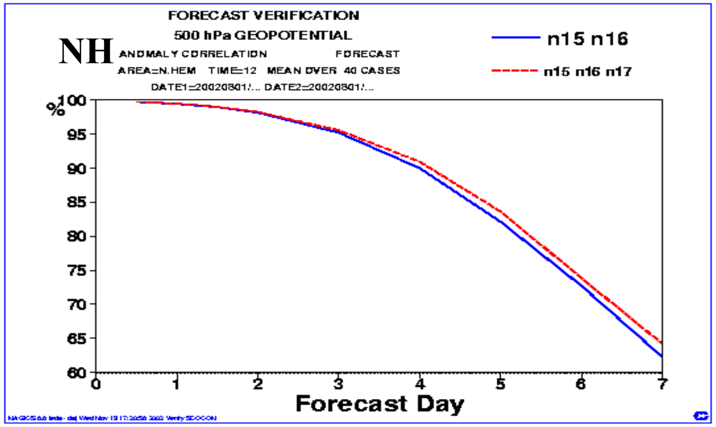


- At any time, NOAA-17 covers large oceanic areas crucial for global NWP forecasts and insufficiently observed by the NOAA-15-16 baseline (e.g. Pacific Ocean at 06 and 12Z)

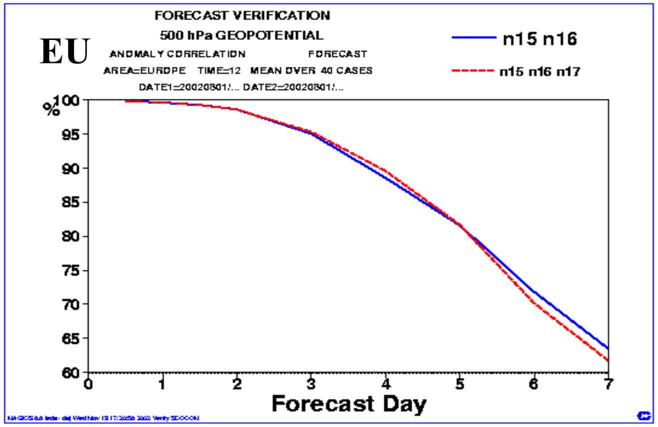
- A time/space uniform coverage can be fully exploited by the ECMWF 4D-VAR system

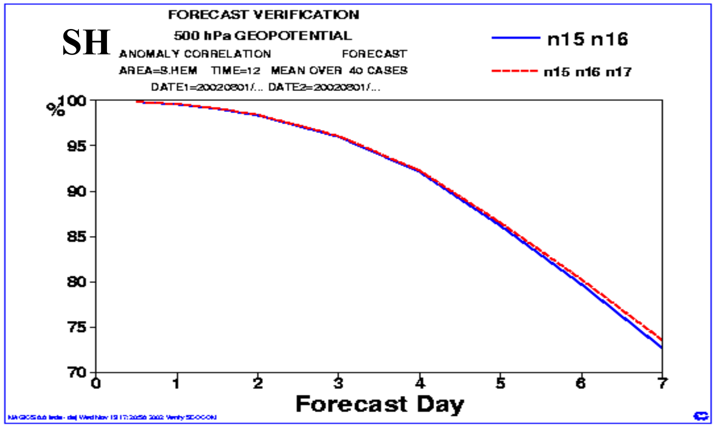
Outcome of the assimilation studies (3SAT versus 2SAT)

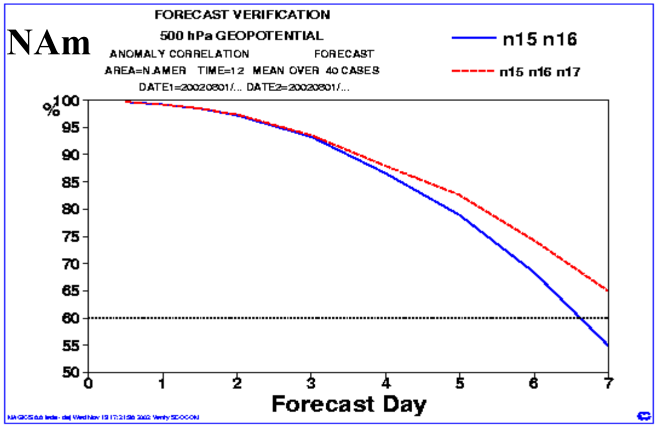
Z500 scores averaged over 40 cases



- 3SAT is better than 2SAT for hemispheric scores
- 3SAT is better than 2SAT up to d-4 over Europe, then worse at d-6
- 3SAT is impressively better than 2SAT over North-America!







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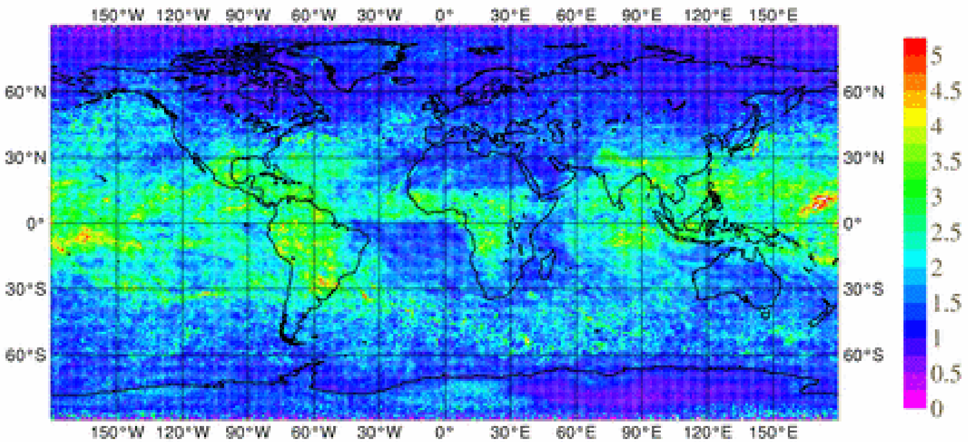
Other (less spectacular?) examples of successful assimilation of satellite data

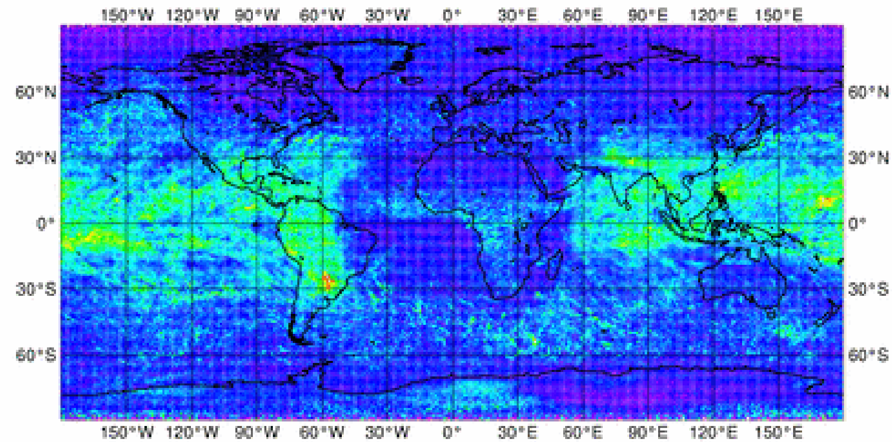
- **Assimilation of geostationary clear-sky water vapour radiances**
  - ➔ Allow a global control of the Upper Tropospheric Humidity in the Tropics
- **Assimilation of ozone observations from MIPAS onboard ENVISAT**
  - ➔ Allow a reasonable distribution of ozone in the ECMWF analysis

Assimilation of Meteosat-7 clear-sky water vapour radiances

Impact of the data: Visible with passive HIRS-12 radiances (NOAA-15)



STDV (HIRS-12 – model first guess)



STDV (HIRS-12 – model analysis)

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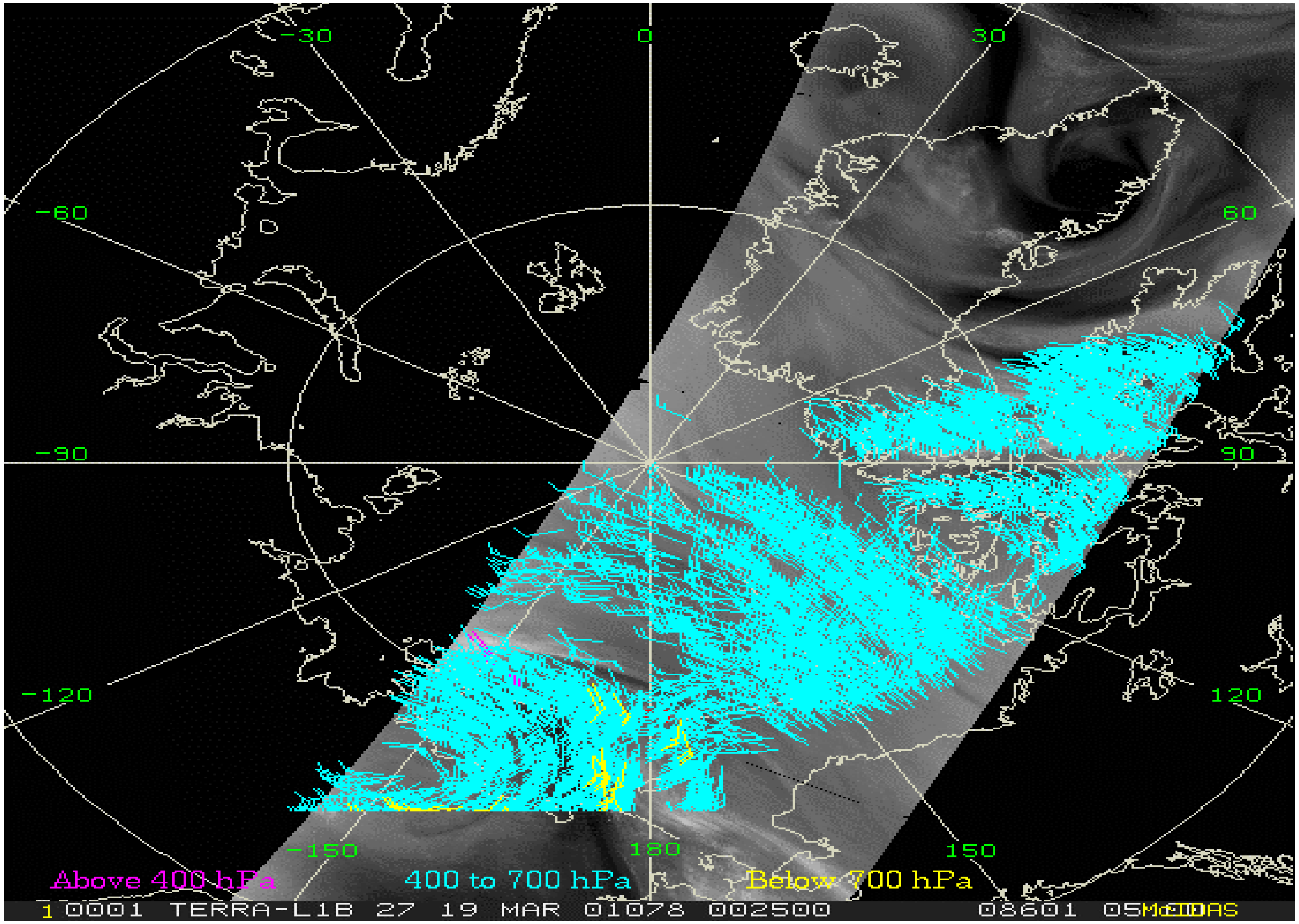
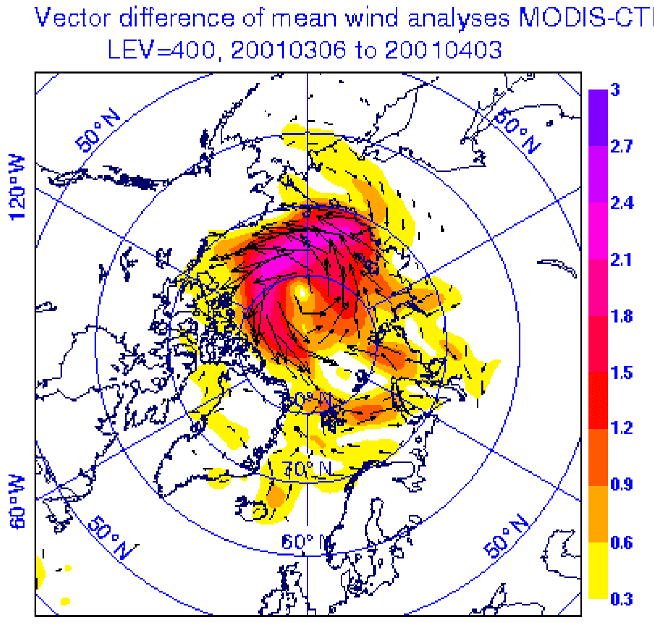
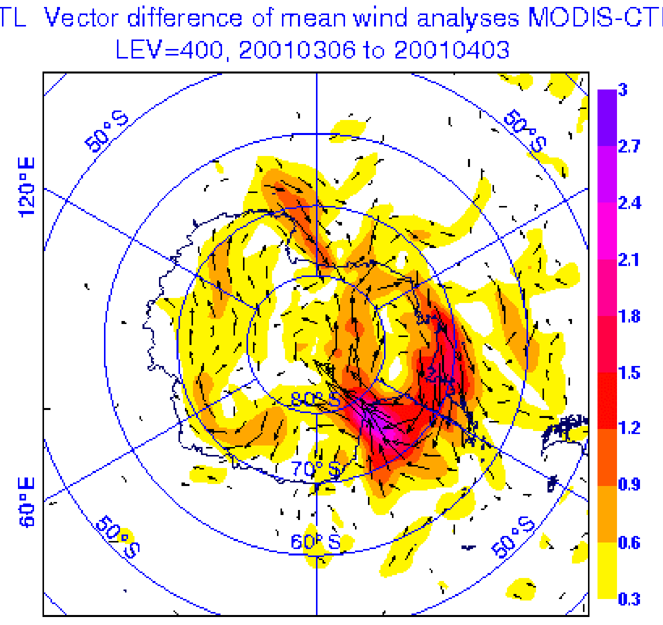
Polar WV winds from MODIS



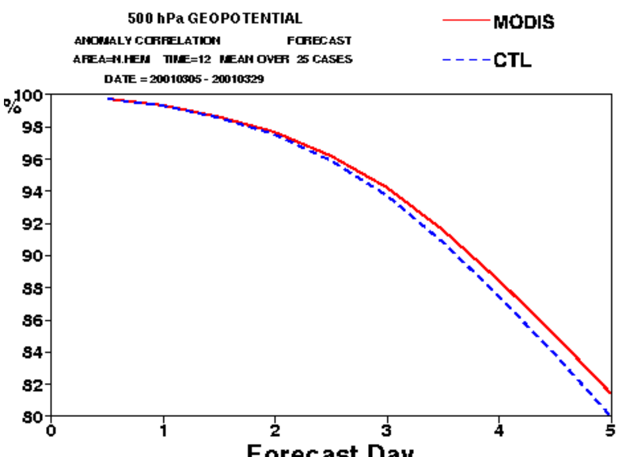
Source: P. Menzel, 2003

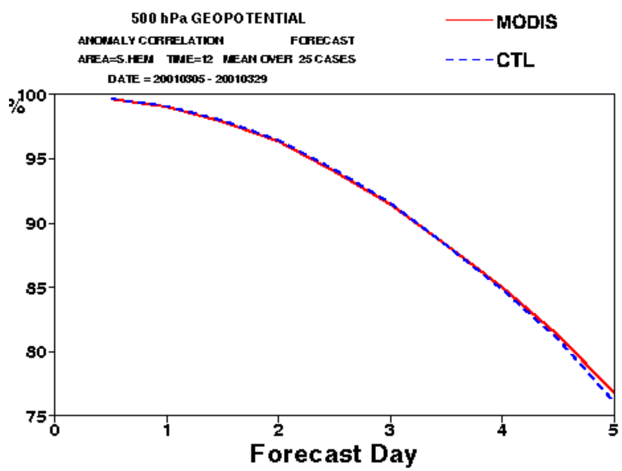
Impact of MODIS polar winds





Difference between the mean wind analyses of the MODIS experiment and the control.

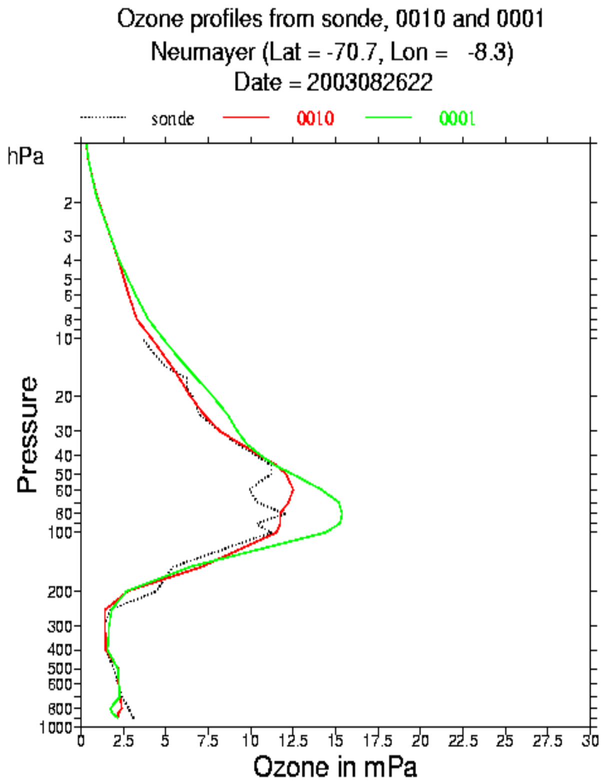




Hemispheric forecast scores for the MODIS experiment and the control.

ECMWF

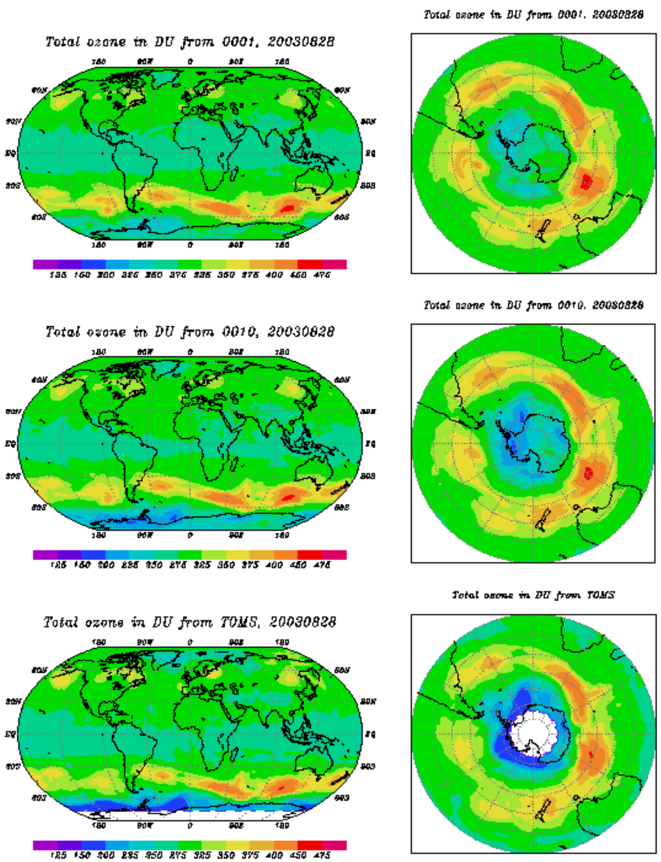
Assimilation of ozone data from MIPAS



No MIPAS

MIPAS

TOMS verif



The inclusion of ozone profiles from MIPAS (ENVISAT) improve substantially the representation of the ozone field in the ECMWF model

Outline

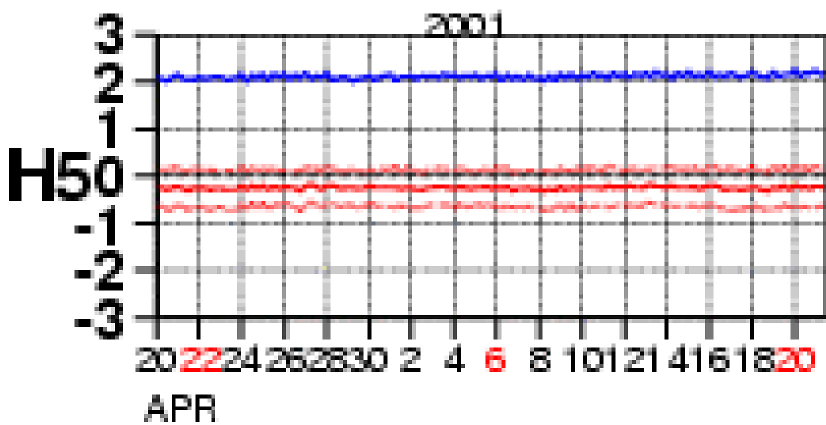
- Introduction to the Satellite Observing System
- What do satellite instruments measure?
- Importance of satellite data in current NWP data assimilation systems
- **Assimilation of satellite data: current issues**
- Future evolution and challenges

Important issues for the assimilation of satellite radiances

- **Biases:**
  - **Systematic errors must be removed before the assimilation (bias correction)**
  - **Various sources of systematic errors:**
    - Instrument error (calibration)
    - Radiative transfer error
    - Cloud/rain detection error
    - Background model error
  - **Difficult to disentangle between various sources**
  - **Importance of MONITORING departures between model background (and analysis) and various observations (*see Talagrand and Andersson's lectures*)**

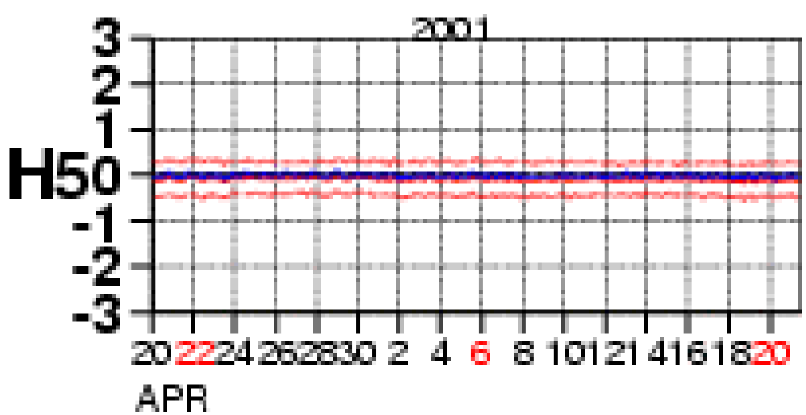
Cross-validation between various instruments (1)

Comparing the model with independent instruments help identifying the source of the bias



HIRS channel 5 (peaking around 600hPa) on NOAA-14 satellite has +2.0K radiance bias against model

Instrument bias likely!



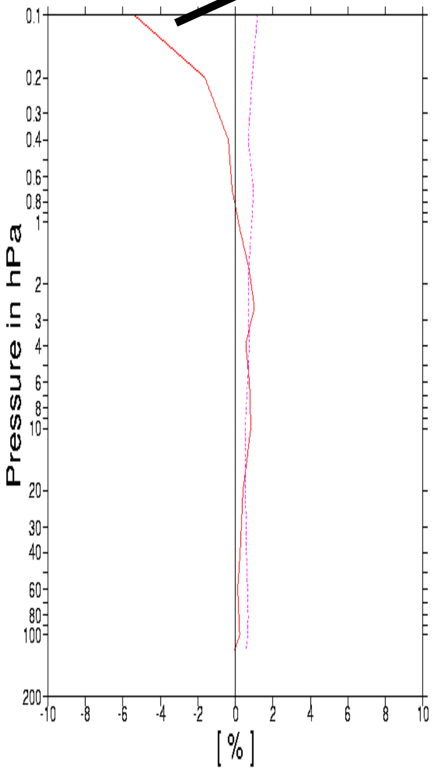
HIRS channel 5 (peaking around 600hPa) on NOAA-16 satellite has no radiance bias against model.

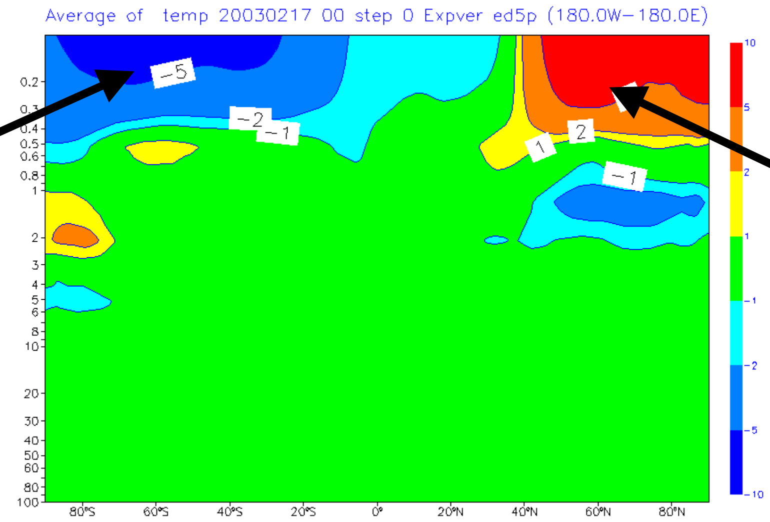
ECMWF

Cross validation between various instruments

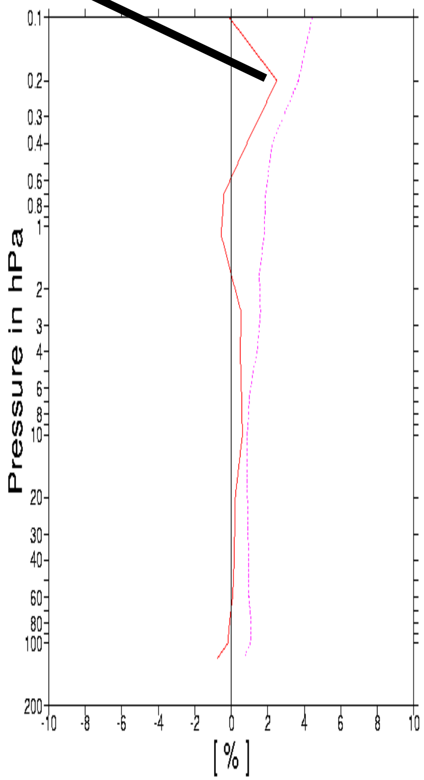
Analysis (+AIRS) minus OPS

MIPAS retrievals (65-90S)
(20030217-20030222)
minus OPS analysis





MIPAS retrievals (65-90N)
(20030217-20030222)
minus OPS analysis



Model bias likely!

Important issues for the assimilation of satellite radiances

- Quality control:
  - To reject data of "bad" quality
  - To reject data that cannot be simulated properly by the model (or the observation operator)
    - Clouds, rain, land surface emission,…
- Thinning:
  - Discrepancy between satellite resolution and background error covariance horizontal scales
  - Computational burden of processing high resolution data
  - Poor representation of observation error correlations

Important issues for the assimilation of satellite radiances

- **Observational error characterization:**
  - **In principle much easier in radiance space**
  - **However,**
    - → *R* should represent instrument, radiative transfer and representativeness error (inter channel correlations)
- **Radiative transfer forward modelling:**
  - **To assimilate channels affected by solar reflection**
  - **To assimilate radiances over land/ice**
  - **To simulate radiances in the UV domain**
  - **To properly account for trace gases, clouds, precipitation, aerosols,…**

Outline

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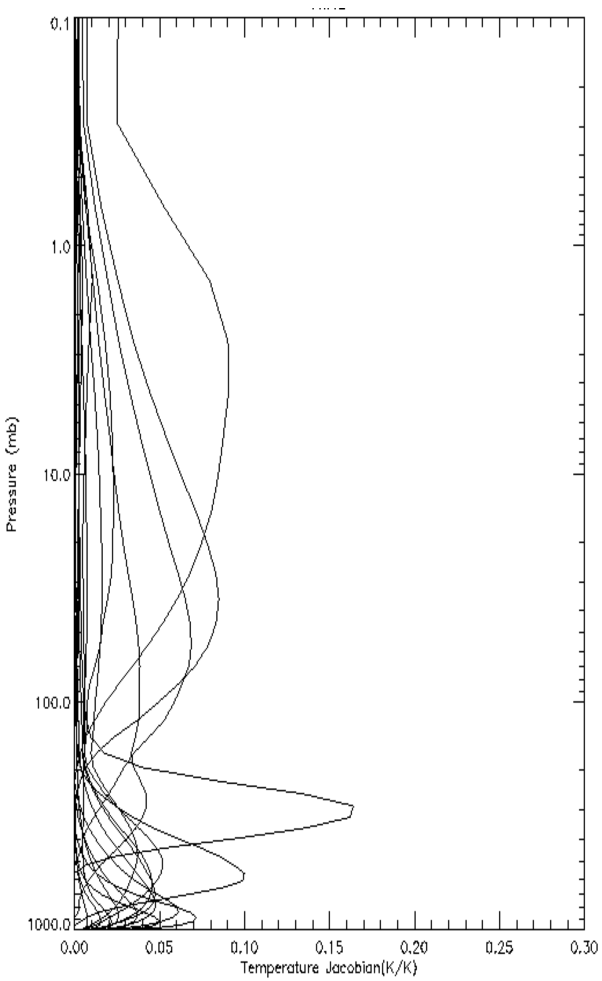
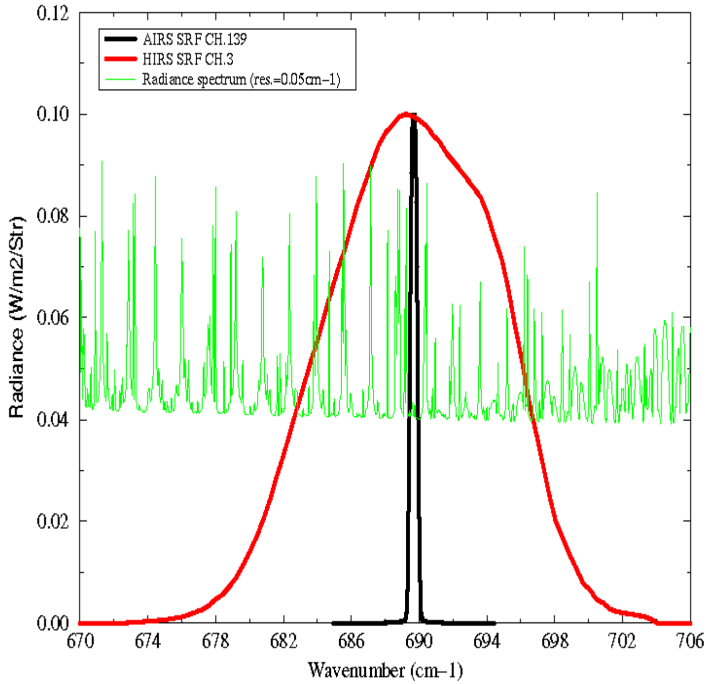
- **Future evolution and challenges**

Future evolution and challenges

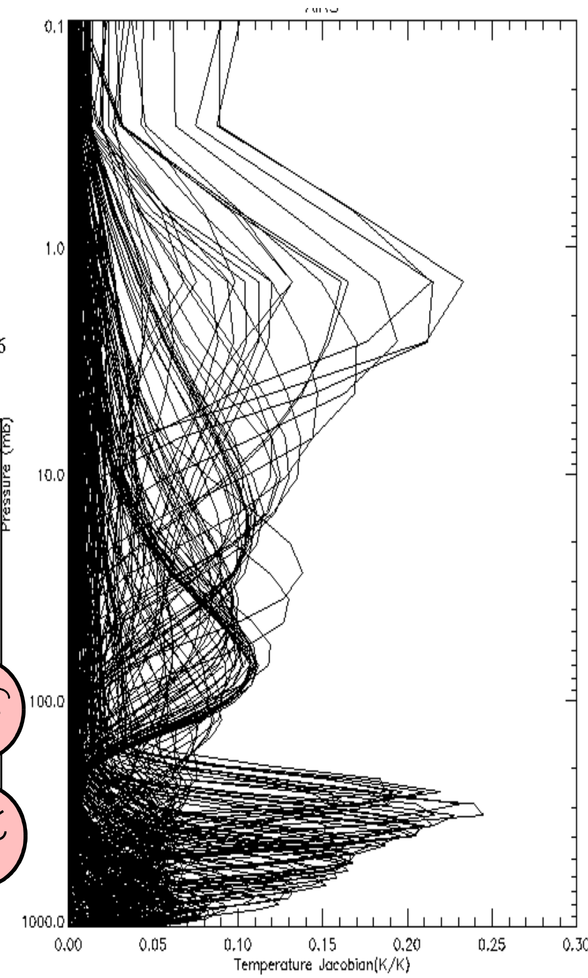
- **Assimilation of advanced IR sounders**
  - **Already happening!**
  - **Main issues are:**
    - Cloud detection
    - Data volume handling
    - Efficient monitoring and bias correction
    - …
  - **Environment opportunities (*see Hollingsworth's lecture*)**
  - **Within a few years, operational missions will fly these instruments (3 advanced sounders in 2006)**

HIRS Jacobians





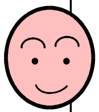
AIRS Jacobians



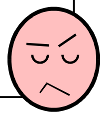
Higher Spectral Resolution from Advanced Sounders

➔

- **Higher vertical resolution and better accuracy**

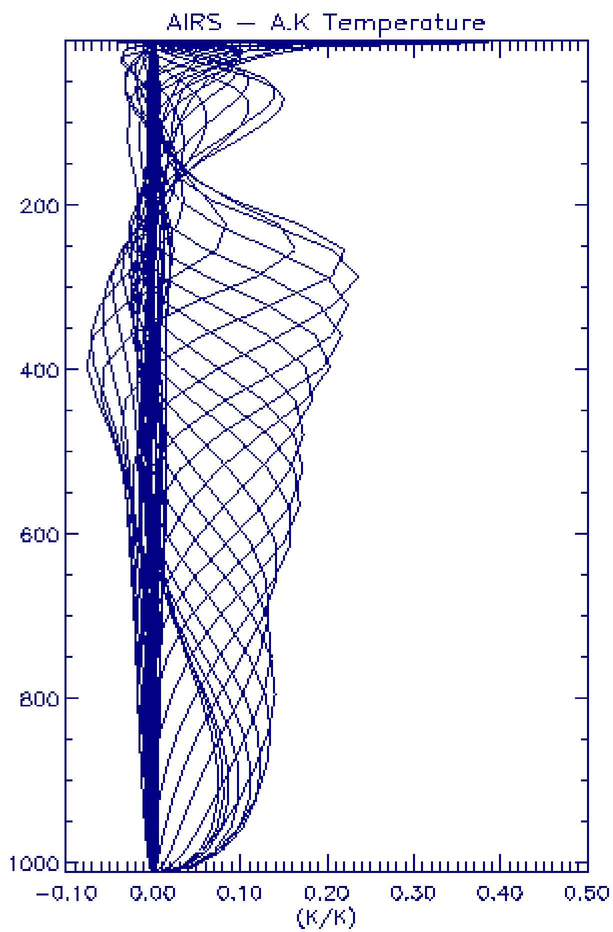


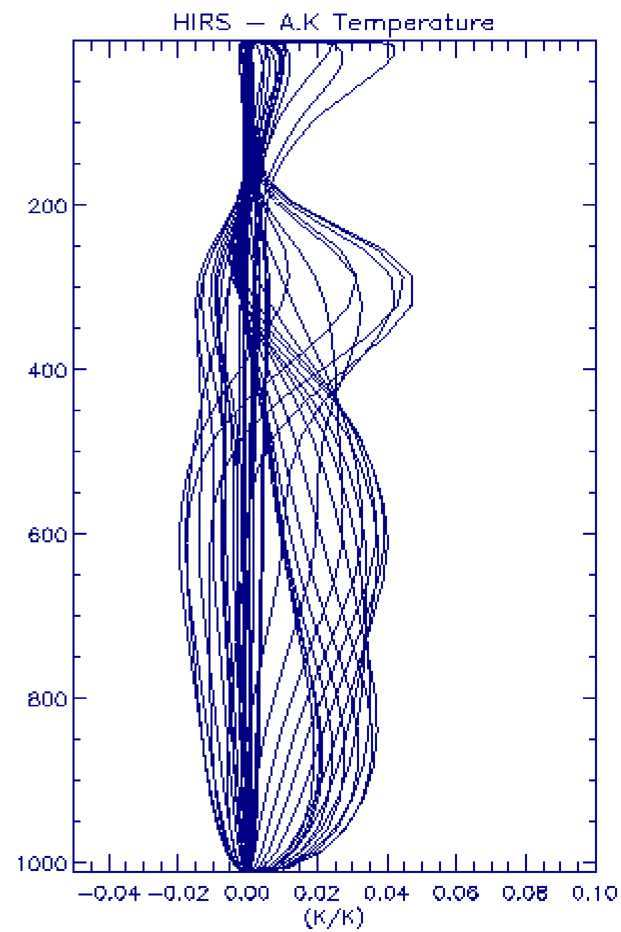
- **a lot of data to handle**



Better measure of improved resolution is provided by the averaging kernels

AIRS





HIRS

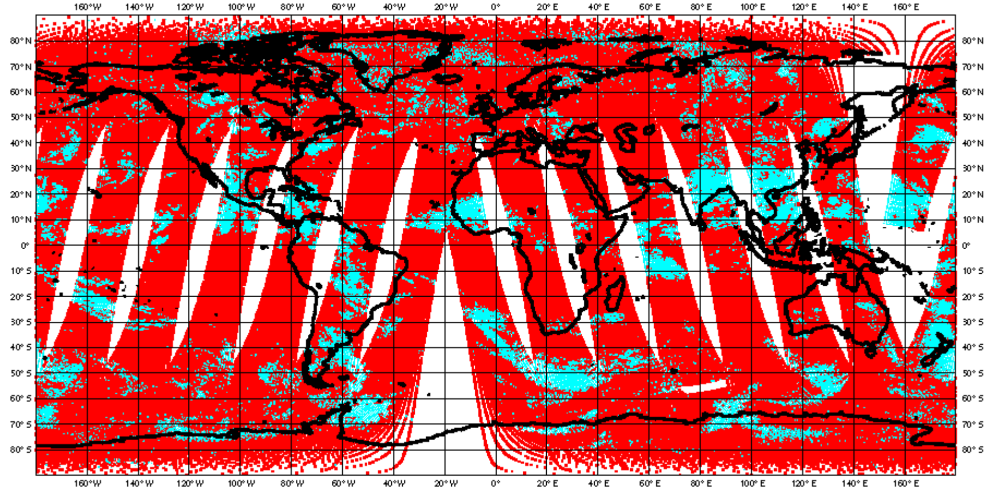
ECMWF

CLEAR CLOUDY

AIRS channel **145** clear data

14.5micron

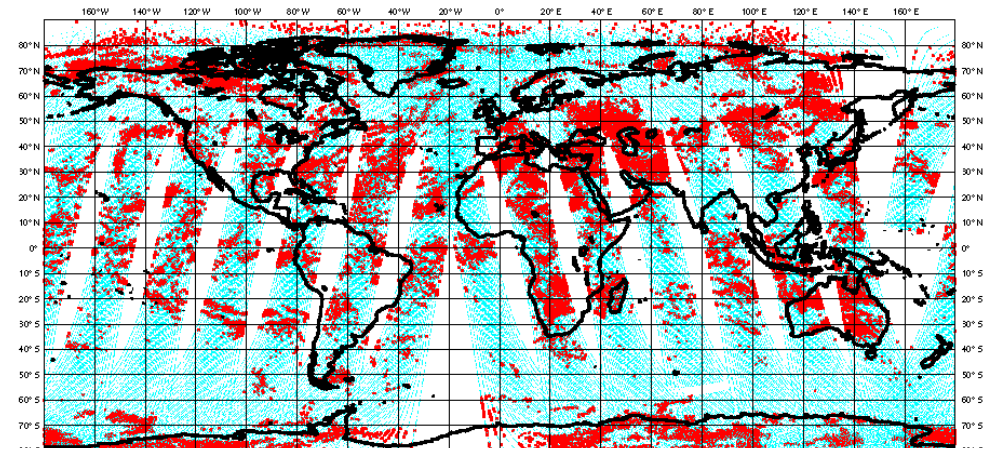
similar to HIRS channel 3 100hPa



AIRS channel **226** clear data

13.5micron

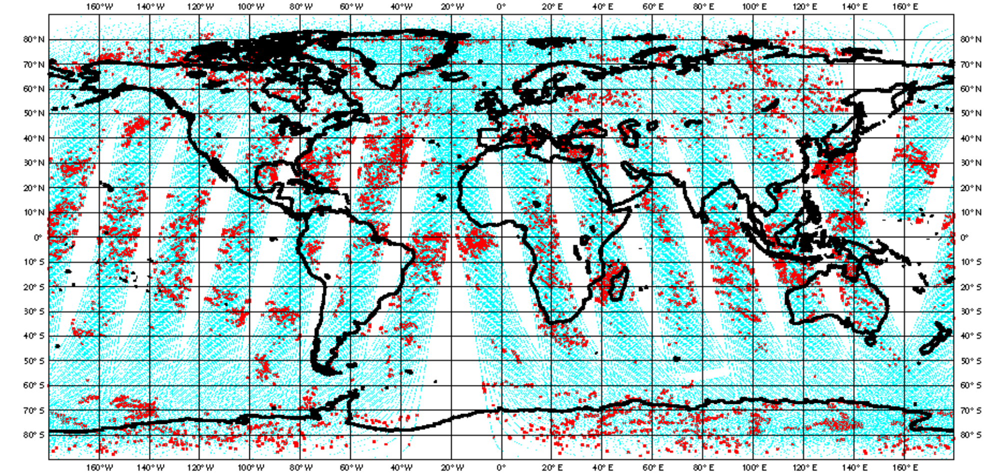
similar to HIRS channel 5 600hPa



AIRS channel **787** clear data

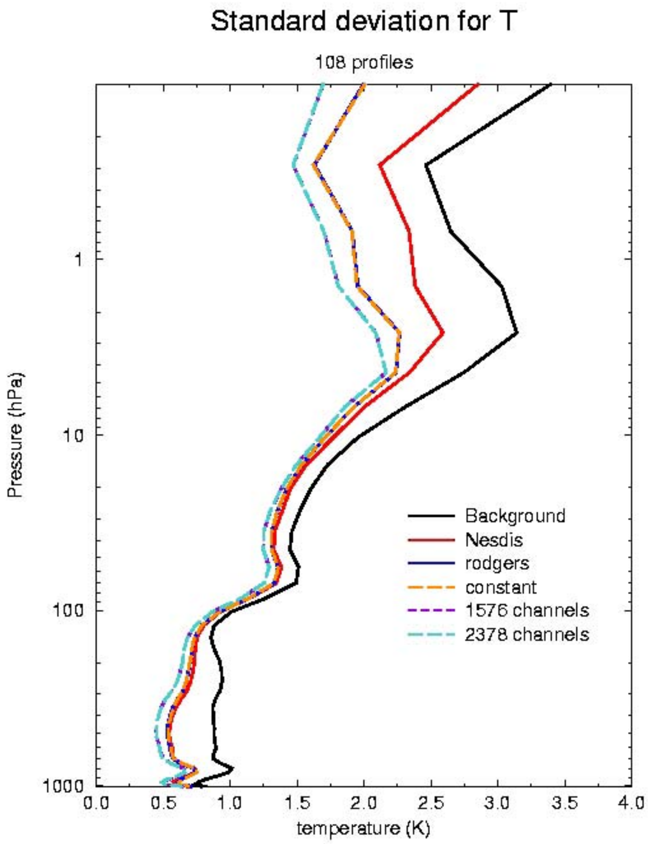
11 micron

similar to HIRS channel 8 window



Data volume handling

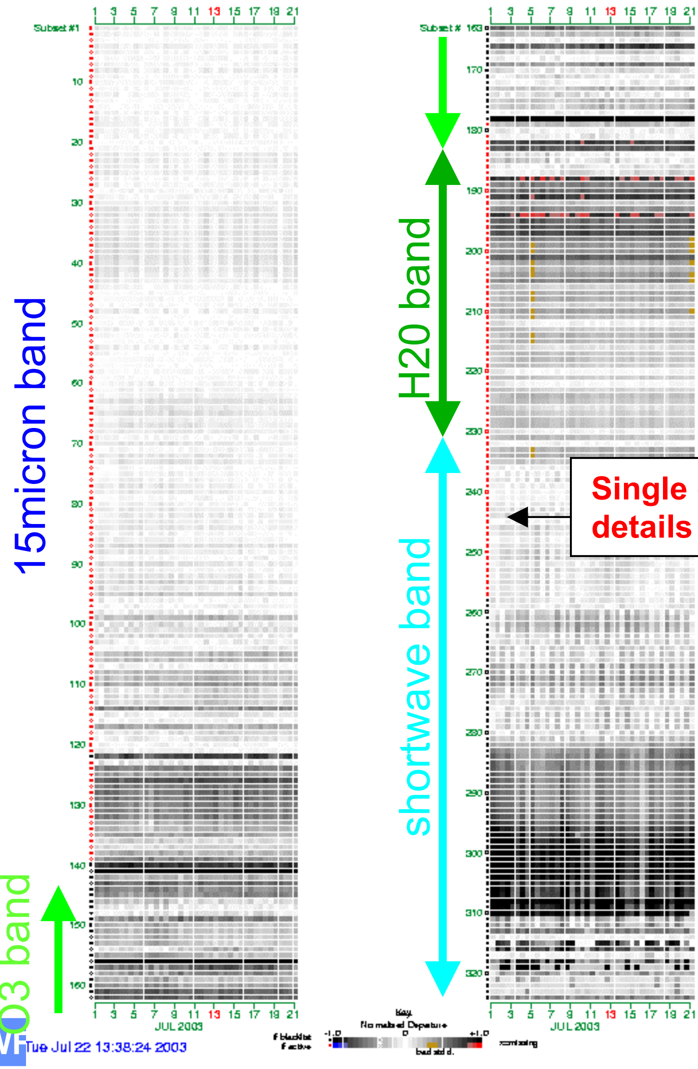
- Every AIRS FOV provides 2300 radiances
- A channel selection/data compression strategy has to be designed
- Day-1 approach using a frozen set of 300 channels performs reasonably well but SNR performance is lost
- Spectral compression using e.g. truncated EOF's is a way to ease the data volume issue and optimally retain the original information in the data (to be tested)



ECMWF

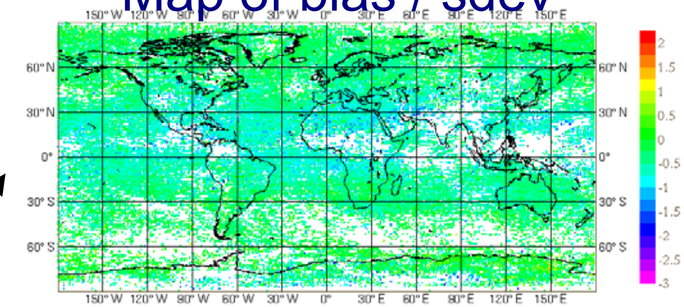
AIRS monitoring

All channels summary

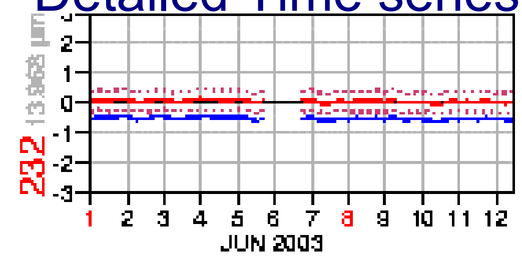


Single channel details

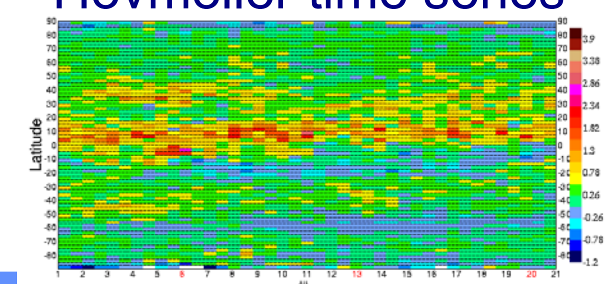
Map of bias / sdev



Detailed Time series



Hovmoller time series



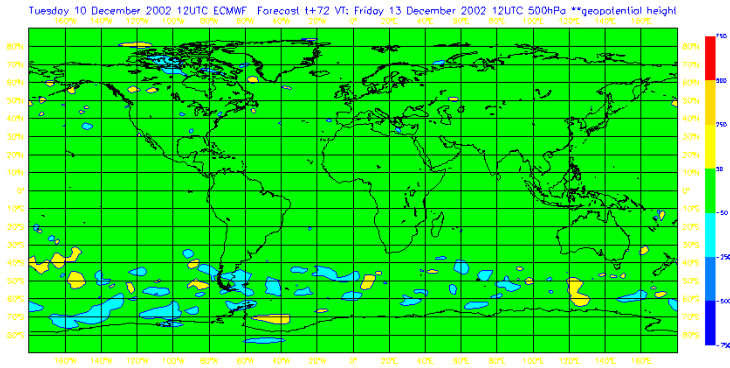
AIRS forecast impact

RMS of 500hPa geopotential forecast error averaged over 40 days (Dec 02/ Jan 03)

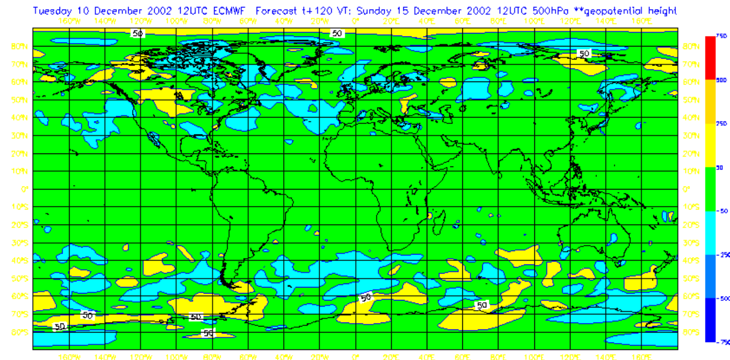
[AIRS error] minus [CTRL error]

The assimilation of AIRS radiances shows a small but consistent positive impact on forecast quality in all areas

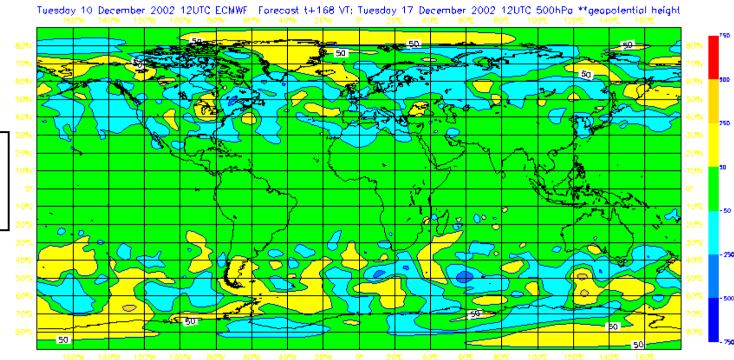
Day-3



Day-5

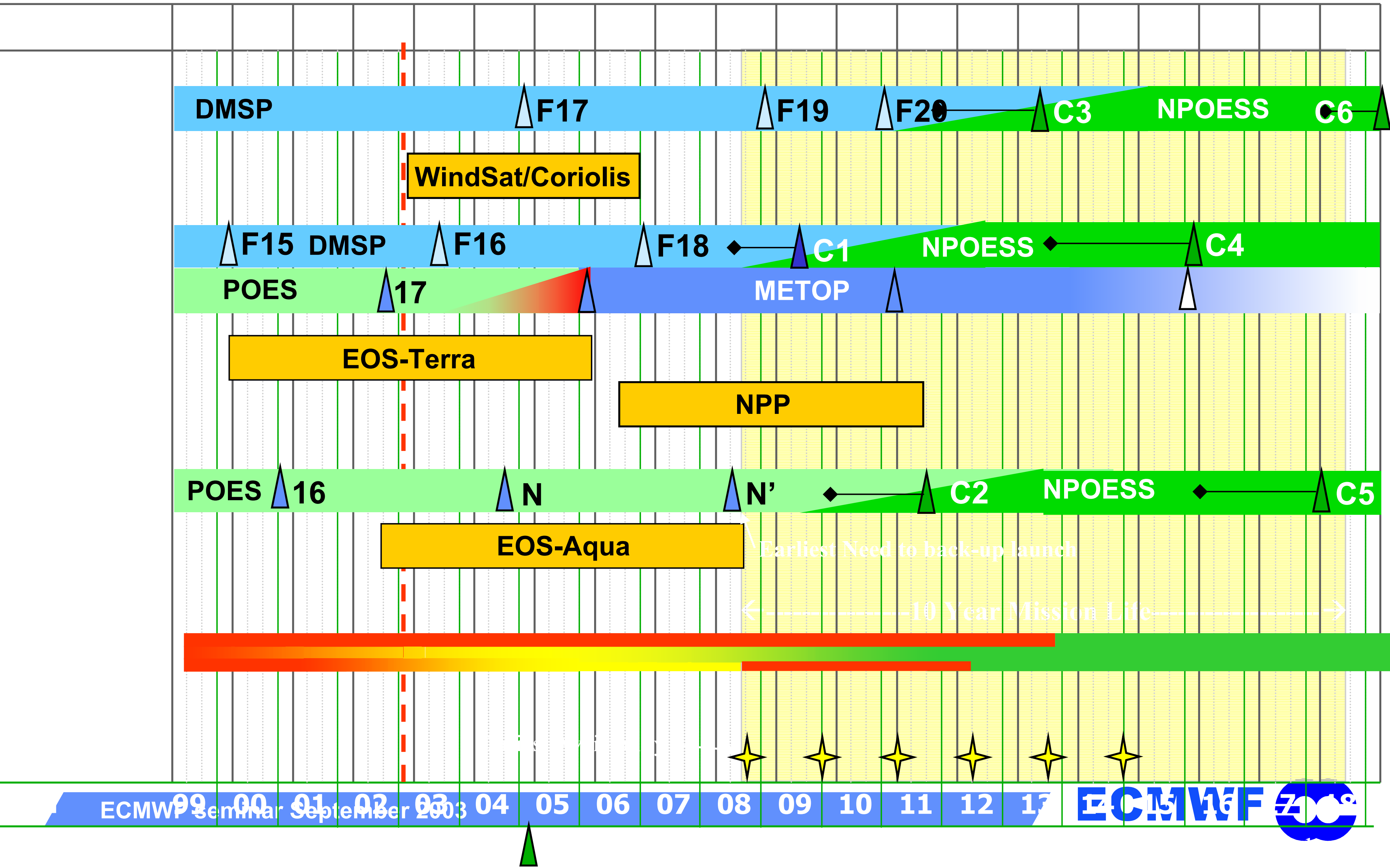


Day-7

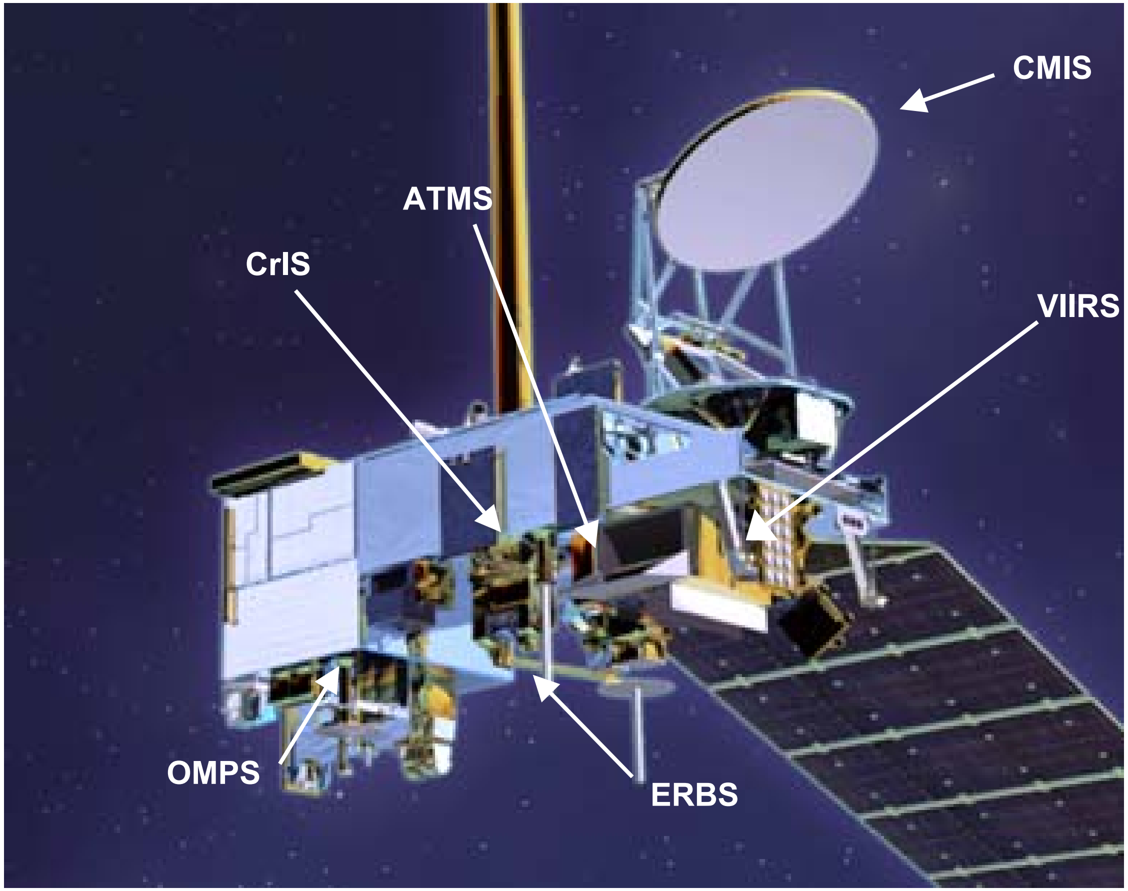


Satellite Transition Schedule

from POES era to NPOESS/EPS (source Hal Bloom)

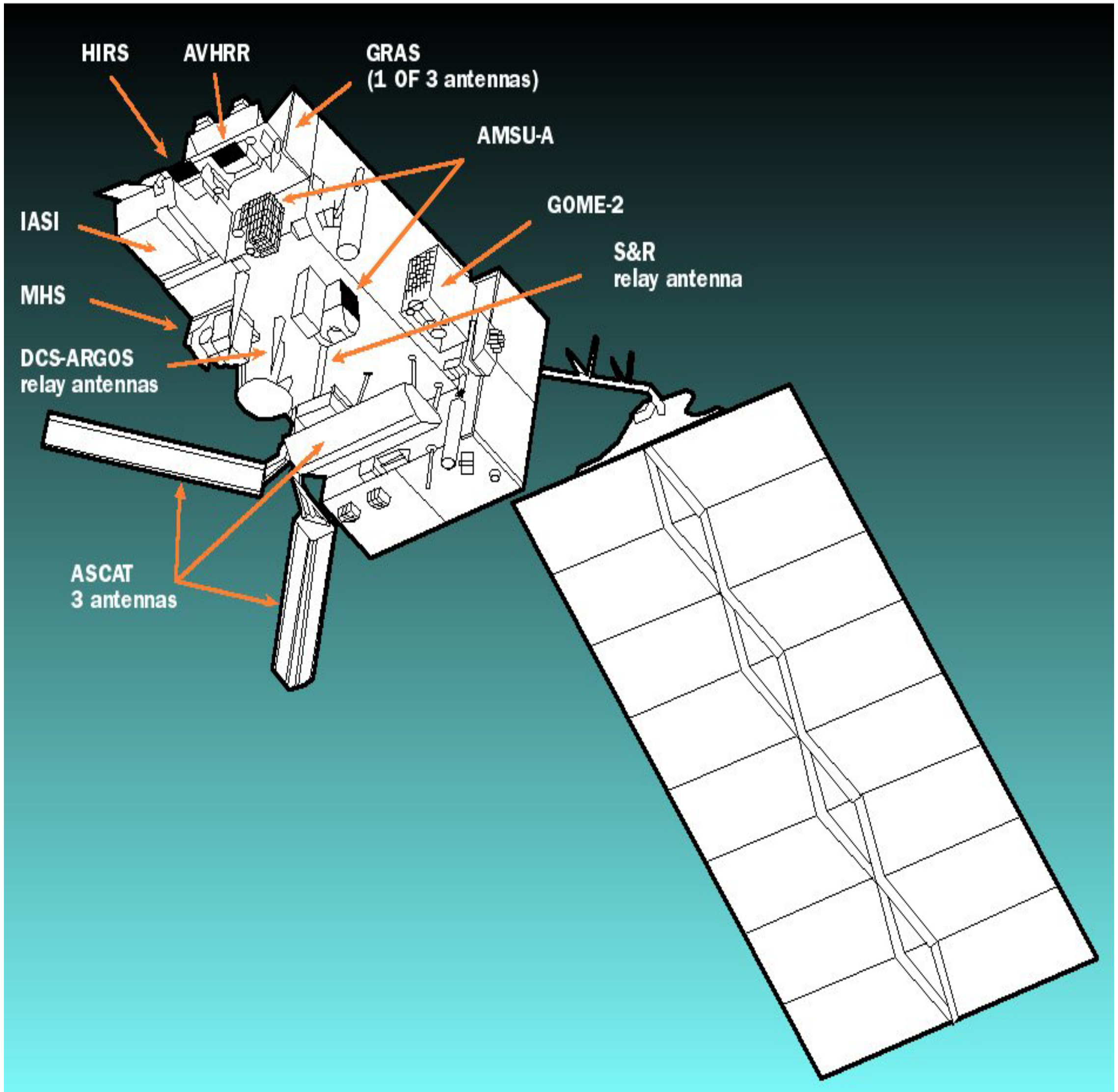


NPOESS Satellite



CMIS - μwave imager
VIIRS - vis/IR imager
CrIS - IR sounder
ATMS - μwave sounder
OMPS - ozone
GPSOS - GPS occultation
ADCS - data collection
SESS - space environment
APS - aerosol polarimeter
SARSAT - search & rescue
TSIS - solar irradiance
ERBS - Earth radiation budget
ALT - altimeter

METOP Satellite



AMSU-A/MHS	- µwave sounder
HIRS	- IR sounder
AVHRR	- vis/IR imager
IASI	- ad. IR sounder
GRAS	- GPS occultation
GOME-2	- ozone
ASCAT	- Scatterometer
S&R	
DCS-ARGOS	

The Initial Joint Polar System

CMIS - µwave imager
VIIRS - vis/IR imager
CrIS - IR sounder
ATMS - µwave sounder

OMPS - ozone
GPSOS - GPS occultation

ADCS - data collection
SESS - space environment
APS - aerosol polarimeter
SARSAT - search & rescue
TSIS - solar irradiance
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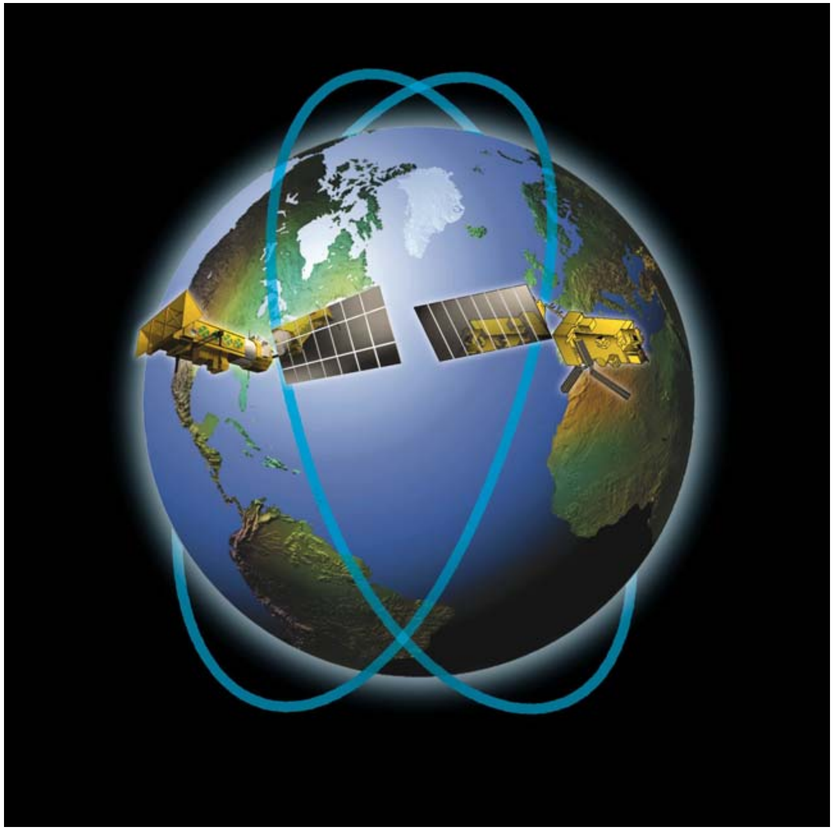
ALT - altimeter



AMSU-A/MHS - µwave sounder
HIRS - IR sounder
AVHRR - vis/IR imager
IASI - ad. IR sounder
GRAS - GPS occultation

GOME-2 - ozone
ASCAT - Scatterometer
S&R
DCS-ARGOS

NPOESS

METOP

Future evolution and challenges

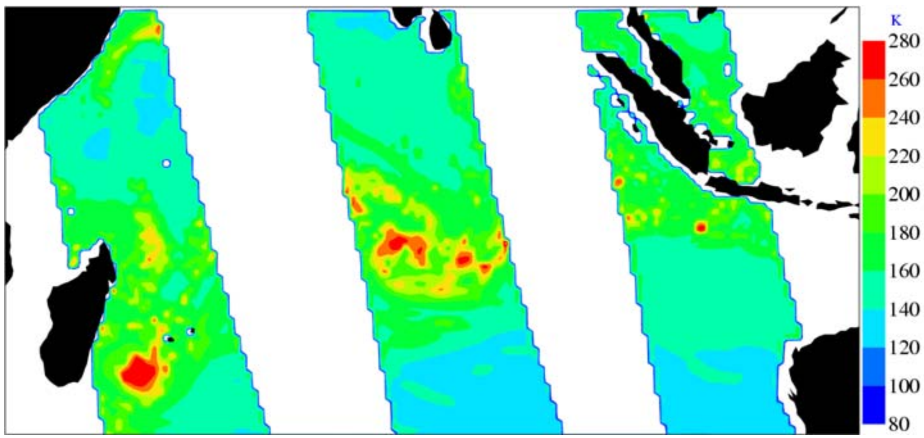
- Assimilation of clouds and precipitation
  - Currently, the assimilation of satellite information concerns only 20% of the globe
  - The ability of atmospheric models to describe cloud and precipitation is continuously improving
  - A number of space missions are already up and major others will come (GPM)
  - Issues:
    - Non smooth processes (*see Janisková's lecture*)
    - Representativeness errors
    - Predictability of the cloudy/rainy systems
    - Radiative transfer and background error modelling

Model vs.Observation: TB_{19h} [K]

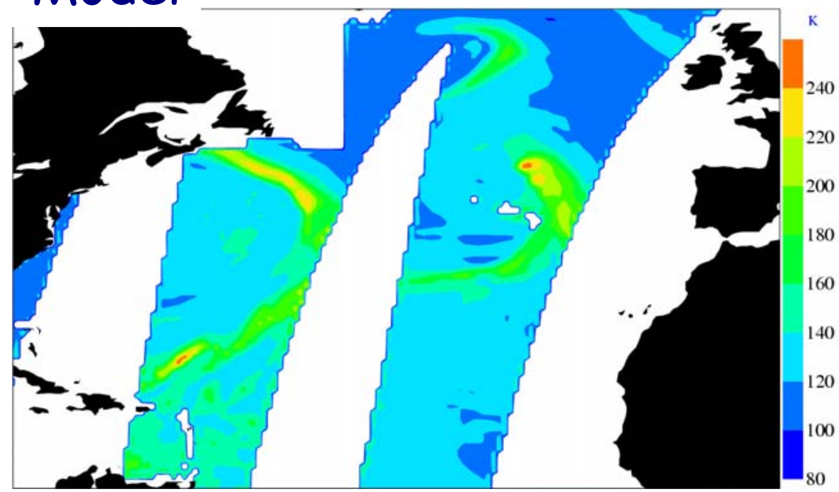
7 January 2001, 15 UTC
Cyclone Ando

7 January 2001, 12 UTC
North Atlantic front

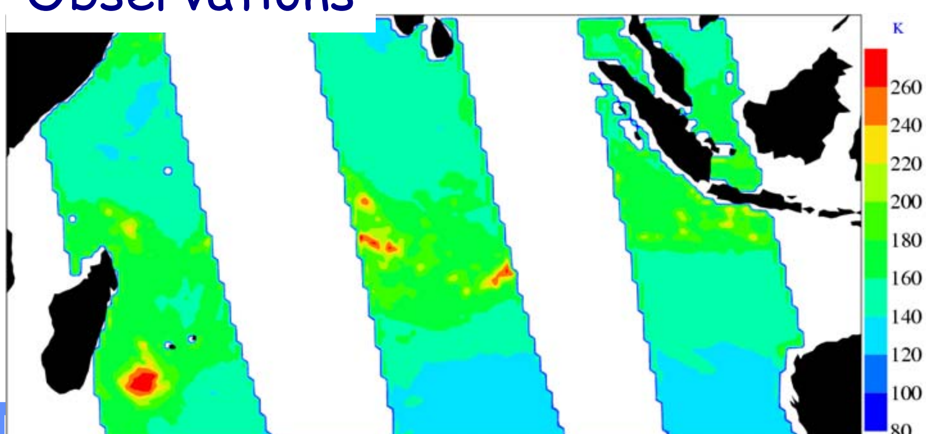
Model



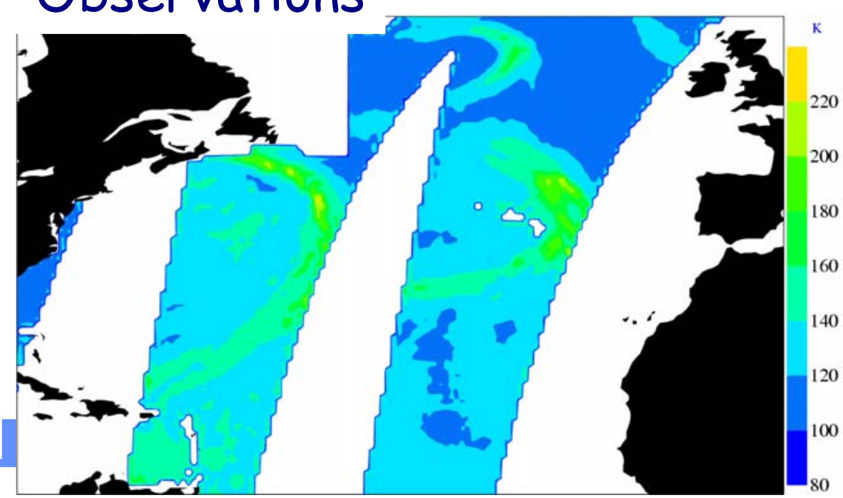
Model



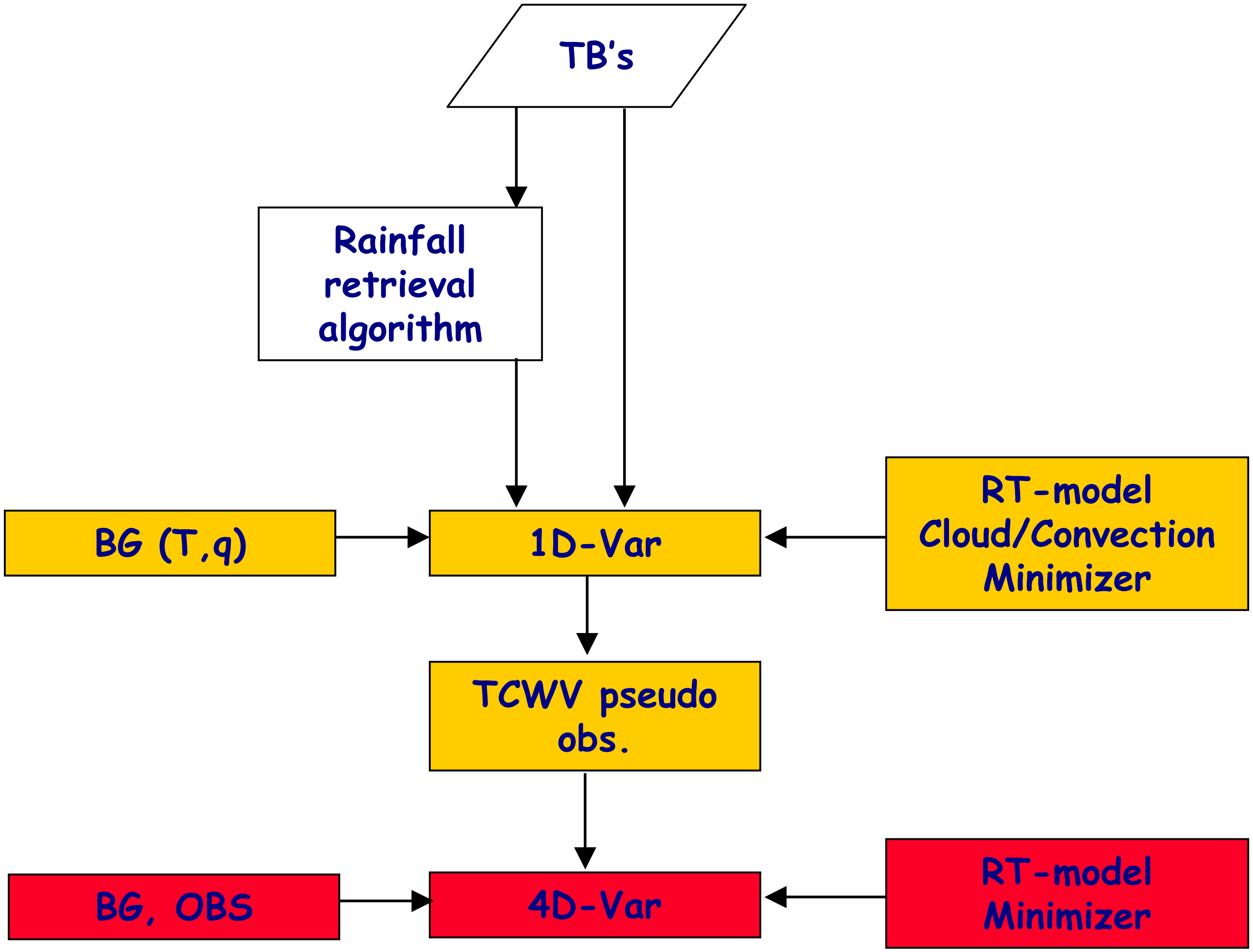
Observations



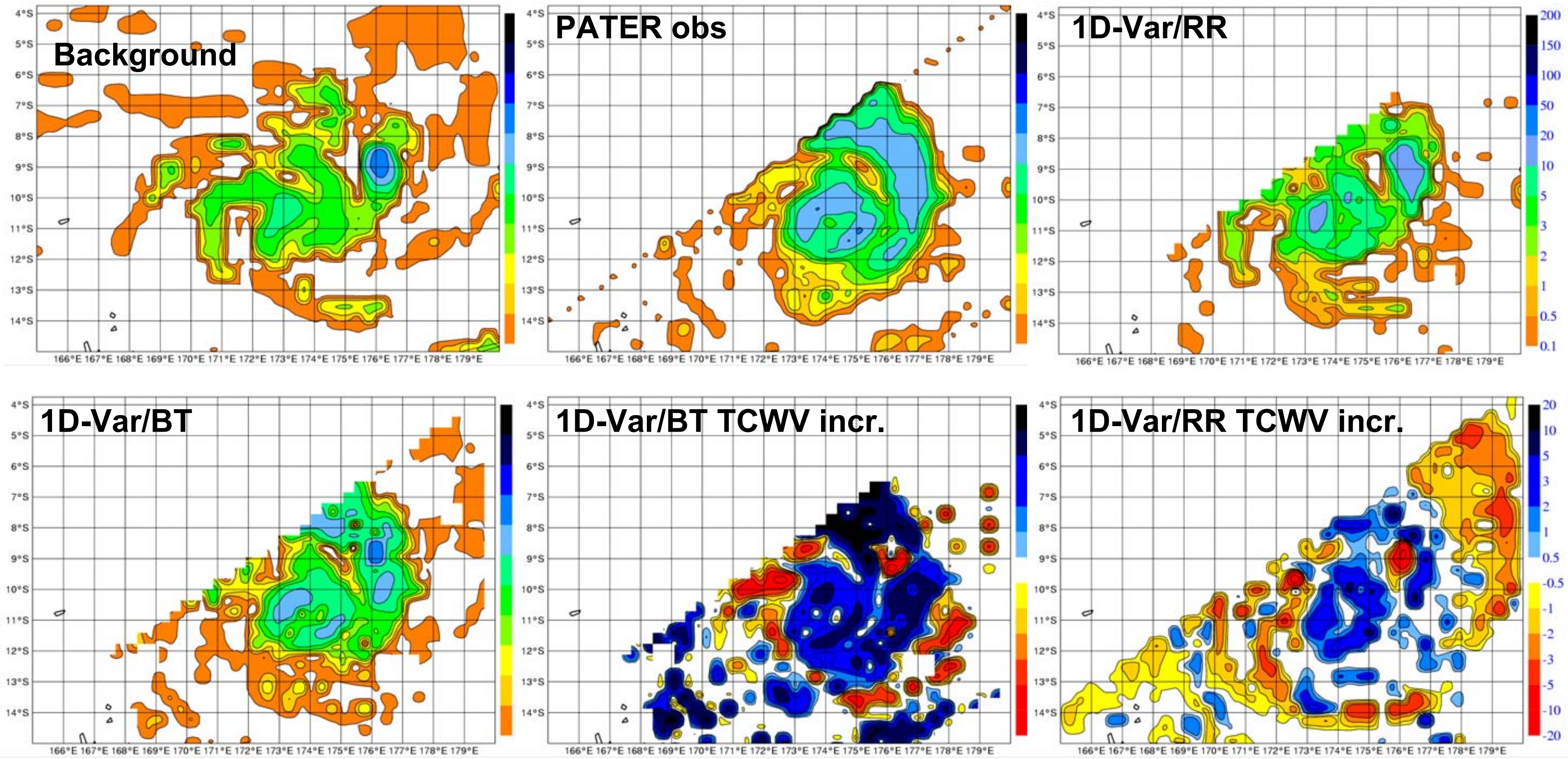
Observations



Exemple: 1D+4D-Var approach to assimilate rain information from satellites



1D-Var results



Case of tropical cyclone ZOE (26 December 2002 @1200 UTC)

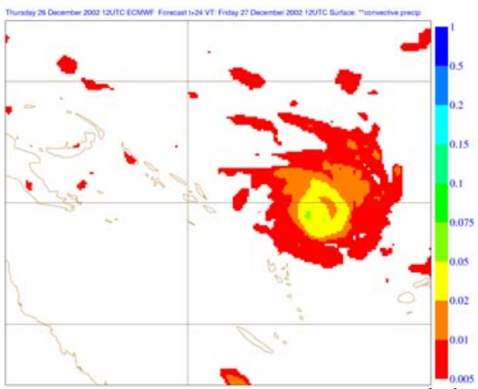
Surface rainfall rates (mm hr^{-1}) and TCWV increments (kg m^{-2})

ECMWF

4D-Var forecast, 26/12/02 12 UTC + 24/48h

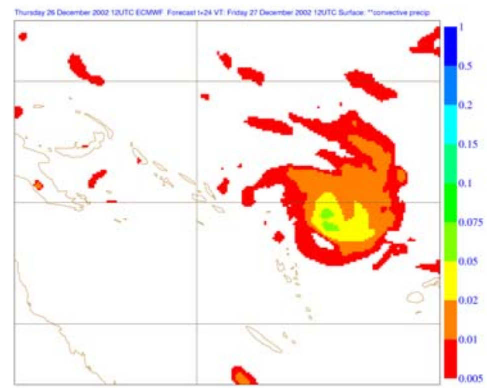
24-12h

control



mm

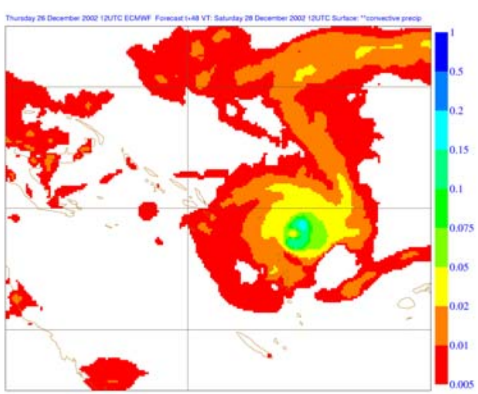
radiance assim



mm

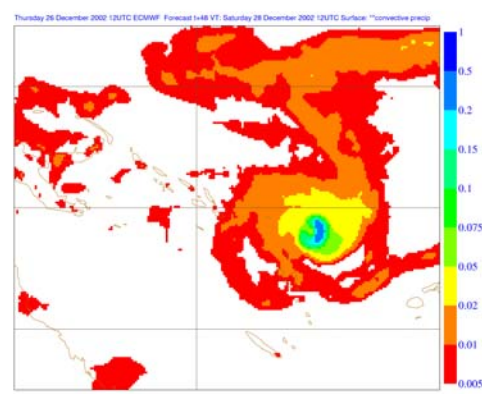
48-36h

control



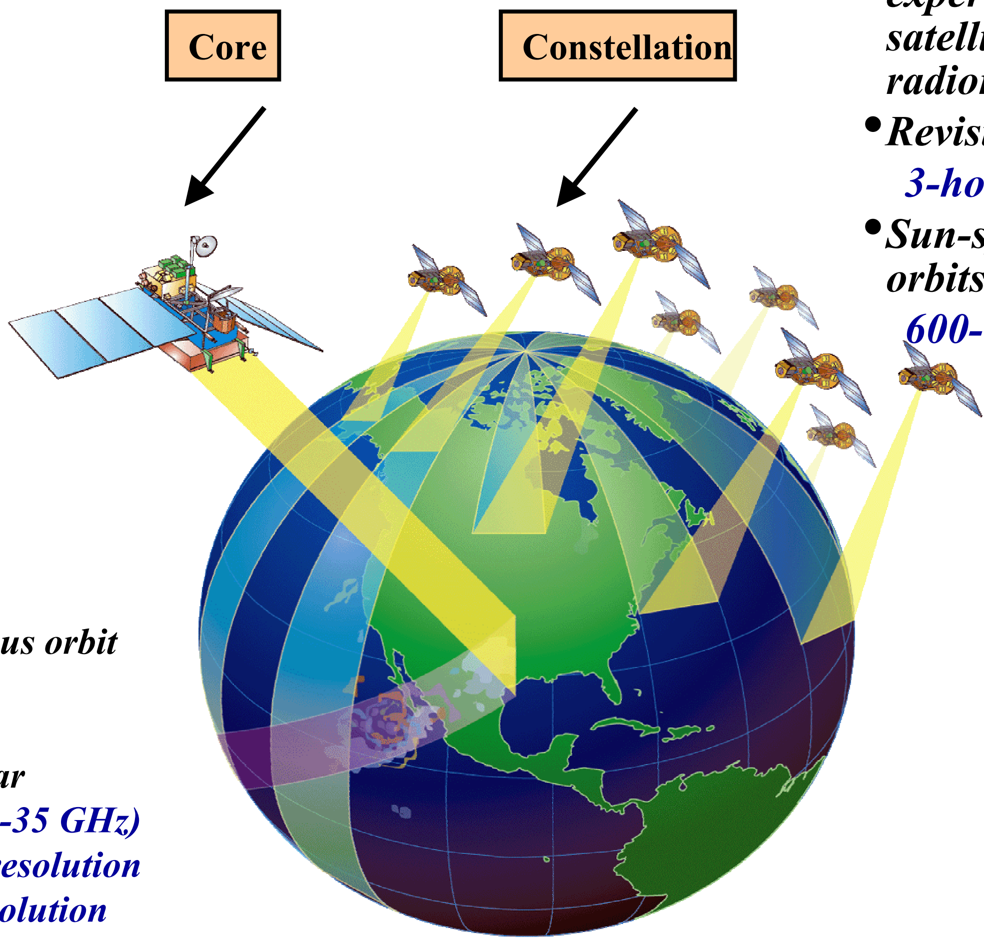
mm

radiance assim



mm

GPM - Global Precipitation Mission



Constellation of Satellites

- *Pre-existing operational-experimental & dedicated satellites with PMW radiometers*
- *Revisit time*
  3-hour goal at ~90% of time
- *Sun-synch & non-sun- synch orbits*
  600-900 km altitudes

Core Satellite

- *Non-sun-synchronous orbit*
  ~ 65° inclination
  ~400 km altitude
- *Dual frequency radar*
  Ku-Ka Bands (13.6-35 GHz)
  ~ 4 km horizontal resolution
  ~250 m vertical resolution
- *Multifrequency radiometer*
  10.7, 19, 22, 37, 85, (150/183 ?) GHz V&H

Source: NASA

Future evolution and challenges

- More generally, ACTIVE TECHNOLOGIES (radars,lidars) will provide detailed vertical information on hydrometeors (Cloudsat, GPM, …), aerosols (EarthCare), wind (ADM-AEOLUS) that data assimilation schemes should exploit (maybe challenging for variational schemes)
- Limb sounding (passive and active) techniques raise new challenges for data assimilation. These instruments will also contribute to improved temperature/moisture/ozone vertical resolution
- Satellite data will increasingly be of interest for:
  - land data assimilation
    - ➔ Surface type, soil moisture,…: MSG, MODIS, AMSR, SMOS,…
  - Ocean data assimilation
    - ➔ SST, sea state, salinity, gravity, ocean colour..: Topex, Jason(2), ERS,SMOS, GRACE, GOCE, MERIS,…

Concluding remarks

- Satellite data have been very succesfully exploited by new data assimilation schemes (DA schemes are such that introducing additional well characterised satellite data improves the system)
- The combined availability of new accurate satellite observations and improvement of models will allow an improved extraction of information content from these new data (parallel upgrades of *B* and *Y)*
- The proliferation of new satellite instruments makes it hard for end-users to keep up (choices will have to be done)
- Massive investment in data handling and monitoring should be done (or pursued)
- Short-loop dialogue between users and space agencies is vital!

THE LIST OF ACRONYMS WILL BE PROVIDED IN THE PROCEEDINGS!