New technologies and applications of satellite data assimilation for NWP, including reanalysis, climate monitoring,..

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(with contributions from Niels Bormann, Tony McNally, Sean Healy, Bill Bell, Qifeng Lu, Paul Poli, Dick Dee, Richard Engelen, Antje Inness, David Tan,…)

Outline

1. **New and future observing systems (examples):**
   1. **GPS RO**
   2. **Aeolus**

2. **NWP and CAL/VAL of Satellite Data**

3. **Reanalysis**

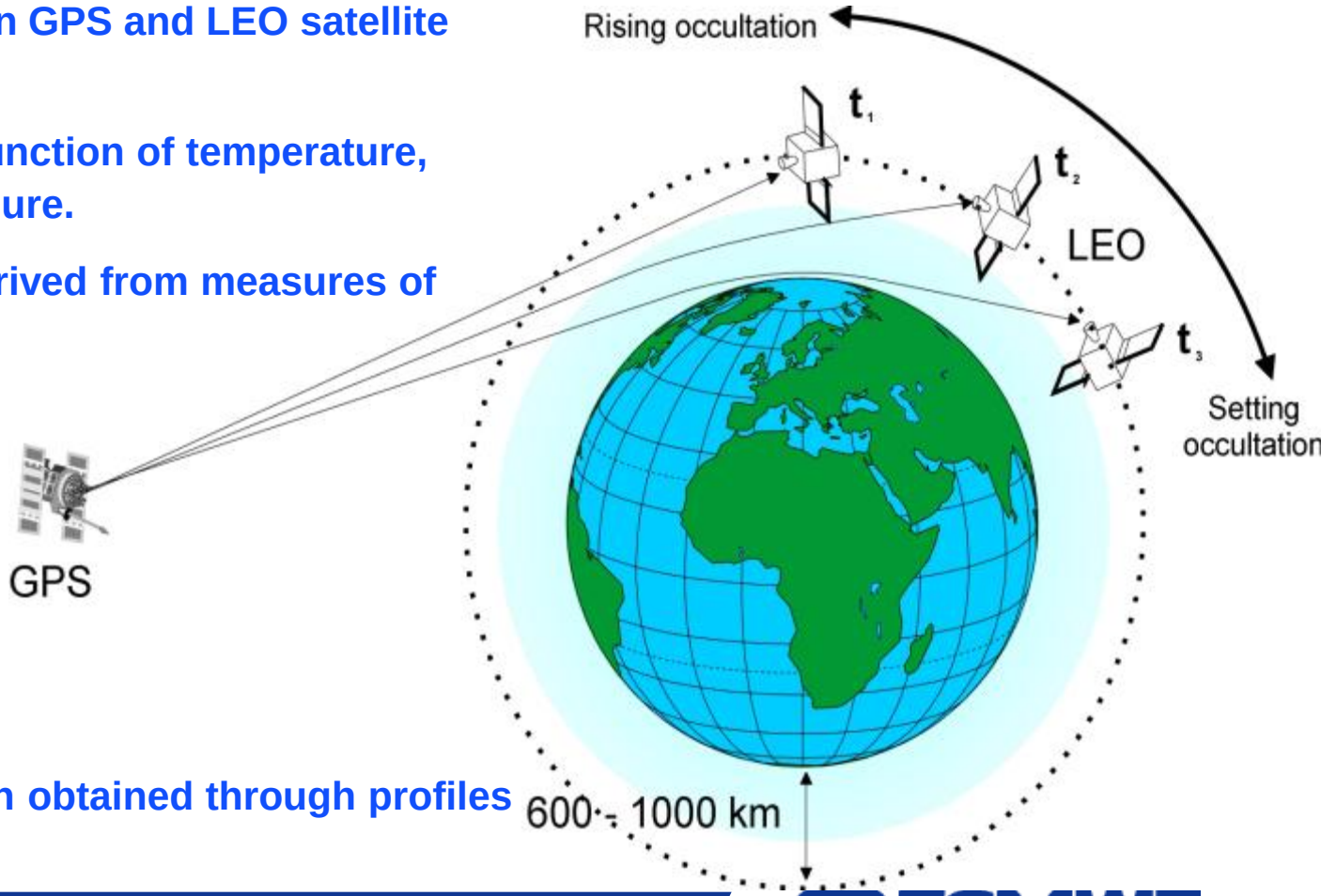
4. **Monitoring Atmospheric Composition and Climate (MACC)**

1.) New and future observing systems:

GPSRO

GPS (GNSS) Radio occultation

- **Limb measurement.**
- **Gradients in refractivity cause bending of a signal path between GPS and LEO satellite (Snell's law).**
- **Refractivity is a function of temperature, humidity and pressure.**
- **Bending angle derived from measures of phase delay.**



- **Profile information obtained through profiles of bending angles.**

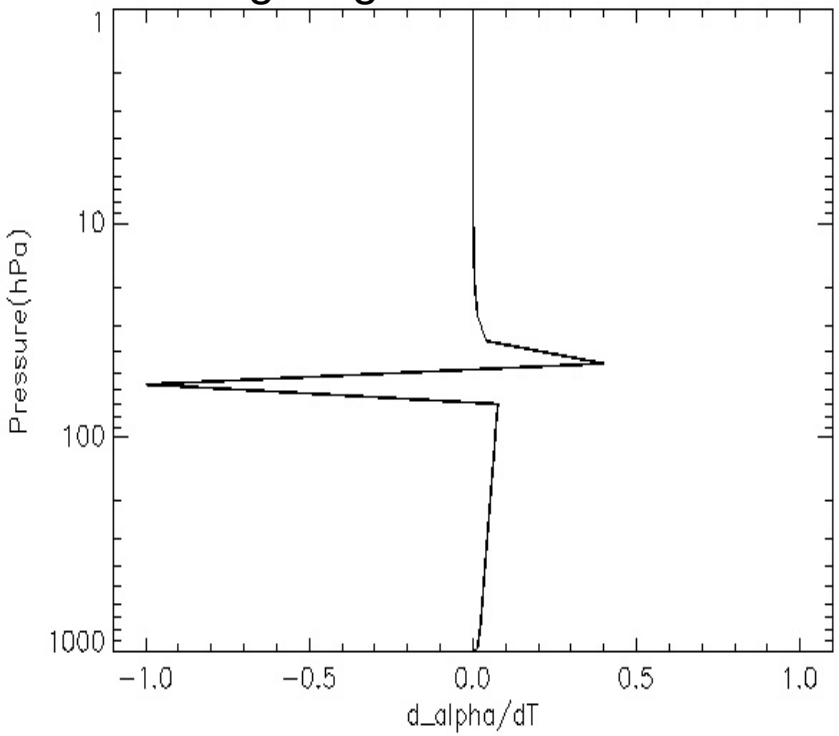
GPS RO characteristics

§ All weather-capability:
  § Not affected by cloud or rain.

§ Largely bias-free. Can help "anchor" bias corrections for radiances.

§ Good vertical resolution. Can see error structures that nadir radiances can't.

1d weighting function:

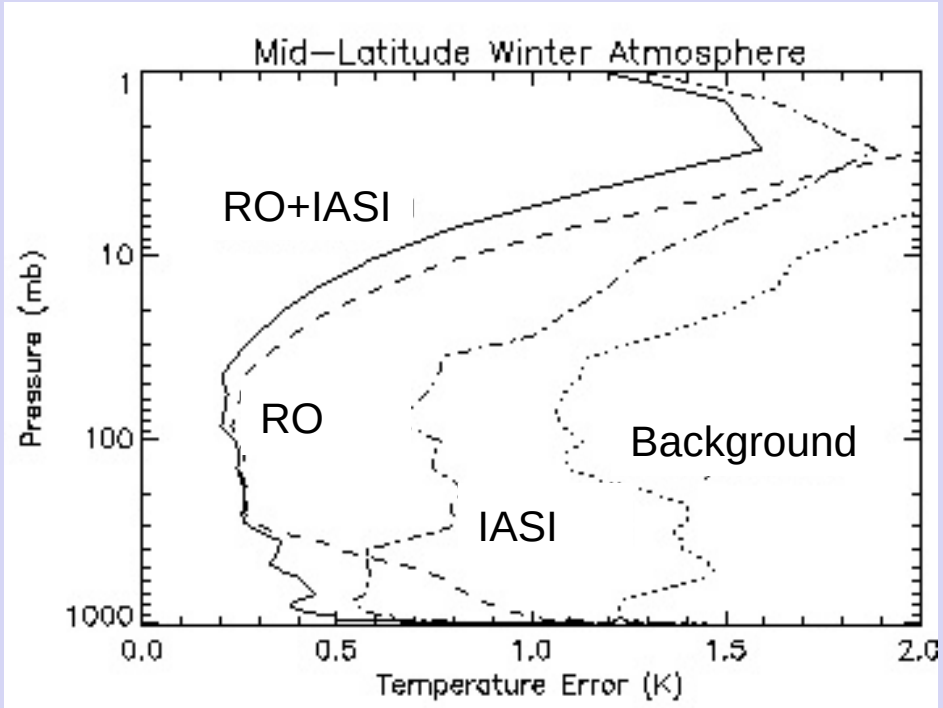


§ But has broad horizontal weighting function! - Around 70% of the bending occurs over a ~450km section of ray-path, centred on the tangent point *(point closest to surface).*

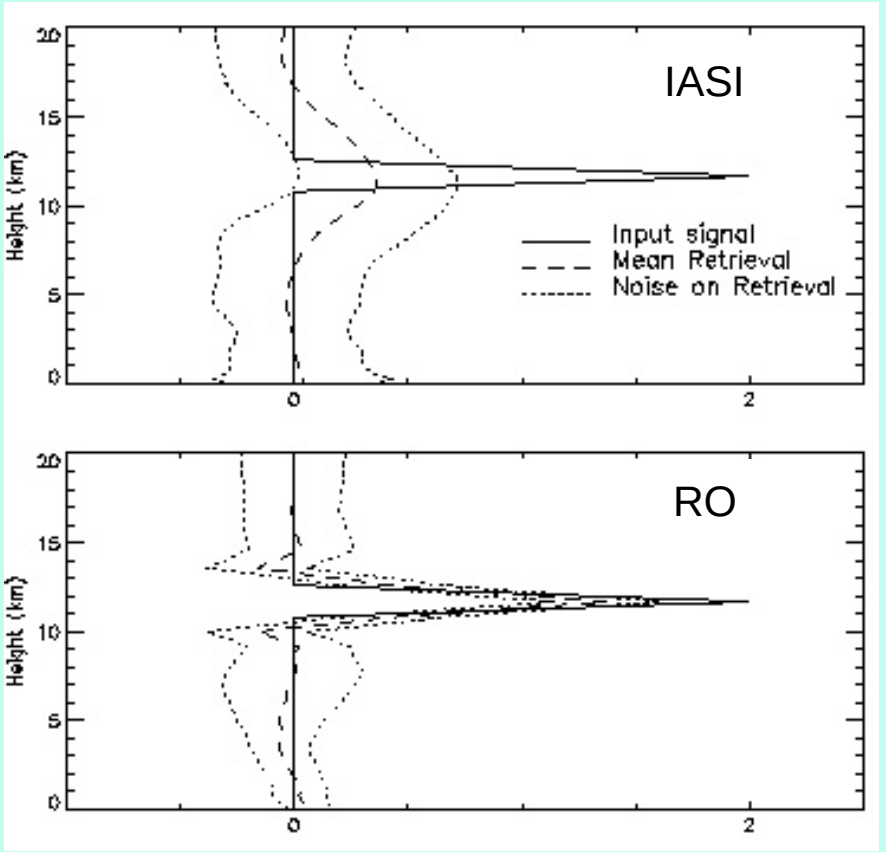
GPS RO vs IASI: 1DVAR simulations

See Healy and Collard 2003, QJRMS:

Expected retrieval error:

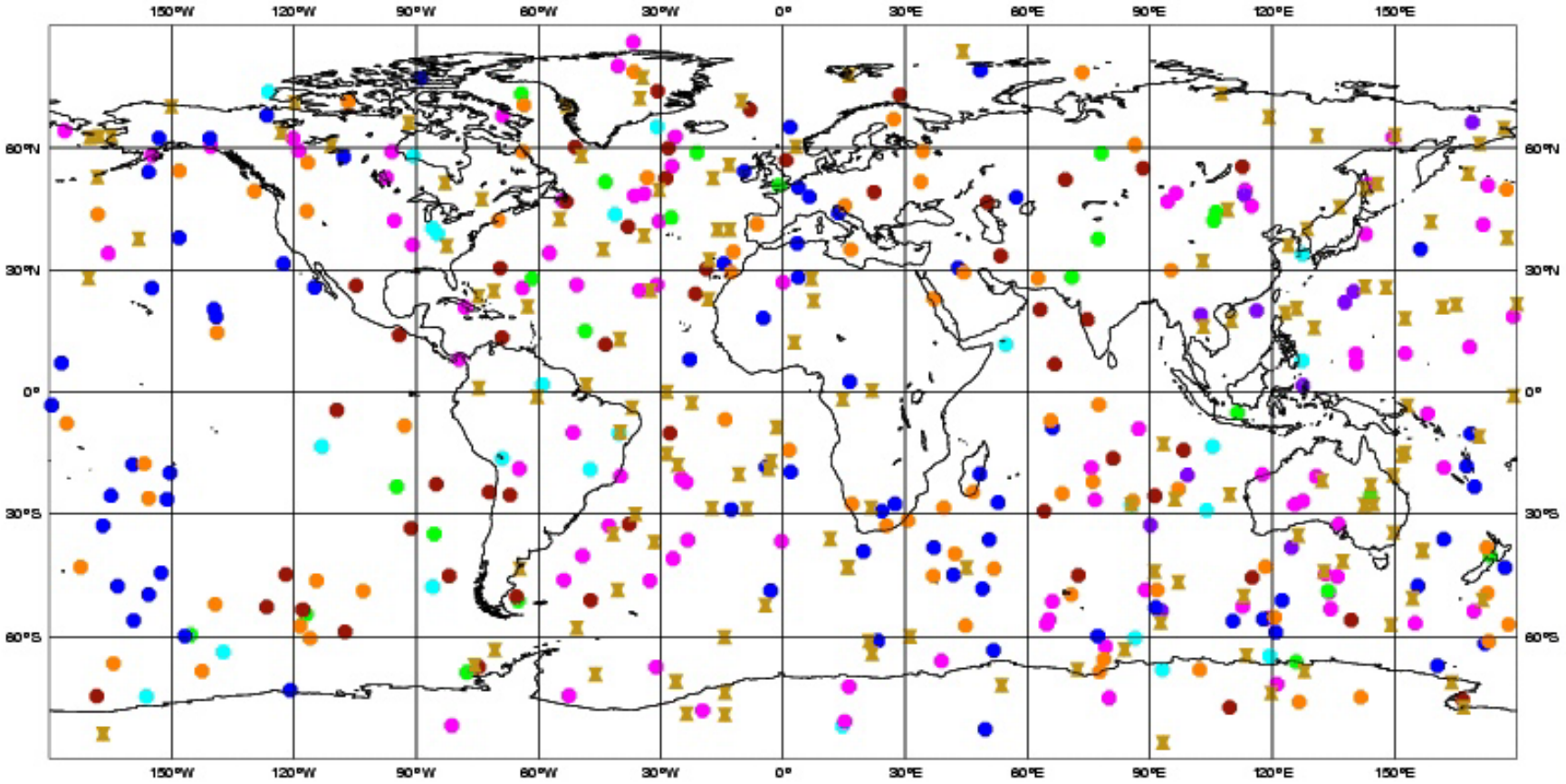


Power to resolve a peak-shaped error in background:



GPS RO data coverage in 6-hour period

Data from **GRACE-A**, **GRAS**,
COSMIC-1, **COSMIC-2**, **COSMIC-3**, **COSMIC-4**, **COSMIC-5**, **COSMIC-6**



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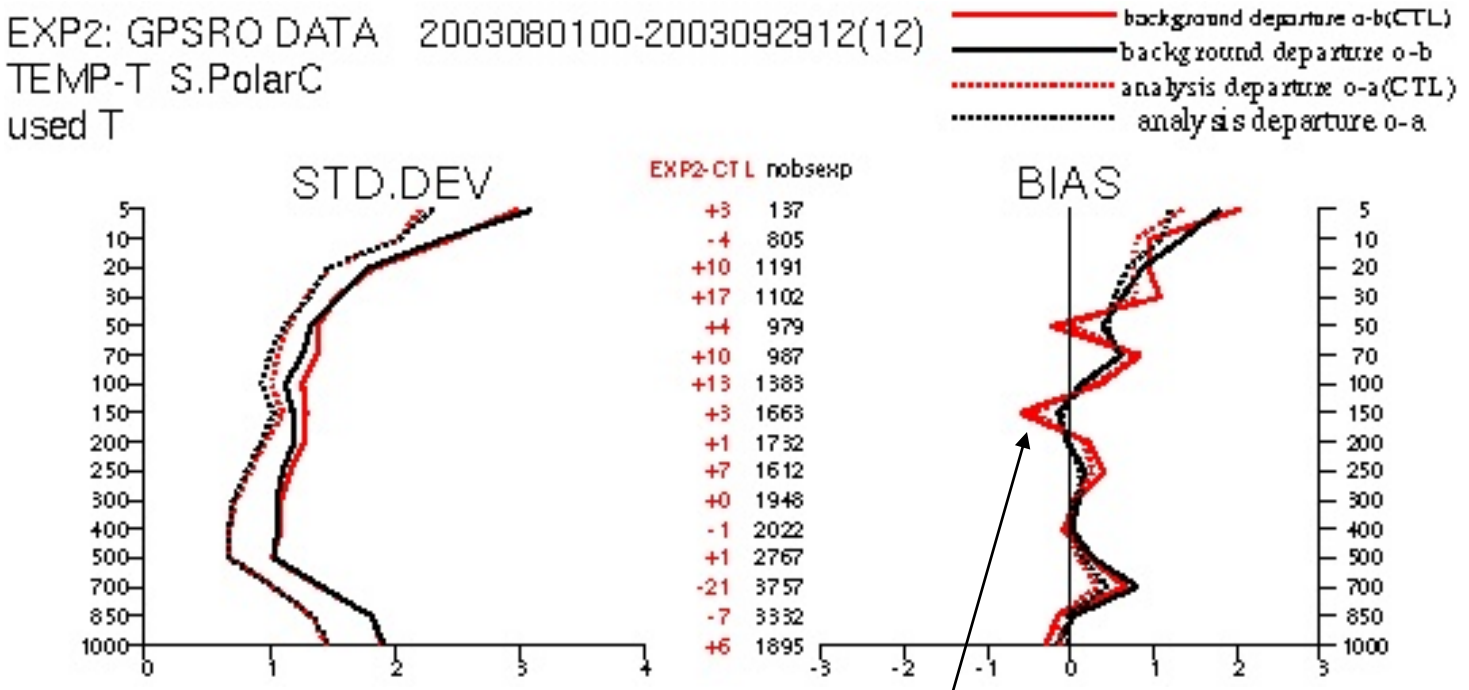
Radiosonde comparisons for Antarctica 12h forecasts



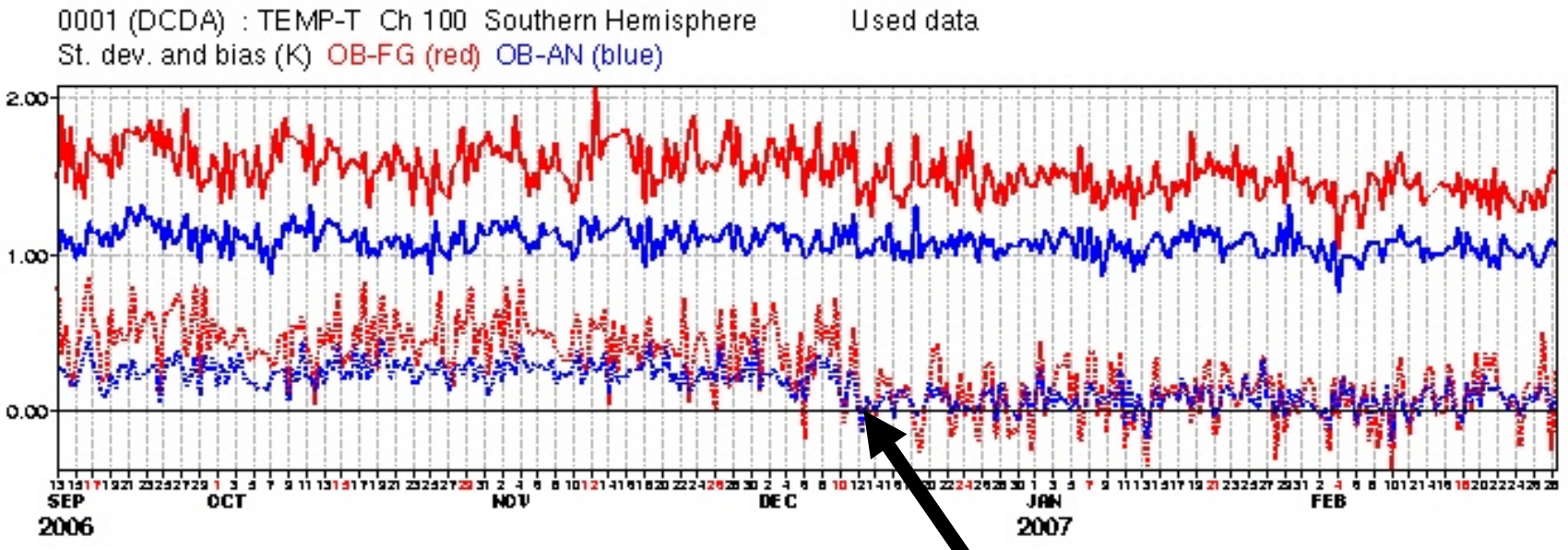
Red lines: Without GPSRO

Black: With GPSRO

Structure in the mean fit thought to be caused by inconsistencies in the AIRS and AMSU bias corrections schemes

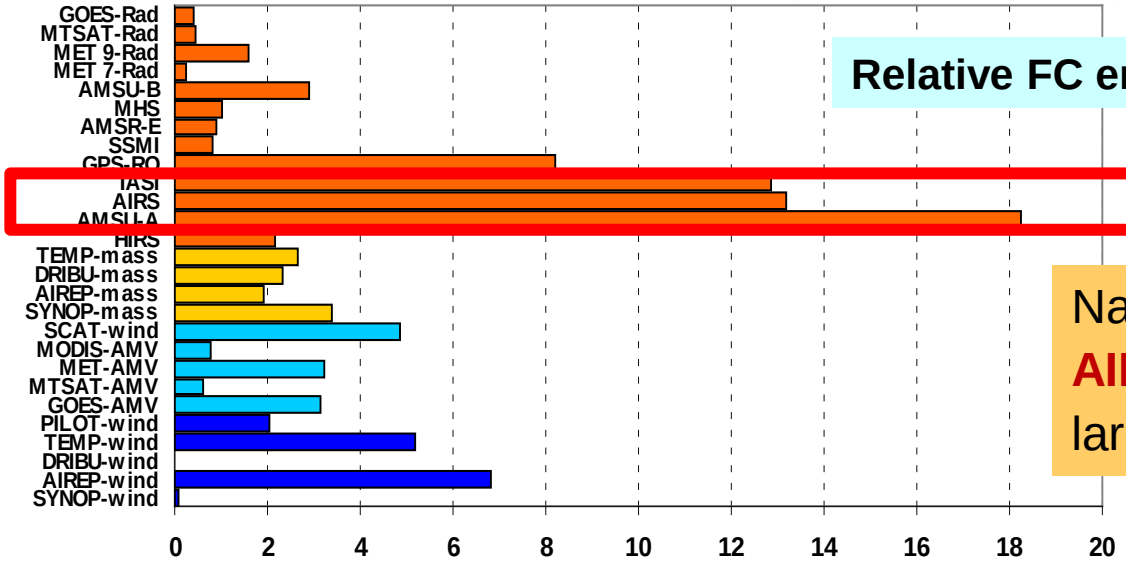
Impact on ECMWF operational analyses

- **We would expect improvements in the stratospheric temperatures. The fit to radiosonde temperatures is improved (eg, 100 hPa, SH).**



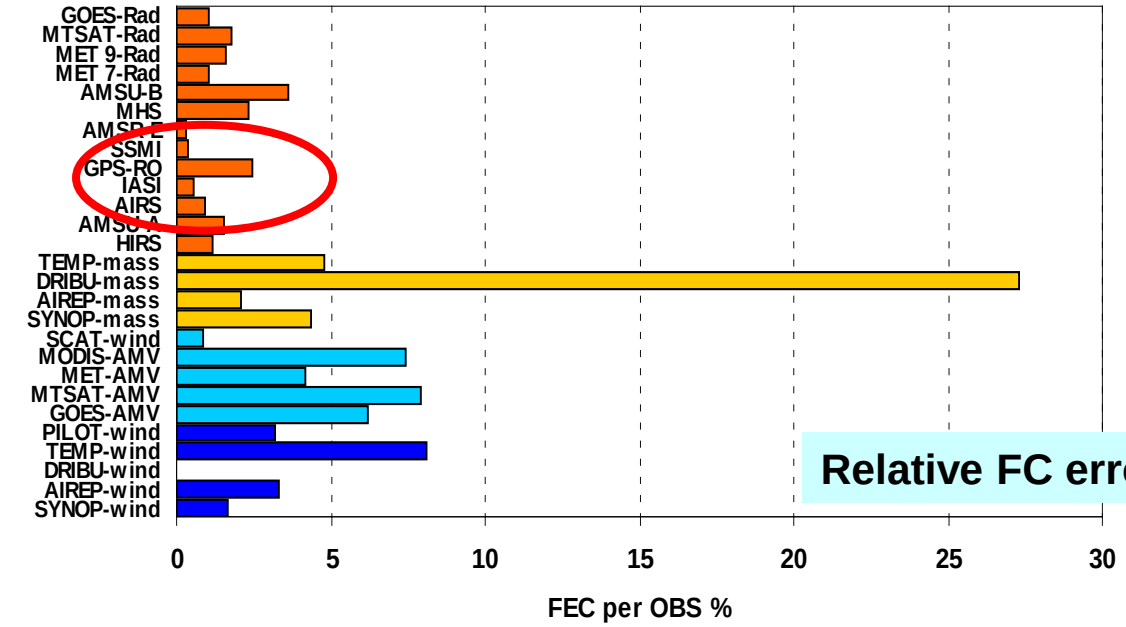
GPSRO used in operations since 12th December, 2007.

Advanced diagnostics (from lecture 1)



Relative FC error reduction per system

Nadir sounders **AMSU-A, AIRS, and IASI** provide largest impact



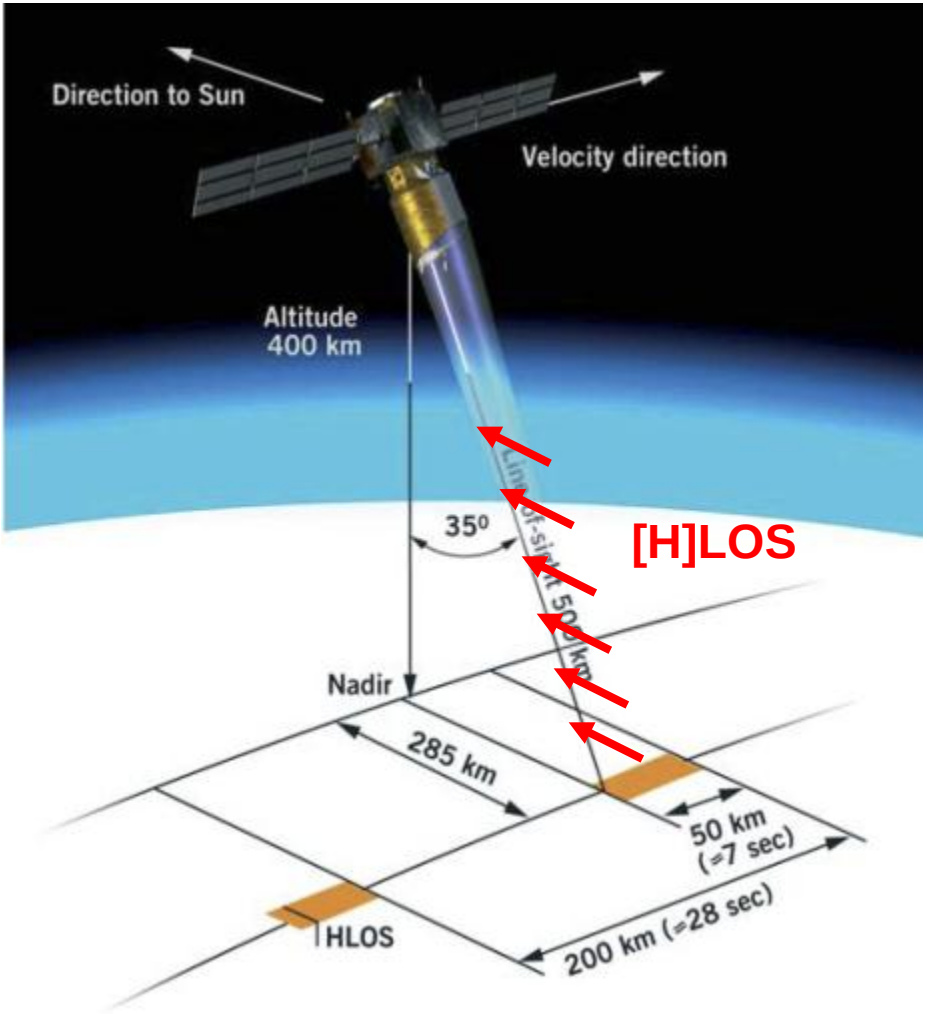
Relative FC error reduction per observation

(From C. Cardinali)

1.) New and future observing systems:

ADM-Aeolus

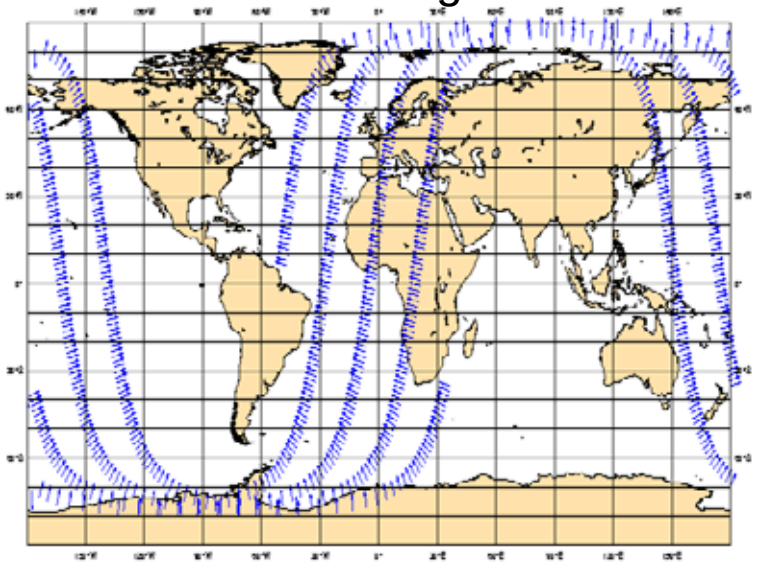
Atmospheric Dynamics Mission ADM-Aeolus



- **ESA Earth Explorer**
- **Doppler wind lidar** to measure line-of-sight (LOS) wind profiles in the troposphere to lower stratosphere (up to 30 km)
- **Vertical resolution** from 250 m - 2 km
- **Horizontal averages** over 50 km every 200 km
- Requirements on **random error** of horizontal LOS wind:
  - <1 m/s (z=0-2 km, for Δz=0.5 km)
  - <2 m/s (z=2-16 km, for Δz= 1 km
- **First wind lidar in space**; will also give information on aerosol/cloud optical properties.
- Launch: not before end of 2014

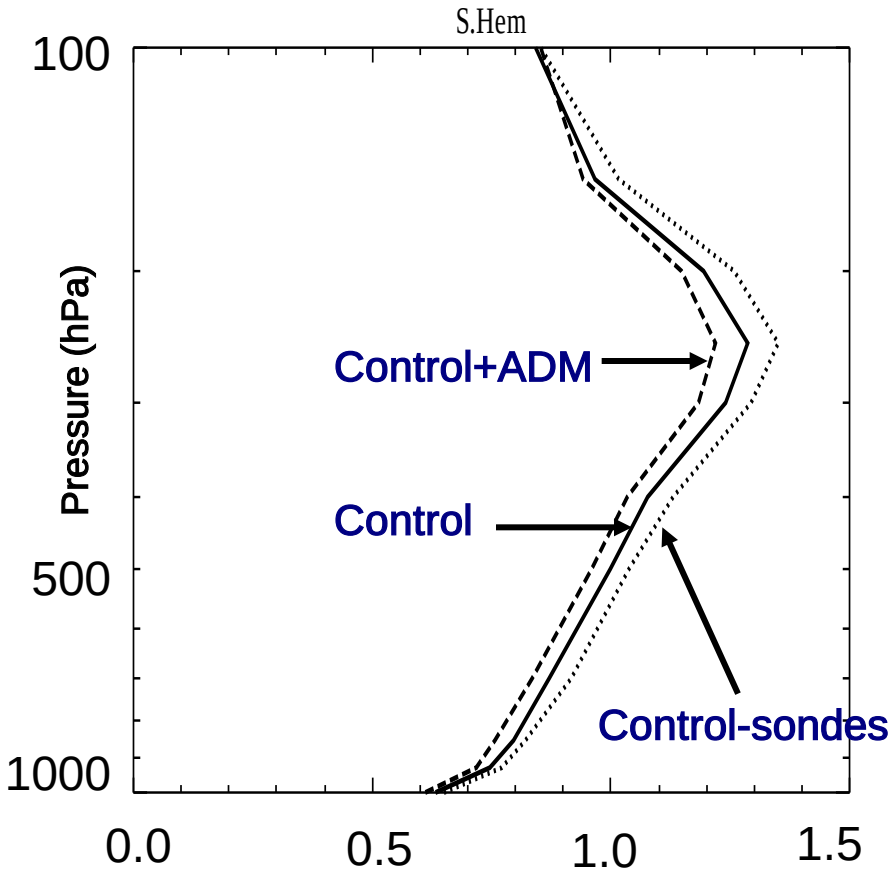
ADM-Aeolus: Simulated impact

6-hour data coverage:



Expected forecast impact for ADM-Aeolus has been simulated using ensemble methods.

Simulated DWL data adds value at all altitudes and well into longer-range forecasts.



Zonal wind forecast error (m/s) for 12-hour forecast.

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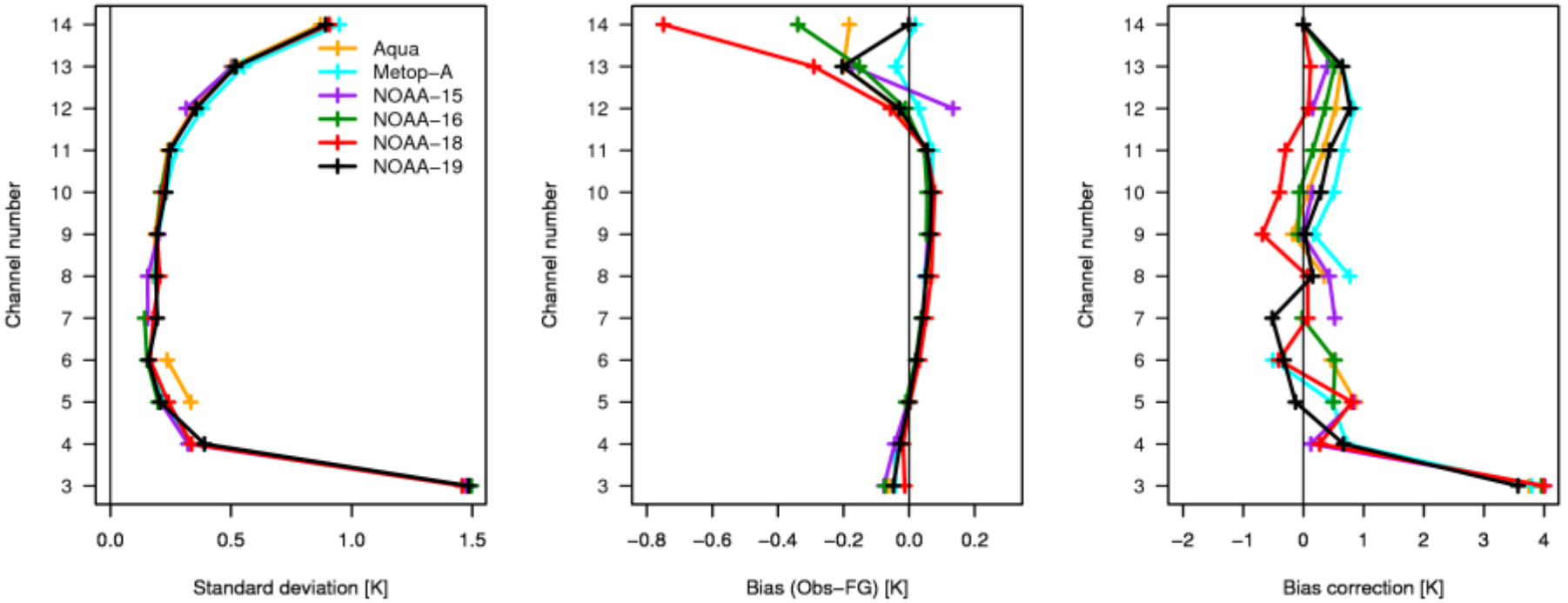
2.) NWP and cal/val of satellite data

Use of NWP systems for characterisation of observations

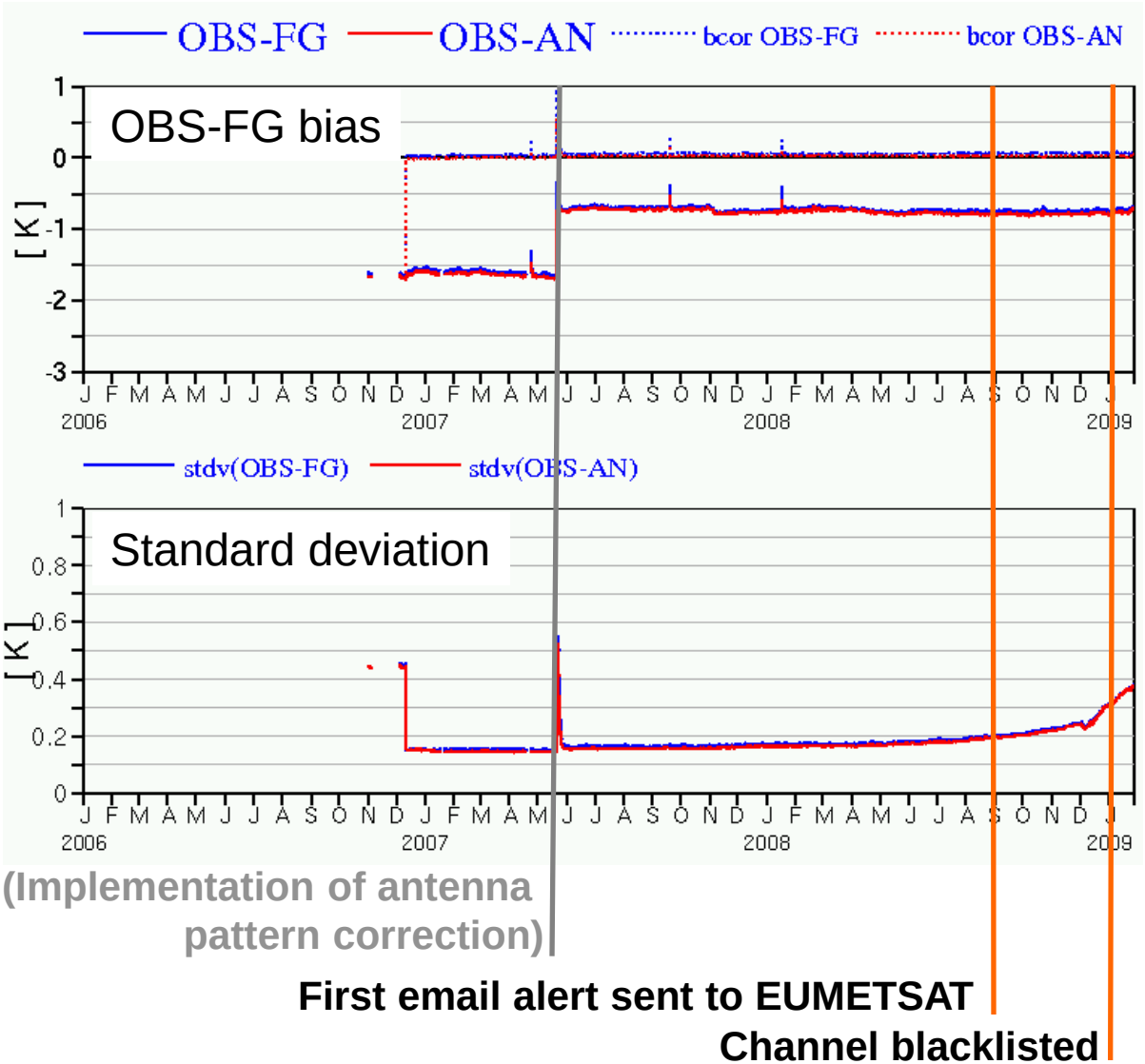
- NWP systems are increasingly used for the evaluation of (new) satellite data.
- Observation-minus-background-departures provide a comparison against a reference with relatively stable characteristics and allows cross-validation with similar instruments.
- E.g., cal/val for NOAA-19 AMSU-A in April 2009:



Early identification of data problems

E.g.,: increase in noise of channel 7 of METOP-A AMSU-A

FG and AN departures for METOP-A, AMSU-A ch 7 (global, clear data):



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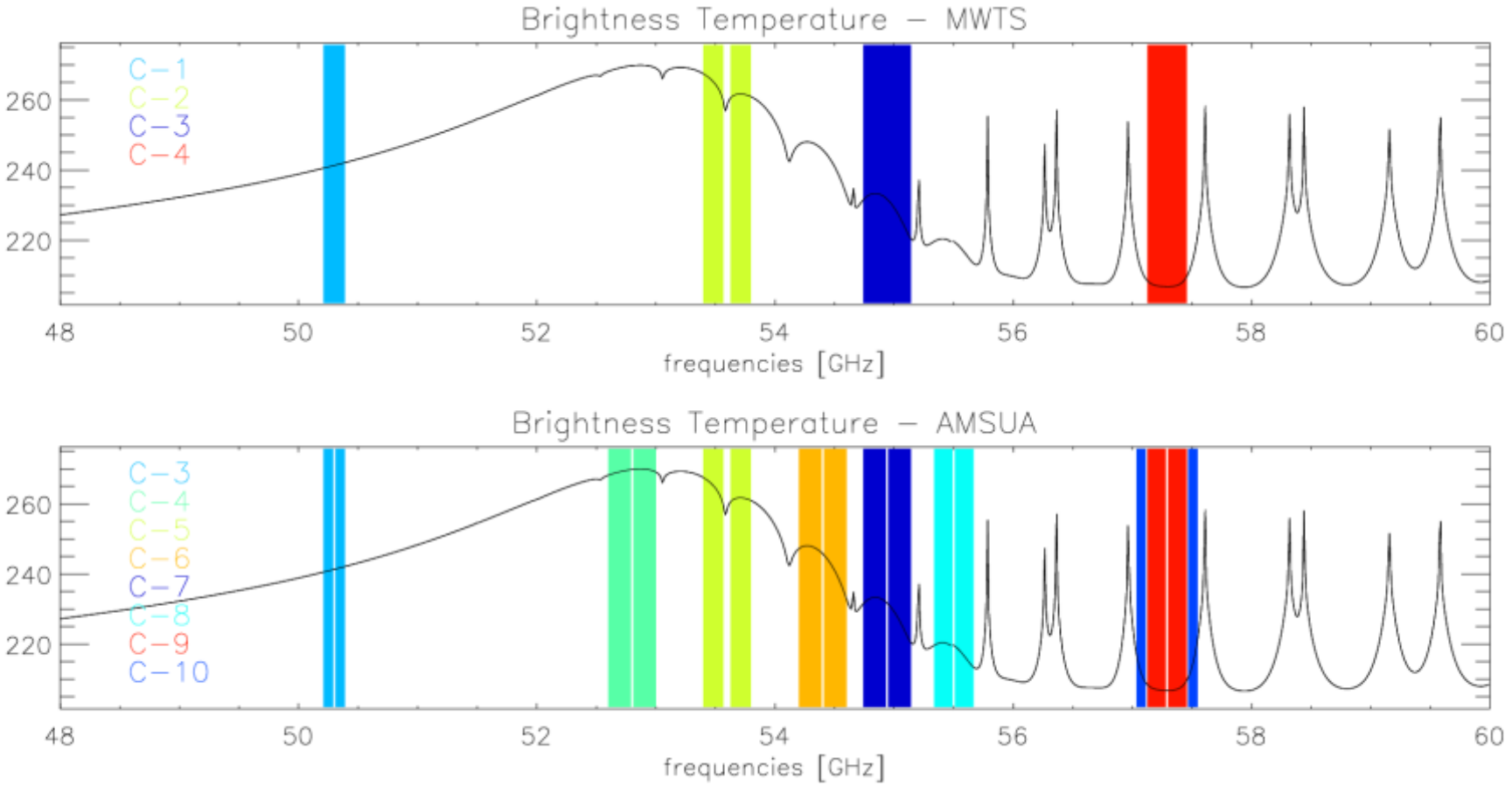
Evaluation of FY-3A MWTS data

Pass-bands for Microwave Temperature Sounder (MWTS) compared to AMSU-A:



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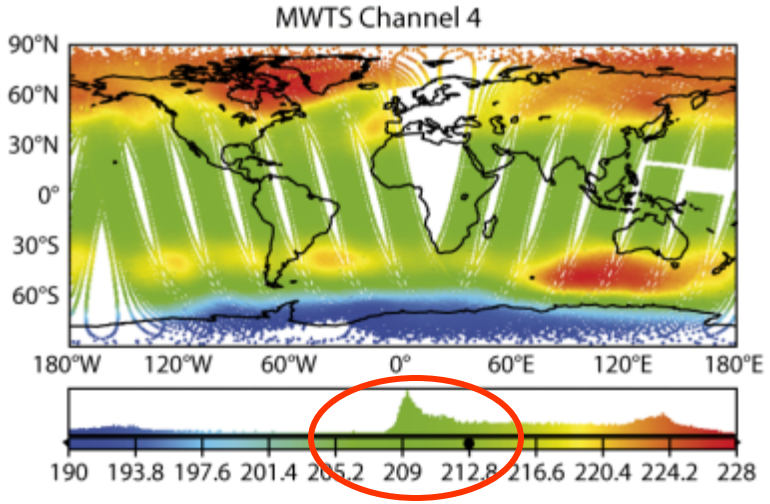
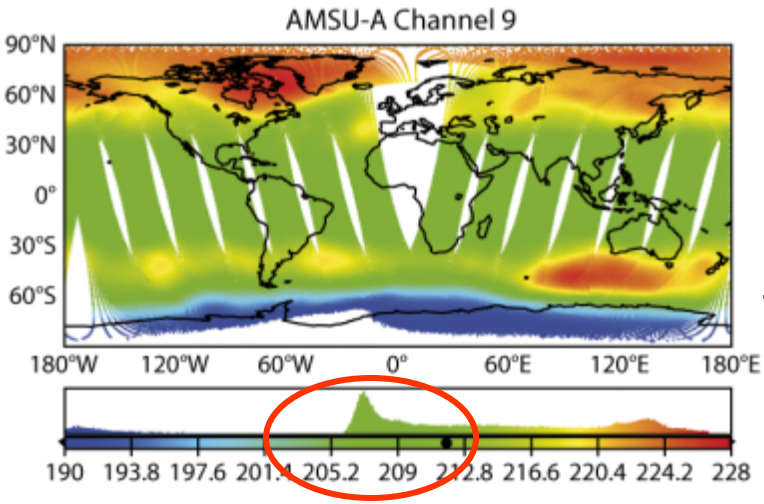
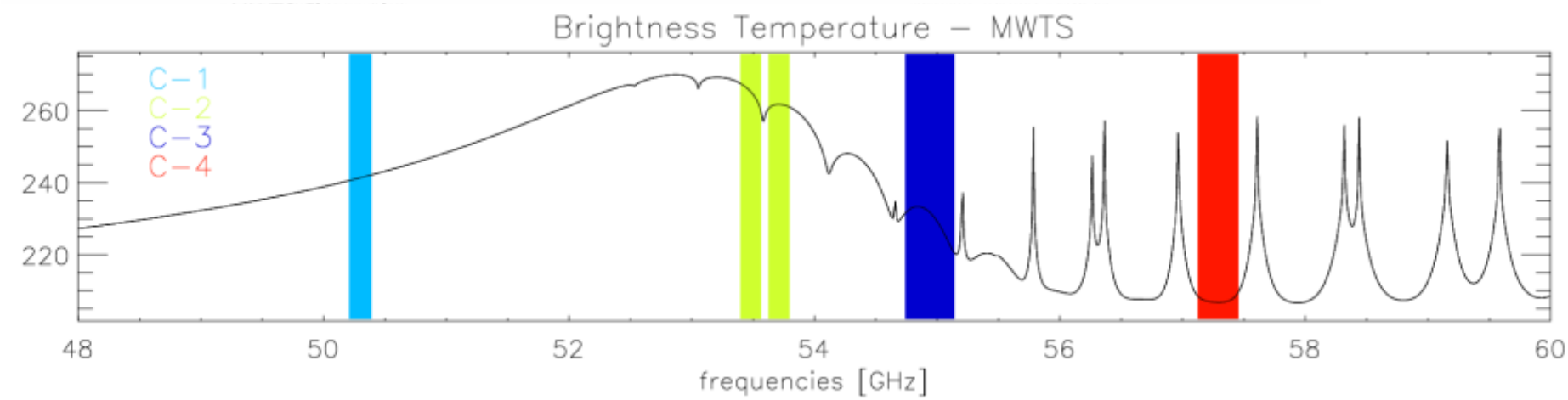
Evaluation of FY-3A MWTS data





Brightness Temperatures [K]



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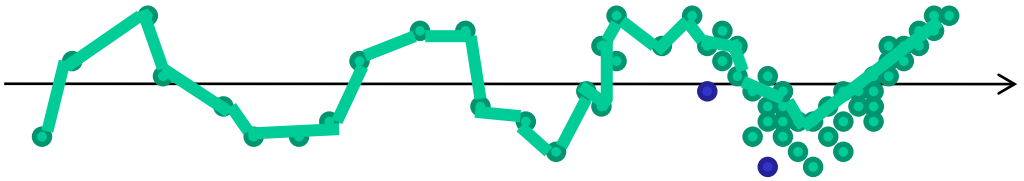
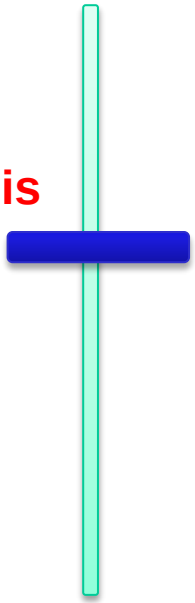
3.) Reanalysis

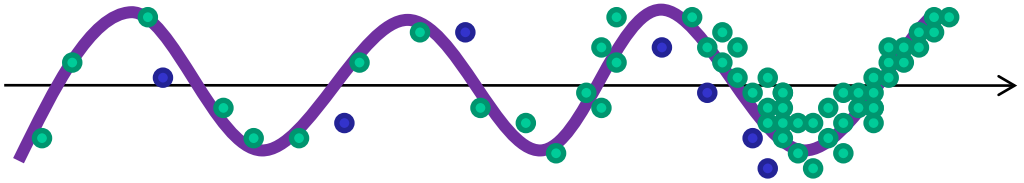
Preamble: How to reconstruct the past?

“Observations-only” climatology

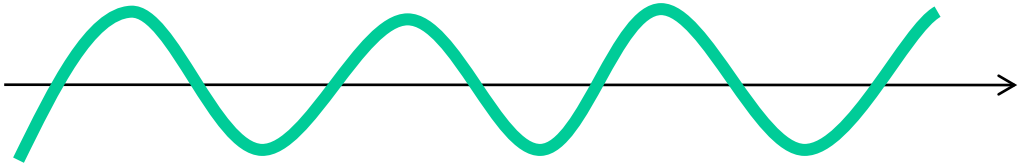


Reanalysis



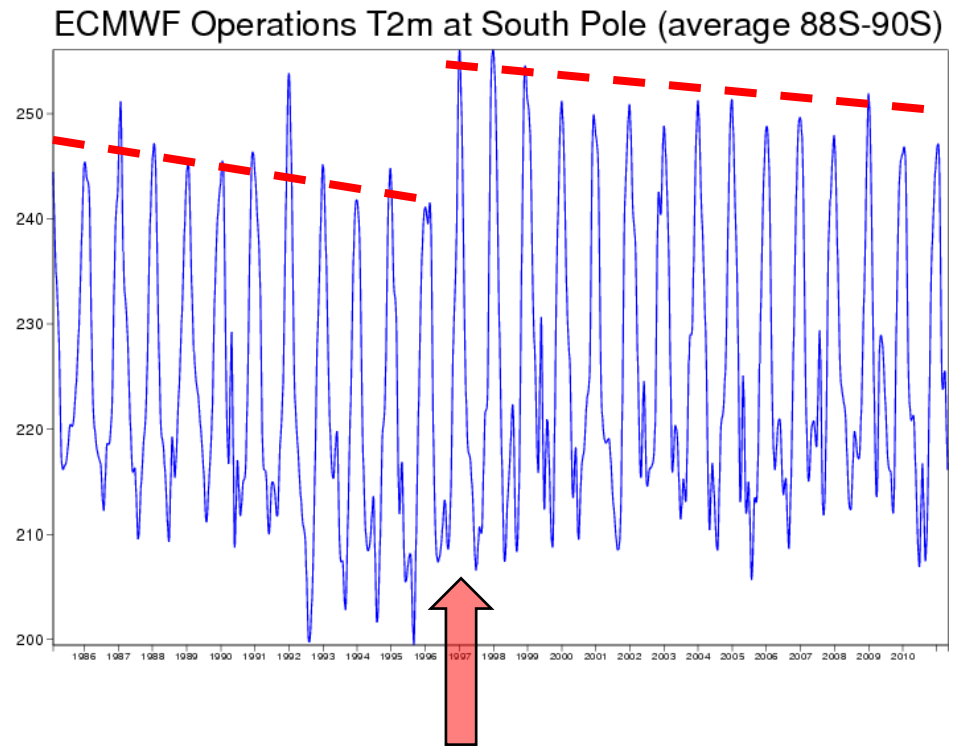


“Model only” integration

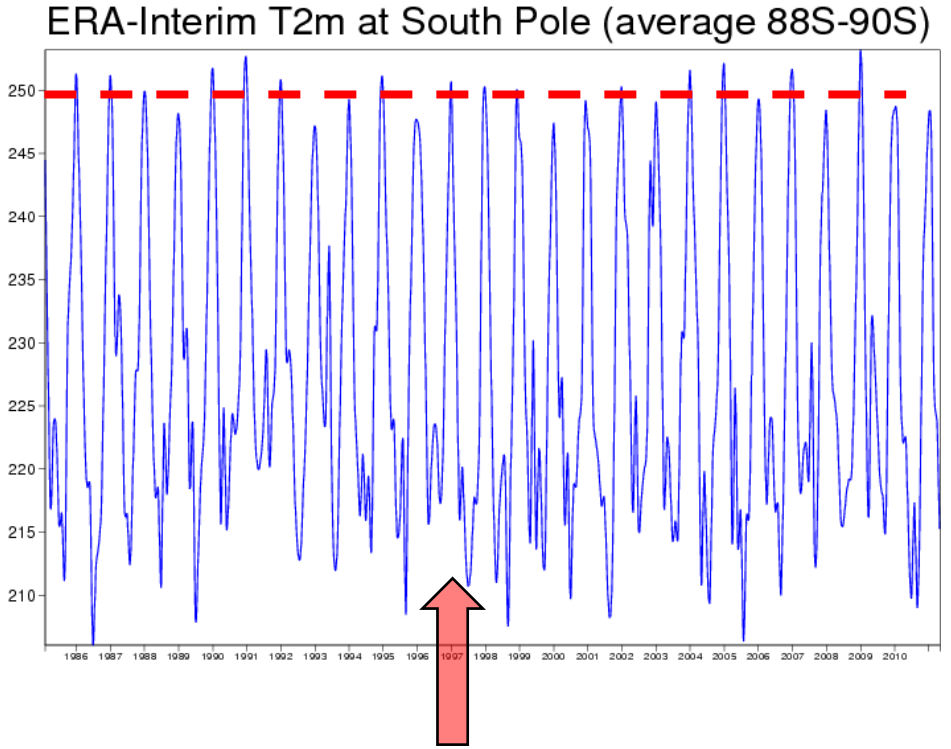


Why reanalysis?

Overall aim is greater time-consistency of the products



Was there a sudden change in South Pole summer variability in 1997?



… probably not

Why reanalysis? (2)

Reanalysis

What is Re-analysis?

Analysis of past (historical) observational data using a **fixed**, tried-and-tested, data assimilation system.

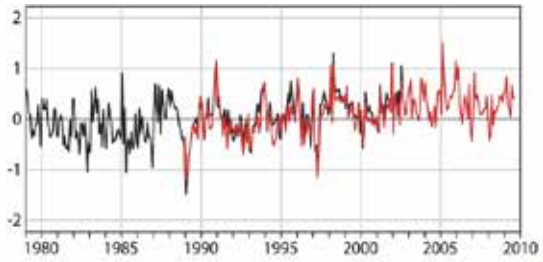
What does it produce?

A comprehensive time series of global analyses (i.e. gridded fields of temperature, humidity, wind etc..) and a homogeneous organized / quality controlled data-set of observations.

What is it used for?

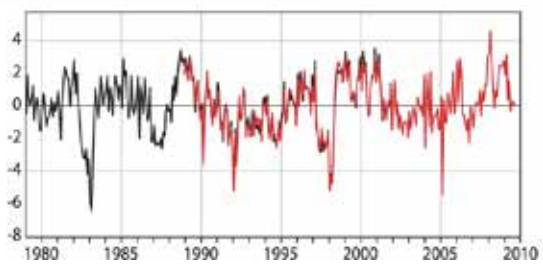
Meteorological research – into processes, composition, low-frequency variability, predictability, model development and general climate studies, …

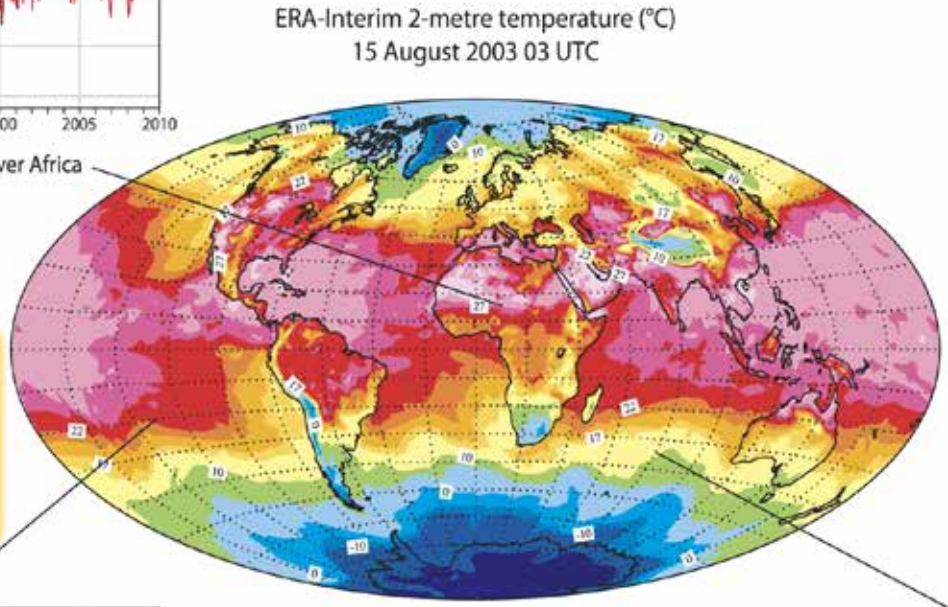
Goal: reanalysis products should be consistent ...



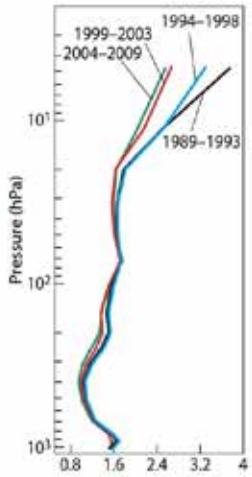
...in Time

...across Atmospheric Parameters





...in the Horizontal



Standard deviation of differences between ERA-Interim and radiosondes temperature (°C) in the southern hemisphere

...in the Vertical

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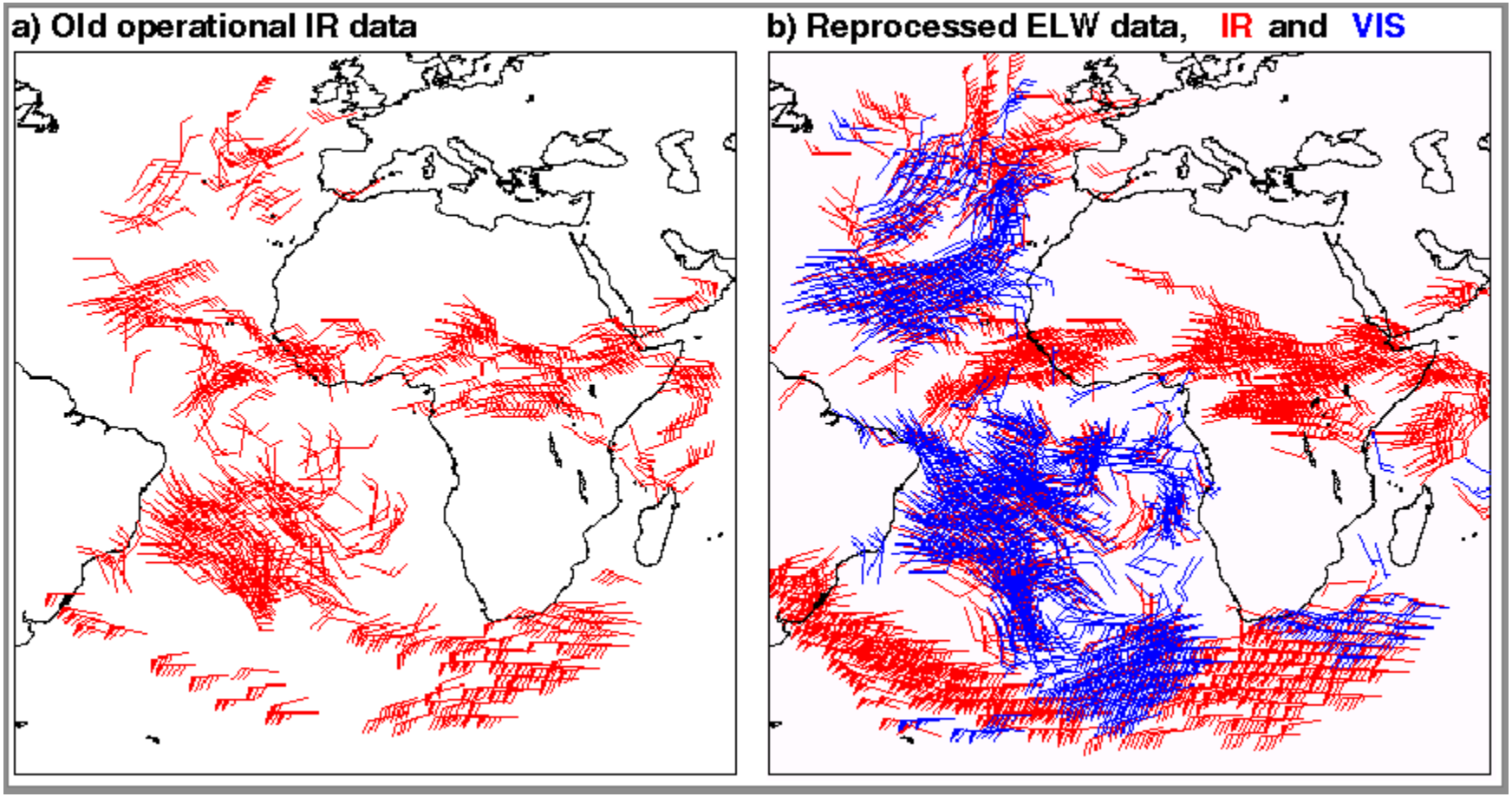
Ingredients for a reanalysis

- **Observations**
  - Try using all available (good) observations
  - Observation recovery
  - Reprocessed observations
  - Observations previously unavailable in real-time
- **Advanced data assimilation scheme**
  - State-of-the-art, but tried-and-tested and affordable
  - Unchanged during the reanalysis production
  - Adequate for variable observation coverage over reanalysis period
  - Capable of dealing with changeable observation biases
  - Robust quality control/data selection
- **Advanced NWP forecast model**
  - State-of-the-art, but tried-and-tested and affordable
  - Unchanged during the reanalysis production
- **Constant monitoring of all aspects during the production!**
  - And learn for the next reanalysis…

Example of improved data coverage: Reprocessed Atmospheric Motion Vectors from Meteosat



Early 1980s

Evolution of the observing system


1945 US Weather Bureau

Satellites

Upper-air soundings

Surface observations

log(number of observations)

1890 | 1938 | 1957 | 1973 | 1979 | Today

Manual stations, limited data exchange

First radiosonde networks, systematic soundings

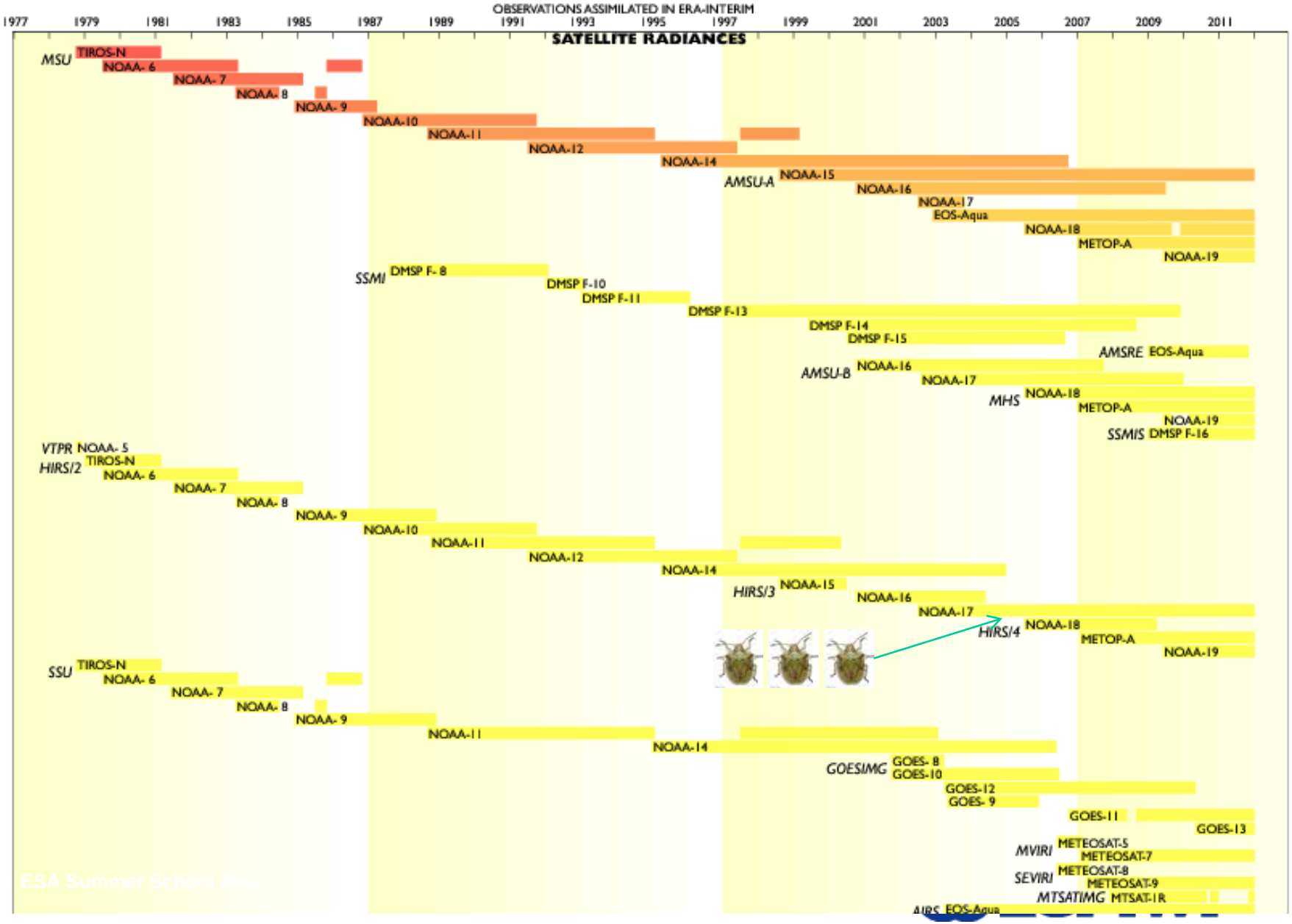
International Geophysical Year: radiosonde network enhanced, especially in the Southern Hemisphere

First operational satellite soundings (NOAA-2)

Improved sounding from polar orbiters; Winds from geostationary orbit; More data from commercial aircraft; Drifting buoys

More satellites, aircraft, buoys, ocean drifters. Radiosondes: fewer, but probe higher. Better knowledge of instrument errors. More obs. per hour per sensor.

Timeline of radiance observations in ERA-Interim



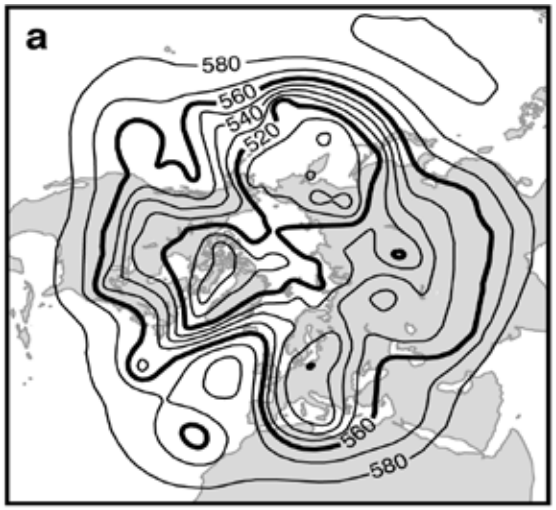
Data assimilation:

From ERA-40 to ERA-Interim

	ERA-40	ERA-Interim
Period	1957-2002	1989-onwards
Resolution	125 km	80 km
Levels	60	60
Data assimilation	6-hour 3DVAR	12-hour 4DVAR
Radiance biases	Static correction	Adaptive variational bias correction
		Improved usage and homogenisation of observations based on ERA-40; additional observations for later period

Benefits of an advanced DA scheme

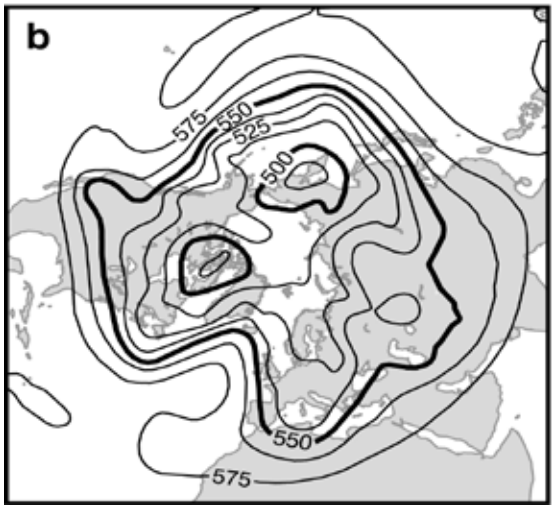
Analysis of
500 hPa geopotential



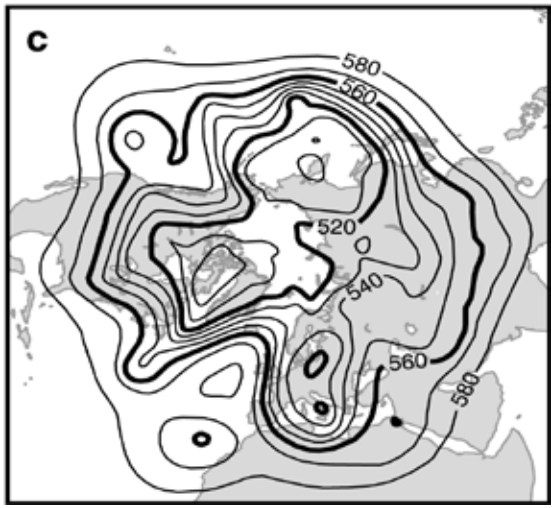
15 February 2005 00 UTC

4D-Var CONTROL

All observations (surface, radiosondes, satellite etc…)



3D-Var

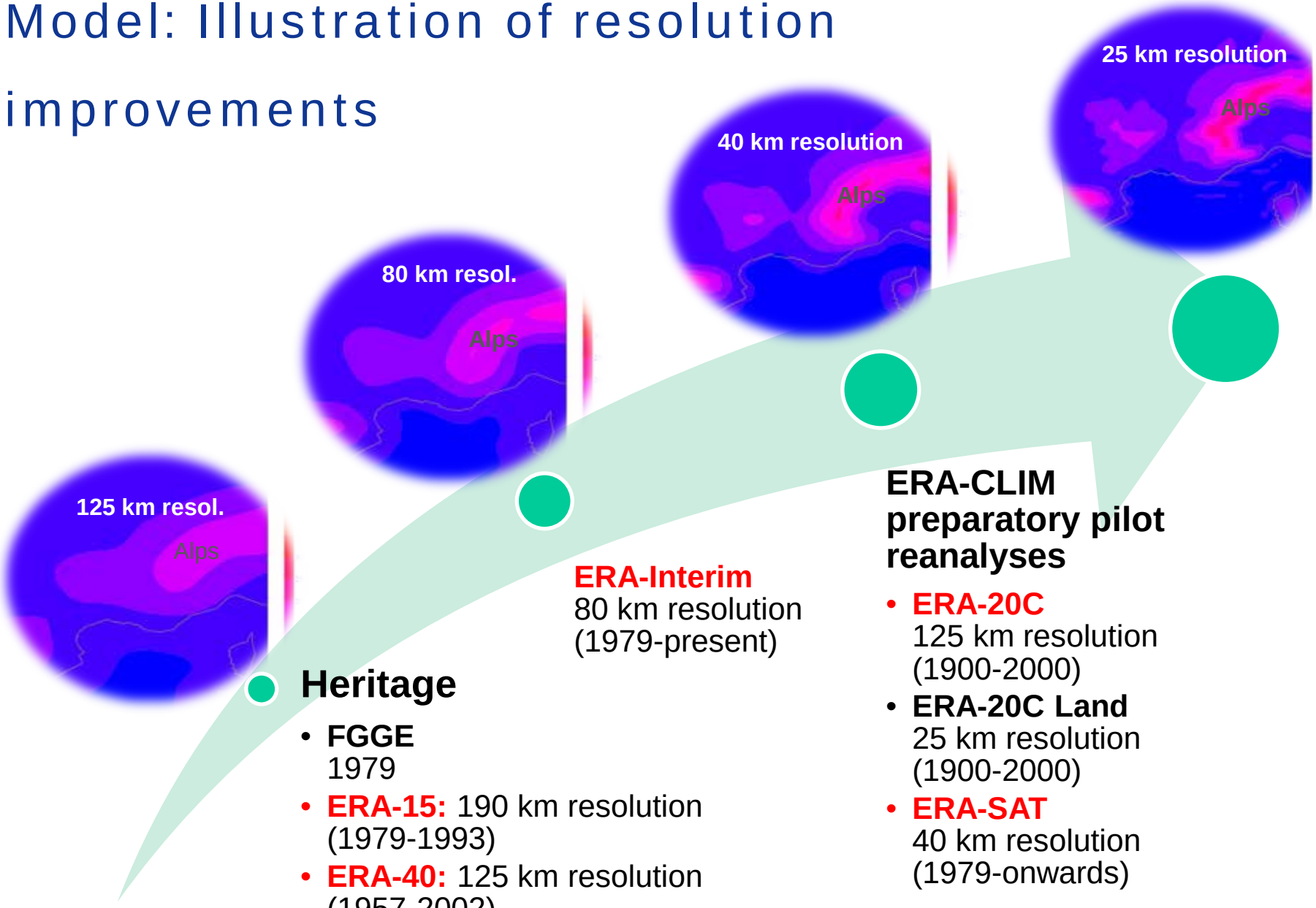


4D-Var

Surface pressure observations only

Advances in data assimilation help extract more information from historic data that could ever be thought possible at the time the observations were collected.

Model: Illustration of resolution improvements



Heritage

- **FGGE**
  1979
- **ERA-15:** 190 km resolution
  (1979-1993)
- **ERA-40:** 125 km resolution
  (1957-2002)

ERA-Interim
80 km resolution
(1979-present)

ERA-CLIM preparatory pilot reanalyses

- **ERA-20C**
  125 km resolution
  (1900-2000)
- **ERA-20C Land**
  25 km resolution
  (1900-2000)
- **ERA-SAT**
  40 km resolution
  (1979-onwards)

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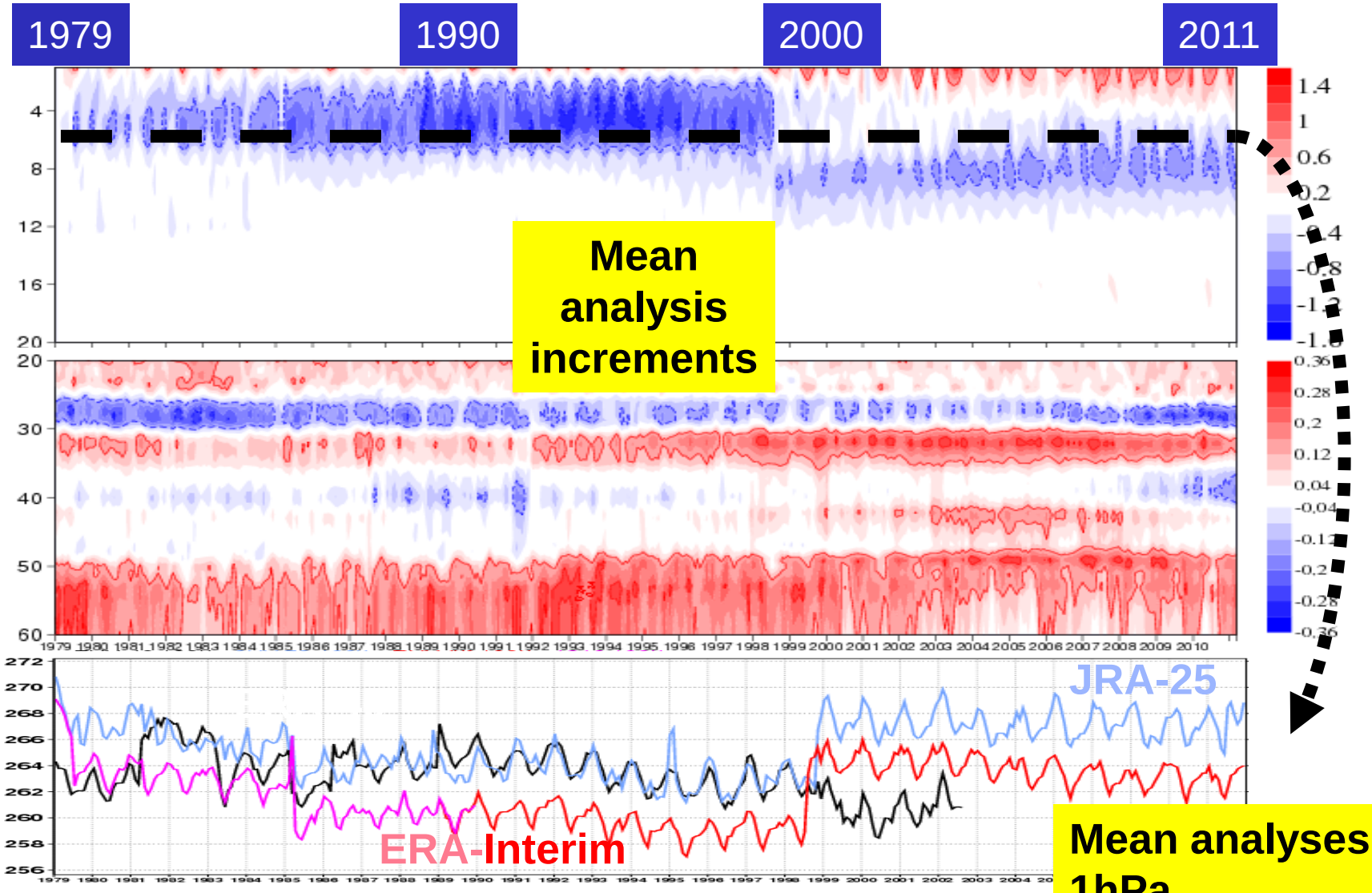
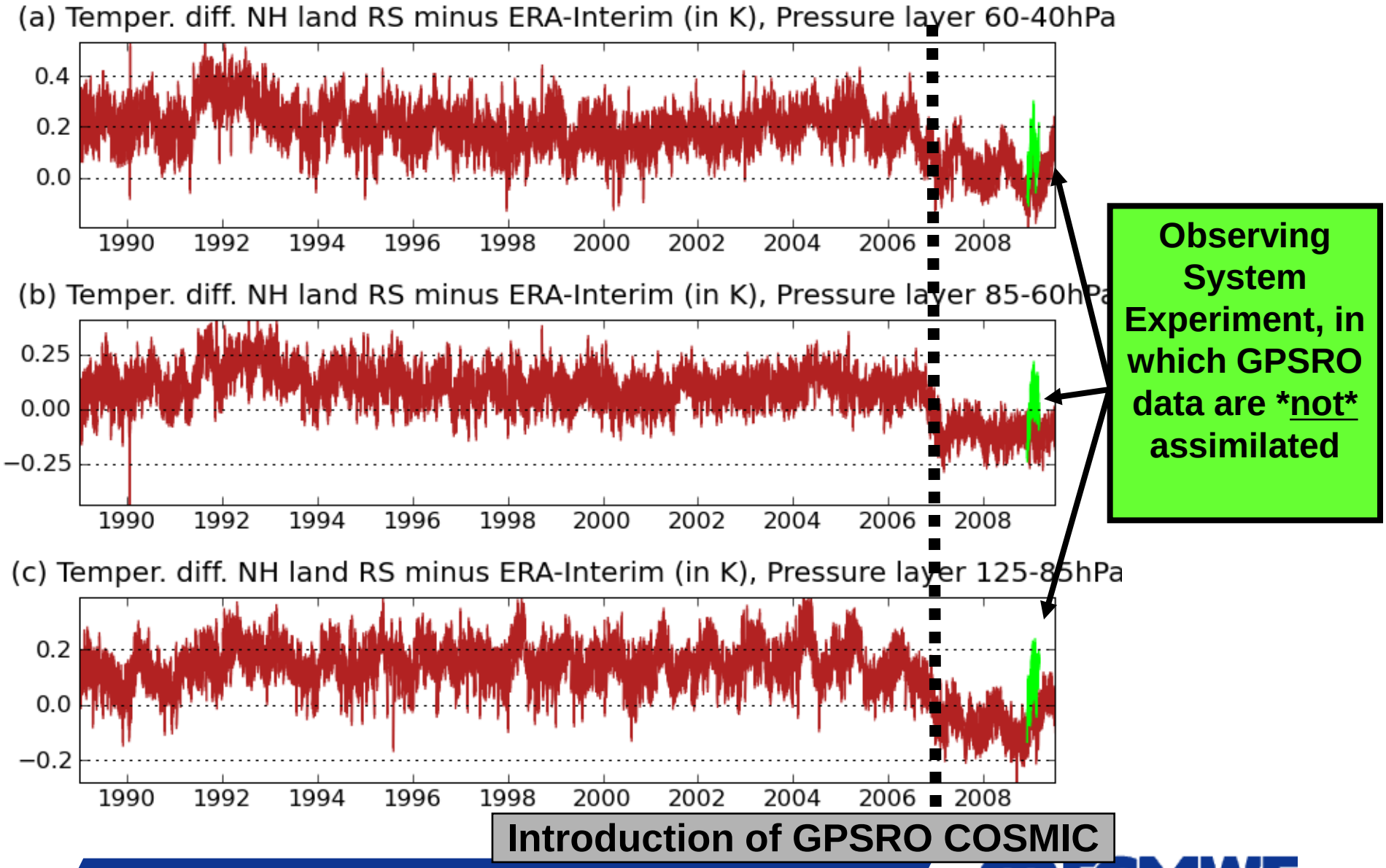
Issues:

Time inconsistency exposed: tropical atmosphere (20S-20N)



Effects of observing system changes: GPSRO



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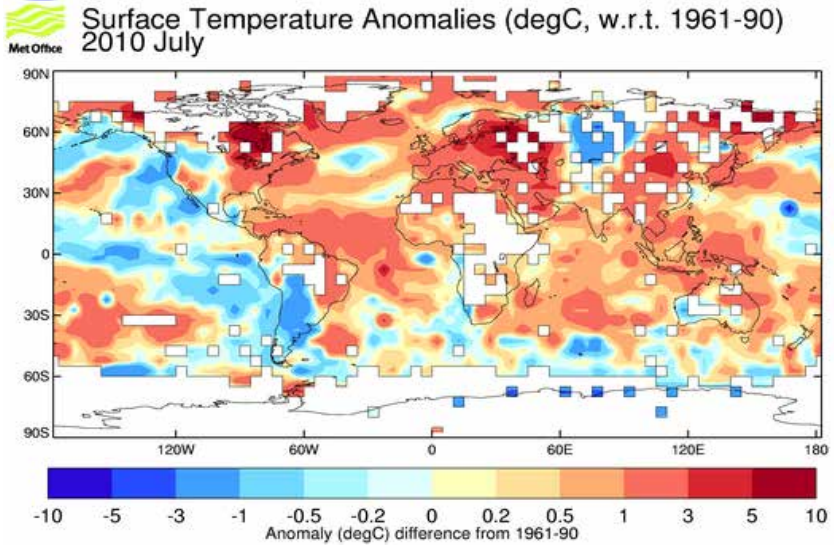
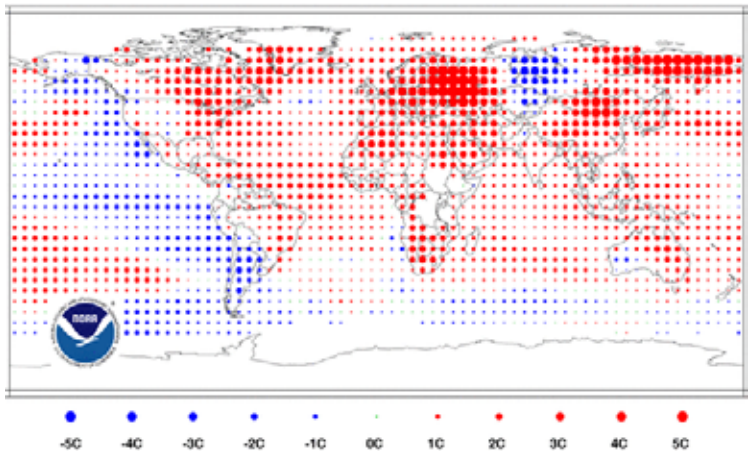
Success: Temperature: Global anomalies July 2010

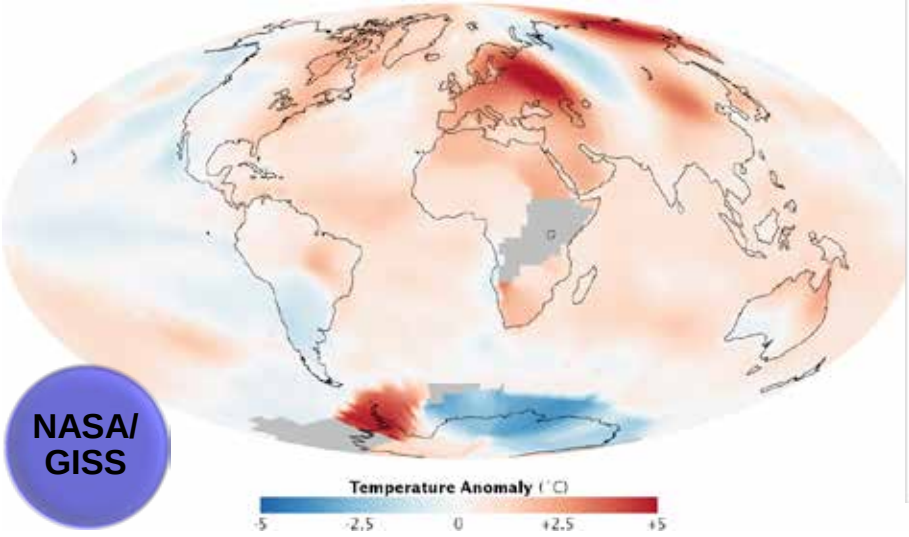
Hadley Centre



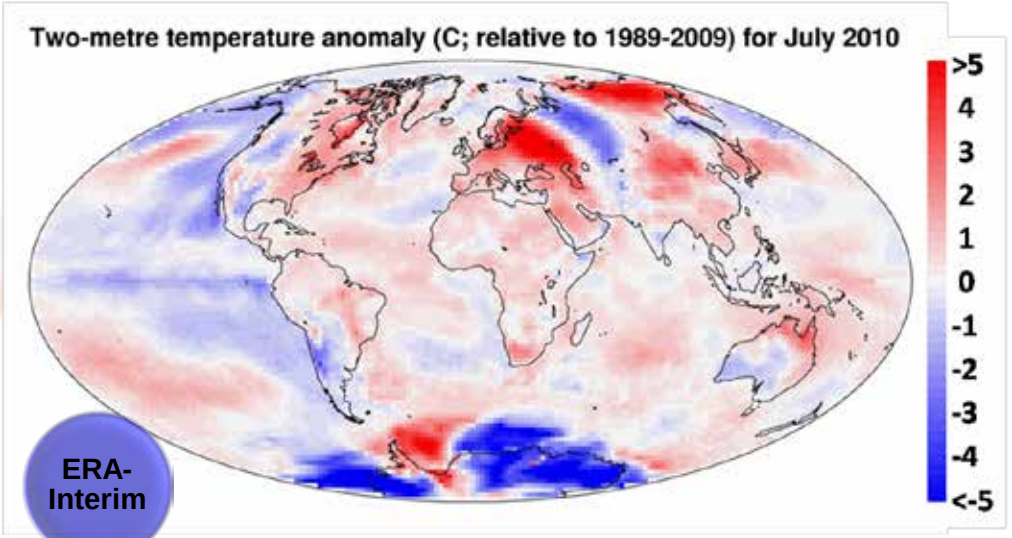
NOAA/ NCDC



NASA/ GISS



ERA-Interim



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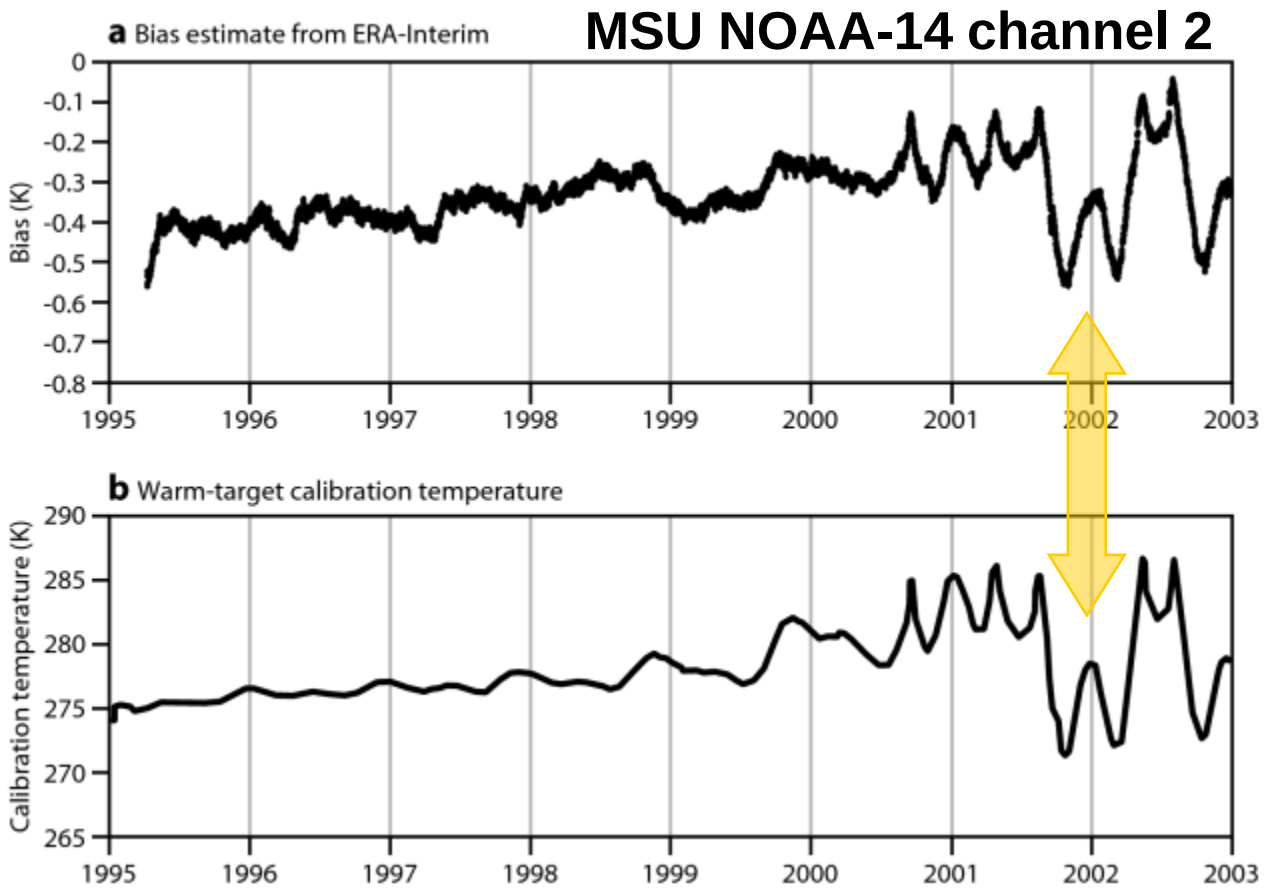
Consistent bias corrections in ERA-Interim: Reference blackbody calibration fluctuations for NOAA-14 MSU



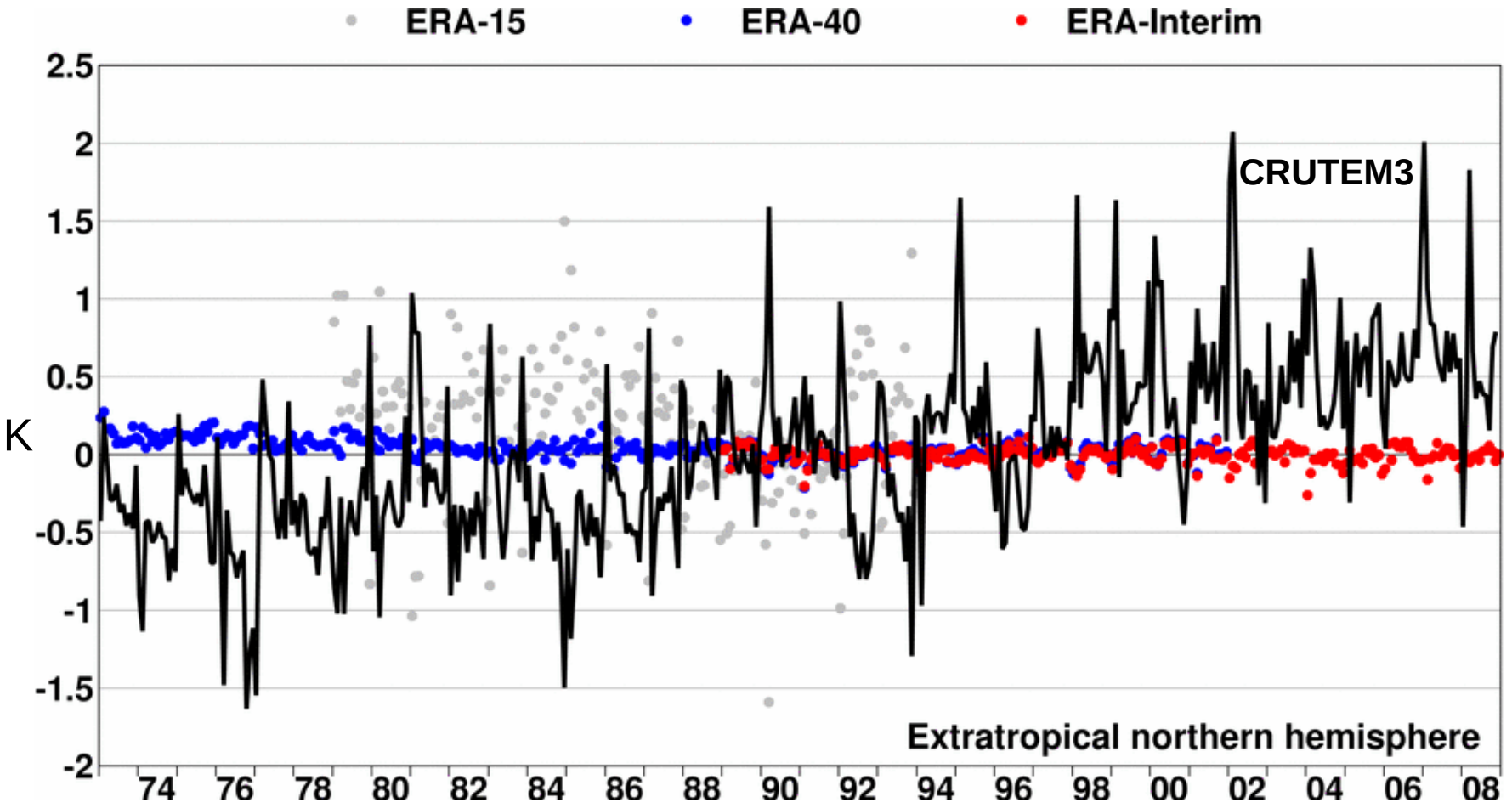
Variational bias estimates for NOAA-14

Actual warm-target temperatures on board NOAA-14 (Grody *et al.* 2004)

Dee and Uppala, 2009

Validation: Fit to 2m land temperature anomalies (K)

Differences of monthly values from CRUTEM3

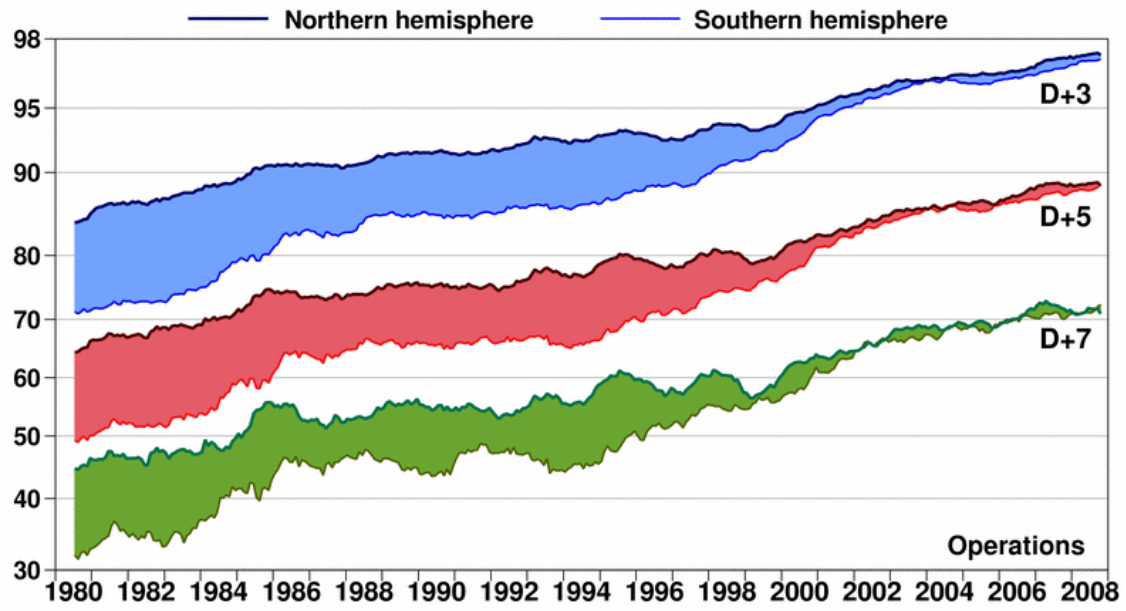


ERA sampled as CRUTEM3 (Brohan et al., 2006) following Simmons et al. (2004)

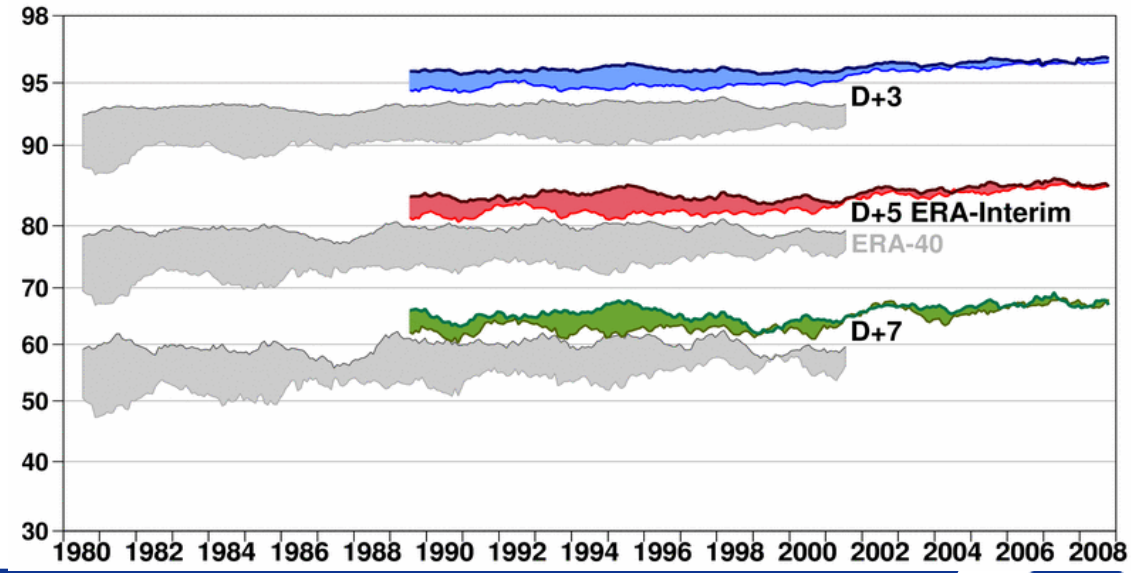
Validation: Forecast skill

Anomaly Correlation (%) for the 500 hPa Geopotential Height

100% = perfect forecast
60% = limit of use



Operations



ERA-Interim

ECMWF

Advantages against “observations-only” multi-decadal gridded datasets … for climate studies

1) How reanalysis deals with “missing data”

- Only assimilate observations when and where we have them
- In between, the “best model available” (NWP!) is used to “fill in the blanks”

2) Produced fields are space- and physically-consistent

- As specified by the NWP model

3) Use the widest variety of observations

- Not just temperatures, or winds, or humidities in isolation of each other…
- … but also pressures, satellite observations, … multi-variate approach

4) All observations are evaluated/used in a consistent way

- Accuracy and precision explicitly taken into account
- Quality control (QC) procedures apply across all observation types
- The background prediction provides QC advantage w.r.t statistical reconstruction

Conclusion

- Yes reanalysis combines lots of difficulties due to changes in observations input…
- Like with ANY OTHER observations-based dataset
- The basic challenge is the same: change in observations’ quality and quantity over time.
- The difference is, we try to do things in a consistent manner, by applying the same methodology of ***data assimilation*** for all observations

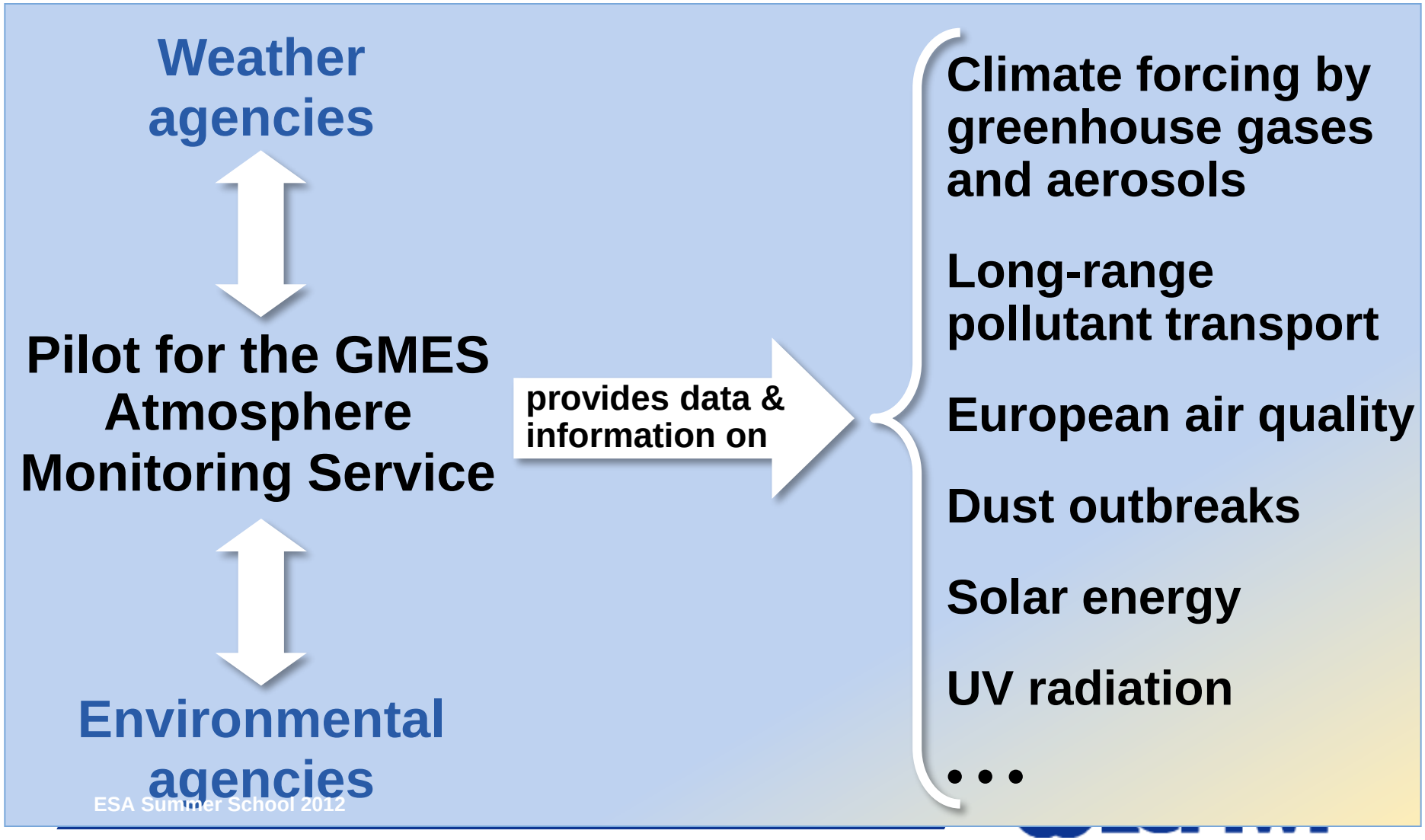
Summary of important reanalysis concepts

- **Reanalysis provides past analyses of "all" available observations.**
  - **Derived within a consistent, state-of-the-art system.**
- **Reanalysis benefits from a long meteorological research and development chain that includes**
  - **observation collection (measurement),**
  - **observation processing,**
  - **numerical weather prediction modelling, and**
  - **data assimilation**

  → Reanalysis needs repeating from time-to-time as ingredients improve.
- **Reanalysis is bridging slowly, but surely, the gap between the "weather datasets" and the "climate datasets"**
  - **Reanalyses cover longer time periods**
  - **Helps different communities work together**
- **Challenges for future reanalysis projects:**
  - **Additional observations**
  - **Treatment of model bias**
  - **Coupling with ocean and land surface**
  - **Making observations used in reanalysis more accessible to users**
  - **Uncertainty estimates for the reanalysis products**

4.) MACC:
Chemical data assimilation

Monitoring and forecasting chemical and particulate concentrations



MACC (and MACC-II) Project(s)

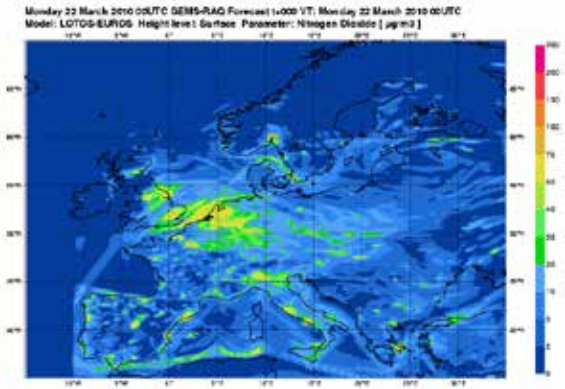
- MACC: **Monitoring Atmospheric Composition and Climate**
- Current pre-operational atmospheric service of the European GMES programme. Provides:
  - ü data records on atmospheric composition for recent years,
  - ü data for monitoring present conditions
  - ü forecasts of the distribution of key constituents for a few days ahead.
- Combines state-of-the-art atmospheric modelling and data assimilation with Earth observation data to provide information services covering European Air Quality, Global Atmospheric Composition, Climate, and UV and Solar Energy.
- Many partner institutes in Europe

- **ECMWF leads development of a coupled NWP/chemical transport model data assimilation system**

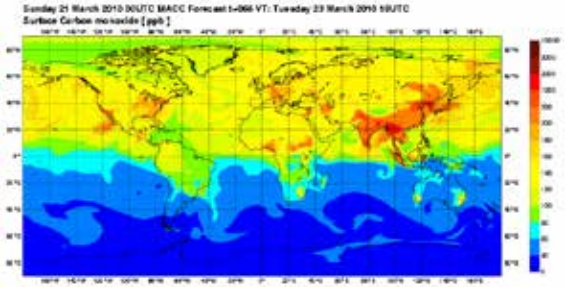
MACC Daily Service Provision

http://www.gmes-atmosphere.eu/

Air quality

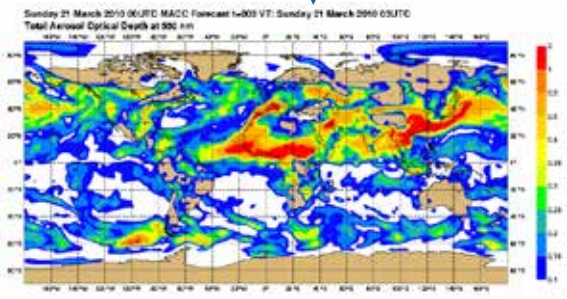


Global Pollution

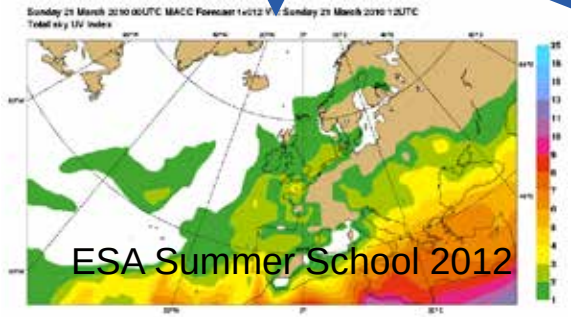


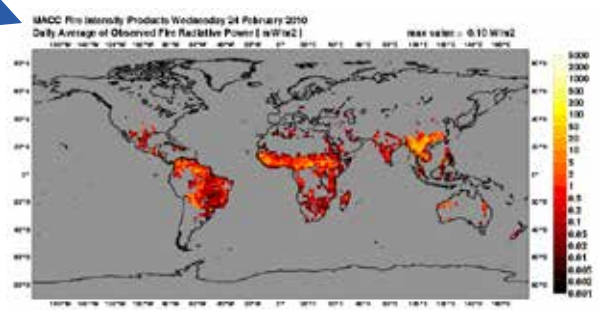
Biomass burning

Aerosol



UV index

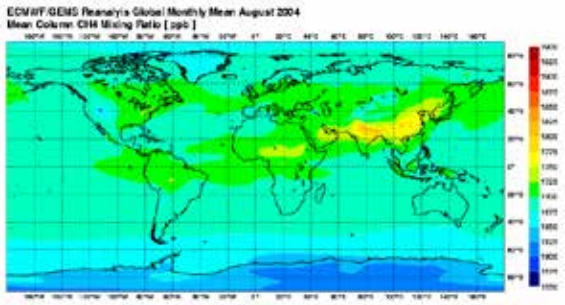




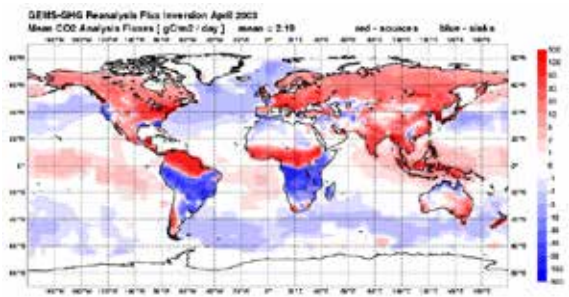
MACC Service Provision (retrospective)

Reanalysis

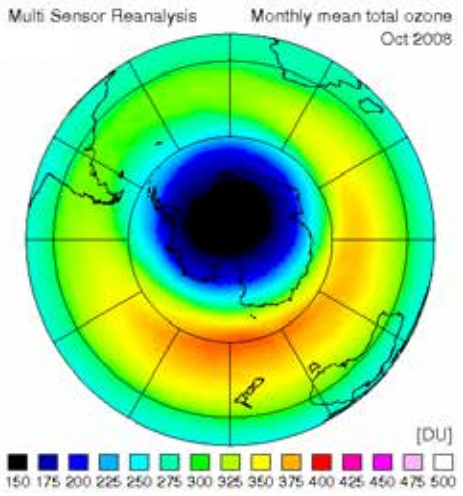
2003-2010



Flux Inversions

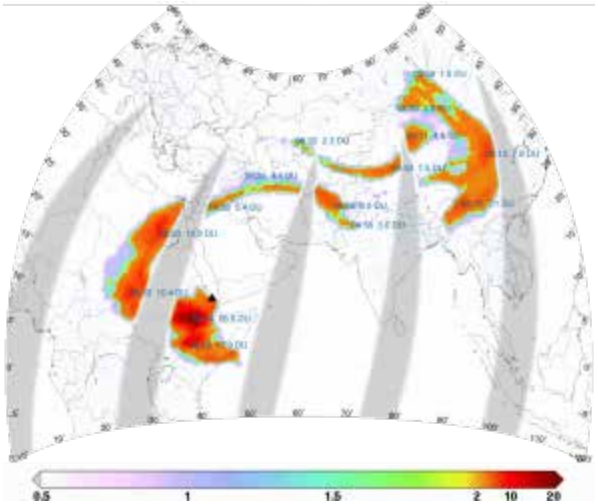


Ozone records

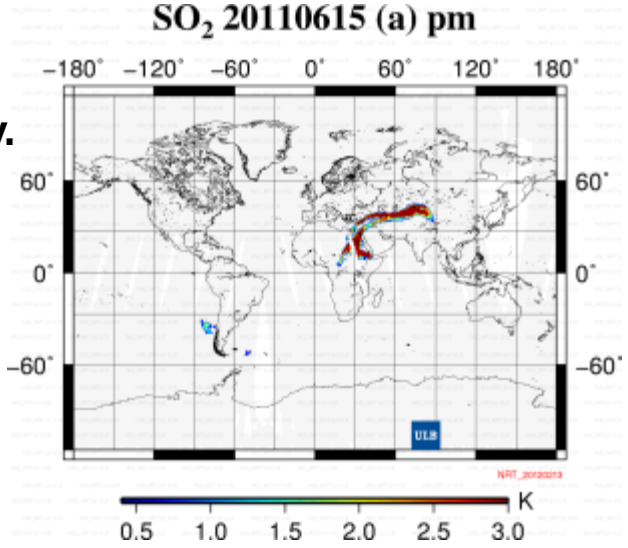


ECMWF

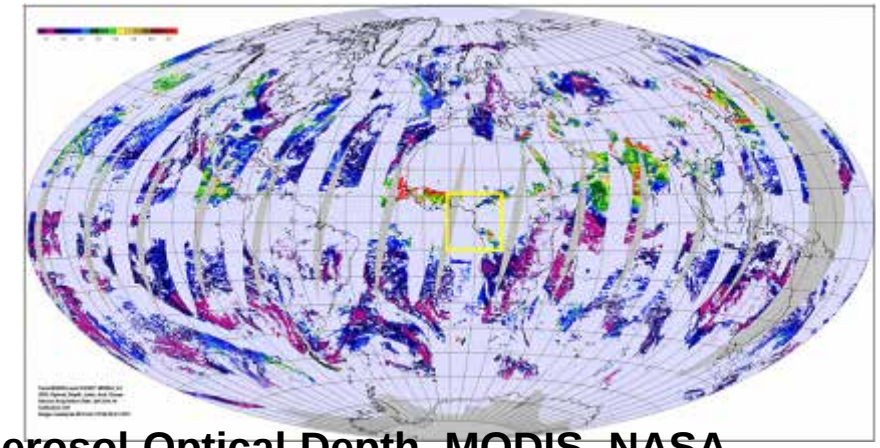
Exciting satellite observations



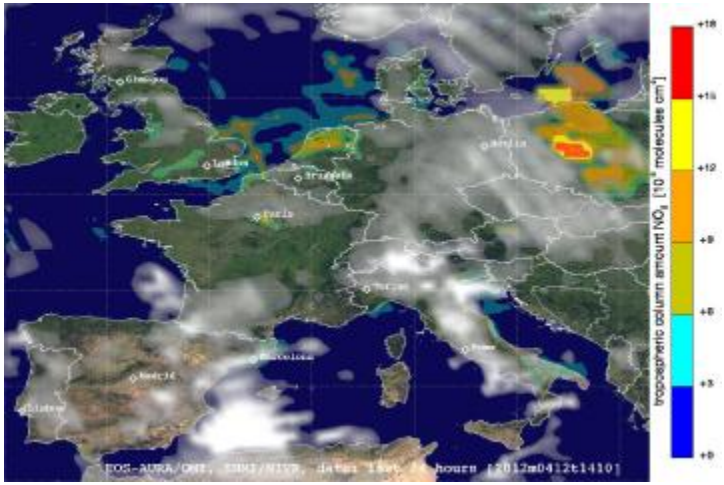
SO_2, GOME-2, SACS, BIRA/DLR/EUMETSAT



SO_2, IASI, Univ. of Brussels/ EUMETSAT



Aerosol Optical Depth, MODIS, NASA



NO_2, OMI, KNMI/NASA

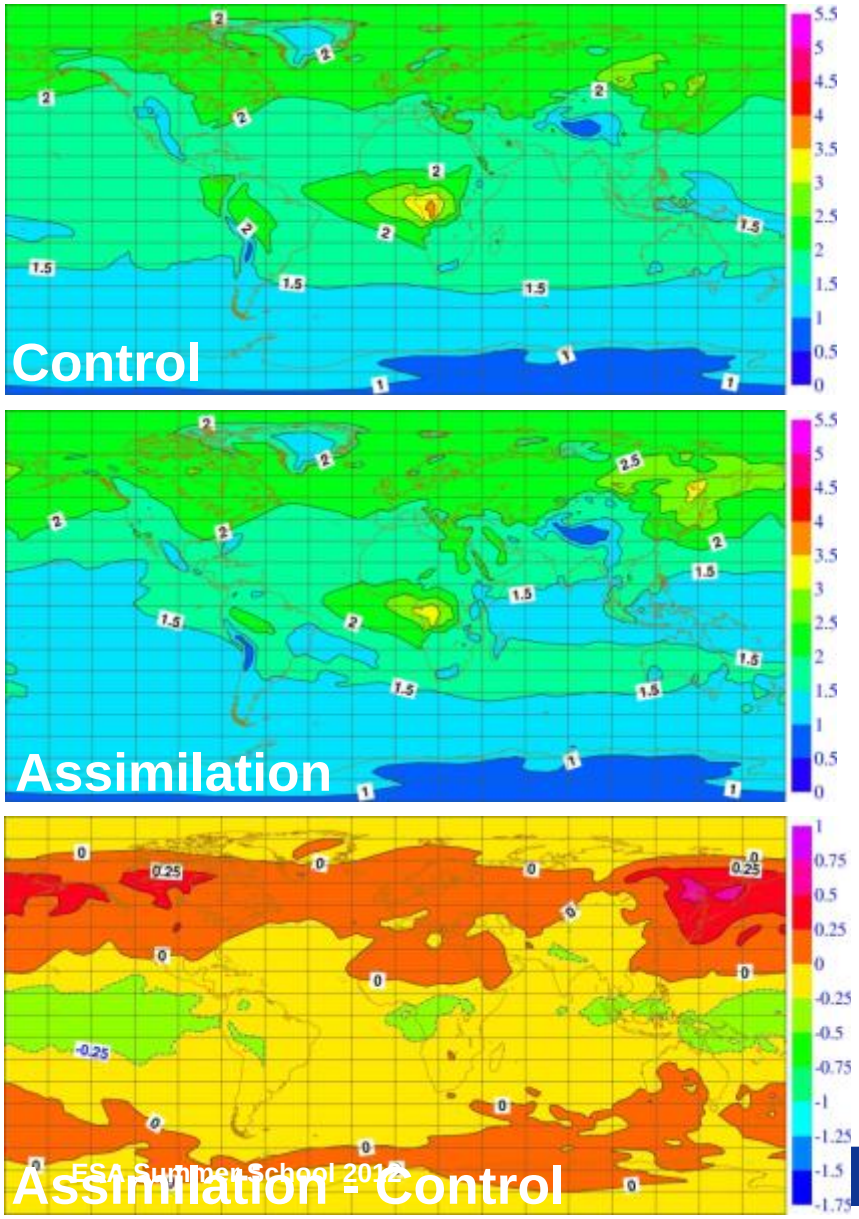
Why Atmospheric Composition at NWP centres?

- Environmental concern
  - Air pollution
  - Ozone hole
  - Climate change
- Expertise in data assimilation of satellite, profile and surface obs.
- Best meteorological data for chemical transport modelling
- Interaction between trace gases & aerosol and NWP
  - radiation triggered heating and cooling
  - precipitation and clouds (condensation nuclei, lifetime …)
  - Satellite data retrievals improved with information on aerosol
  - Hydrocarbon (Methane) oxidation is water vapour source

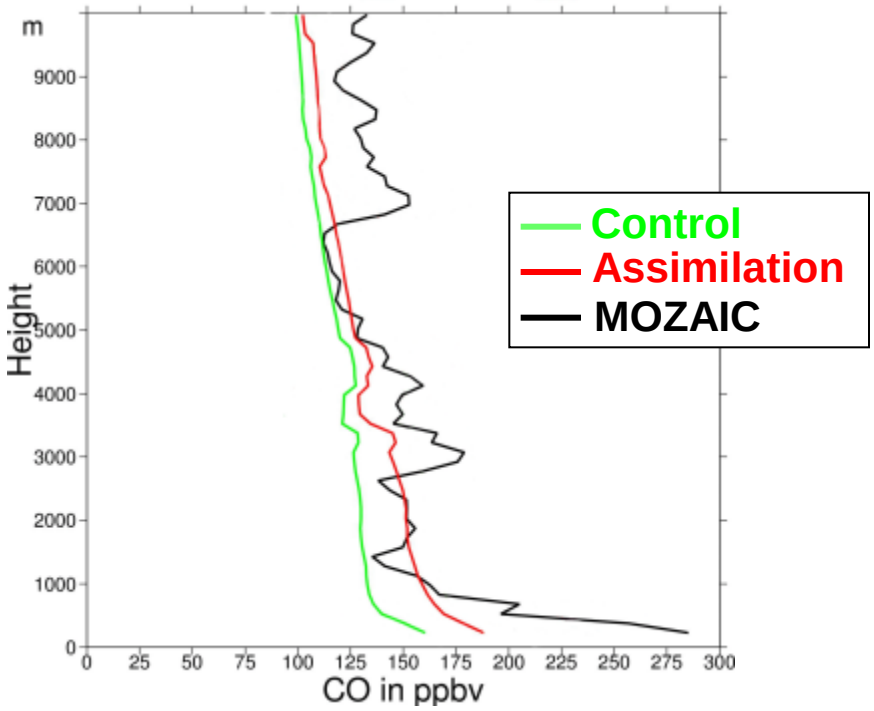
Atmospheric Composition at ECMWF

- Operational NWP
  - Climatologies for aerosol, green house gases ozone + methane
  - Ozone with linearized stratospheric chemistry and assimilation of ozone (TC)
- GMES Atmospheric Service development (**GEMS / MACC/ MACC II**)
  - 2005 – 2014 … (“Atmospheric Composition” division at ECMWF since 2012 !!)
  - aerosol and global-reactive-gases modules in IFS
  - Data assimilation of AOD and trace gases (ozone, CO, SO_2, NO_2, HCHO, CO_2 CH_4) retrievals (TC) with IFS 4D-VAR
  - Near-real-time Forecast and re-analysis of GRG, GHG and Aerosol

Mean CO from 15 to 30 July 2003 from assimilation of MOPITT total-column data



Comparison with MOZAIC aircraft data over Osaka



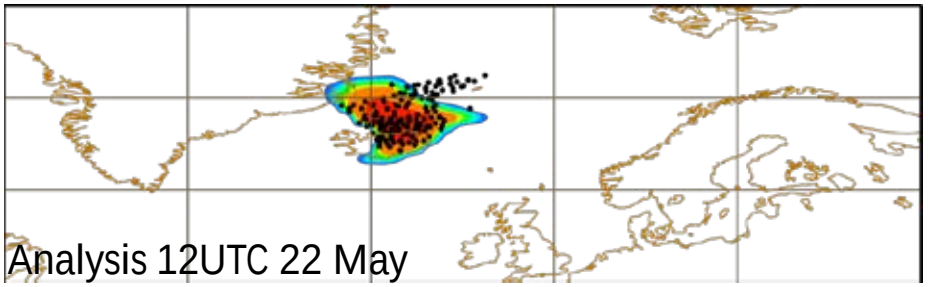
Unit: 10^{18} molec/cm^2

ECMWF

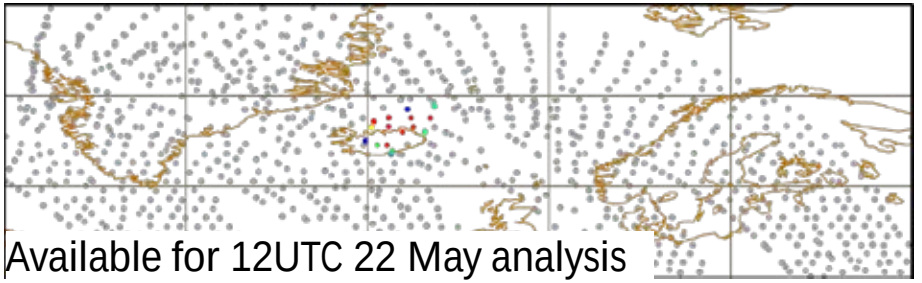
GRG/AER: Volcanic eruptions (Grimsvötn, May 2011)

SO_2 Model values and IASI detection

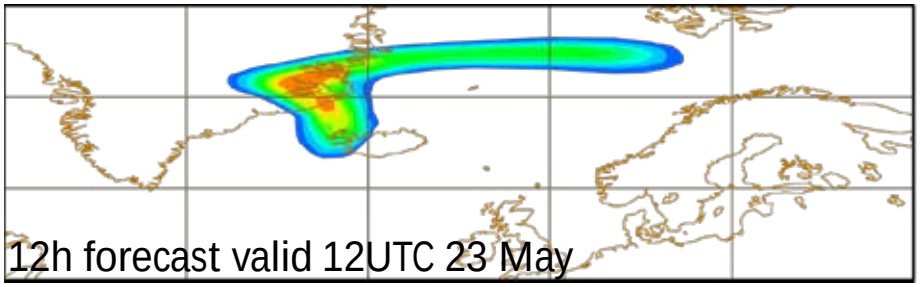
OMI observations



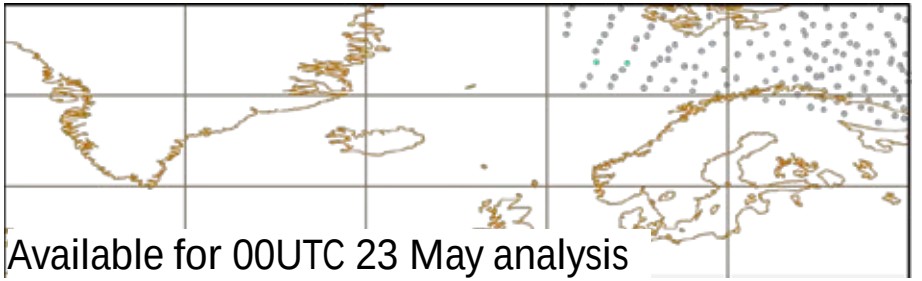
Analysis 12UTC 22 May



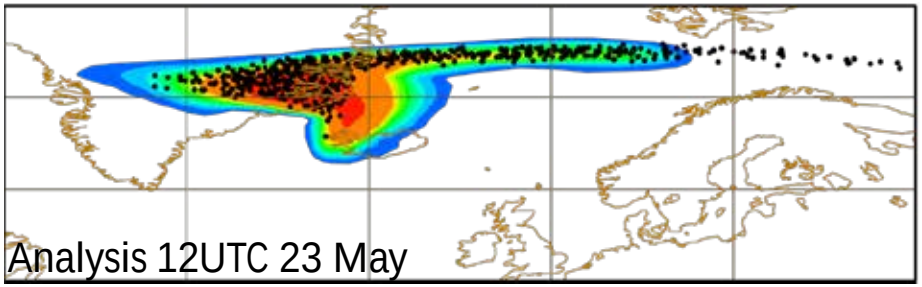
Available for 12UTC 22 May analysis



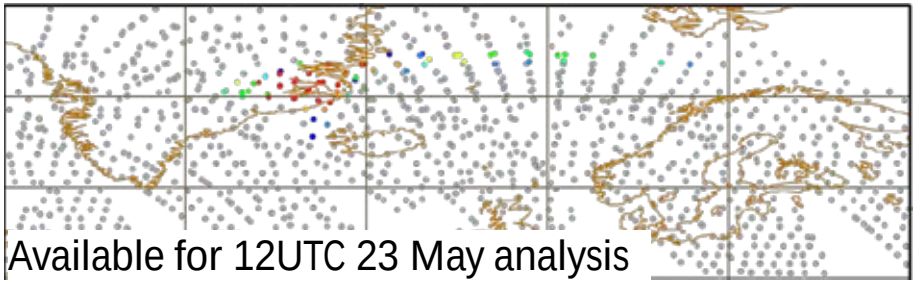
12h forecast valid 12UTC 23 May



Available for 00UTC 23 May analysis



Analysis 12UTC 23 May



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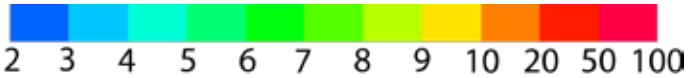
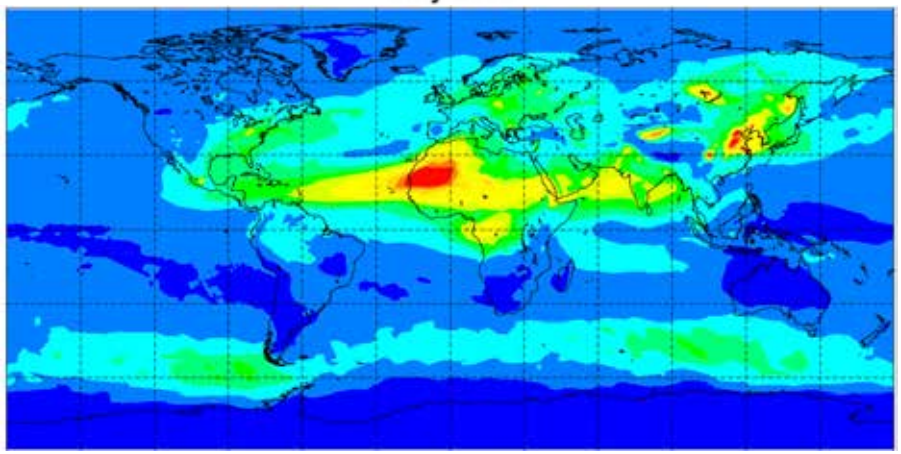
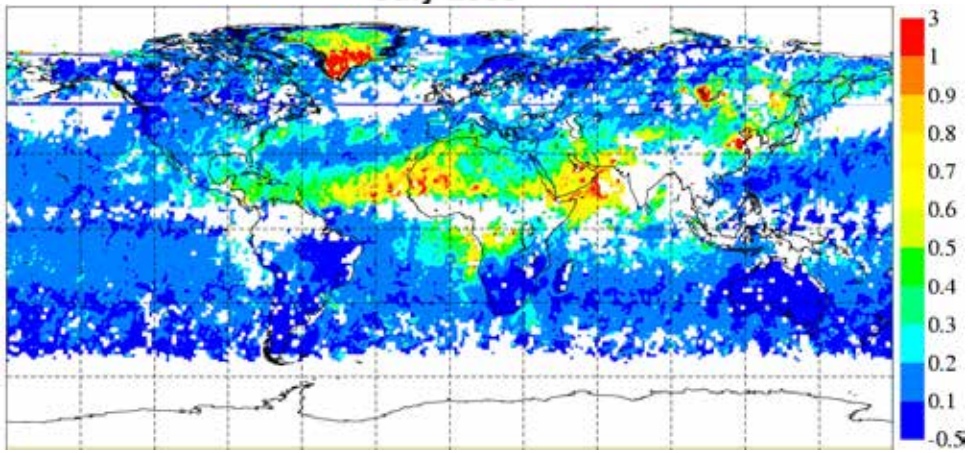


Simulated and analysed aerosol optical depth with MODIS and MISR for July 2003

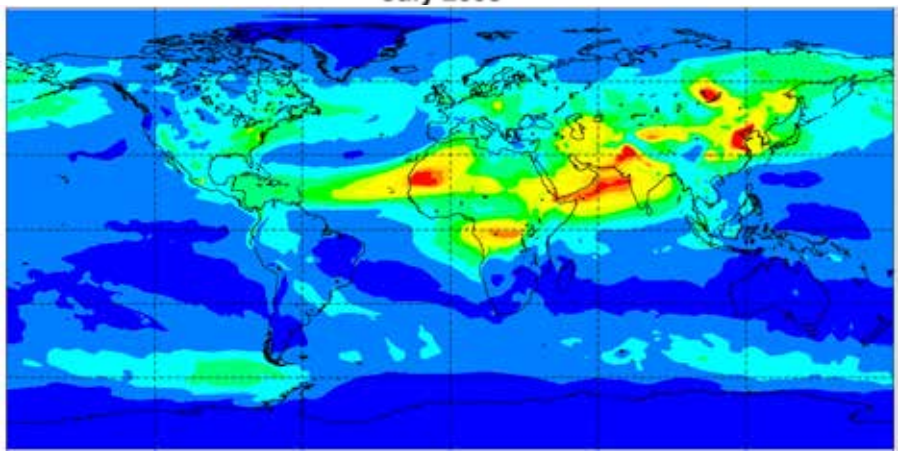
Aerosol Optical Depth at 550 nm from Unconstrained Model Run
July 2003



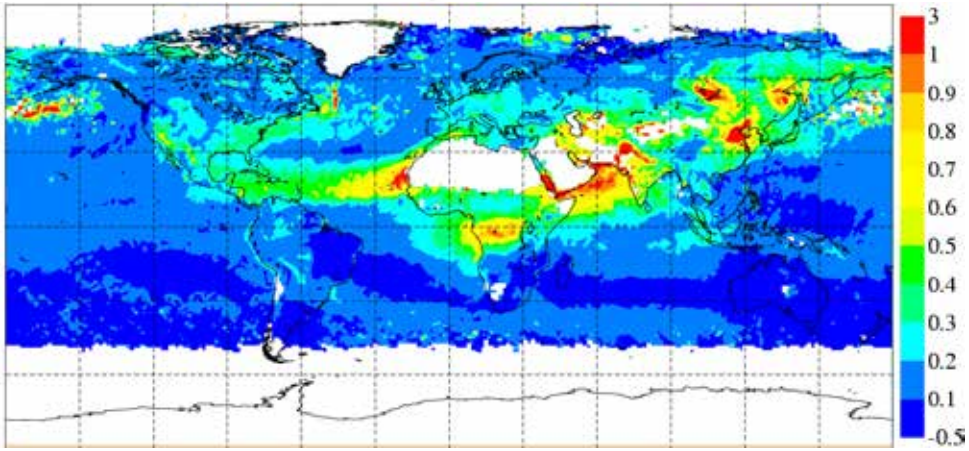
MISR Terra Aerosol Optical Depth at 557.5 nm [unitless]
July 2003



Aerosol Optical Depth at 550 nm for Reanalysis using MODIS AOD
July 2003



MODIS Terra MOD08-M3.005 Aerosol Optical Depth at 550 nm [unitless]
July 2003



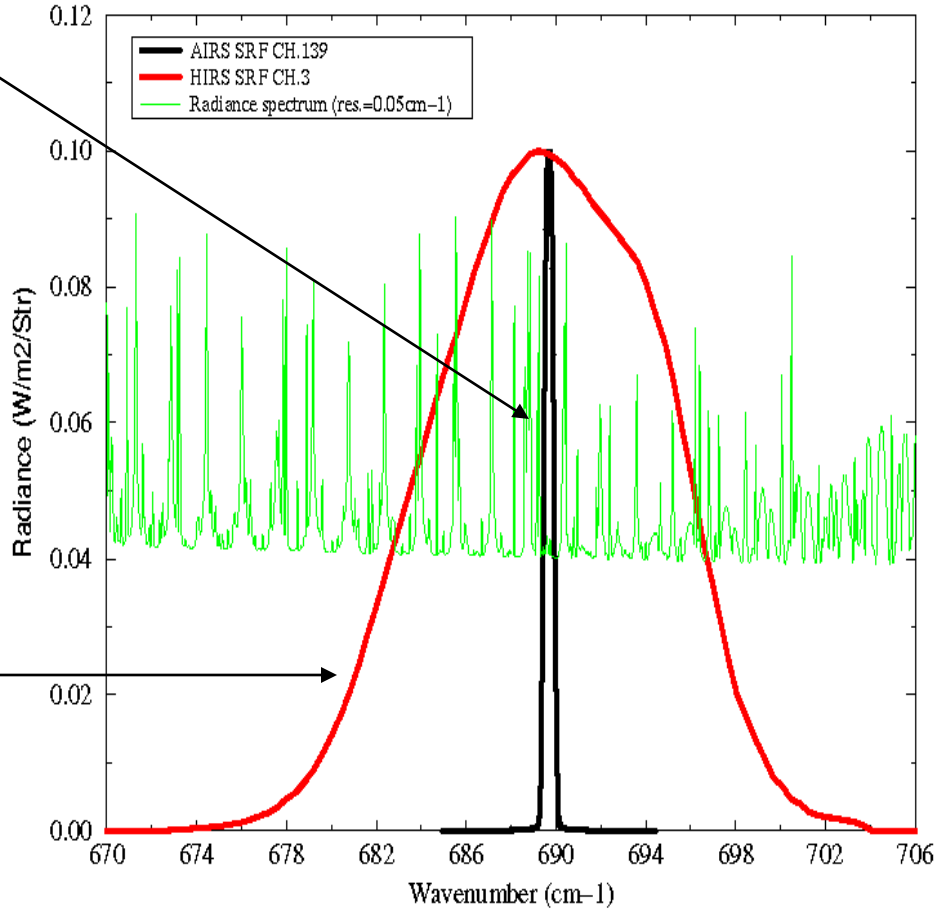
ECMWF

Radiance assimilation for MACC (AIRS/IASI)

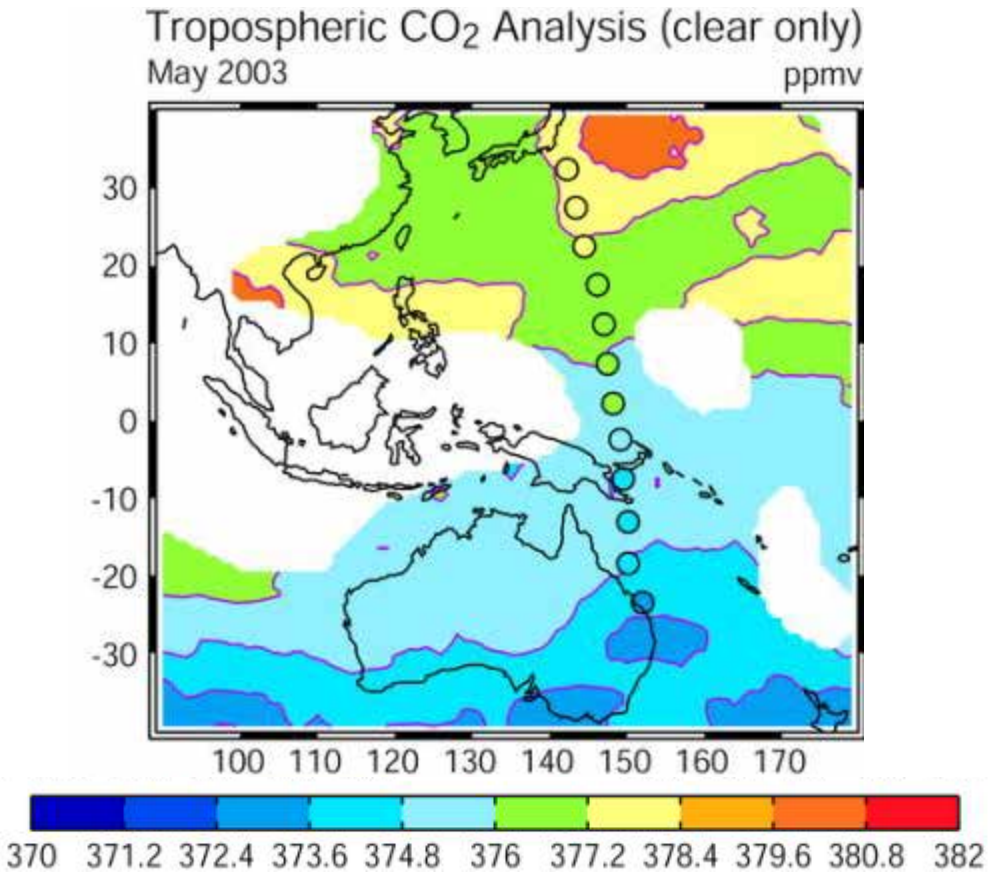
- By sampling the IR spectrum at very high resolution (R=1200) we can measure radiation that is only dependent on temperature and the atmospheric CO_2 concentration (small groups of **pure lines**)

- If we have **accurate temperature information** (from the ECMWF analysis driven by AMSUA data) we can separate out the CO_2 signal.

- Instruments with coarse spectral resolution (e.g. HIRS) sample radiation that is a mixture of absorbing species (e.g. CO_2 / N_20 / O_3 and H_2O) and cannot resolve the CO_2



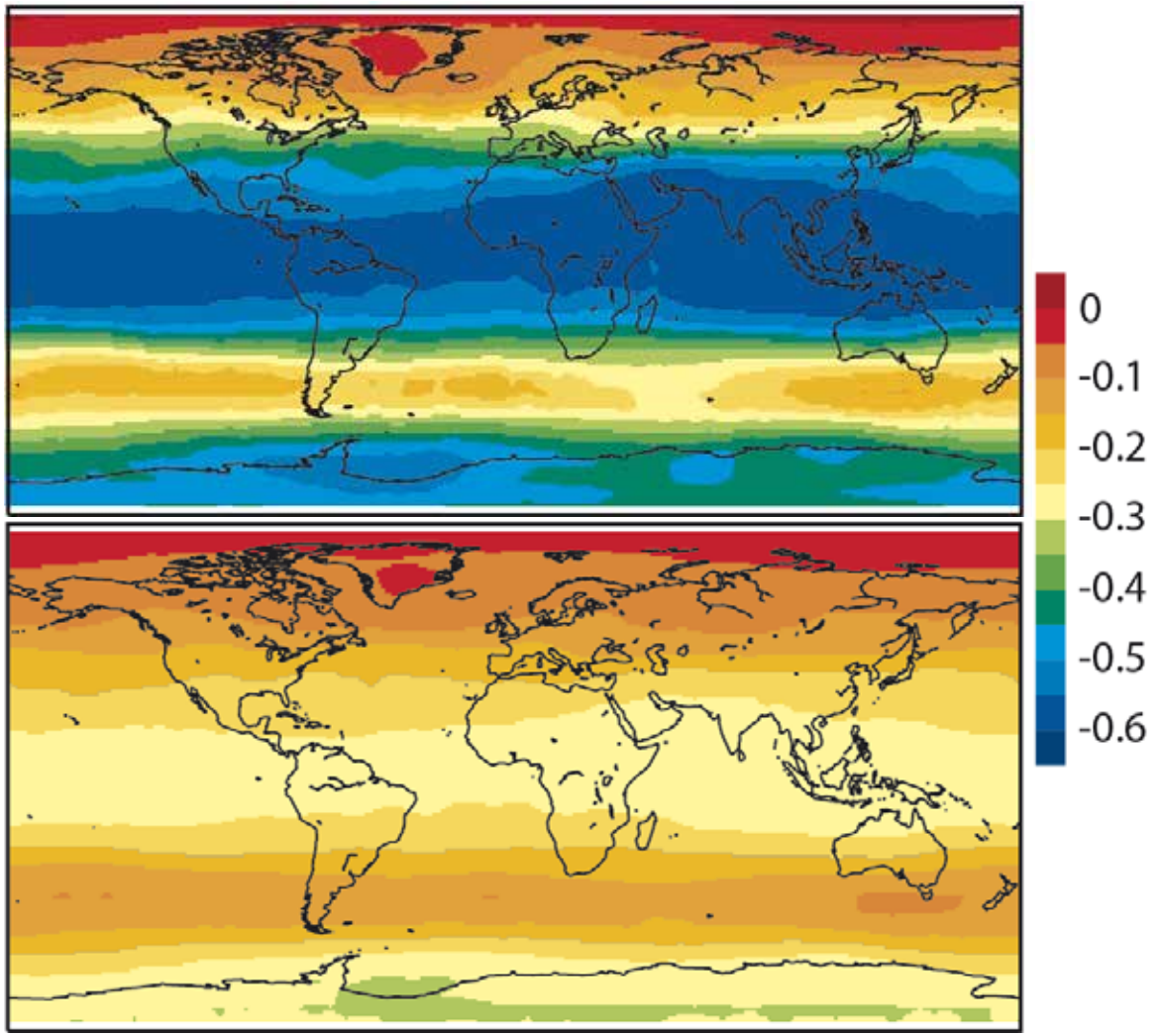
Mean column CO_2 from assimilation of AIRS radiances: Validation with aircraft



ECMWF

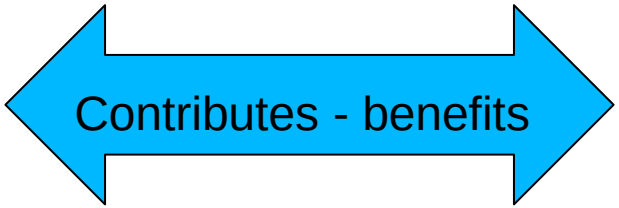
GHG: CO2 variability and NWP users

CO_2 modelling allows a drastic reduction of the bias correction for assimilation

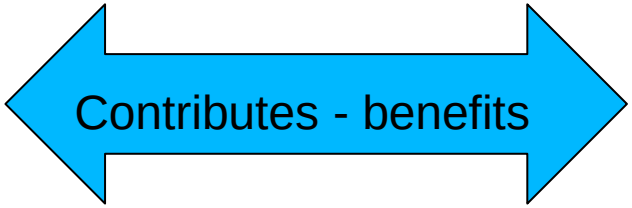


Conclusions

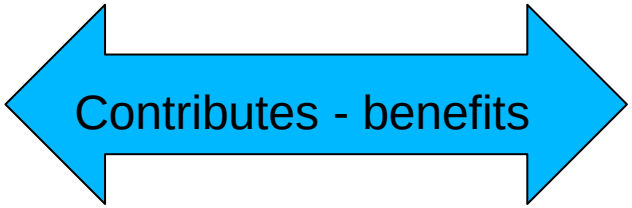
- **NWP: Active developments to ingest new technologies**



- **NWP** **satellites cal/val**



- **NWP** **Reanalysis + Climate monitoring**



- **NWP** **Monitoring and forecasting Atmospheric Composition**