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

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Outline

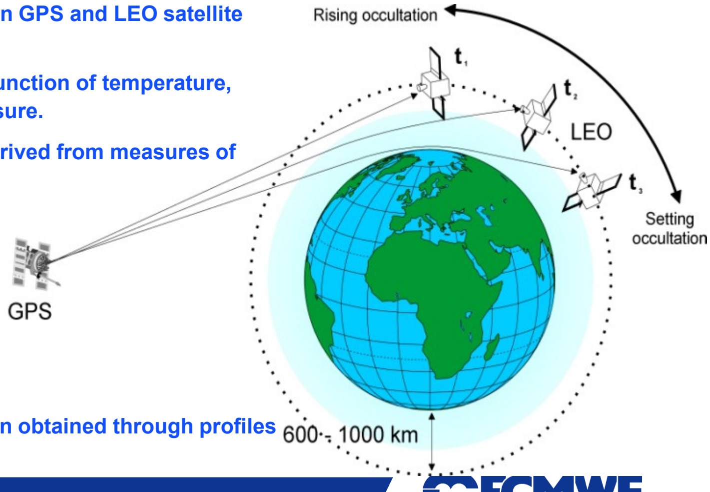
1. New and future observing systems:
    1. GPS RO
    2. Aeolus
2. NWP and cal/val of satellite data
3. MACC
4. Reanalysis
5. Summary

1.) New and future observing systems:

GPSRO

GPS (GNSS) Radio occultation

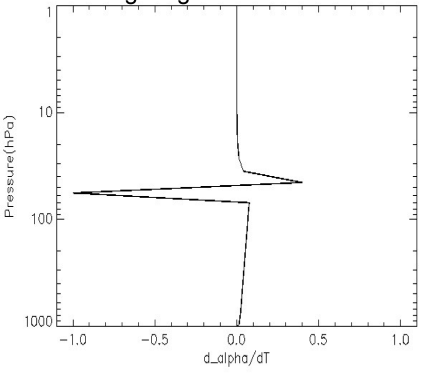
- Limb measurement.
- Gradients in refractivity cause bending of a signal path between GPS and LEO satellite (Snell's law).
- Refractivity is a function of temperature, humidity and pressure.
- Bending angle derived from measures of phase delay.



- Profile information obtained through profiles of bending angles.

GPS RO characteristics

1d weighting function:

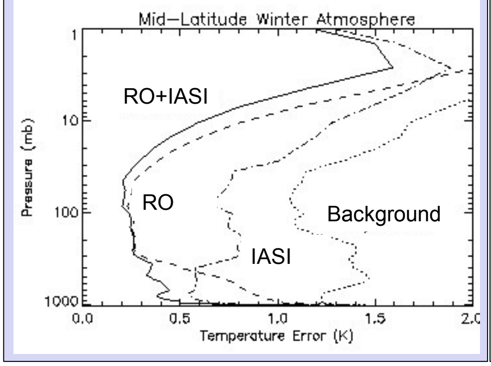


- All weather-capability:
  - Not affected by cloud or rain.
- Largely bias-free. Can help "anchor" bias corrections for radiances.
- Good vertical resolution. Can see error structures that nadir radiances can't.
- But has broad horizontal weighting function! - Around 70% of the bending occurs over a ~450km section of ray-path, centred on the tangent point *(point closest to surface).*

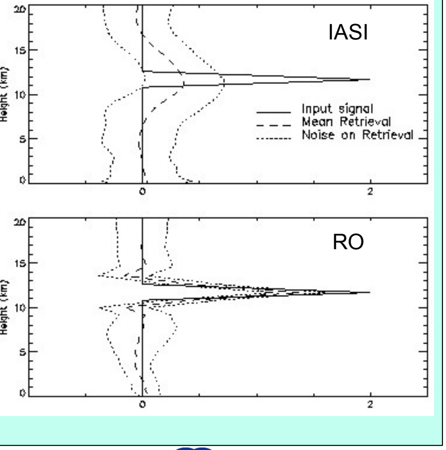
GPS RO vs IASI: 1DVAR simulations

See Healy and Collard 2003, QJRMS:

Expected retrieval error:

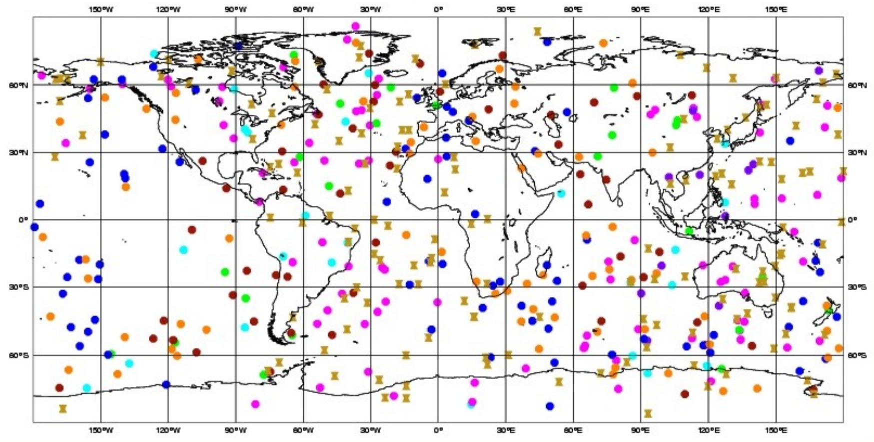


Power to resolve a peak-shaped error in background:

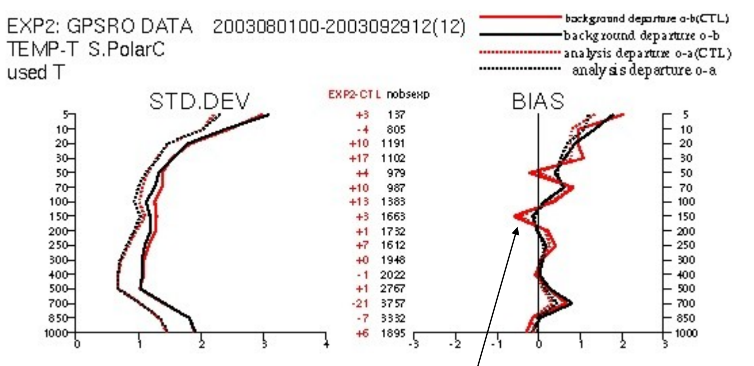


GPS RO data coverage in 6-hour period

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



Radiosonde comparisons for Antarctica 12h forecasts

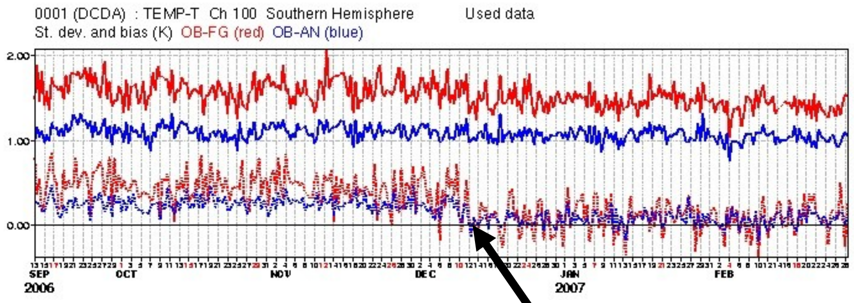


Red lines: Without GPSRO
Black: With GPSRO

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).

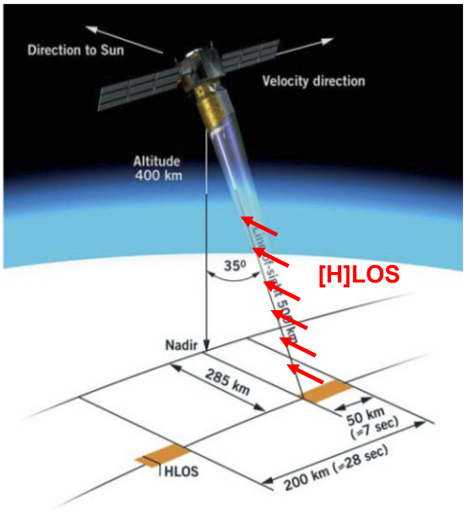


GPSRO used in operations since 12th December, 2007.

1.) New and future observing systems:

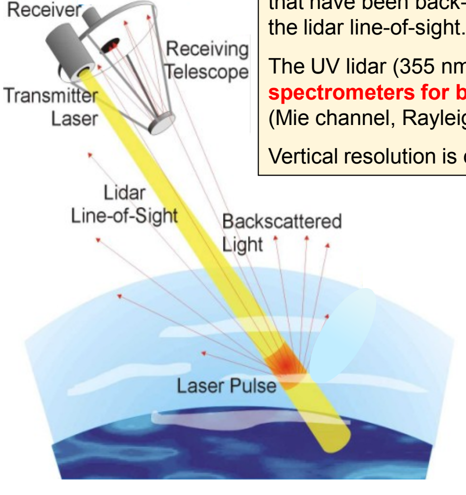
ADM-Aeolus

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 2012

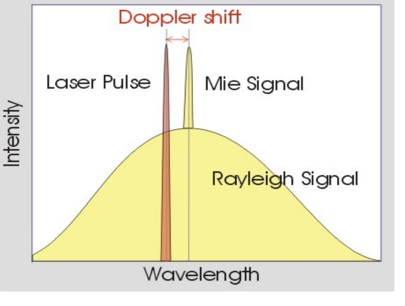
Doppler wind lidar: Measurement principle



The wind profiles are derived from the **Doppler shifted signals** that have been back-scattered by particles and molecules along the lidar line-of-sight.

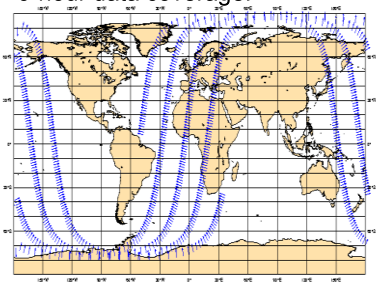
The UV lidar (355 nm) operates in burst mode, with **spectrometers for both particle and molecular backscatter** (Mie channel, Rayleigh channel).

Vertical resolution is configurable during flight.



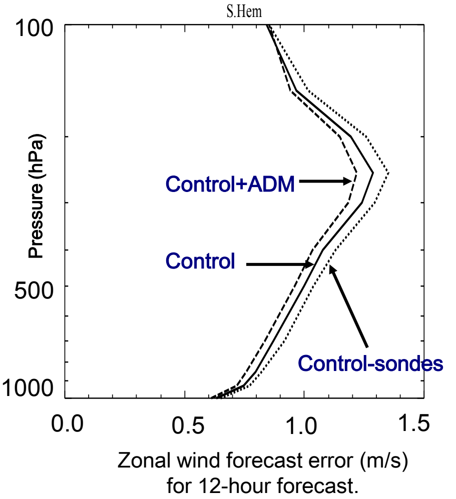
ADM-Aeolus: Simulated impact

6-hour data coverage:



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

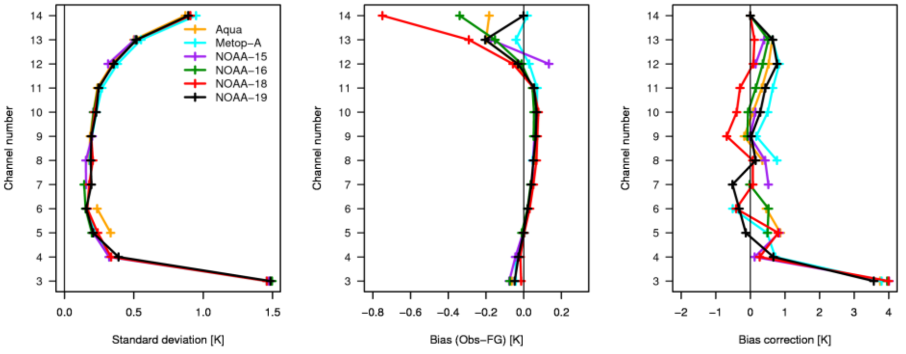
Simulated DWL data adds value at all altitudes and well into longer-range forecasts.



2.) NWP and cal/val of satellite data

Use of NWP systems for characterisation of observations

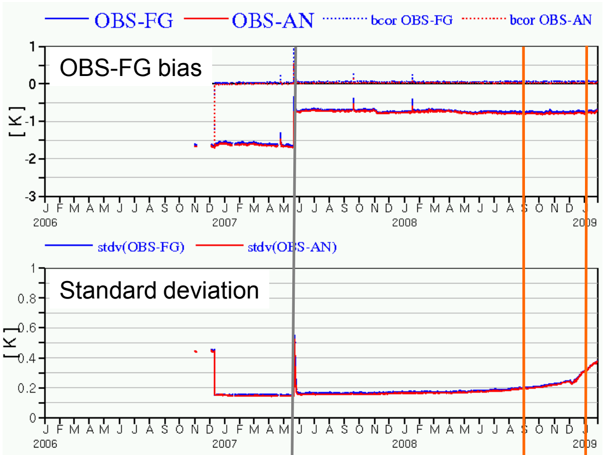
• NWP systems are increasingly used for the evaluation of (new) satellite data.
• Observation-minus-background-departures provide a comparison against a reference with relatively stable characteristics and allows cross-validation with similar instruments.
• E.g., cal/val for NOAA-19 AMSU-A in April 2009:



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):



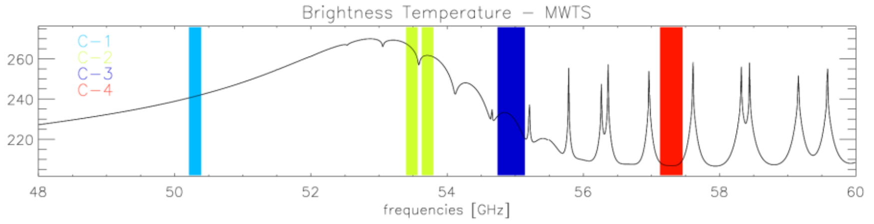
(Implementation of antenna pattern correction)

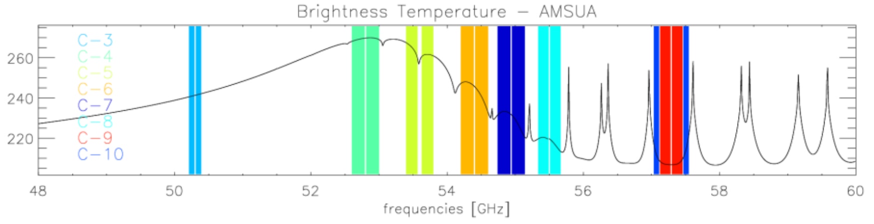
First email alert sent to EUMETSAT

Channel blacklisted

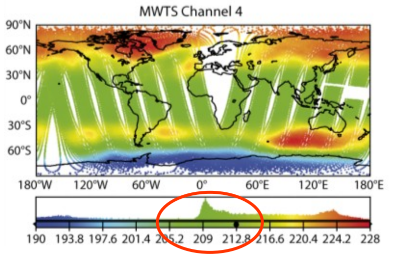
Evaluation of FY-3A MWTS data

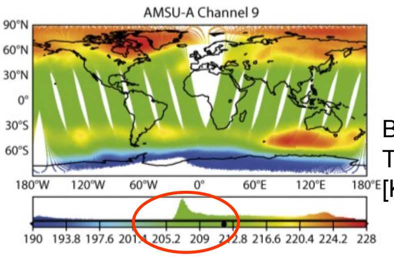
Pass-bands for Microwave Temperature Sounder (MWTS) compared to AMSU-A:



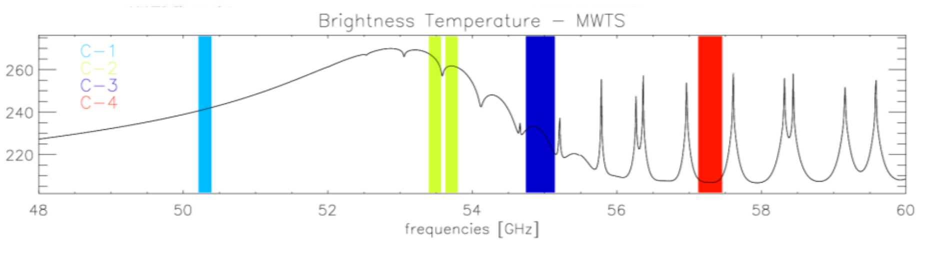


Evaluation of FY-3A MWTS data





Brightness Temperatures [K]



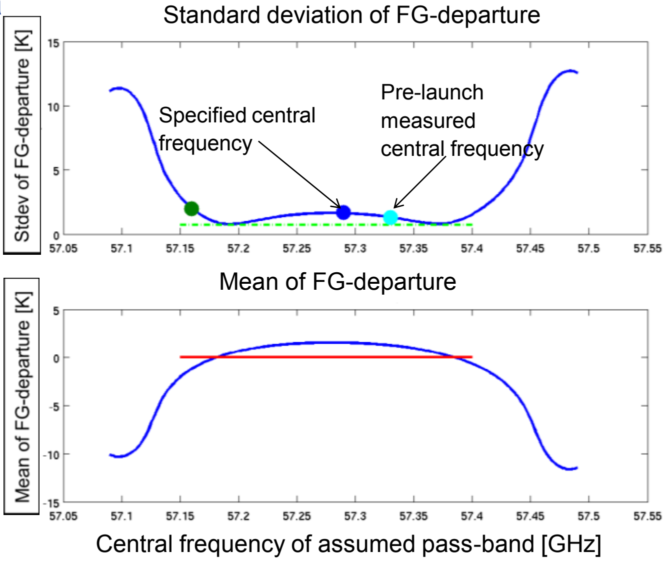
Evaluation of pass-band shift for FY-3A MWTS data

• FY-3A MWTS channel 4

• Both STD(FG_deps) and Mean(FG_deps) support the hypothesis of a very significant pass-band shift (~80MHz).

• NWP fields are very powerful in diagnosing these effects.

• Importance of accurate pre-launch instrument characterisation.



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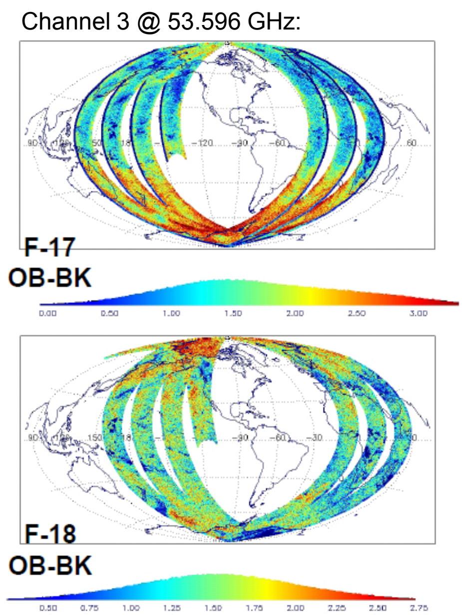
SSMIS Cal/Val

• SSMI/S is a microwave instrument, combining sounding and window channels.

• Conical scanner.

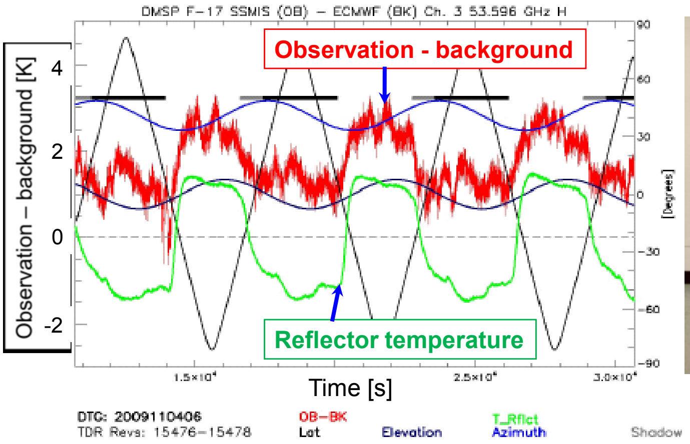
• 3rd instrument launched recently.

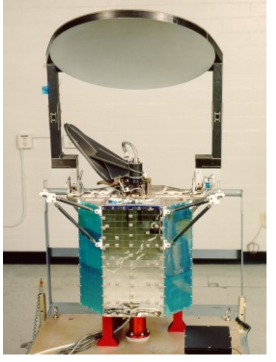


ECMWF

Reflector-emission signatures in FG-departures for F-17 SSMI/S

Reflector of F17 SSMI/S is not a perfect reflector, so observations are a combination of Earth's radiation and reflector emissions.





3.) MACC:

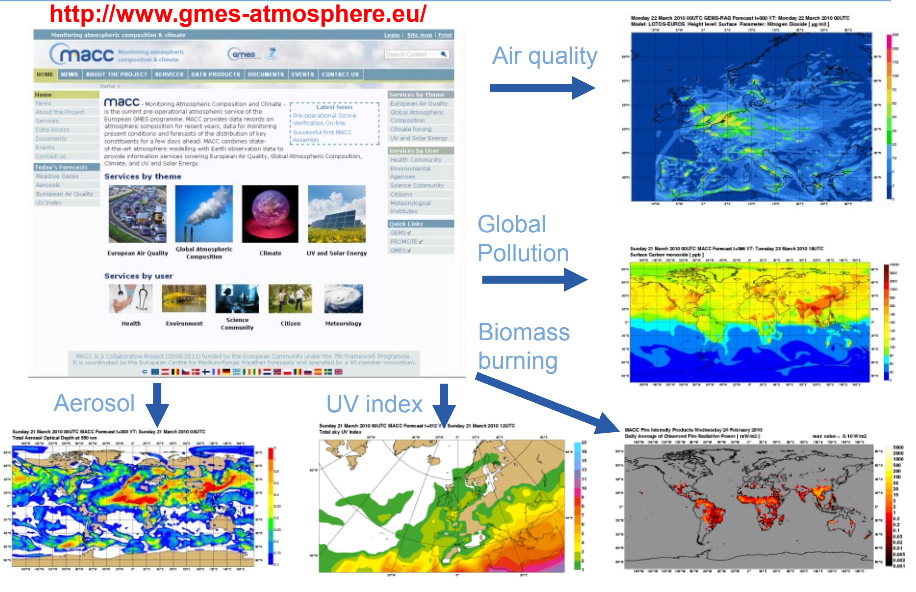
Chemical data assimilation

MACC Project

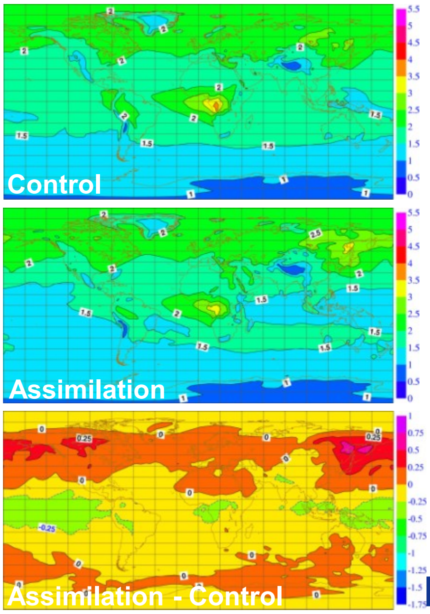
- MACC: **Monitoring Atmospheric Composition and Climate**
- Current pre-operational atmospheric service of the European GMES programme. Provides:
  - ✓ data records on atmospheric composition for recent years,
  - ✓ data for monitoring present conditions
  - ✓ forecasts of the distribution of key constituents 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.
- 45 partner institutes in Europe
- ECMWF leads development of a coupled NWP/chemical transport model data assimilation system

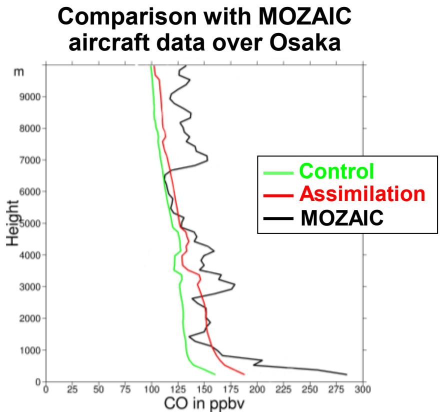
MACC Daily Service Provision

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



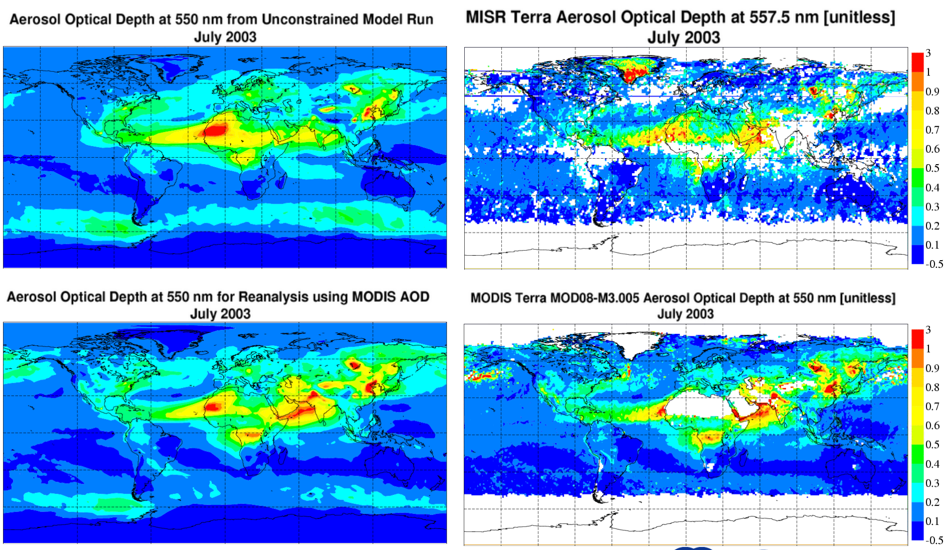
Mean CO from 15 to 30 July 2003 from assimilation of MOPITT total-column data





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

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

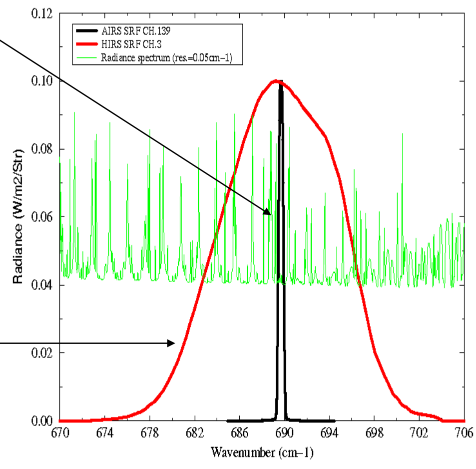


Radiance assimilation for MACC (AIRS/IASI)

• 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**)

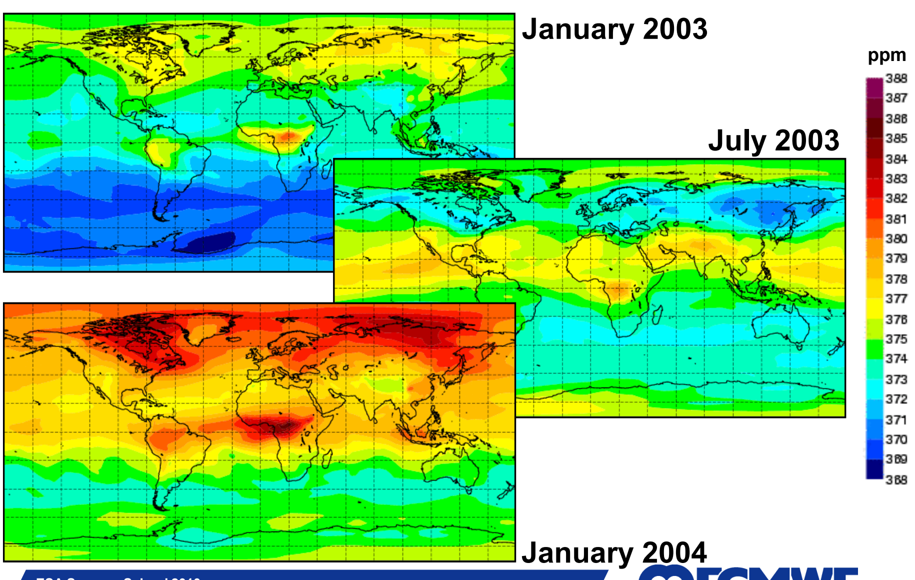
• If we have **accurate temperature information** (from the ECMWF analysis driven by AMSUA data) we can separate out the CO_2 signal.

• 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



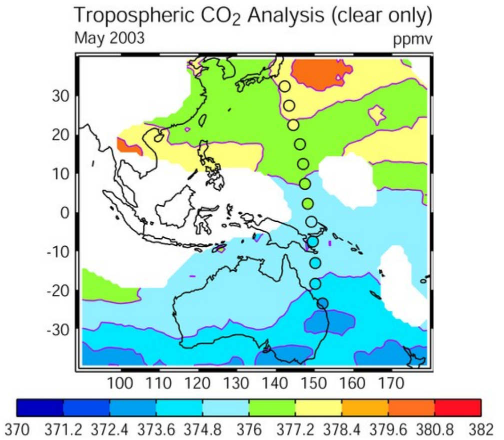
ECMWF

Mean column CO_2 from assimilation of AIRS radiances



ECMWF

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



4.) Reanalysis

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, …

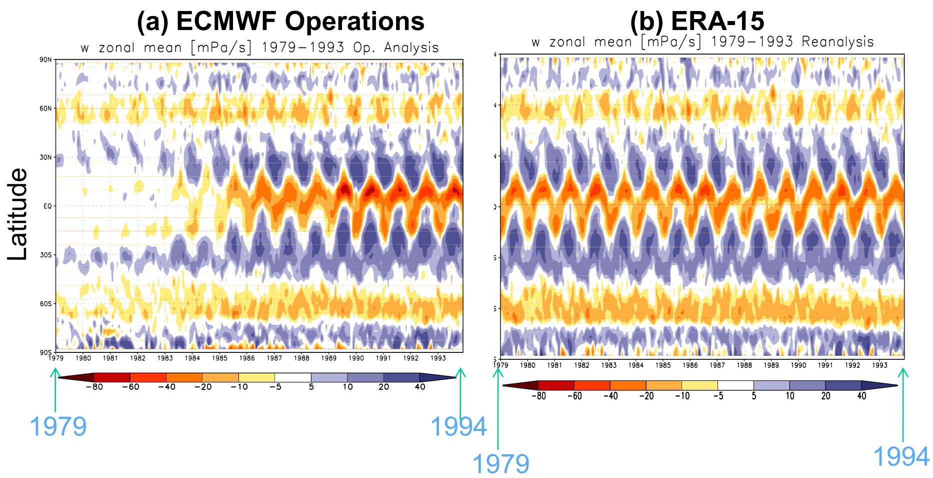
Atmospheric reanalysis: Global products

- **Three centres took initiative in mid 1990s: first generation**
  - **ERA-15 (1979 - 1993) from ECMWF – with significant funding from USA**
  - **NASA/DAO (1980 - 1993) from USA**
  - **NCEP/NCAR (1948 - present) from USA**

- **Second generation of reanalyses followed**
  - **ERA-40 (1958 - 2001) from ECMWF – with significant funding from EU**
  - **JRA-25 (1979 - 2004) from Japan**
  - **NCEP/DOE (1979 - present) from USA**

- **Now in third generation of comprehensive global reanalysis**
  - **ERA-Interim (1989 - present) from ECMWF**
  - **JRA-55 (1958 - 2012) from Japan**
  - **NASA/GMAO-MERRA (1979 - present) from USA**
  - **NCEP-CFSRR (1979 - 2008) from USA**

Why reanalysis?



Zonal mean vertical velocity at 500 hPa

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…

Observations used in ERA-40 (I)

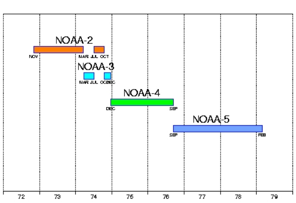
- **Conventional observations**
  - **Radiosonde and pilot-balloon soundings** — **1957 - 2002**
  - **Surface data from land stations and ships** — **1957 - 2002**
  - **Flight-level data from commercial aircraft** — **1973 - 2002**
  - **Surface data from ocean buoys** — **1979 - 2002**
- **Satellite data**
  - **NOAA VTPR radiances** — **1973 - 1978**
  - **NOAA TOVS/ATOVS radiances** — **1979 - 2002**
  - **Winds from geostationary orbit** — **1979 - 2002**
  - **TOMS/SBUV ozone retrievals** — **1979 - 2002**

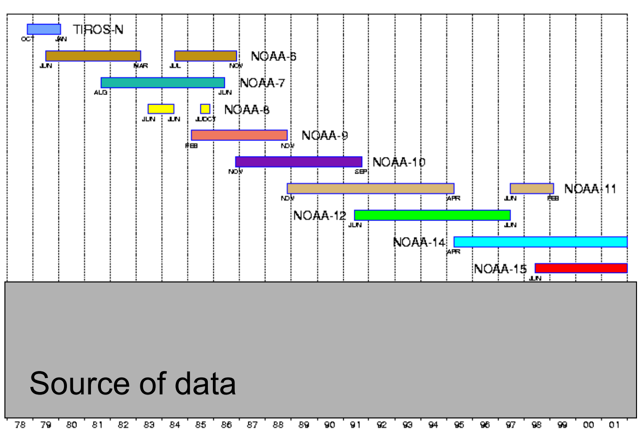
Observations used by ERA-40 (II)

The ERA-40 Re-analysis used 41 satellite instruments carried by 15 different NOAA polar satellites

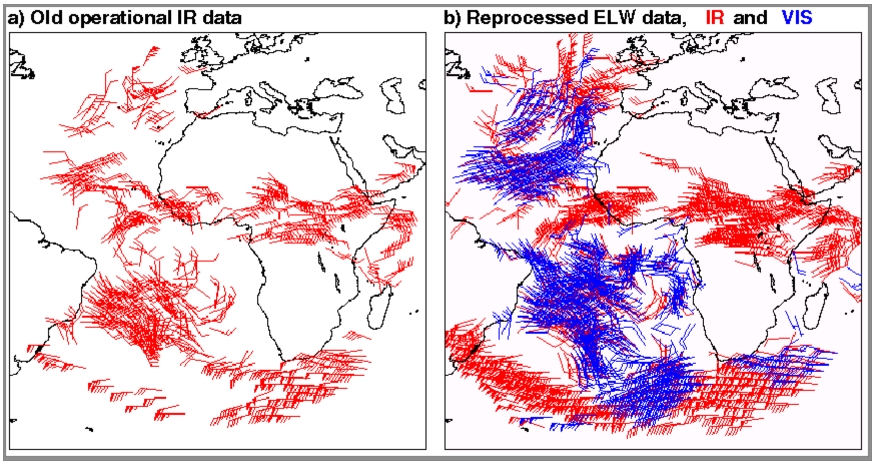
VTPR instrument 72-78

HIRS/MSU/SSU/AMSU instruments 78-02





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



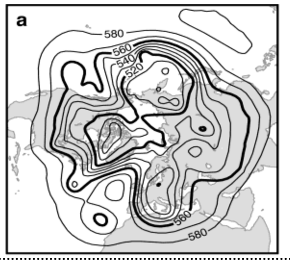
Early 1980s

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

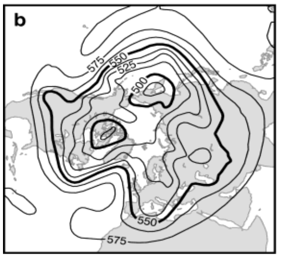
Analysis of
500 hPa geopotential



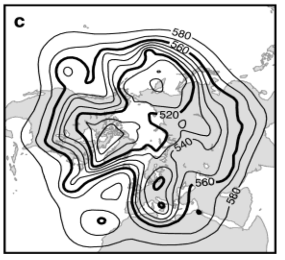
15 February 2005 00 UTC

4D-Var CONTROL

All observations
(surface, radiosondes,
satellite etc…)



3D-Var



Surface pressure
observations
only

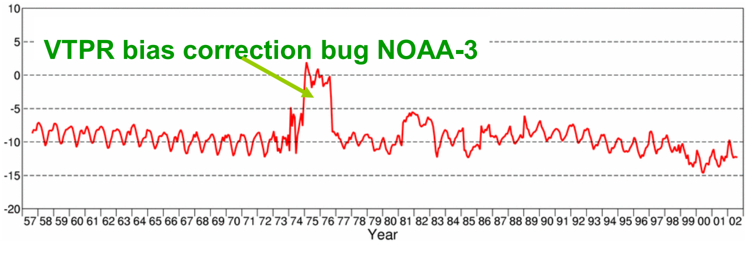
4D-Var

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

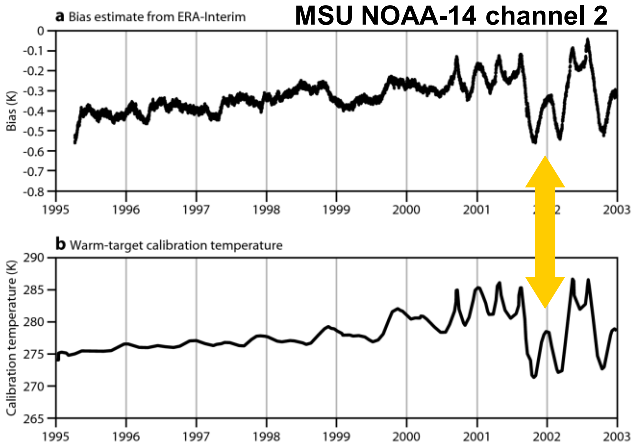
Bias correction problems in ERA-40

- ERA-40 used a static bias correction for radiance data, updated manually
- Error-prone, and some effects can be seen in the reanalysis products:

1 hPa global mean temperature:



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

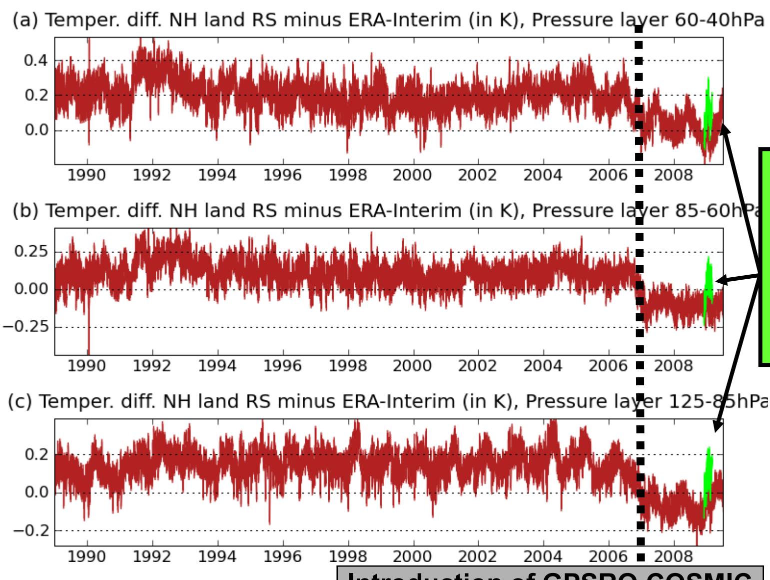


Variational bias estimates for NOAA-14

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

Dee and Uppala, 2009

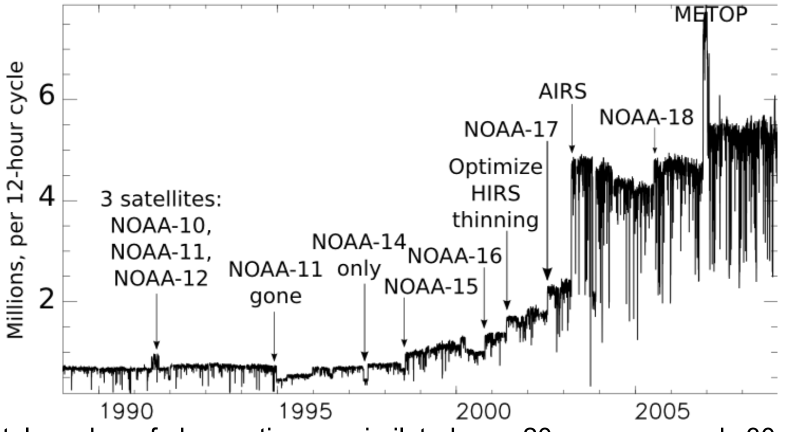
Effects of observing system changes: GPSRO



Observing System Experiment, in which GPSRO data are *not* assimilated

ESA Summer School 2010

Observations assimilated in ERA-Interim



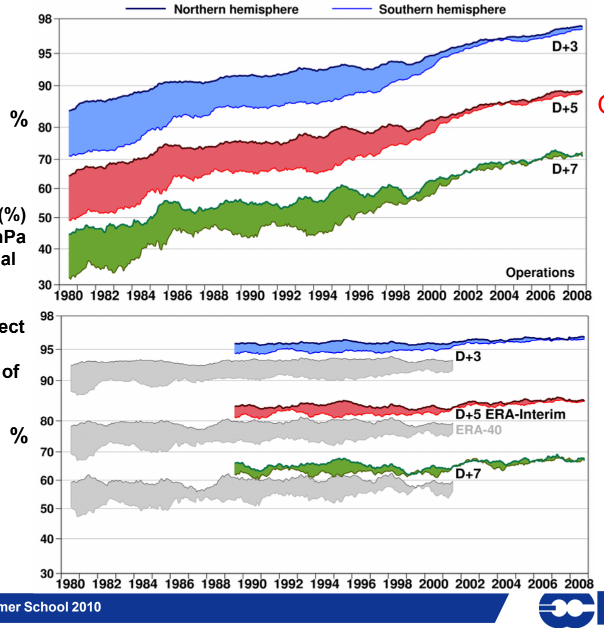
Total number of observations assimilated over 20 years: exceeds 30×10^9

Reanalyses have to deal with very large numbers of observations, whose quantity vary over time

Validation: Forecast skill

Anomaly Correlation (%) for the 500 hPa Geopotential Height

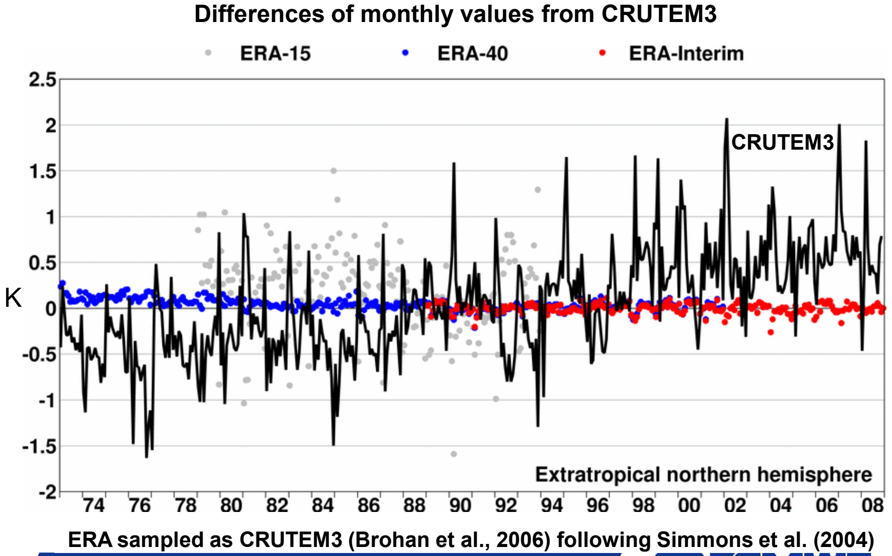
100% = perfect forecast
60% = limit of use



Operations

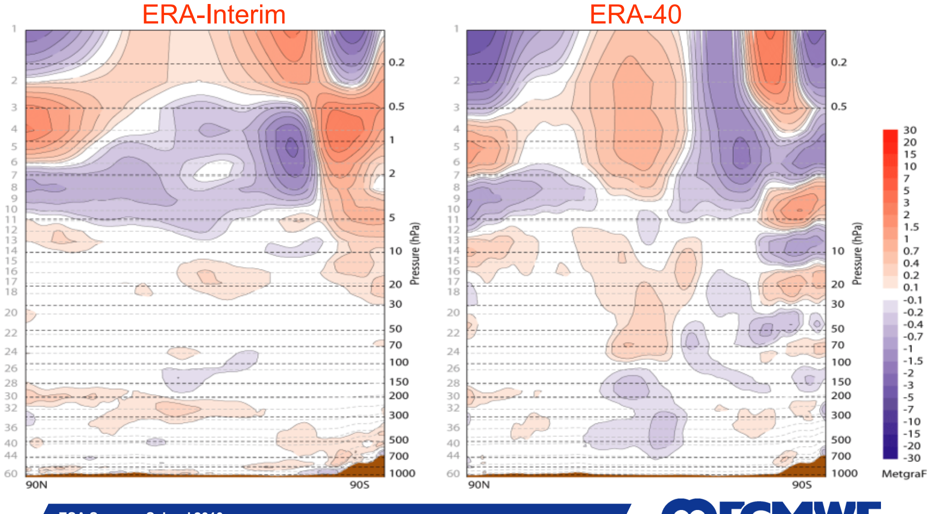
ERA-Interim

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



Progress in time consistency: analysis increments

Zonal mean temperature analysis increments for August 2001



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