Copernicus Climate Change Service

How do reanalysis support climate services ?

Climate Change

Entebbe, Uganda, 31 October – 2 November 2018

Cedric BERGERON, European Centre for Medium-Range weather forecast (ECMWF)

Acknowledgement: ECMWF & ERA colleagues

Copernicus Europe's eyes on Earth | European Commission | ECMWF

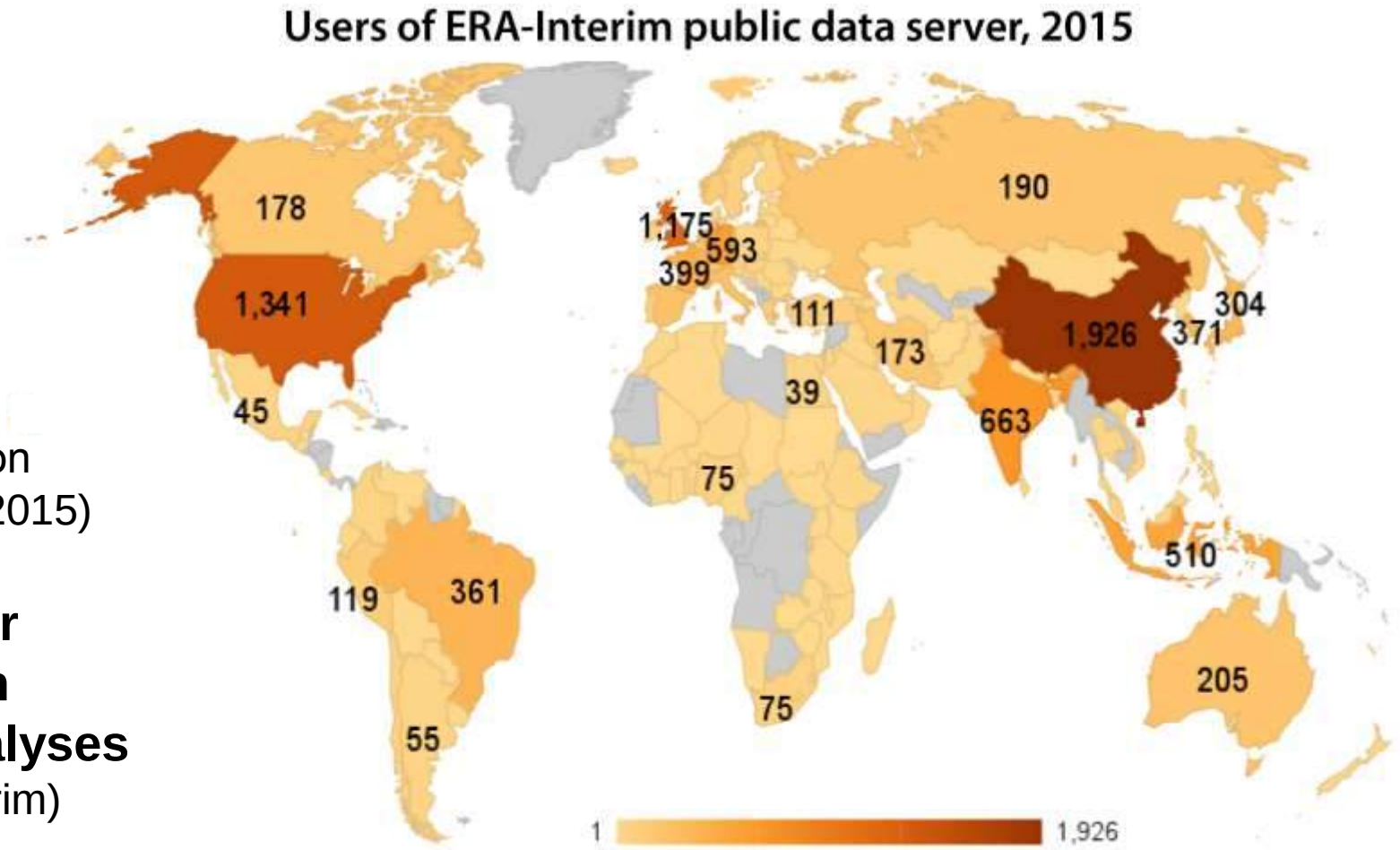
Climate Change

Interest for reanalysis data

Downloads from data servers to tens of thousands of users

with widespread applications (“Climate” is surveyed users’ most common field of work; Gregow *et al*., 2015)

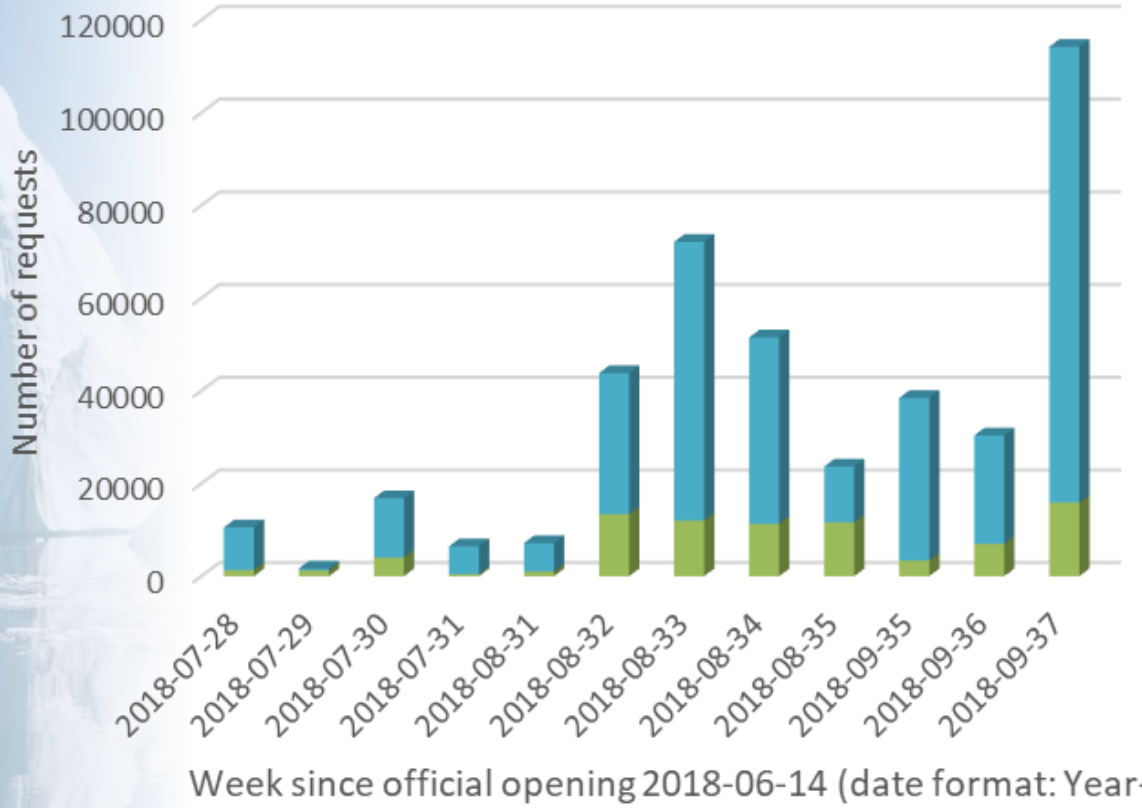
~1000 citations per year for reference papers on the most popular reanalyses (NCEP/NCAR and ERA-Interim)

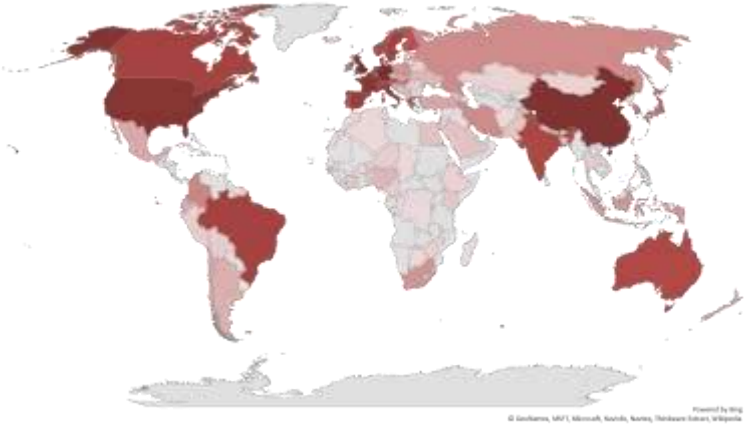


Continued use of older products can be problematic: spread among different generations of reanalyses has been wrongly cited as evidence that products in general are unsuitable

Interest for reanalysis data

Climate Change





> 250Tb in 3months

Origin	Product type	Users	Requests	Request/day	Data TBs
API	reanalysis	310	419334	4414	179.66
Interactive	reanalysis	513	4335	45	75.72

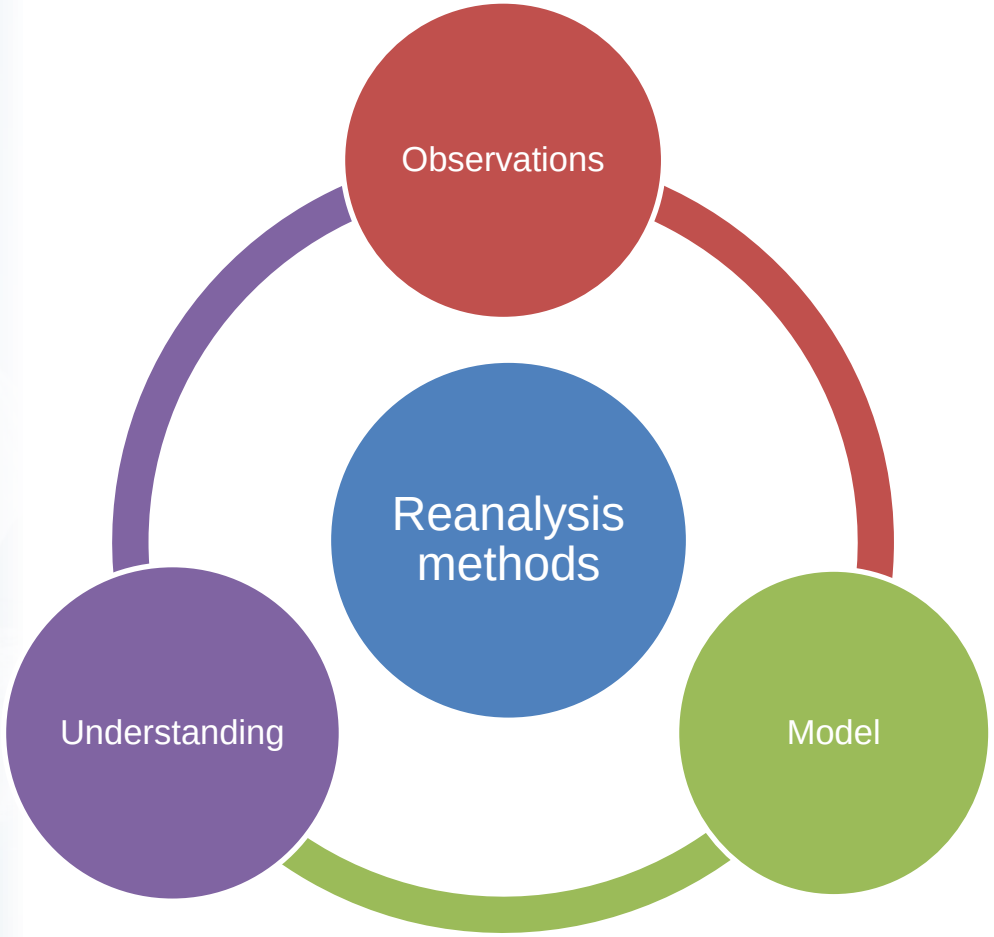
ECMWF opernicus Europe's eyes on Earth European Commission

Climate
Change

Let’s start from the beginning …

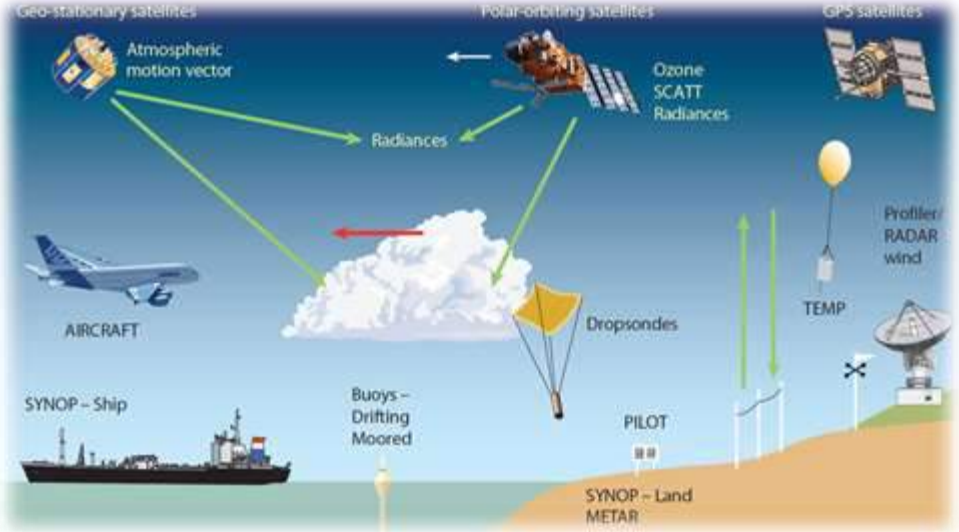
Climate Change

Earth science has three pillars



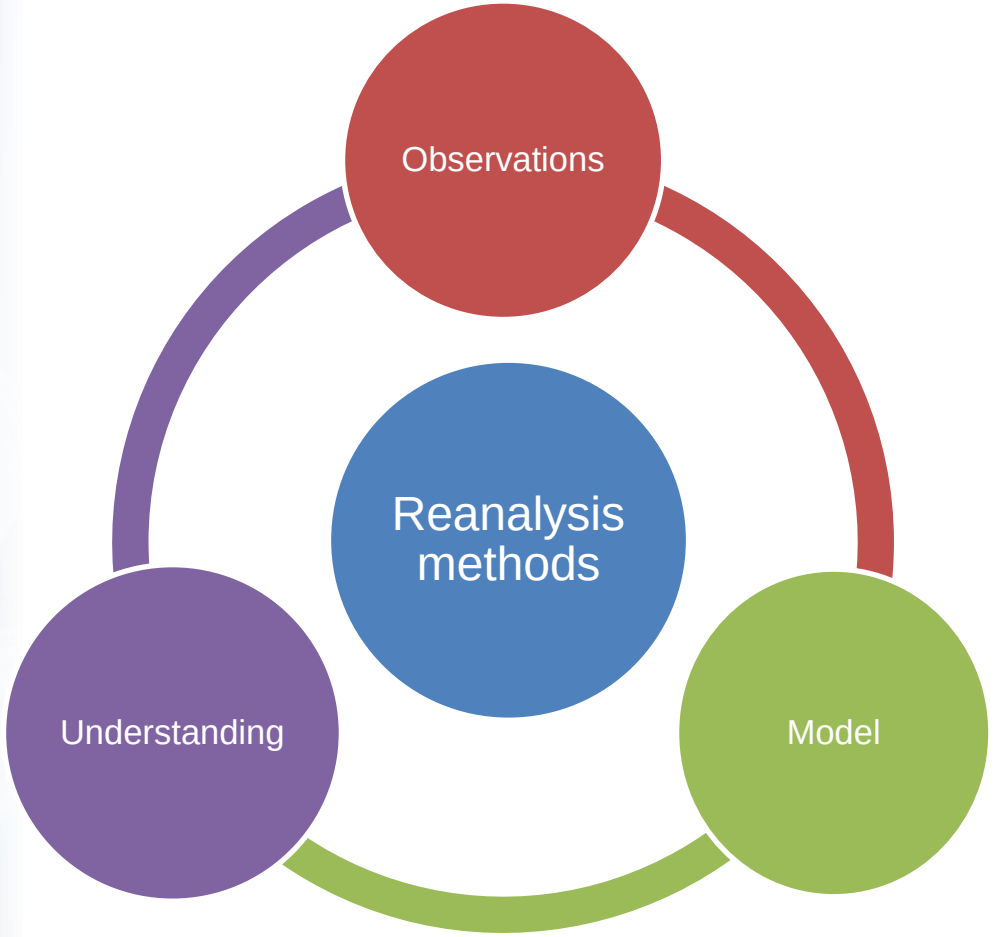
Earth Observations

Measurements from many platforms with different types of sensors



Climate Change

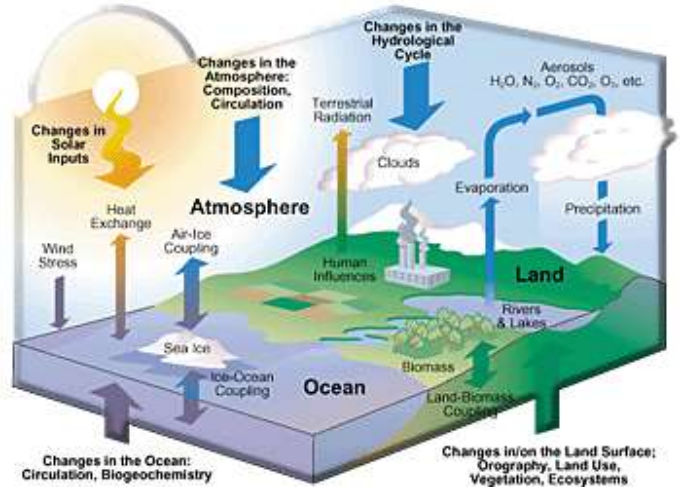
Earth science has three pillars



Earth Modelling

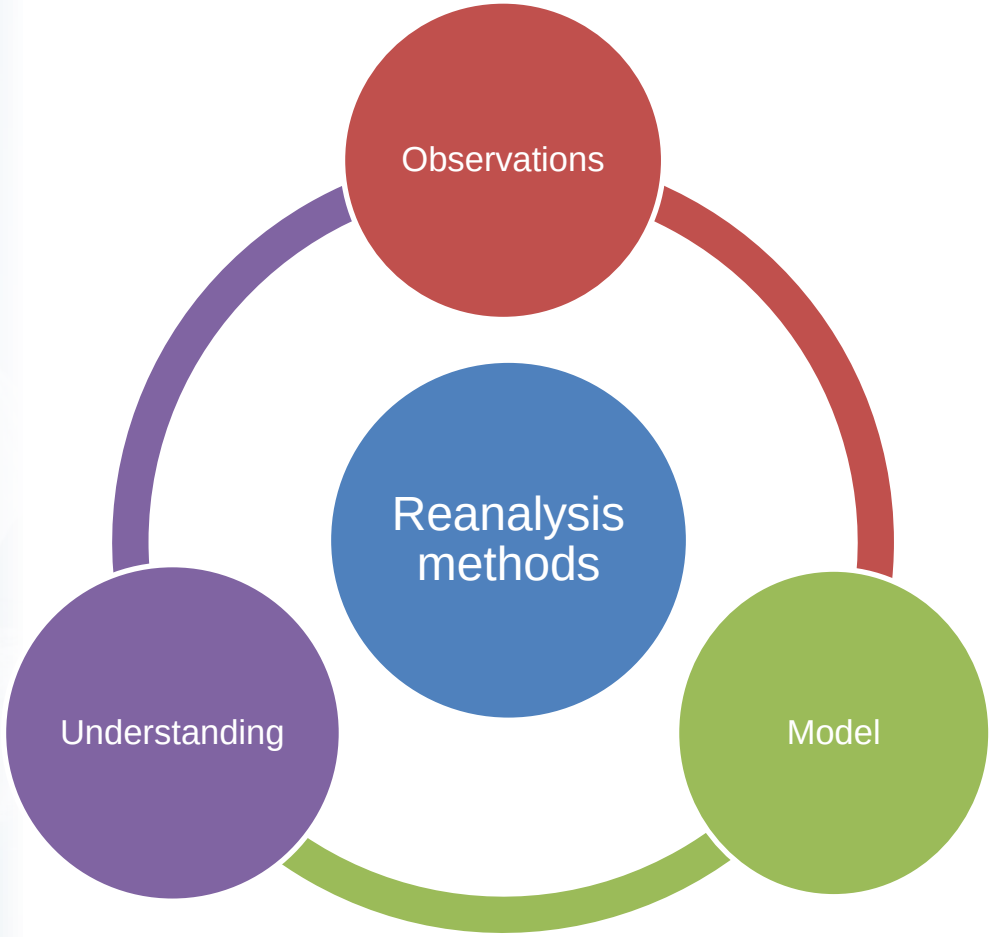
State-of-the-art numerical models based on physical laws

- link geophysical variables
- enforce balance
- ensure mass conservation



Climate Change

Earth science has three pillars



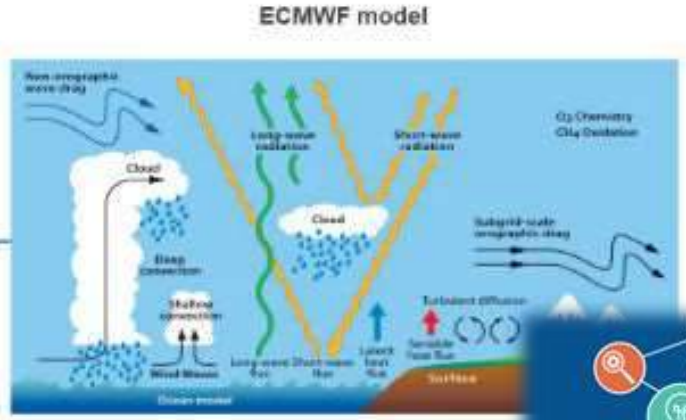
Earth Understanding

Confronting the models with the observations to identify limitations
- imperfections in the observations
- mistakes in model concepts
- systematic errors (bias)

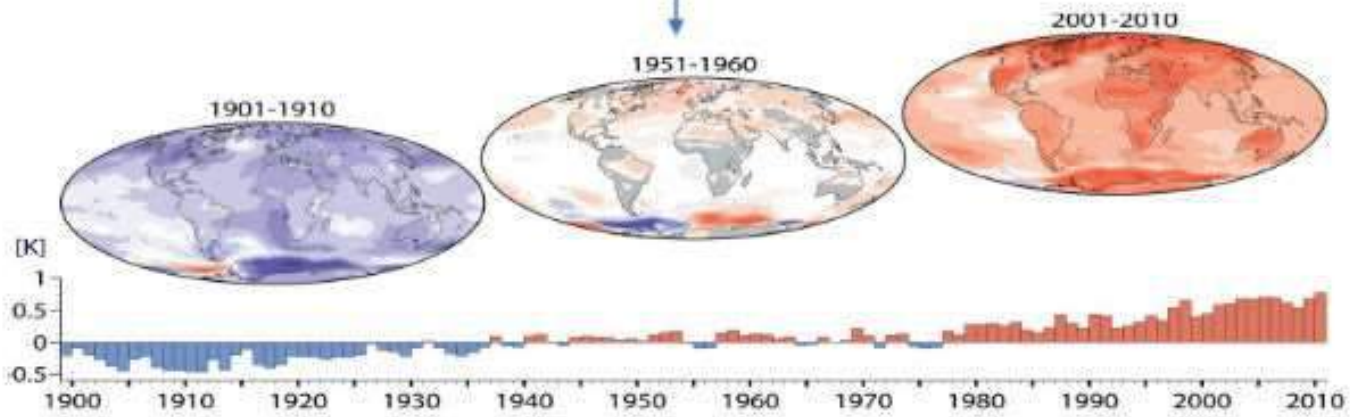
From there, we can improve the instruments, and refine the models (infinite loop)

Climate Change

… and here are the reanalysis …



Data assimilation



IMPLEMENTED BY

ECMWF Copernicus European Commission

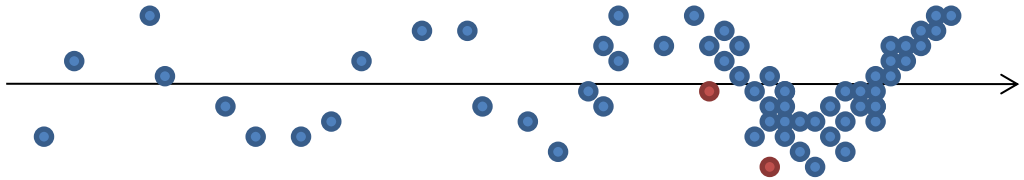
Climate
Change

Let’s go a bit further …

Climate Change

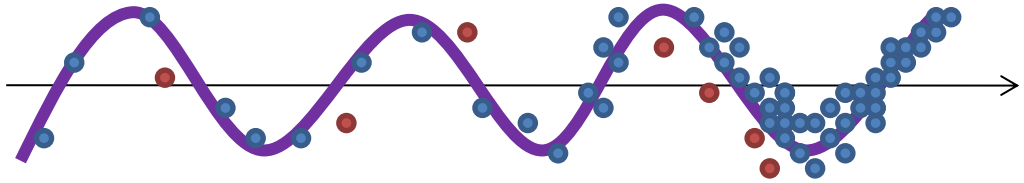
Different methods to reconstruct the past climate and/or weather

“Observations-only” climatology



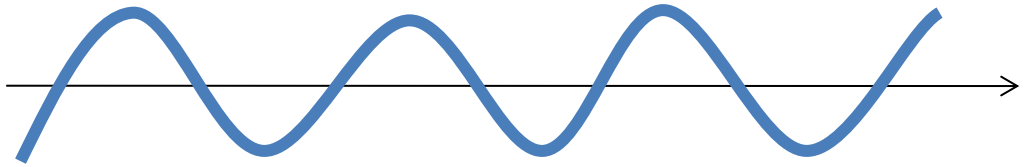
Reconstruction based on observations, little use of model

Reanalysis



Balance between use of observations and model

“Model only” integration



Reconstruction based on a model, little use of observations

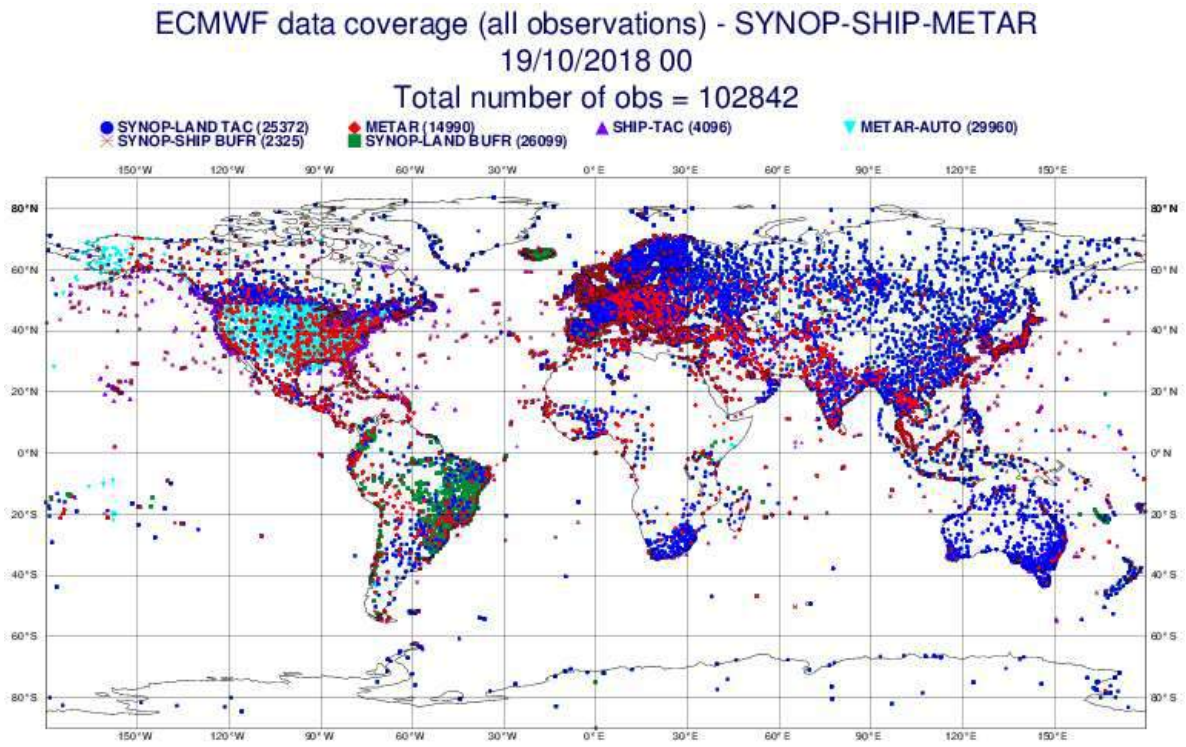
ECMWF Copernicus Europe's eyes on Earth European Commission

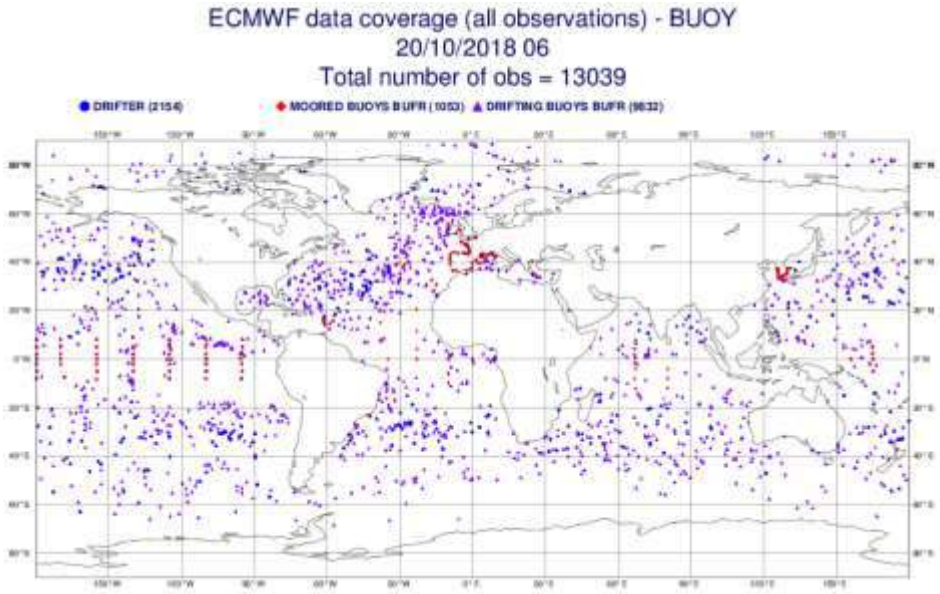
Climate Change

Observational data only

Historical in-situ surface and upper observational data have been collected for several decades in many institutions

- High quality climate dataset can be generated at the observation station and surrounding region





ECMWF Copernicus Europe's eyes on Earth European Commission

Climate Change

Observational data only

However, the regions and variables are limited…

ECMWF Copernicus Europe's eyes on Earth European Commission

Climate Change

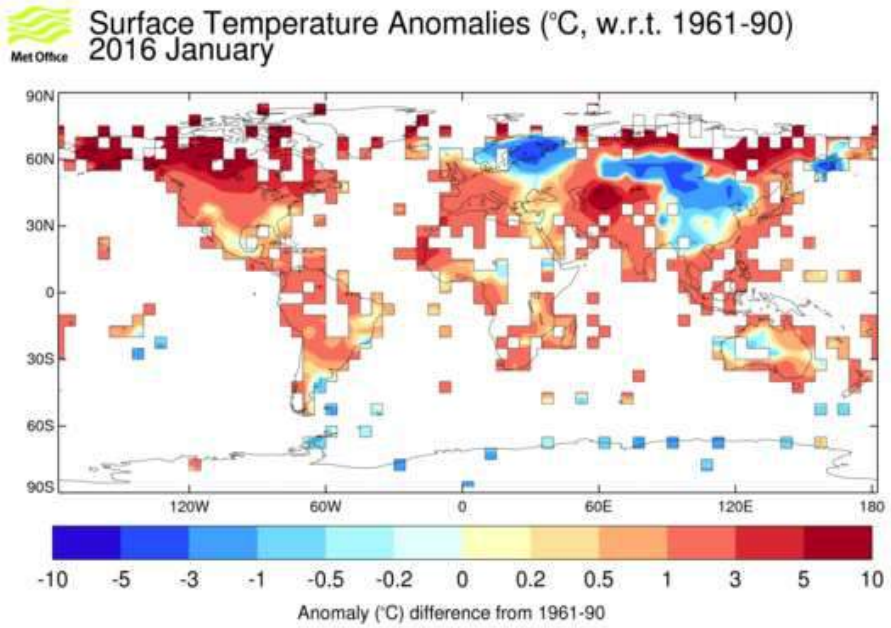
Observational data only

An example: “Observations-only” climatology - CRUTEM4

Observations: archive of monthly mean temperatures provided by 5500 weather stations distributed around the world

Method:

- each station temperature is converted to an anomaly from the 1961-90 average temperature for that station.
- each grid-box value is the mean of all the station anomalies within that grid box.



A gridded dataset (5 degree grid) of historical near-surface air temperature anomalies over land available for each month from January 1850 to present

ECMWF Copernicus Europe's eyes on Earth European Commission

Climate Change

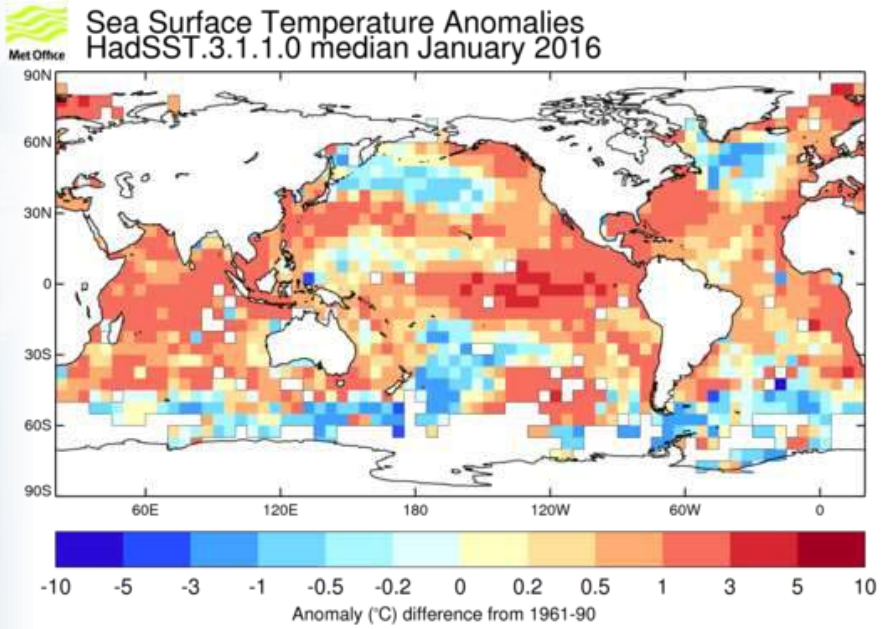
Observational data only

Example: "Observations-only" climatology - HadSST3

Observations: in-situ measurements of Sea Surface Temperature (SST) from ships and buoys coming from ICOADS and GTS archives

Method:

- the measurements are converted to anomalies.
- bias adjustments to reduce the effects of spurious trends caused by changes in SST measuring practices



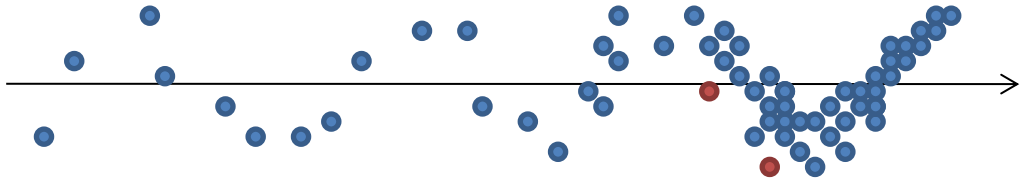
A gridded dataset (5 degree grid) of historical SST anomalies available for each month from January 1850 to present

ECMWF Copernicus Europe's eyes on Earth European Commission

Climate Change

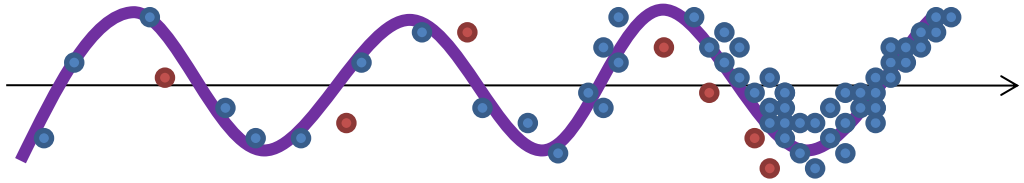
Different methods to reconstruct the past climate and/or weather

“Observations-only” climatology



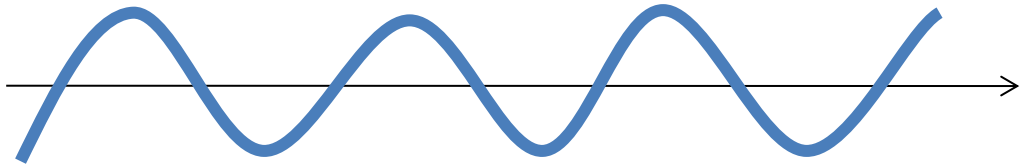
Reconstruction based on observations, little use of model

Reanalysis



Balance between use of observations and model

“Model only” integration



Reconstruction based on a model, little use of observations

ECMWF Copernicus Europe's eyes on Earth European Commission

Climate Change

Model only

Numerical integration of the basic equations of atmosphere using General Circulation Model (GCM) and supercomputer

- Grid Point Values with many type of variables are generated based on consistent dynamics and physics of the model

However, calculation by model-alone is not enough to produce dataset with high accuracy

ECMWF Copernicus Europe's eyes on Earth European Commission

Climate Change

Model only

Model: the IFS atmospheric model developed for NWP at low resolution (125 km)

Method:

- the model is integrated from 1900 to 2010
- observations are not assimilated but the model is constrained by atmospheric forcings

CMIP5 atmospheric forcing are used:

- Solar irradiance (CMIP5)
- Greenhouse gases (CMIP5)
- Ozone for radiation (CMIP5)
- Tropospheric aerosols (CMIP5)
- Stratospheric aerosols (CMIP5)
- Sea-surface temperature and sea-ice cover (Hadley Centre)

These forcings are based indirectly on observations!

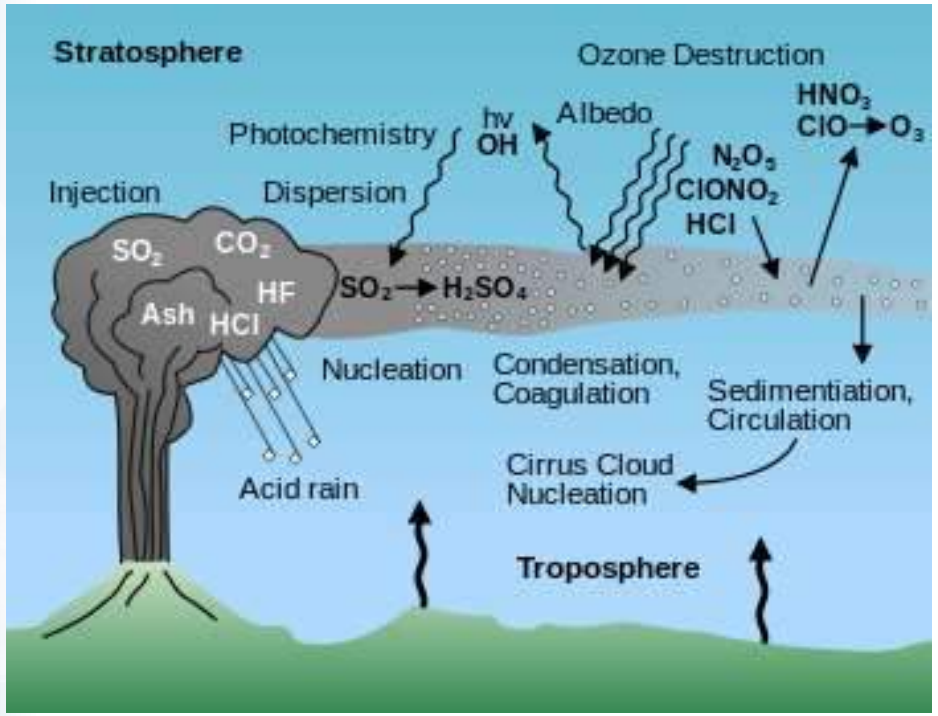
ECMWF Copernicus Europe's eyes on Earth European Commission

Climate Change

The example of stratospheric aerosols

Stratospheric aerosols mainly have a volcanic origin

Volcanic sulphate can remain in the stratosphere for many months, where it mixes within large predominantly zonal bands, increasing atmospheric opacity

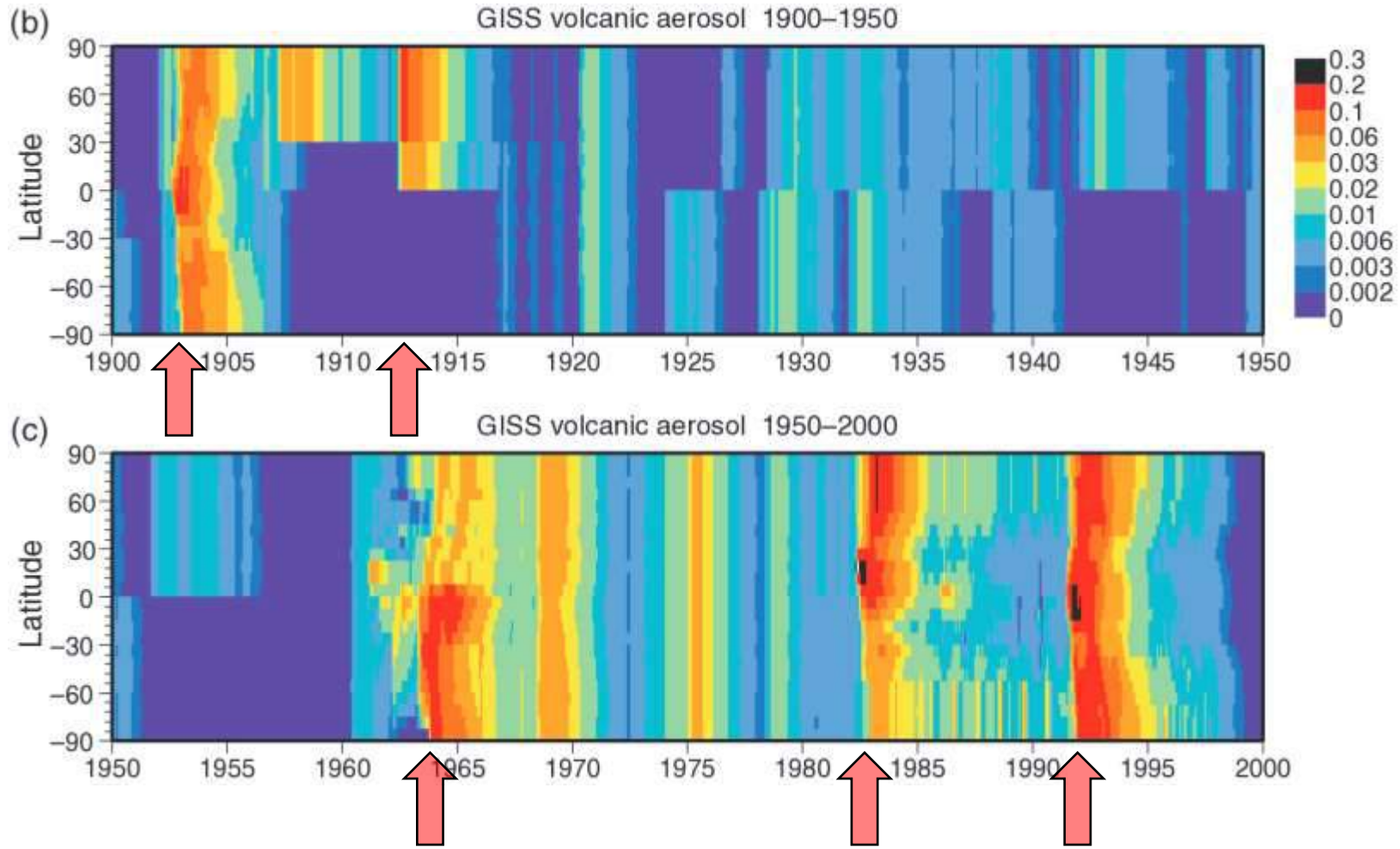


In the IFS model used in operation, volcanic sulphate is assumed to be constant (evenly distributed over the stratosphere, assuming a constant volume-mixing ratio)

Climate Change

Stratospheric aerosols in ERA-20CM

CMIP5 dataset reconstructs the evolution of volcanic sulphate (1850 to present)



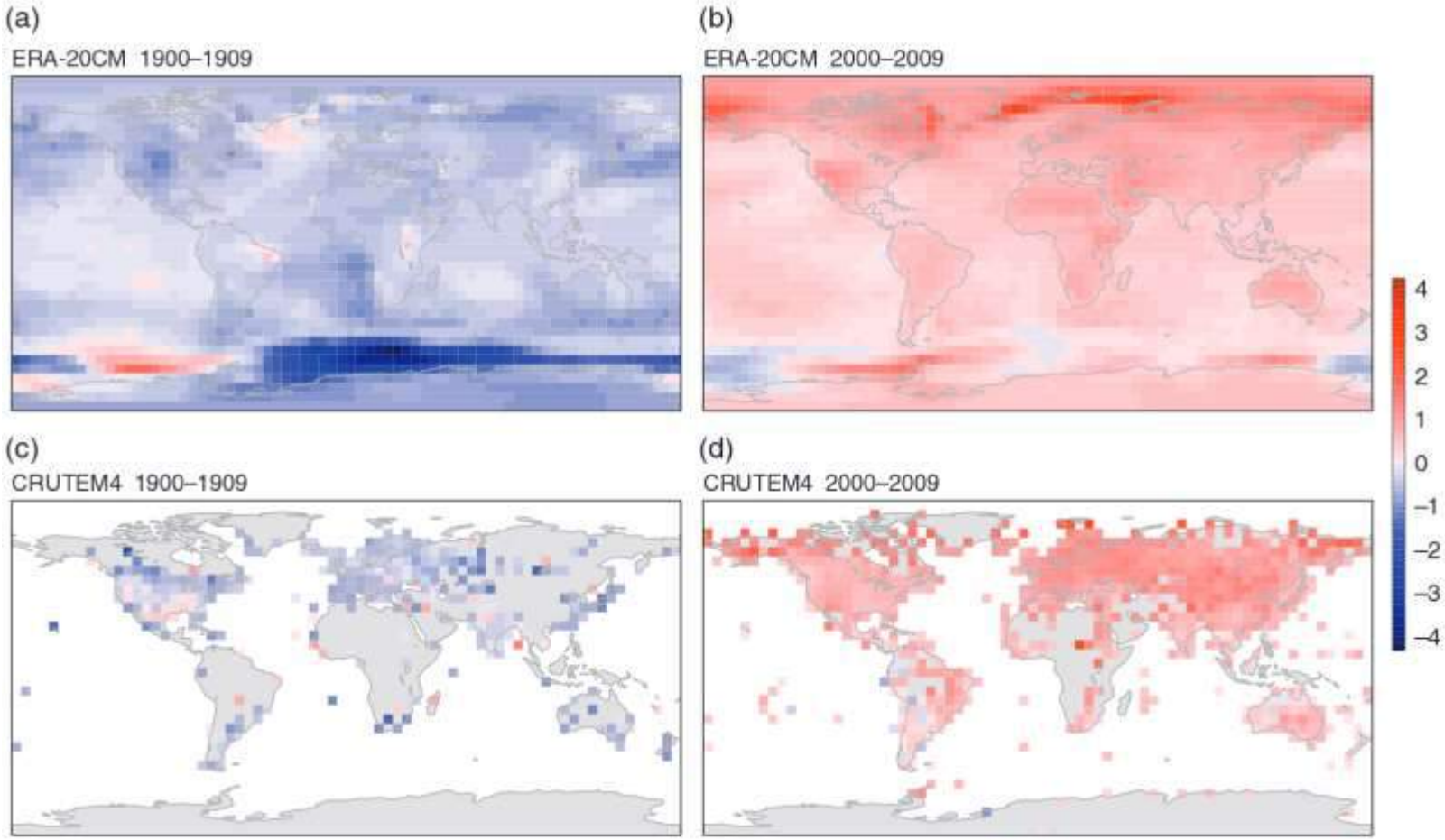
Major eruptions are clearly visible: Santa Maria (1902), Novarupta (1912), Agung (1963), Fernandina (1968), El Chichon (1982) and Pinatubo (1991)

ECMWF Copernicus Europe's eyes on Earth European Commission

Climate Change

Comparison between ERA-20CM with CRUTEM4

Temperature anomalies for 1900-1909 (left) and 2000-2009 (right)



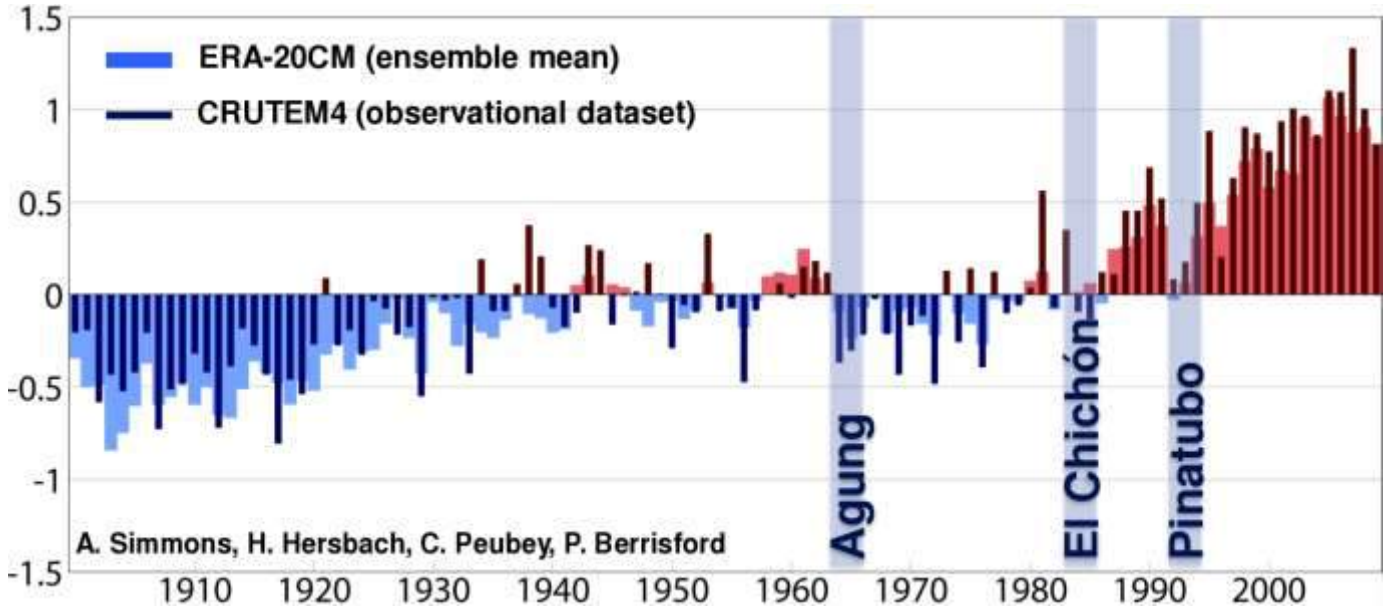
Similar global warming in the “model-only” and the “observation-only” reconstructions
Differences in Southern United States for 1900-1909

ECMWF Copernicus Europe's eyes on Earth European Commission

Climate Change

Comparison between ERA-20CM with CRUTEM4

Annual mean anomalies for ERA-20CM (light) and CRUTEM4 (dark)



ERA-20CM reproduces the long term variation and capture interannual variability after volcanic eruptions

"Model only" integration:

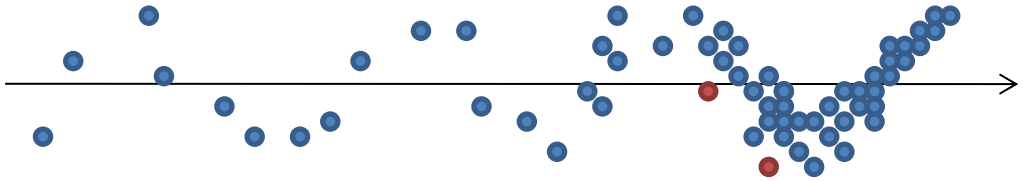
- long record (extending back to 1900), based on a forced NWP model
- space and time consistency
- capture interannual variability, not expected to reproduce actual synoptic weather

ECMWF Copernicus Europe's eyes on Earth European Commission

Climate Change

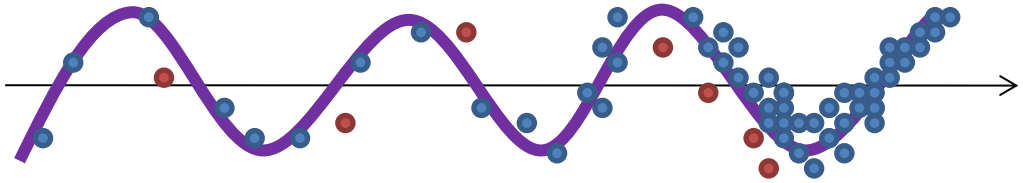
Different methods to reconstruct the past climate and/or weather

“Observations-only” climatology



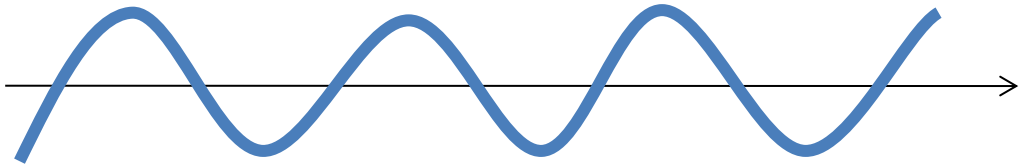
Reconstruction based on observations, little use of model

Reanalysis



Balance between use of observations and model

“Model only” integration



Reconstruction based on a model, little use of observations

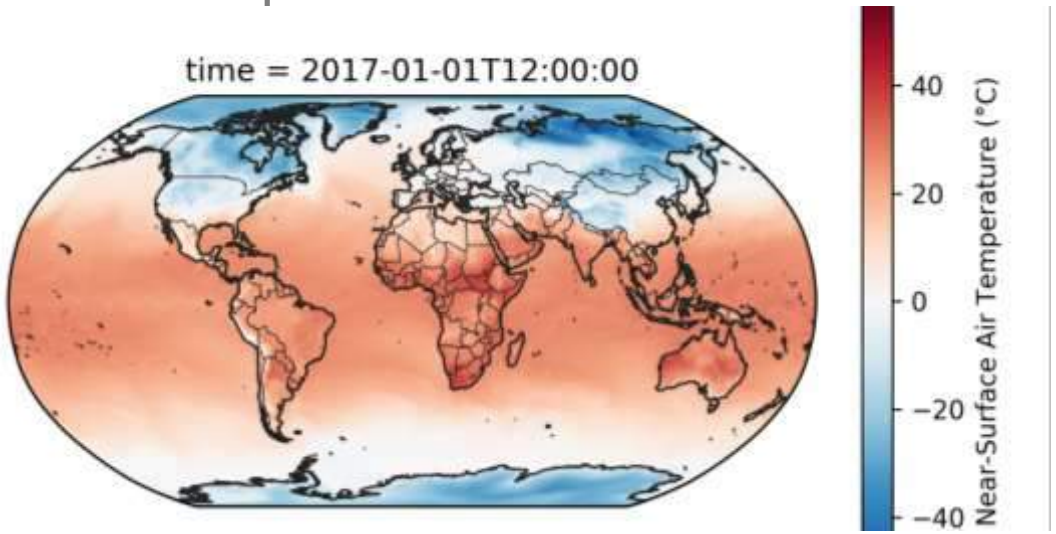
ECMWF Copernicus Europe's eyes on Earth European Commission

Climate Change

What is climate reanalysis?

A climate reanalysis gives a numerical description of the recent climate, produced by combining models with observations.

It contains estimates of atmospheric parameters such as air temperature, pressure and wind at different altitudes, and surface parameters such as rainfall, soil moisture content, and sea-surface temperature.



The estimates are produced for all locations on earth, and they span a long time period that can extend back by decades or more.

Climate reanalysis generate large datasets that can take up many terabytes of space

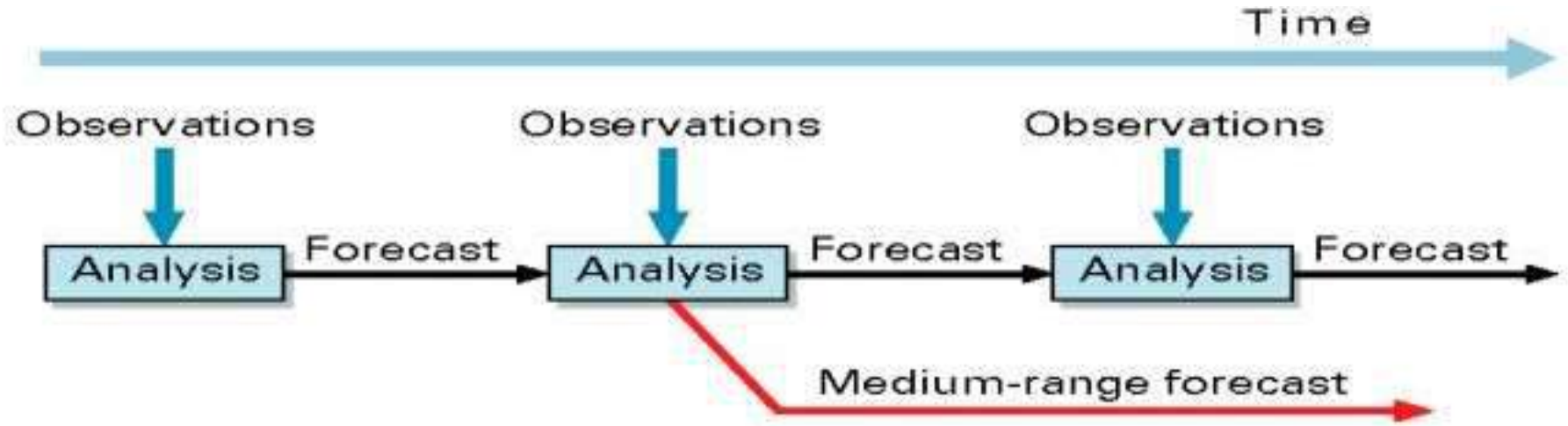
ECMWF Copernicus Europe's eyes on Earth European Commission

Climate Change

Combining models with observations?

This principle is called **DATA ASSIMILATION.** *(Data assimilation was first proposed in the 1950s and has been widely used to start numerical weather forecasts since the 1970s)*

It is based on the method used by Numerical Weather Prediction centres, where every n hours (12 hours at ECMWF) a previous forecast is combined with newly available observations in an optimal way to produce a new best estimate of the state of the atmosphere, called analysis, from which an updated, improved forecast is issued.



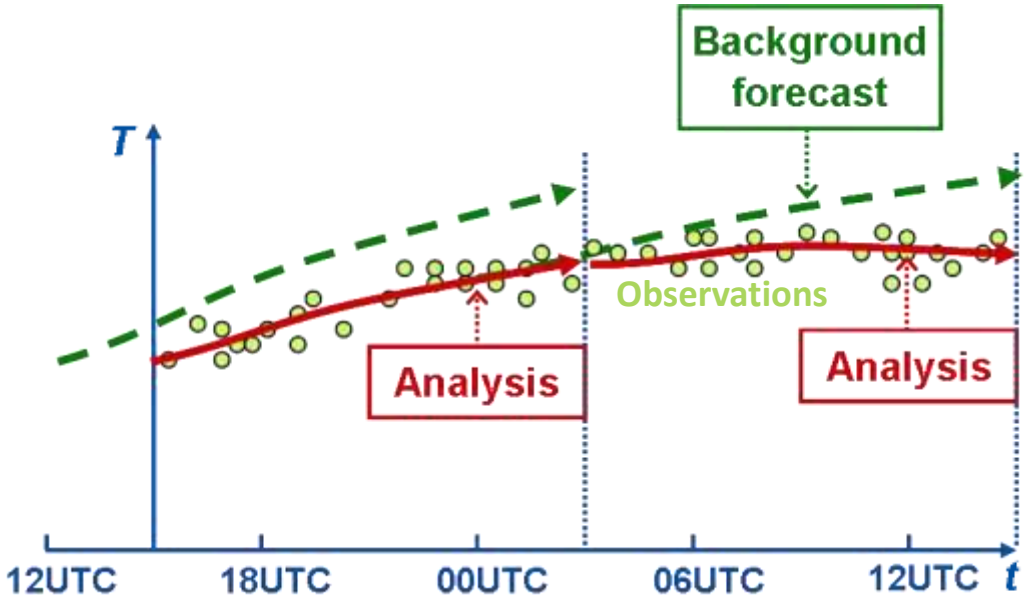
ECMWF Copernicus Europe's eyes on Earth European Commission

Climate Change

Data assimilation

Data assimilation blends information from:

- observations
- a short “background” model forecast
- estimates of observational and background errors
- dynamical relationships built into the representation of background errors



4D variational assimilation as used in ERA-Interim

The model carries information from earlier observations forward in time and spreads it in space

Information is spread from one variable to another by the model and by background-error relationships

Better estimates of the state of the Earth system can come either from better observations or from better data assimilation

ECMWF Copernicus Europe's eyes on Earth European Commission

Data assimilation and reanalysis

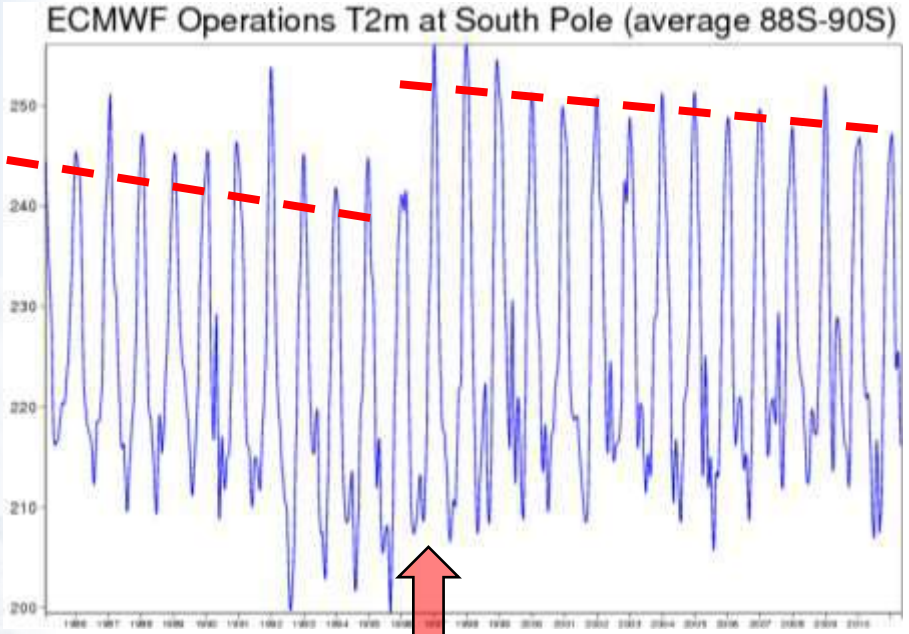
Reanalysis applies a fixed, modern assimilation system to a sequence of past observations, generally extending over decades

Reanalysis does not have the constraint of issuing timely forecasts, so there is more time to collect observations, and when going further back in time, to allow for the ingestion of **improved versions of the original observations, which all benefit the quality of the reanalysis product.**

Climate Change

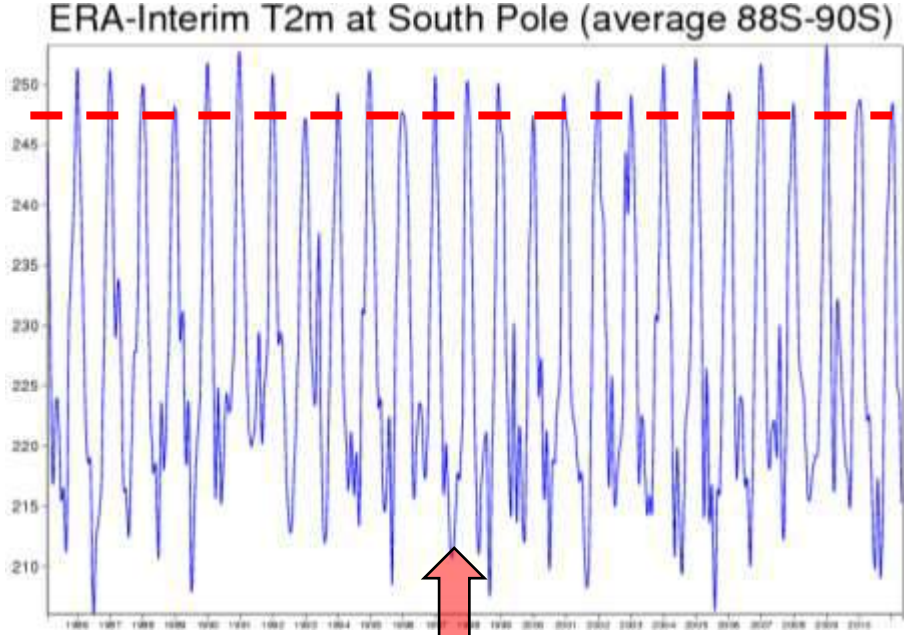
Why not use simply operational NWP analysis?

The models and data assimilation methods have improved a lot over time, so analysis timeseries feature spurious changes.



1 Feb 1985 — **1 May 2011**

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



1 Feb 1985 — **1 May 2011**

No.

To remove these spurious sources of variability, model and data assimilation systems are frozen and rerun to produce a reanalysis dataset

ECMWF Copernicus Europe's eyes on Earth — European Commission

Climate Change

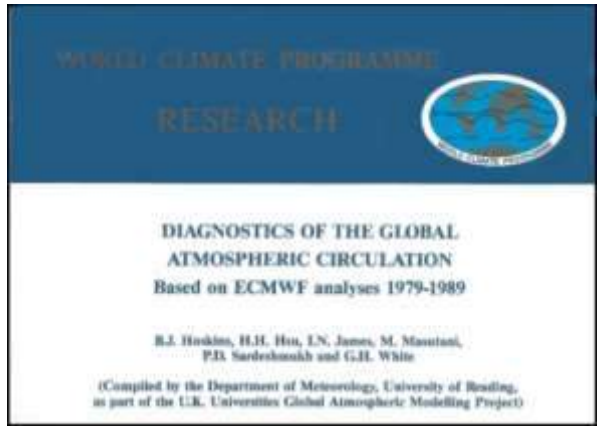
Atmospheric reanalysis: starting points

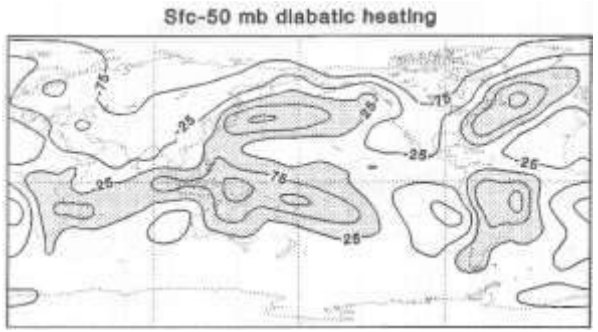
Has its origins in the production of datasets by ECMWF and GFDL for the 1979 Global Weather Experiment

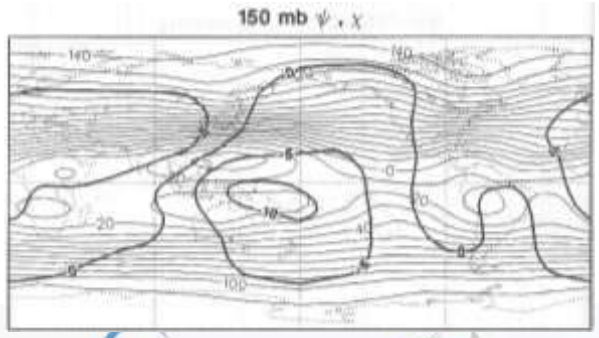
- widely used, but superseded by use of multi-year operational NWP analyses
- but that use was hampered by the frequent changes made to the operational systems

Subsequently proposed for climate-change studies by Bengtsson and Shukla (1988) and Trenberth and Olson (1988)

- with responses from the 1990s onwards







Climate Change

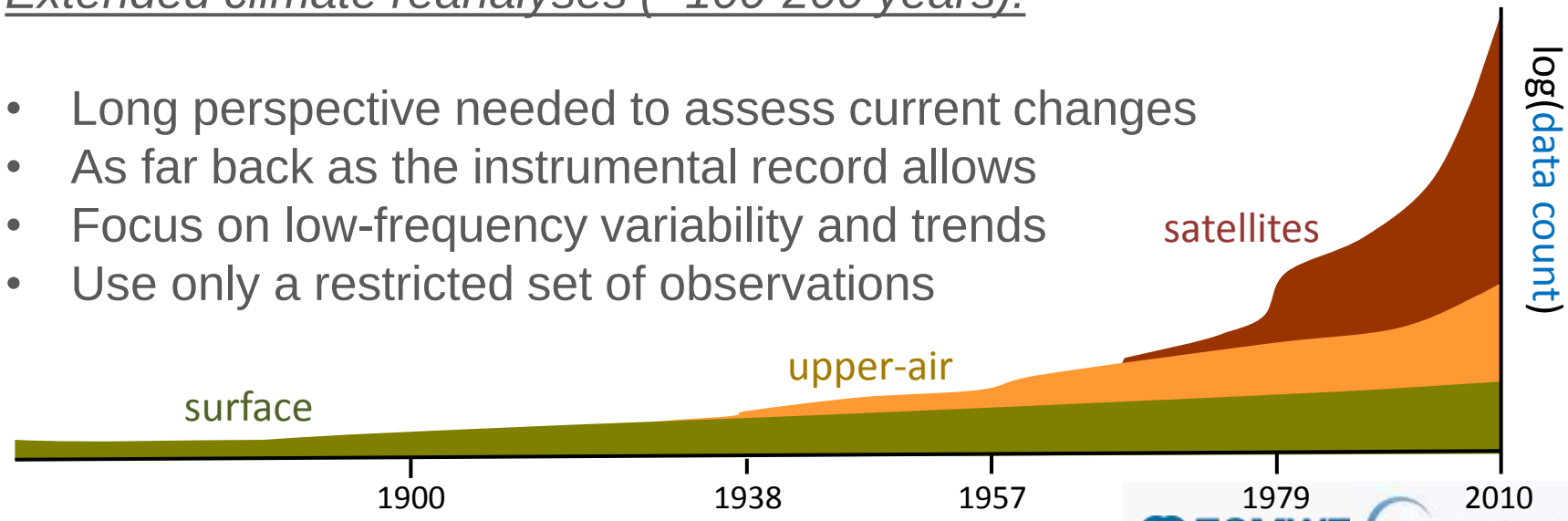
Atmospheric reanalysis: Two types

Reanalyses of the modern observing period (~30-50 years):

- Produce the best estimate at any given time
- Use as many observations as possible, including from satellites
- Closely tied to forecast system development (NWP and seasonal)
- Near-real time product updates suitable for climate monitoring

Extended climate reanalyses (~100-200 years):

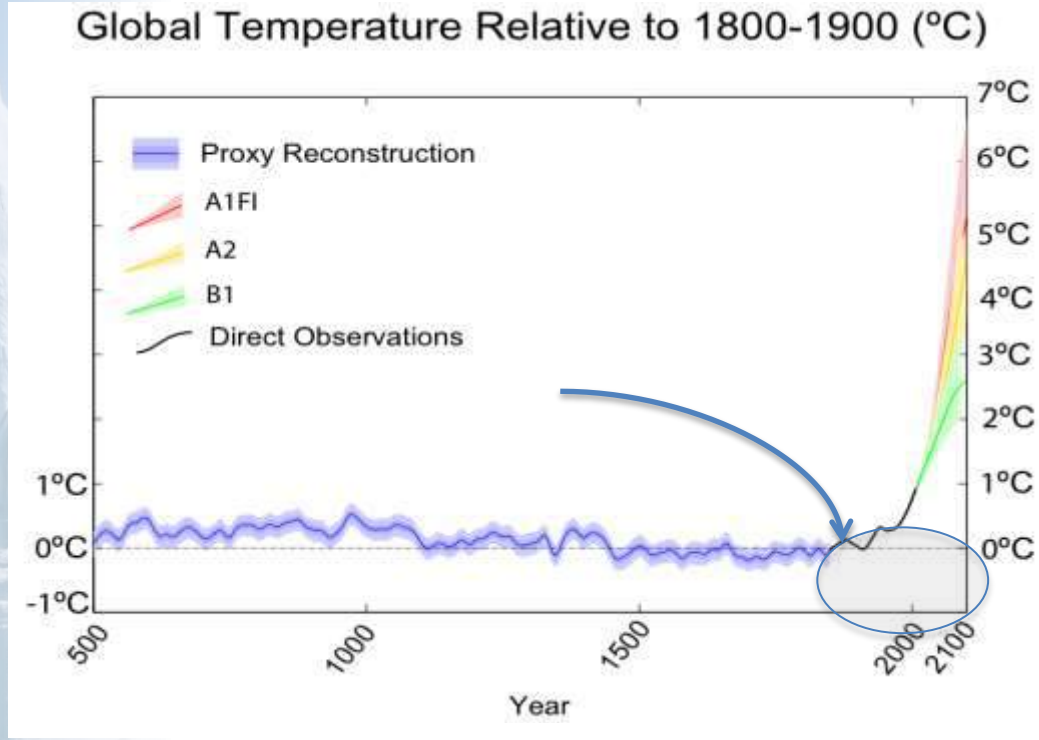
- Long perspective needed to assess current changes
- As far back as the instrumental record allows
- Focus on low-frequency variability and trends
- Use only a restricted set of observations



ECMWF Copernicus Europe's eyes on Earth European Commission

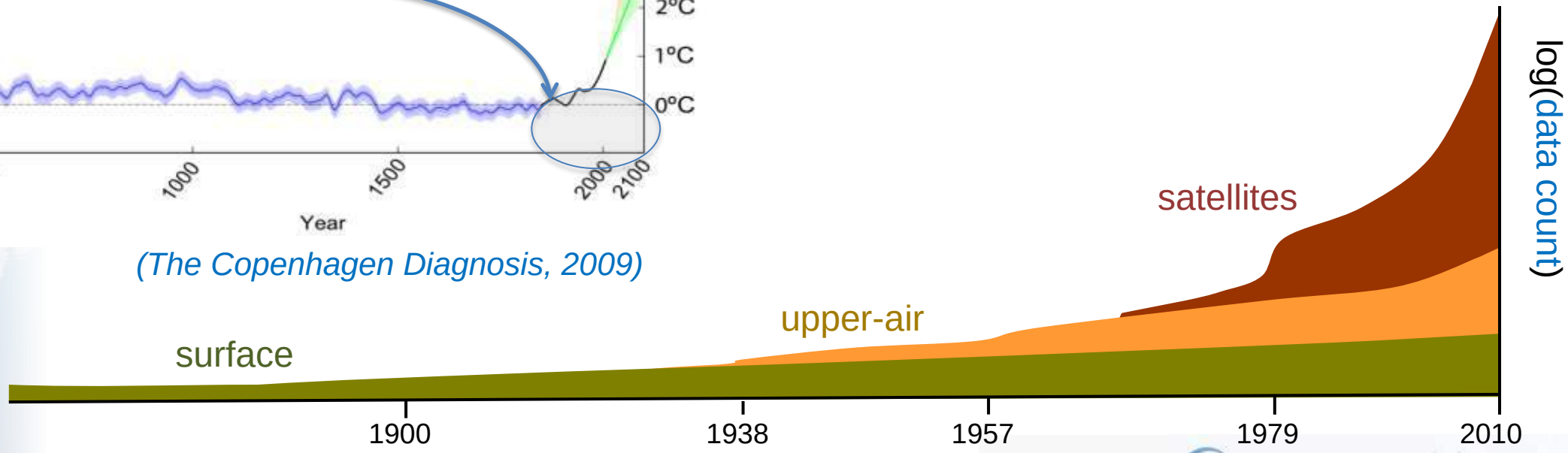
Atmospheric reanalysis: Reaching further back in time: Key challenges

Climate Change



(The Copenhagen Diagnosis, 2009)

- Which observations are available?
- How best to make use of them?
- What is the role of models?
- How to deal with shifts and biases?
- Can we achieve “climate quality”?
- How to quantify uncertainties?



ECMWF Copernicus Europe's eyes on Earth European Commission

Climate Change

Global atmospheric reanalyses from ECMWF, JMA, NASA and NCEP

The first three responses were in the early to mid 1990s

- ERA-15 (1979 - 93), NASA/DAO (1980 - 93) and NCEP/NCAR (1948 - …)

A second round of production followed

- ERA-40 (1958 - 2001), JRA-25 (1979 - 2014) and NCEP/DOE (1979 - …)

And a third

- ERA-Interim (1979 - …), JRA-55 (1958 - …), NASA/MERRA (1979 - 2016) and NOAA/CFSR (1979 - 2011; extended to present with CFSv2 system)

A fourth round has begun

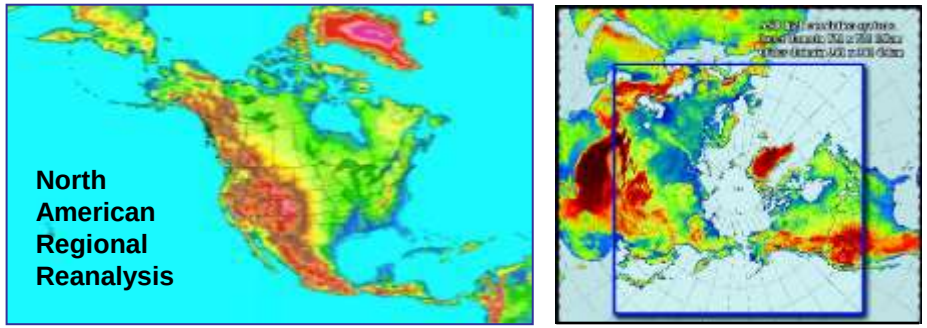
- MERRA-2 (1979 - …) is now up-to-date and continued close to real time
- ERA5 has entered production, under the auspices of Copernicus/ECMWF, first set are delivered through the C3S Climate Data Store
- JRA-3Q is planned to enter production in Japanese Fiscal Year 2018

ECMWF Copernicus Europe's eyes on Earth European Commission

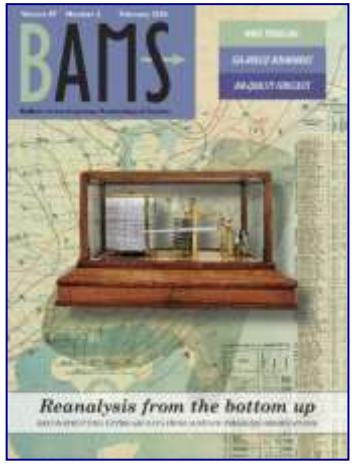
Climate Change

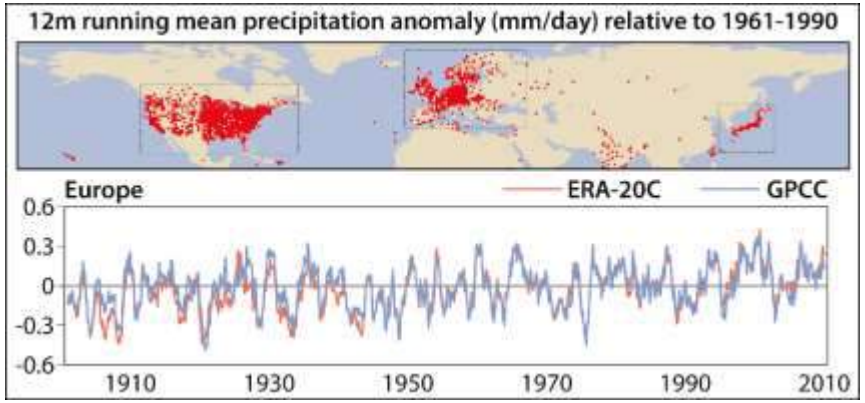
Reanalysis: becoming more diverse

Regional atmospheric reanalysis

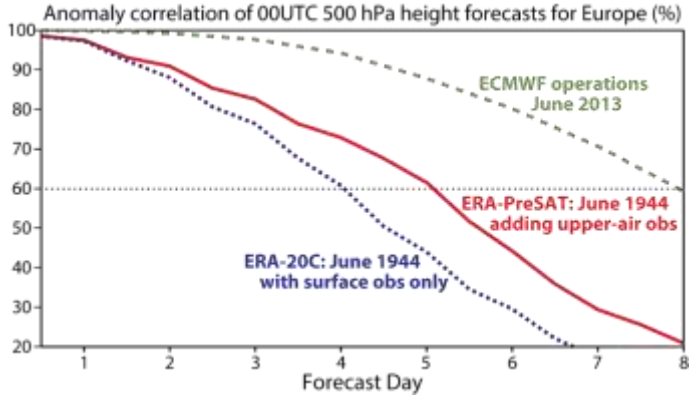


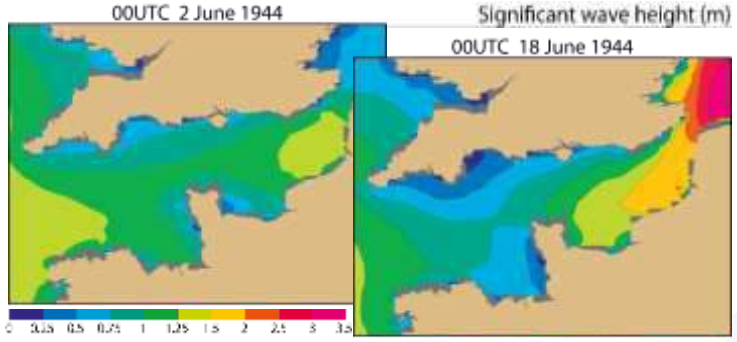
Century-scale reanalysis assimilating only surface observations





Reanalysis assimilating early upper-air observations





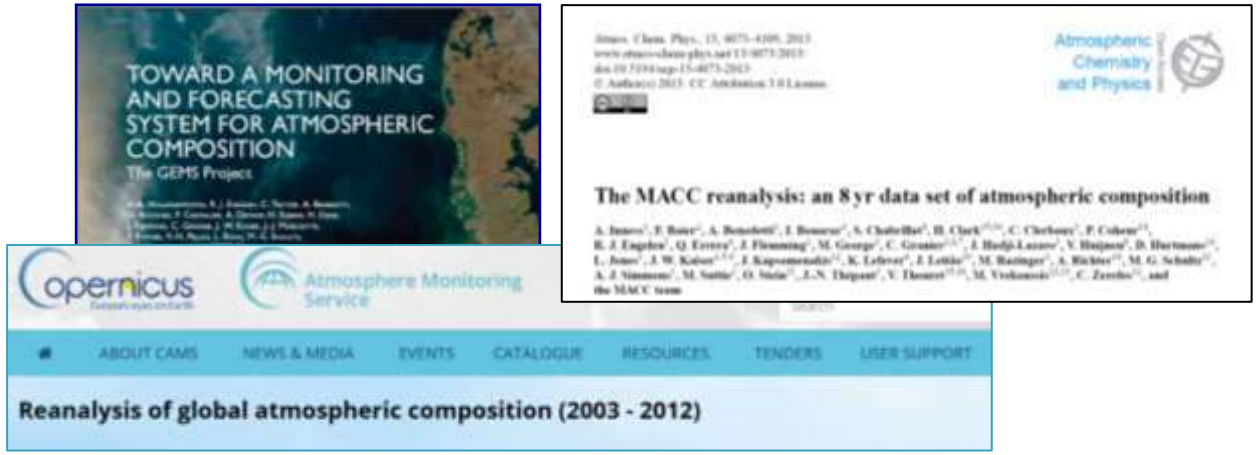
From ~11km ocean-wave model, driven by short-range ~16km forecasts that downscale the ~125km ERA-PreSAT reanalysis

European Commission

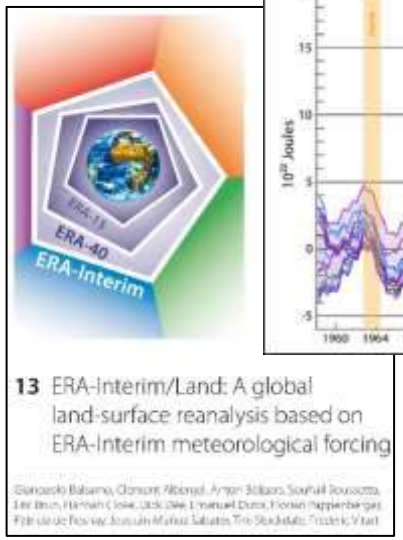
Climate Change

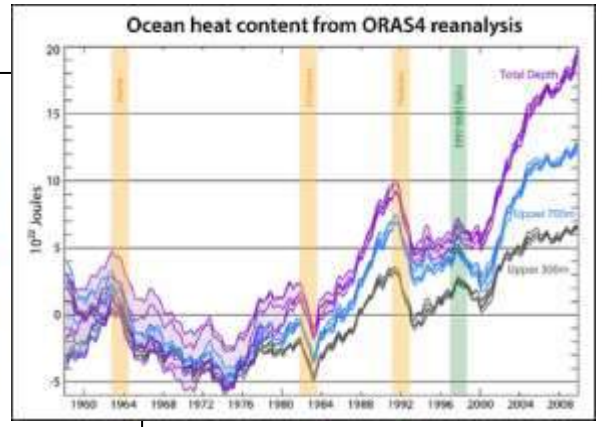
Reanalysis: becoming more diverse

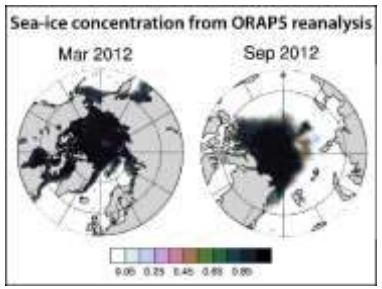
Including aerosols, greenhouse gases, and reactive gases that influence air quality



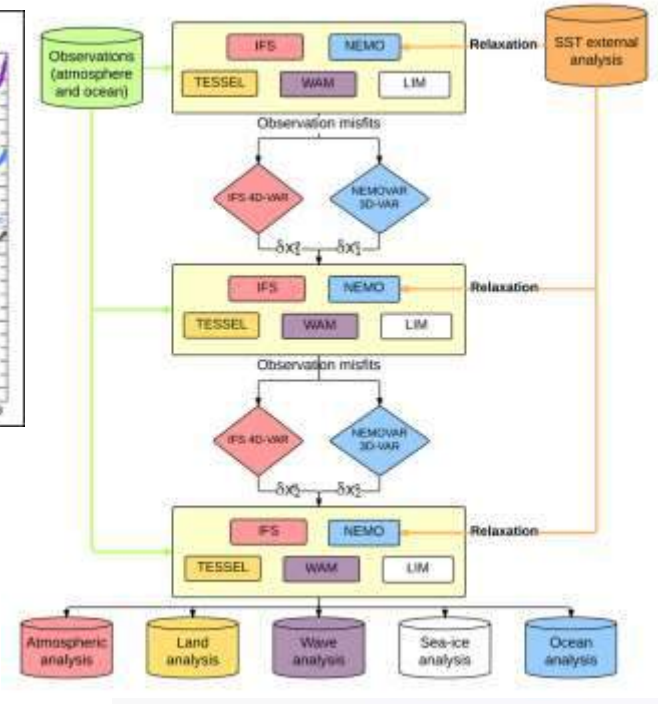
Ocean and land-surface reanalysis







Coupling atmosphere, ocean and more



European Commission

Climate Change

ECMWF reanalysis products

Atmosphere/land *including ocean waves*

1) 1979 - 1981 FGGE	2) 1994 - 1996 ERA-15	3) 2001 - 2003 ERA-40	4) 2006 - … ERA-Interim	5) 2016 - … ERA5

Ocean *including sea ice*

2006 ORAS3	2010 - … ORAS4	2016 - … ORAS5

ERA CLIM / ERA CLIM 2

Centennial

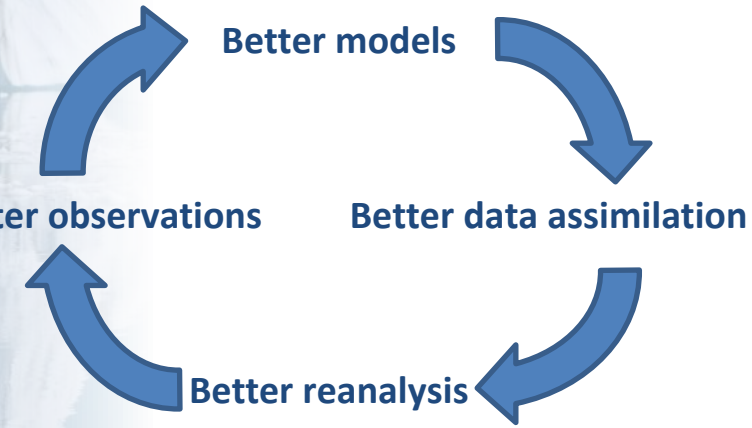
2013 - 2015 ERA-20CM/20C	2016 CERA-20C

Enhanced land

2012 ERA-Int/Land	2014 ERA-20C/Land	2017 - … ERA5L

Atmospheric composition

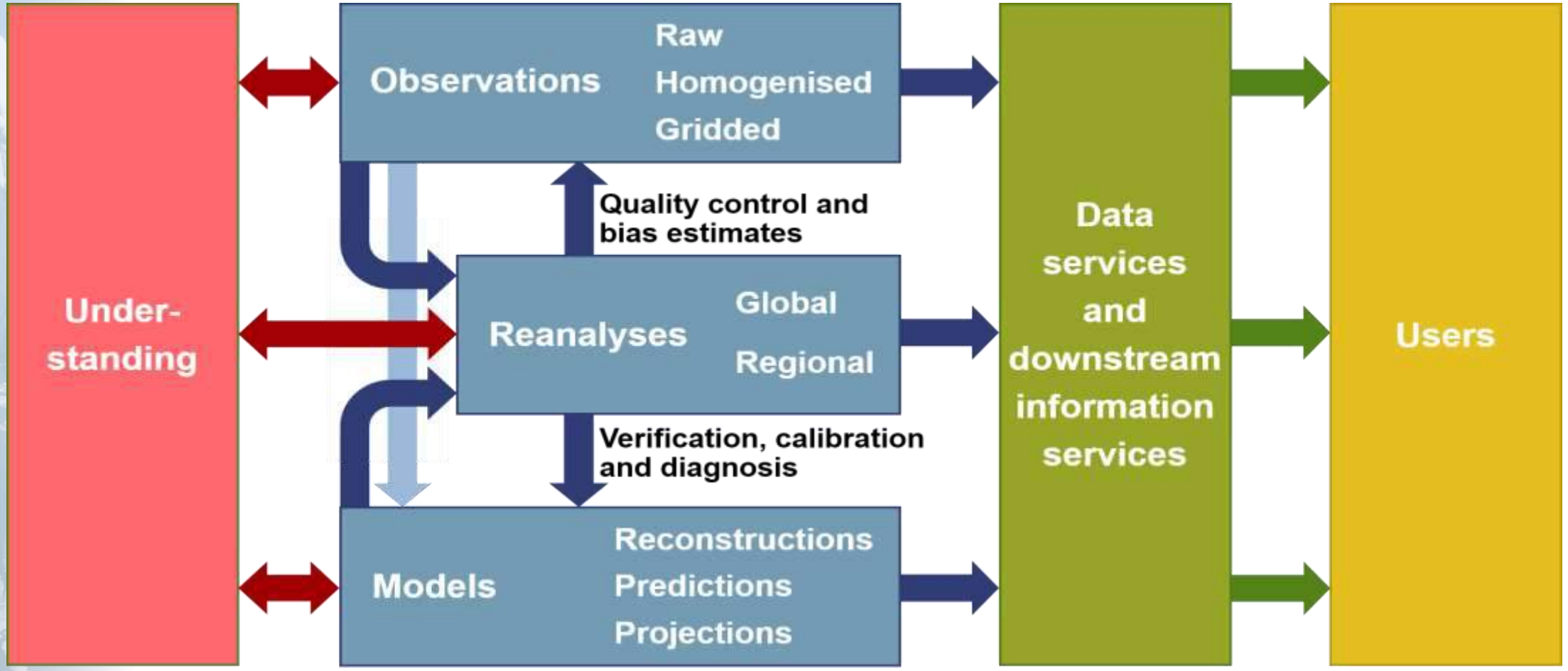
2008 - 2009 GEMS	2010 - 2011 MACC	2017 - … CAMS



ECMWF Copernicus Europe's eyes on Earth European Commission

Climate Change

Reanalysis at the centre of the provision of global and regional climate services

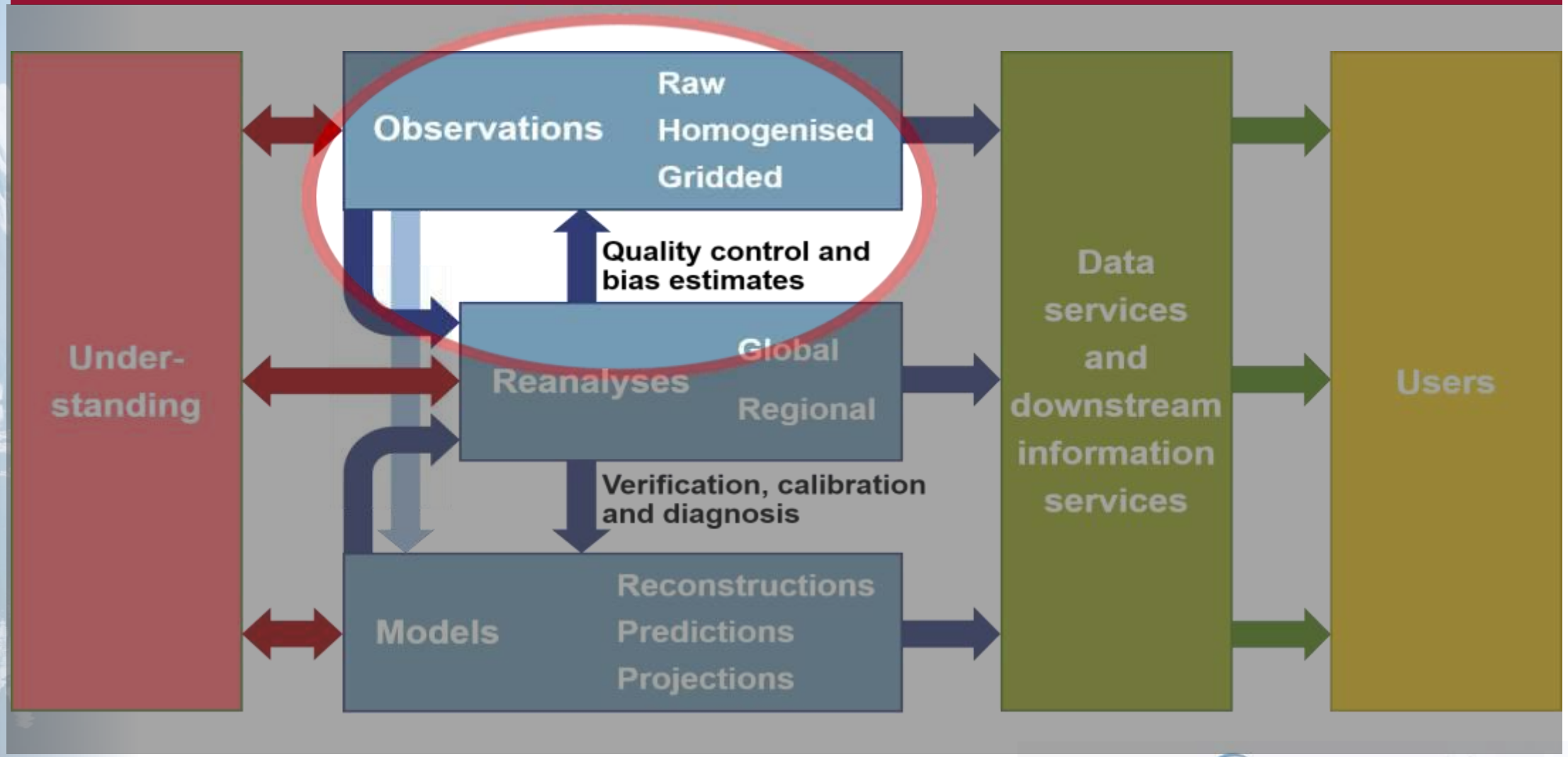


Adapted from a 2009 talk, with acknowledgments to Kevin Trenberth and organisers of the 2009 World Climate Conference-3

ECMWF Copernicus Europe's eyes on Earth European Commission

Climate Change

Reanalysis at the centre of the provision of global and regional climate services



Adapted from a 2009 talk, with acknowledgments to Kevin Trenberth and organisers of the 2009 World Climate Conference-3

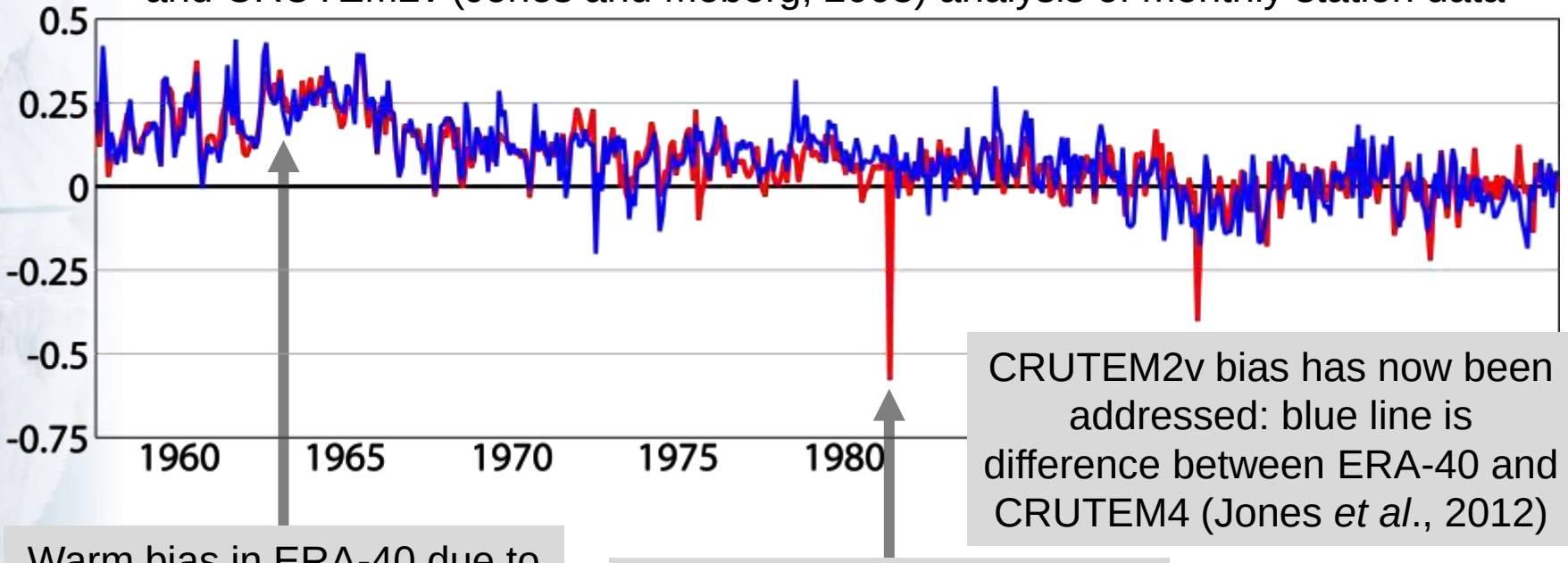
ECMWF Copernicus Europe's eyes on Earth European Commission

Climate Change

Reanalysis as a provider of quality control and bias estimates for the observing system

Surface air temperature anomaly (^{O}C) relative to 1987-2001: Comparisons of ERA-40 with CRUTEM2V and CRUTEM4

Red line is difference over Europe between ERA-40 analysis of synoptic data and CRUTEM2v (Jones and Moberg, 2003) analysis of monthly station data



Warm bias in ERA-40 due to model bias and insufficient SYNOP coverage to correct it

Warm bias in CRUTEM2v due to erroneous station data

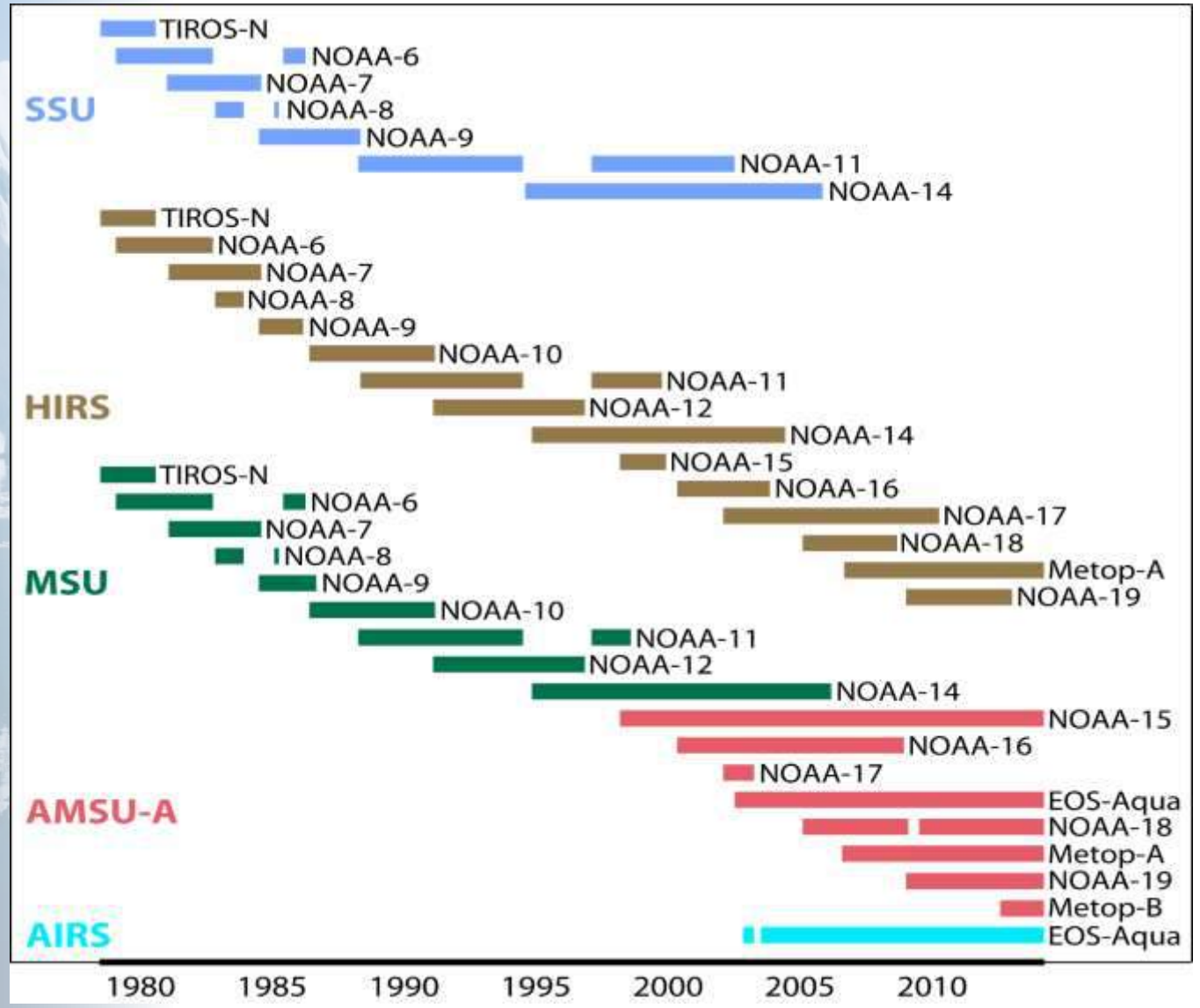
CRUTEM2v bias has now been addressed: blue line is difference between ERA-40 and CRUTEM4 (Jones *et al*., 2012)

ECMWF Copernicus Europe's eyes on Earth European Commission

Climate Change

Reanalysis as a provider of quality control and bias estimates for the observing system

Satellites providing soundings of lower stratospheric temperature used in ERA-Interim



Data are not assimilated from recent instruments (IASI, ATMS, CrIS) as reanalysis uses a frozen processing system

Bars show periods of data availability for channels sounding the lower to middle stratosphere

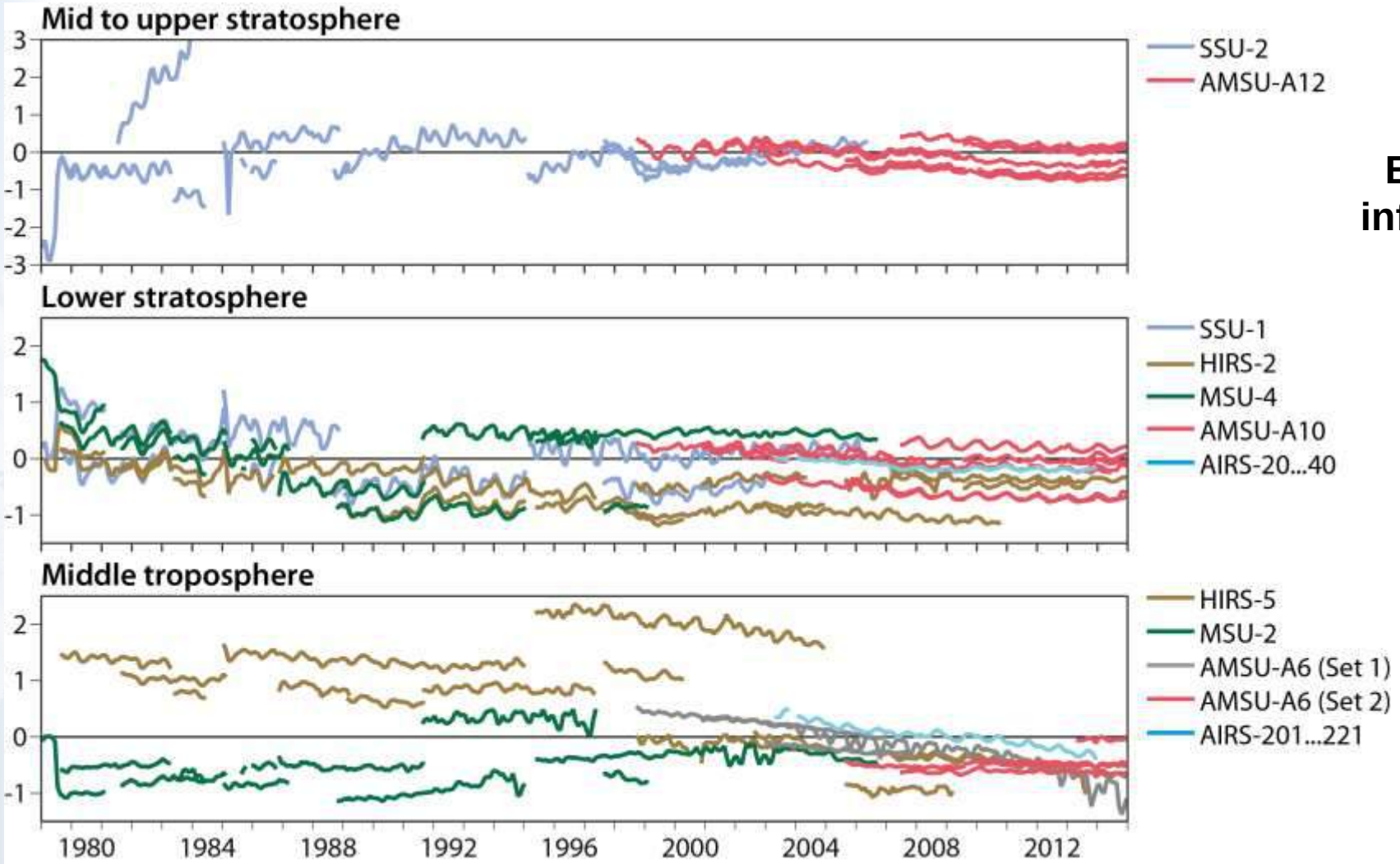
Satellites are mainly US ones, but the SSU was a UK instrument, and Metop-A and Metop-B are European platforms

Chinese FY-3 series will be a future provider

ECMWF Copernicus Europe's eyes on Earth European Commission

Climate Change

Reanalysis as a provider of quality control and bias estimates for the observing system

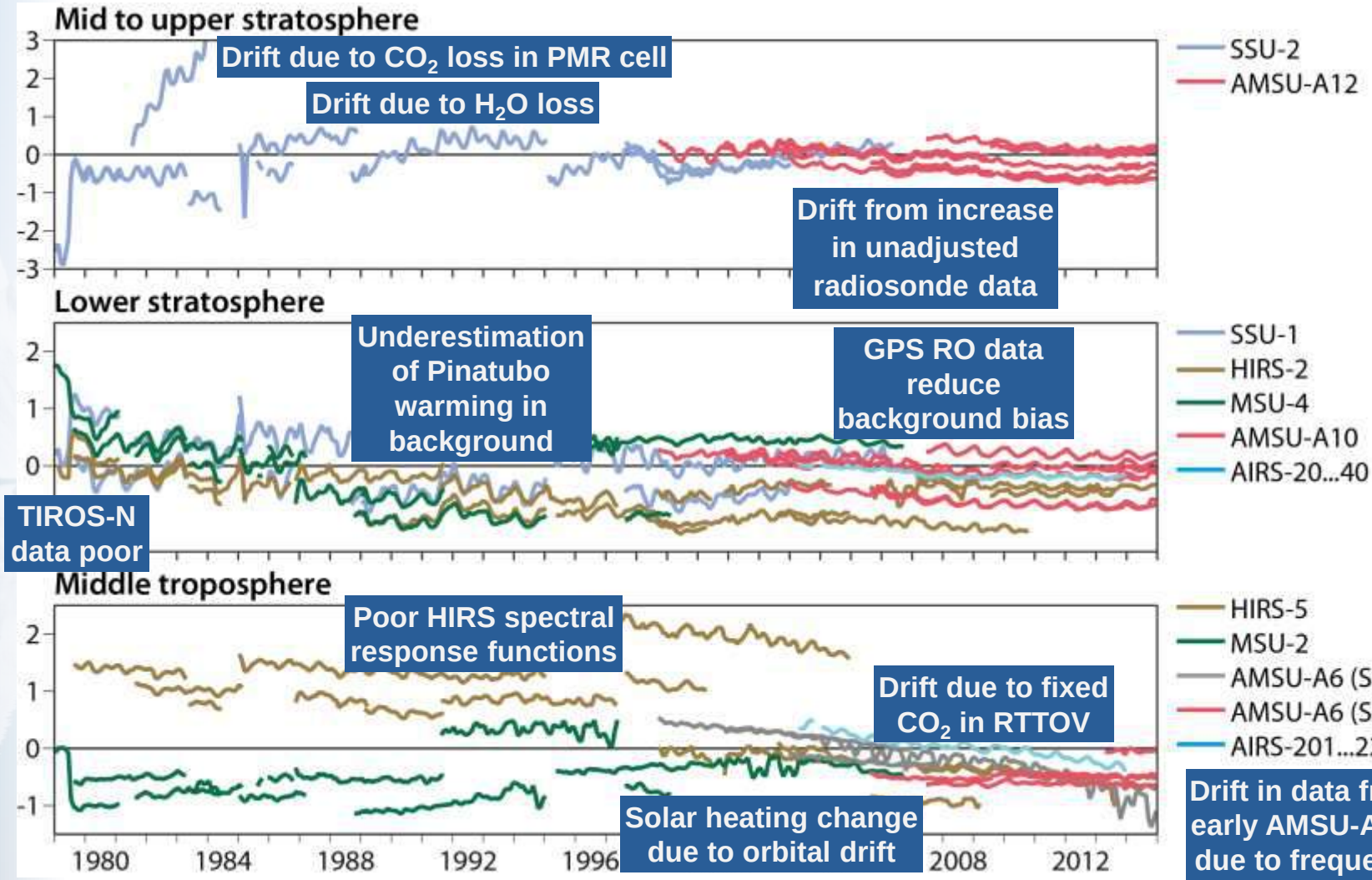


Bias adjustments (K) inferred by ERA-Interim for some sounding channels

ECMWF Copernicus Europe's eyes on Earth European Commission

Climate Change

Reanalysis as a provider of quality control and bias estimates for the observing system



Bias adjustments (K) inferred by ERA-Interim for some sounding channels

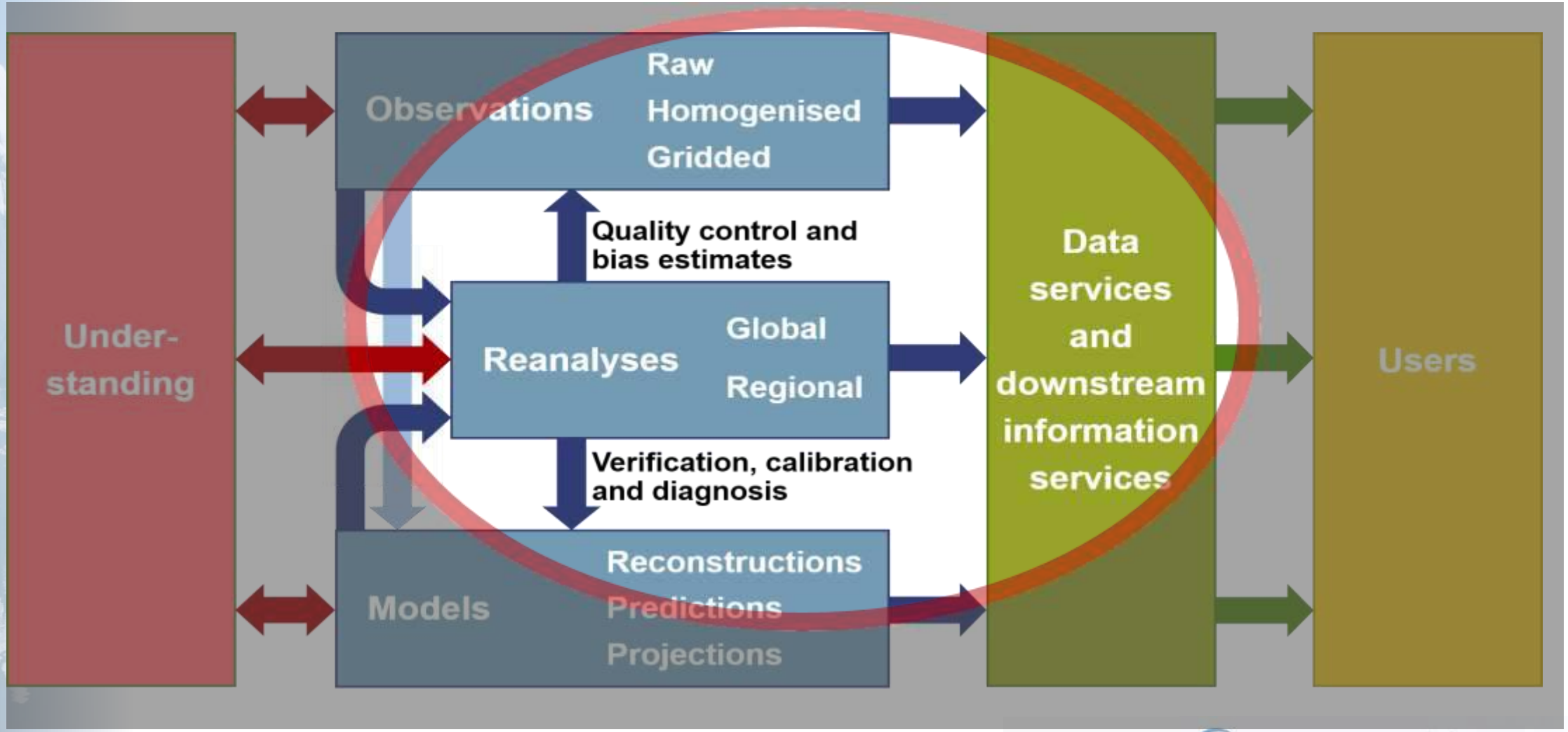
Cao et al. (2009), Dee and Uppala (2009), Kobayashi et al. (2009), Chung and Soden (2011), Nash and Saunders (2013), Saunders et al. (2013), Lu and Bell (2014), Simmons et al. (2014), …

opernicus Europe's eyes on Earth

European Commission

Climate Change

Reanalysis at the centre of the provision of global and regional climate services



Adapted from a 2009 talk, with acknowledgments to Kevin Trenberth and organisers of the 2009 World Climate Conference-3

ECMWF Copernicus Europe's eyes on Earth European Commission

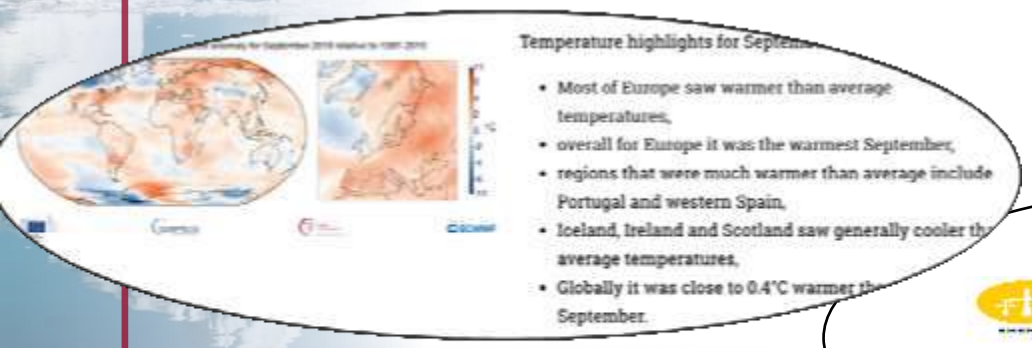
Climate Change

How do reanalysis support climate services ?

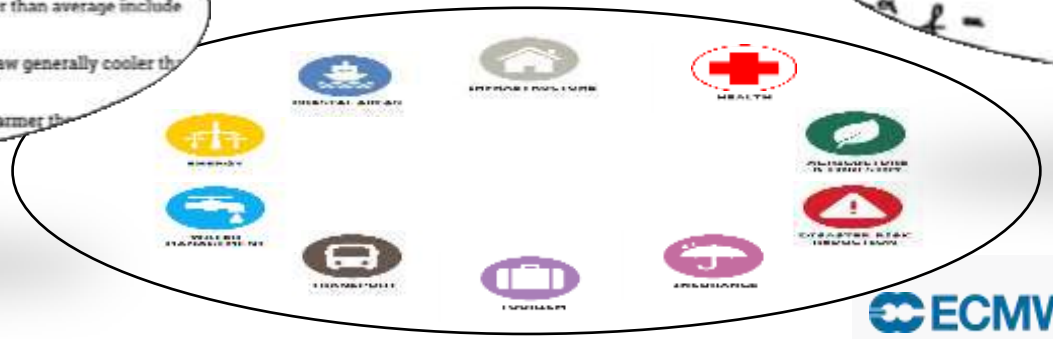
Reanalysis provides high-quality climate datasets:

- **Covering the globe for several decades**
- **Including as many variables and time scales as possible**
- **Spatially and temporally consistent**
- **Relatively straightforward to handle from a processing standpoint**

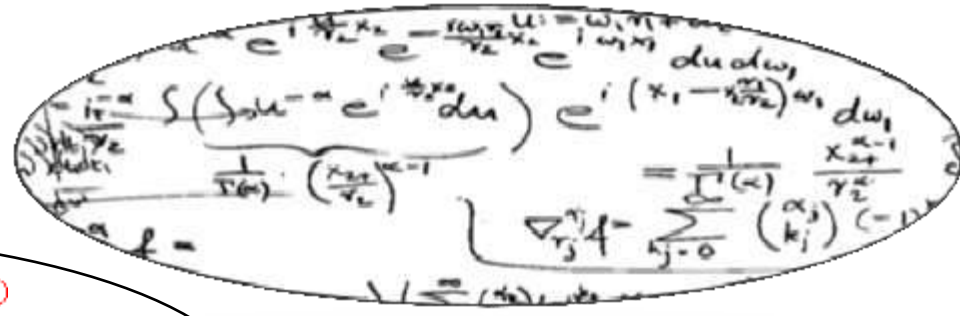
(although file sizes can be very large)



Climate monitoring



Downstream modeling applications



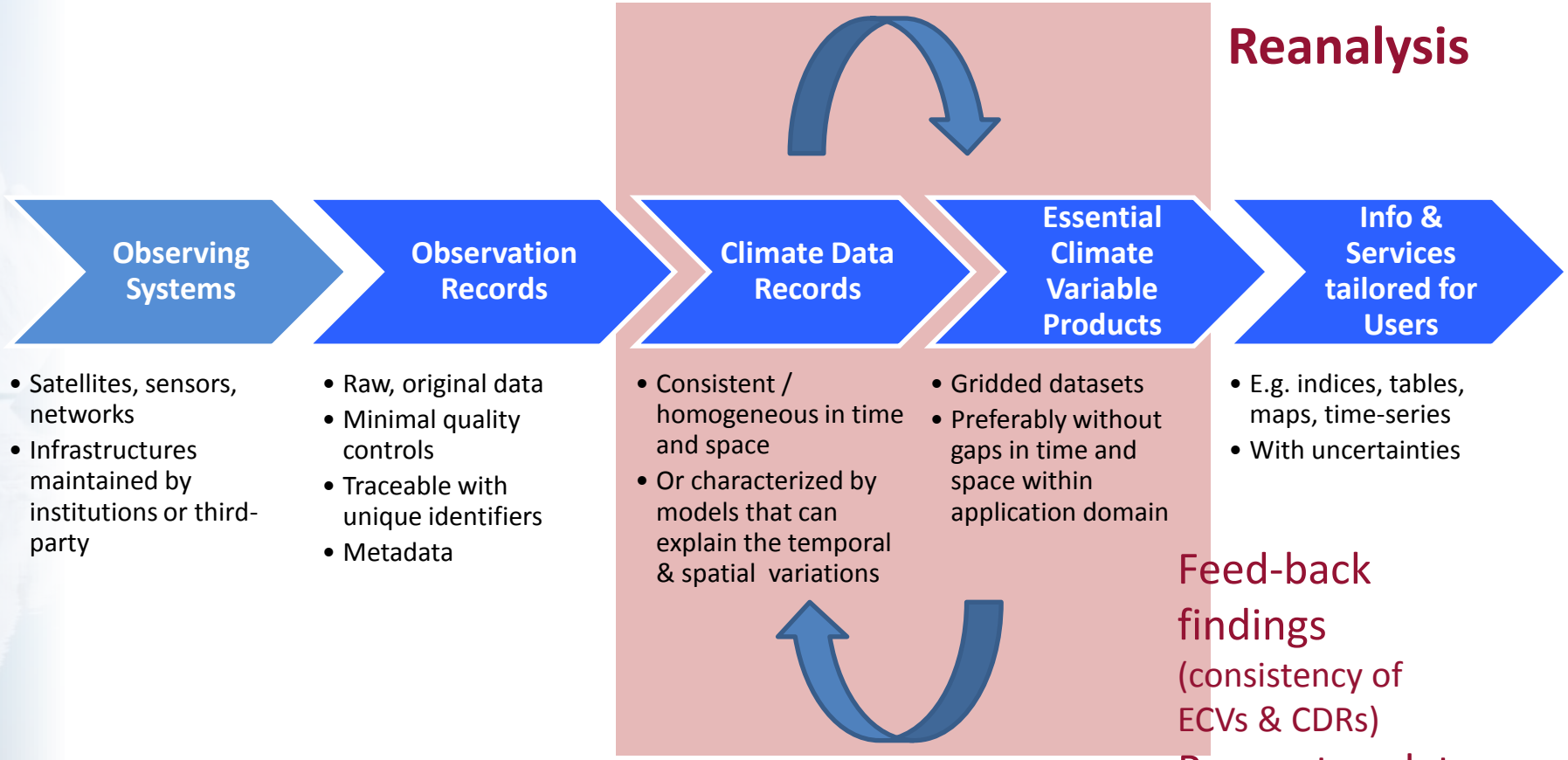
Academic research, climate change ...

ECMWF Copernicus Europe's eyes on Earth European Commission

Climate Change

How do reanalysis support climate services ?

Reanalysis within a Climate Service



ECMWF Copernicus Europe's eyes on Earth European Commission

Climate Change

How to improve reanalysis for climate services ?

Better data sets:

- Coupled Earth system reanalysis
- Improved model data (e.g. land use)
- Increased spatial resolution
- Uncertainty information

Better observations:

- Sustained data rescue and QC
- Satellite data reprocessing
- Access to reanalysis feedback

Better data access:

- Expanded data services
- Access to raw observations
- Interactive visual products
- User outreach and support

C3S Climate Data Store

ECMWF Copernicus Europe's eyes on Earth European Commission

Climate Change

Summary of important concepts

Key aspects that require particular attention in reanalysis

- external forcing fields for the NWP model
- biases in the model and observations
- changes in the observing system
- specification of background and observation errors

Reanalysis neither produces “gridded observations” nor “model data”

- extract information from observations using the model to propagate the information in space and time, and across variables

Reanalysis is worth repeating as all ingredients continue to evolve

- models, data assimilation, observation reprocessing and data rescue
- with each new reanalysis, understanding of model/observations biases is improved

ECMWF Copernicus Europe's eyes on Earth European Commission

Summary of important concepts

Some limitations

- Observational constraints, and therefore reanalysis reliability, can considerably vary depending on the location, time period, and variable considered
- The changing mix of observations, and biases in observations and models, can introduce spurious variability and trends into reanalysis output
- Diagnostic variables relating to the hydrological cycle, such as precipitation and evaporation, should be used with extreme caution

Climate Change

Concluding Remarks

Reanalysis is essential for ECMWF model development:

- Verification, diagnostics, and calibration of forecast products
- Reference data sets for model development
- Technical advances related to observation handling
- Data assimilation research and development

Climate services and climate research:

- **High benefit to society**

  Private sector, academic community, etc.
- **Ambitious**

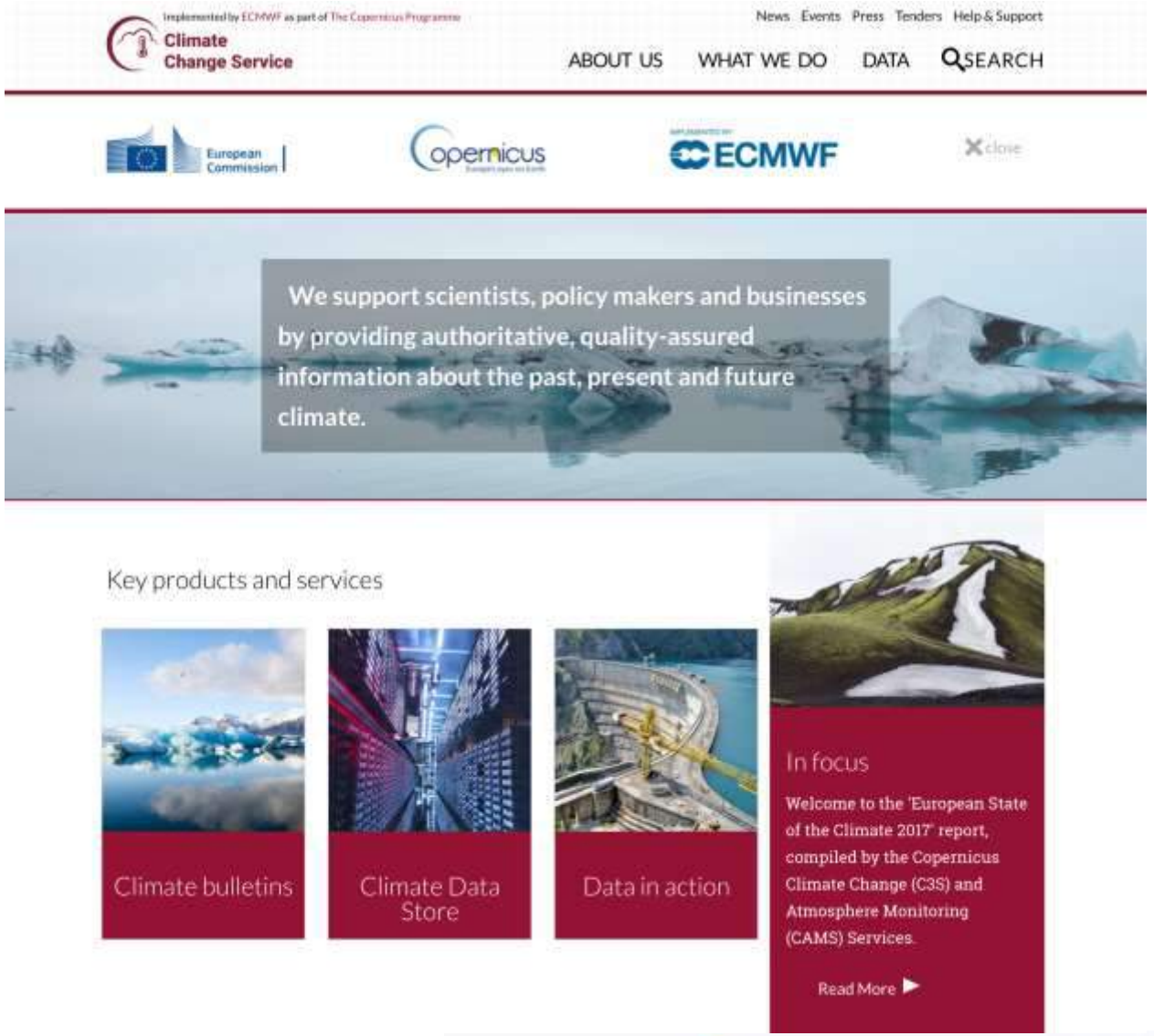
  Work on observations, coupled data assimilation, HPC requirements, data services, etc.
- **Central role in many initiatives**

  Copernicus climate change services, WMO GFCS, etc.

ECMWF Copernicus Europe's eyes on Earth European Commission

Climate Change

climate.copernicus.eu



Thank You

ECMWF Copernicus Europe's eyes on Earth European Commission

Climate Change

Climate Change