

# Introduction to Reanalysis

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Planet-A consulting

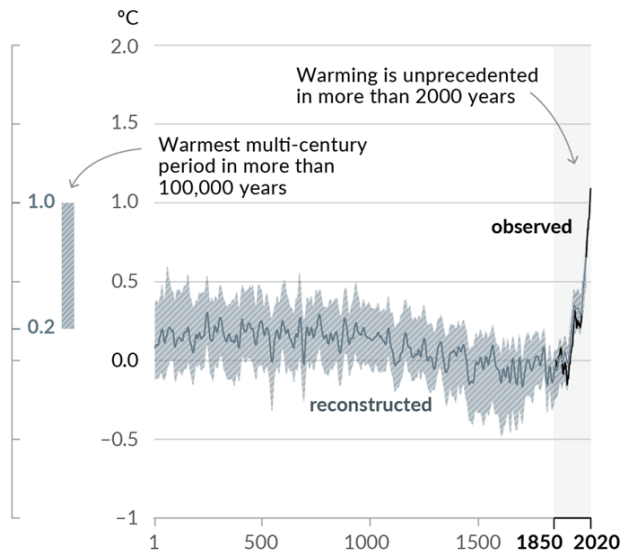


# The context

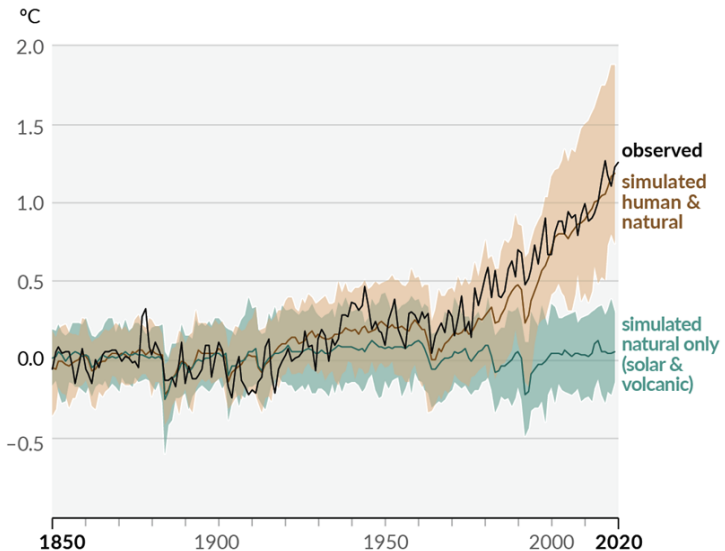
Human influence has warmed the climate at a rate that is unprecedented in at least the last 2000 years

## Changes in global surface temperature relative to 1850–1900

(a) Change in global surface temperature (decadal average) as **reconstructed** (1–2000) and **observed** (1850–2020)



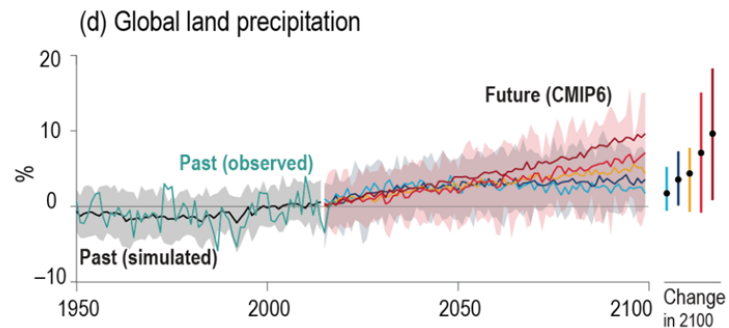
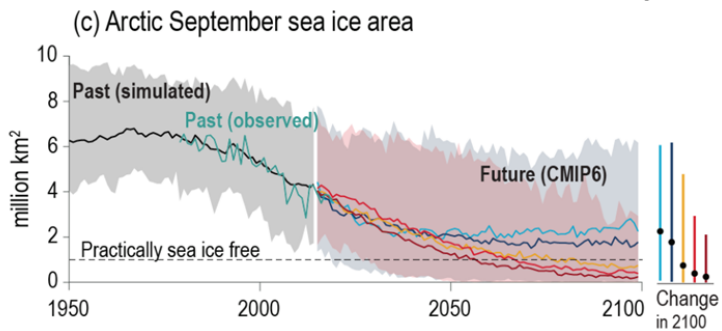
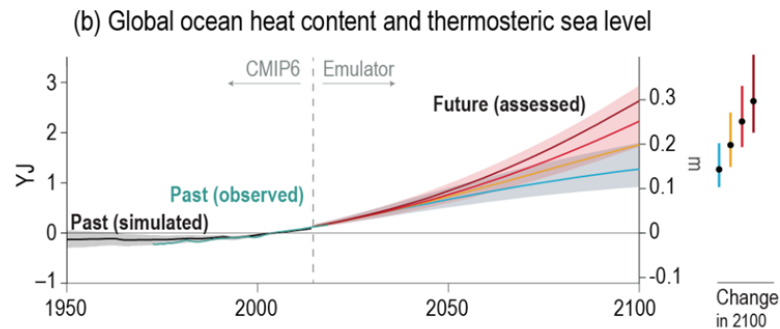
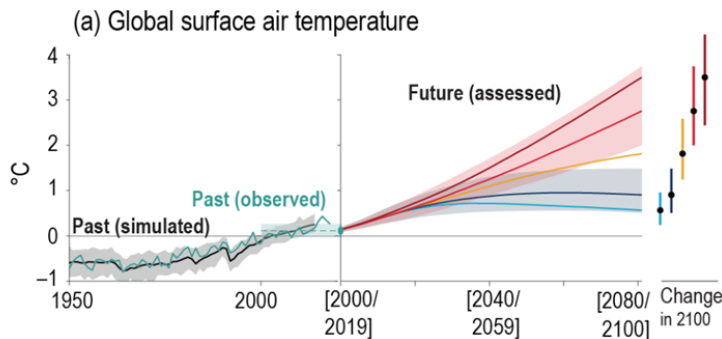
(b) Change in global surface temperature (annual average) as **observed** and simulated using **human & natural** and **only natural** factors (both 1850–2020)



# The context

## Recent and future change of four key indicators of the climate system

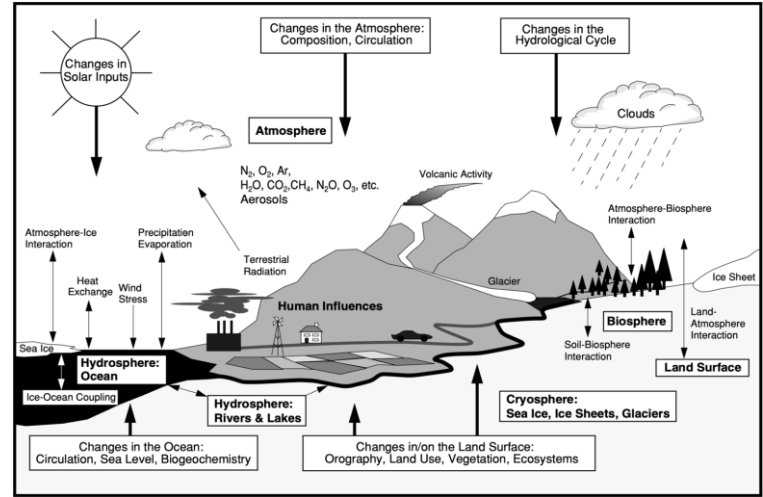
Atmospheric temperature, ocean heat content, Arctic summer sea ice, and land precipitation



# The role of reanalysis

To learn as much as possible about past weather and climate, using all information available to us:

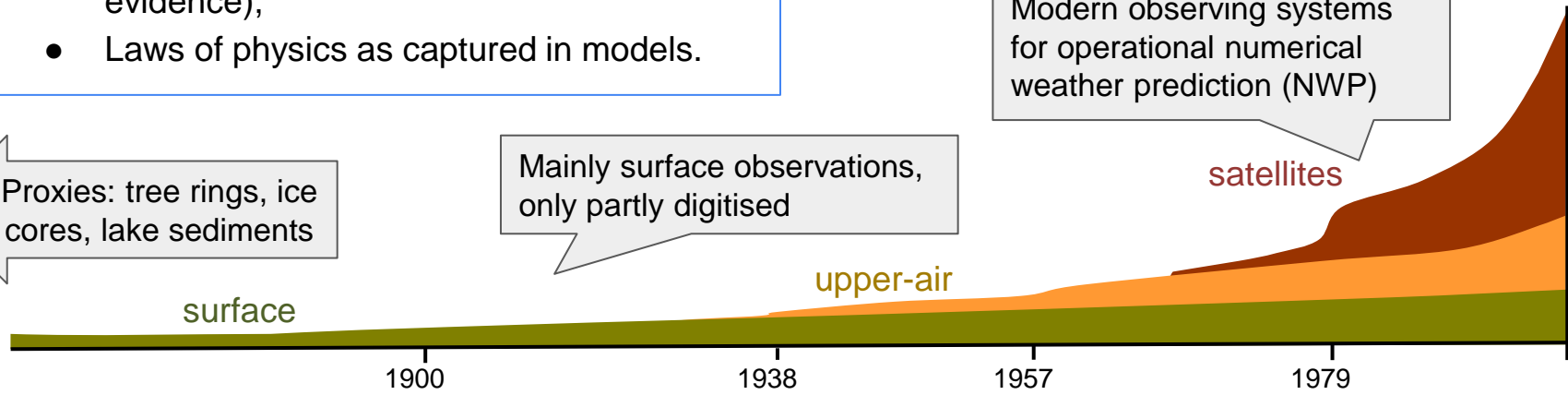
- Modern observing systems (satellites, balloons, aircraft, ...),
- Historic data records (log books, climatologies, proxy data, documentary evidence),
- Laws of physics as captured in models.



Modern observing systems for operational numerical weather prediction (NWP)

Proxies: tree rings, ice cores, lake sediments

Mainly surface observations, only partly digitised



# The role of models in reanalysis

## Is twofold:

- Describe the dynamics of the climate system.
- Describe how observations relate to the model variables.

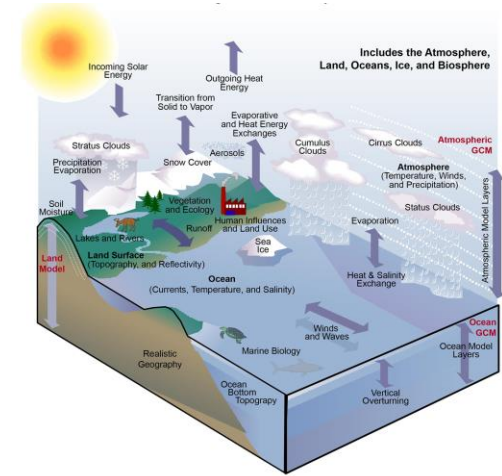
## As a result, a reanalysis can:

- Assimilate many types of observations.
- Produce estimates of all modeled variables, even those that are not directly observed.
- Ensure that estimates of multiple variables are physically consistent (*but only to the extent that the models are*).
- Produce output on regular space/time grids, in principle at any resolution.

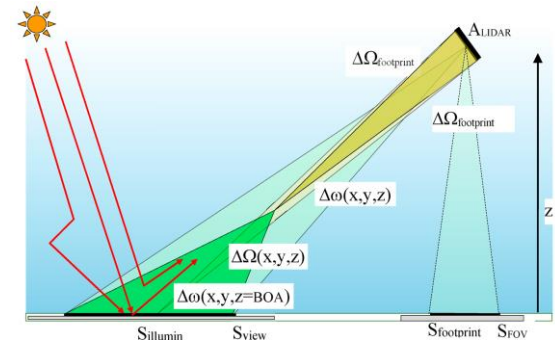
## Major caveat:

- The models (both types) have limitations.
- There are never enough observations.

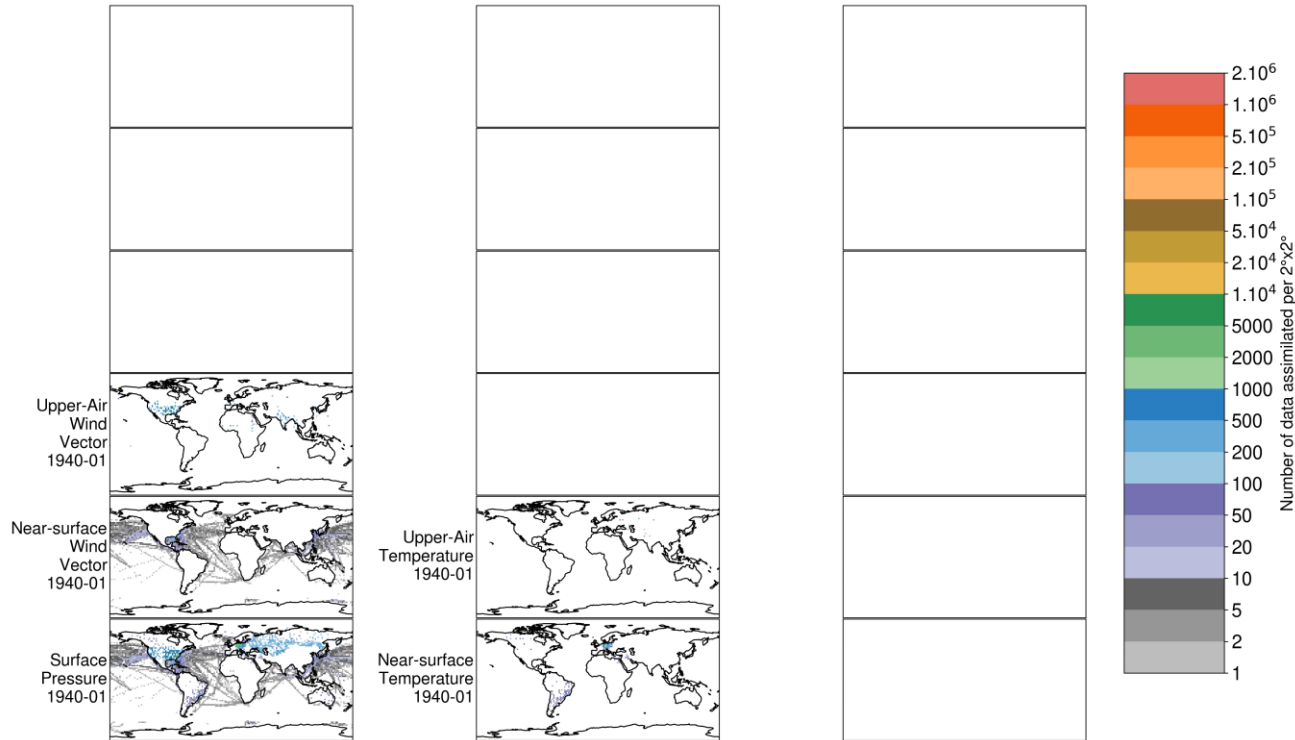
## Climate models



## Measurement models

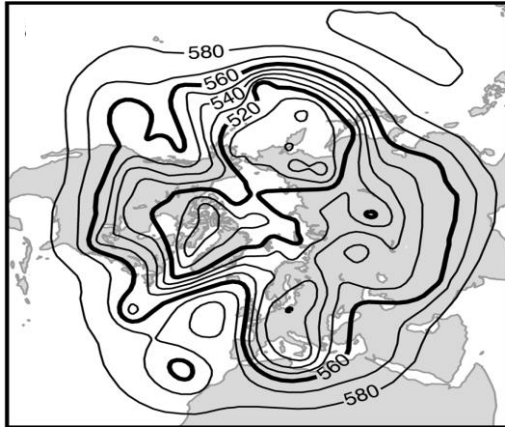


# Meteorological observations used in ERA5: 1940-2022

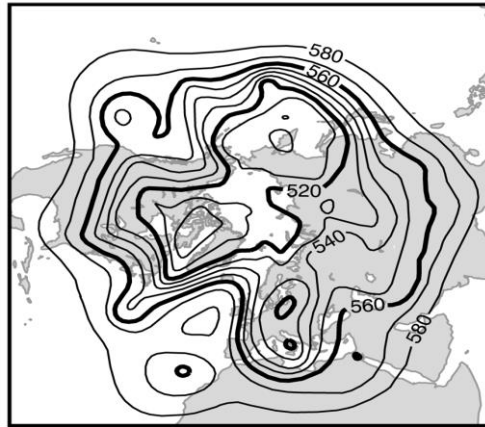


# Ability to reconstruct unobserved variables

Analysis of geopotential height at 500 hPa



Using the complete  
observing system



Using surface pressure  
observations only



# Different types of reanalysis

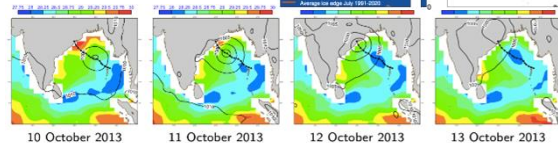
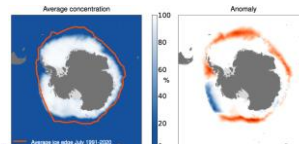
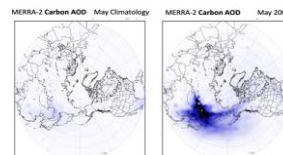
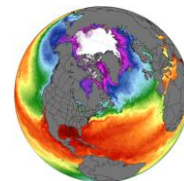
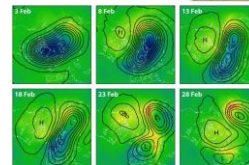
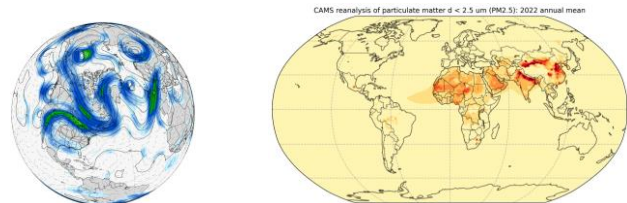
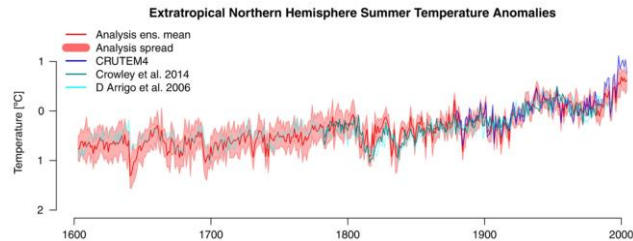
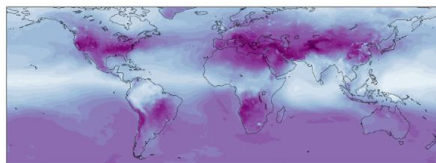
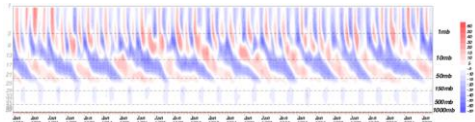
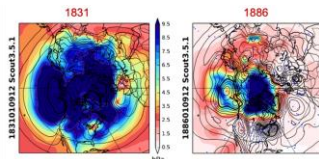
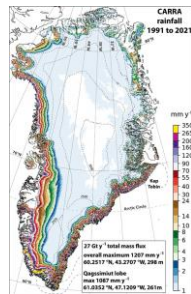
Based on:

**Different time periods** (modern observing era, centennial, paleo)

**Climate system components** (atmosphere, ocean, sea ice, land surface)

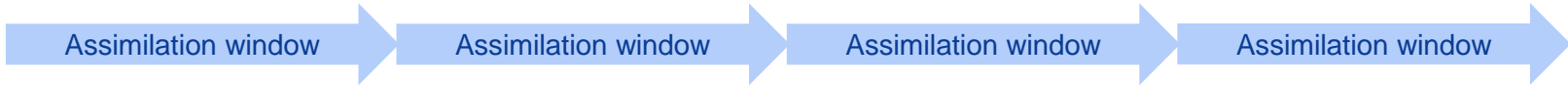
**Spatial domains** (global, regional)

*Could we unify all of these in a single reanalysis of the climate system?*

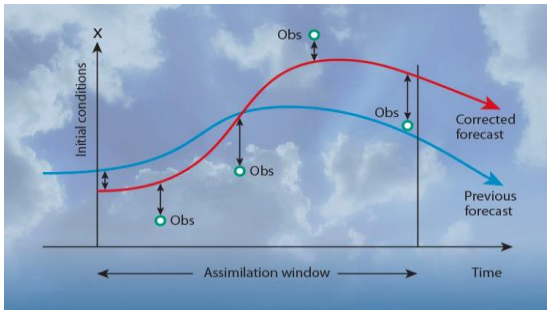




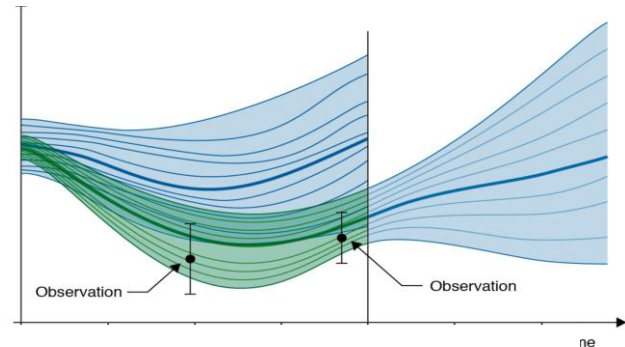
# Reanalysis is produced by stepwise data assimilation



- Moving forward in time, comparing model re-forecasts with past observations, making small adjustments to the model state.
- The adjustments are based on statistical assumptions about uncertainties in models and observations.
- **The result is a (large) dataset containing (long) time series of (many) 2D and 3D climate variables.**



variational analysis



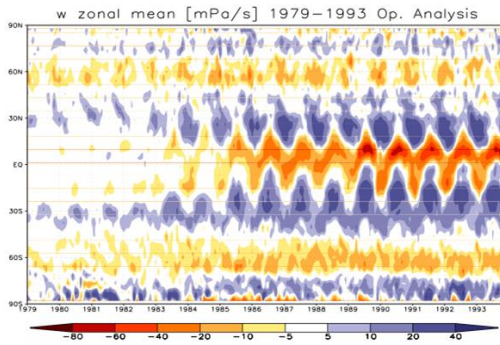
using ensembles

# How does reanalysis differ from numeric weather prediction?

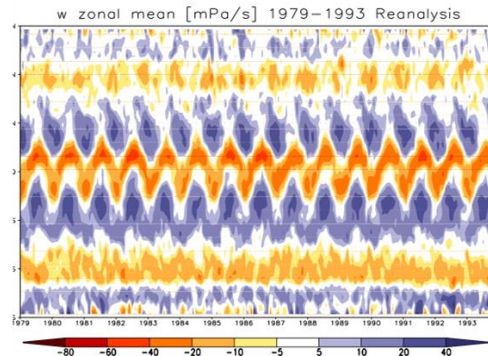
Reanalysis and NWP often use similar methods and infrastructure, but:

- NWP systems are continuously upgraded to generate the best possible forecast.
- A reanalysis must use a “frozen” system to ensure temporal consistency of the output.

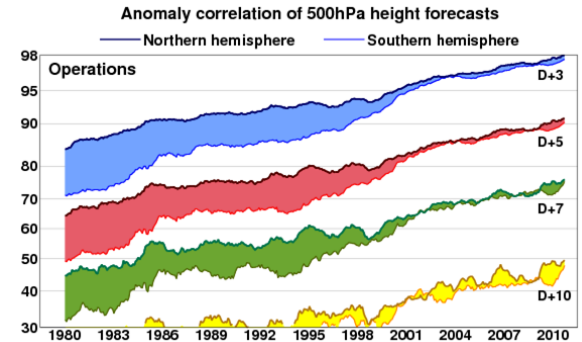
From ECMWF Operations



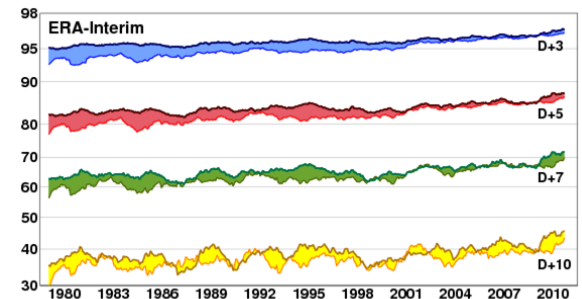
From reanalysis (ERA-15)



ECMWF forecast skill



ERA-Interim re-forecast skill



# How does reanalysis differ from numeric weather prediction?

## Reanalysis has the benefit of hindsight:

- Quality control and bias correction of observations (e.g. reprocessed satellite data records).
- Additional observations not used in NWP may be available for reanalysis.
- Data assimilation methods can be adjusted (e.g. assimilation window, error covariances).

## Using “old” observations presents special challenges:

- Modern NWP systems may not support them.
- Observation operators (i.e. measurement models) may be incorrect.
- Quality control and bias correction can be very difficult.



## Production:

- Reanalysis output must be generated faster, e.g. months per day.
- Production monitoring is more demanding and based on different performance measures.
- Reanalysis production can stop and repeat if needed, but with a cost.

# Some key challenges for climate reanalysis

## Dealing with changes in the observing systems

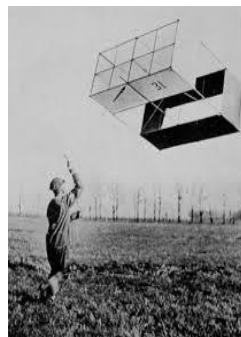
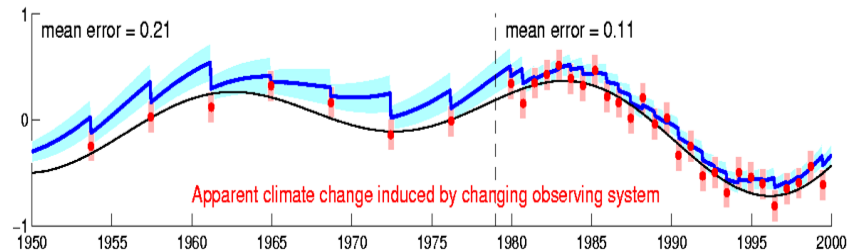
- Model biases and other model limitations
- Reducing biases in observations

## Data assimilation

- Specification of error statistics
- Methods for coupled models
- Quantifying uncertainties

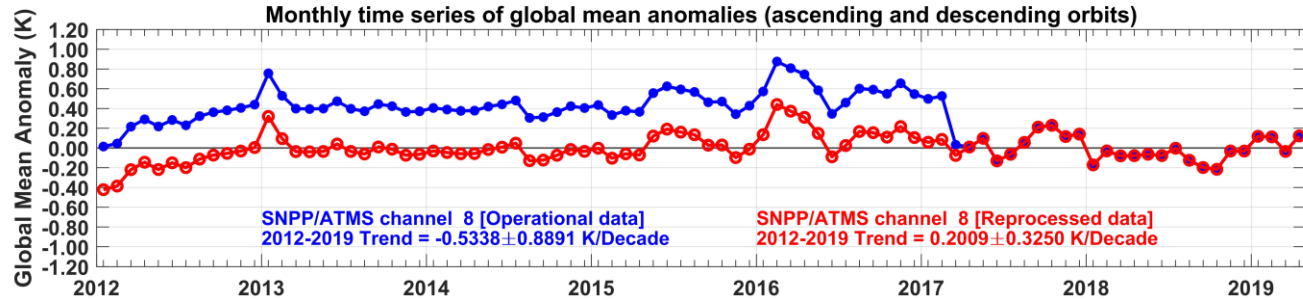
## Extending back in time

- Data rescue (*before it is too late!*)
- Quality control
- Seamless production

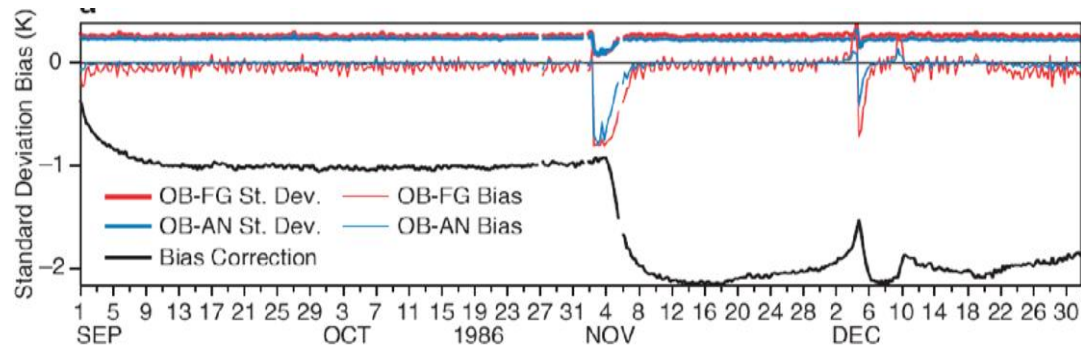


# Bias correction of satellite observations

Existing satellite data records can often be improved by reprocessing:

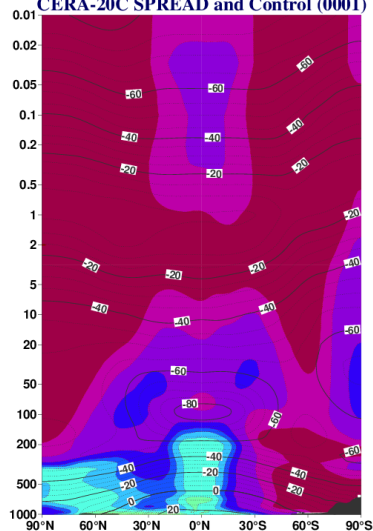


Bias correction can also be integrated with data assimilation method:



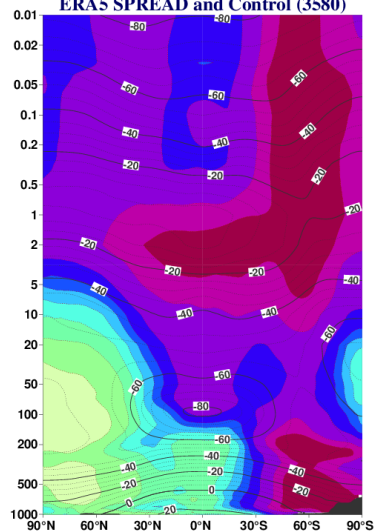
# Ensemble spread used as a measure of uncertainty

Temperature (Celsius) in MAM 1971  
CERA-20C SPREAD and Control (0001)



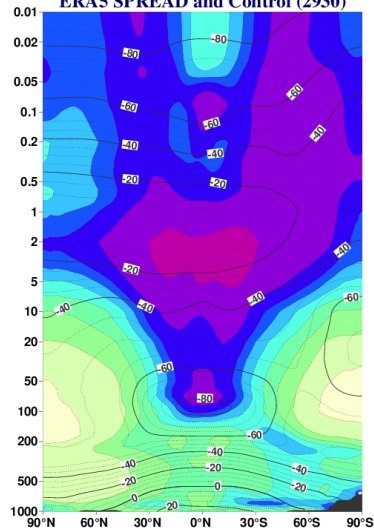
**1971 CERA-20C:**  
Surface pressure,  
marine wind, only

Temperature (Celsius) in MAM 1971  
ERA5 SPREAD and Control (3580)



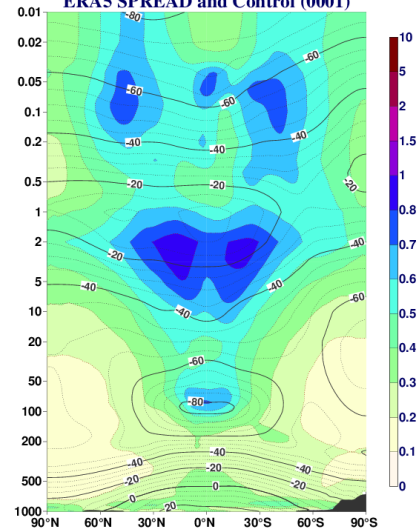
**1971 ERA5:**  
Upper-air data

Temperature (Celsius) in MAM 1980  
ERA5 SPREAD and Control (2930)



**1980 ERA5:**  
Early-satellite era

Temperature (Celsius) in MAM 2018  
ERA5 SPREAD and Control (0001)



**2018 ERA5:**  
Current observing system

# Reanalysis as an operational service

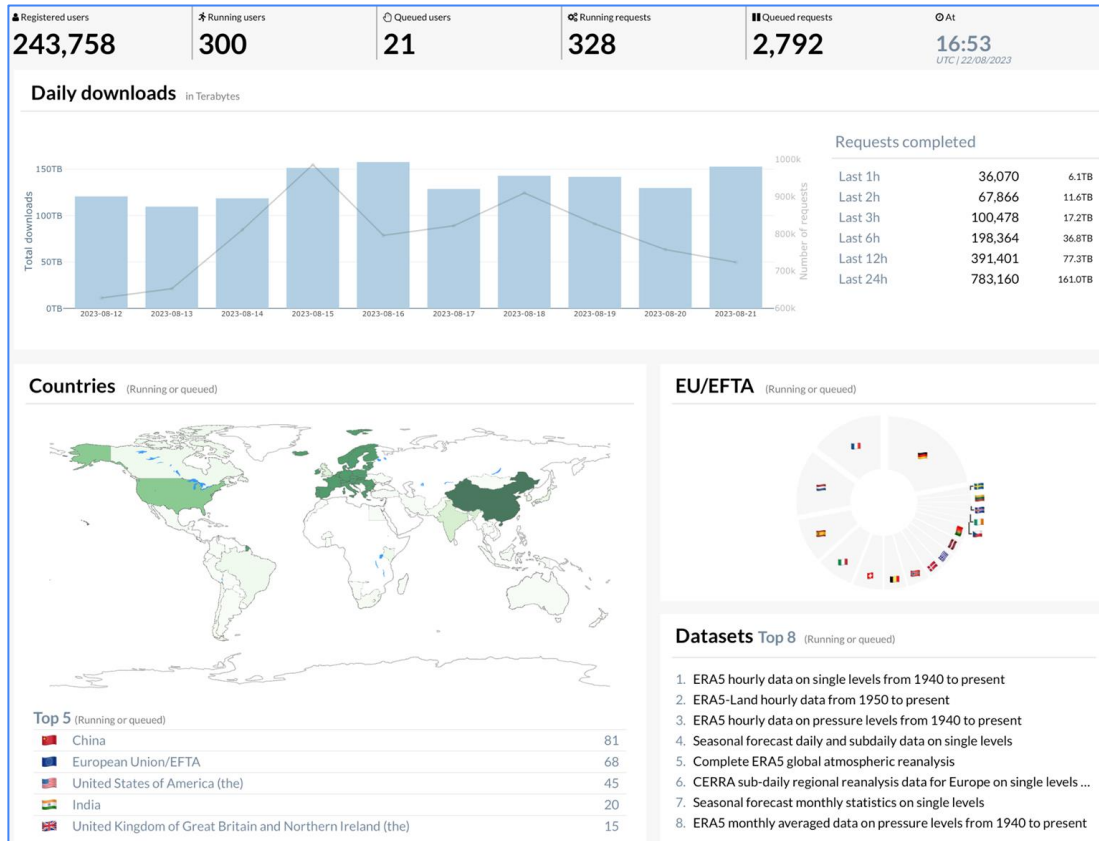
## Reanalysis activities in Europe are coordinated and supported by the Copernicus Earth Observation Programme:

- Development and production of global reanalyses: ERA5, ERA5-Land, CAMS reanalyses, CARRA and CERRA.
- Development and production of regional reanalyses for Europe (CERRA) and the Arctic (CARRA).
- Work to improve input observations: Data rescue services, satellite data recovery and reprocessing.
- Data management and data services: The Climate Data Store
- User support and user training services.





# The Climate (and Atmosphere) Data Store



- 250,000 registered users
- 1 PB downloads weekly
- 95% reanalysis data

# Final thoughts

- Reanalysis is indispensable for research, climate science and climate services.
- Most cited datasets in the scientific literature.
- ERA5 has 240 citations in the IPCC AR6 WGI report.
- Reanalysis is the backbone for Copernicus services.
- Reanalysis provides fundamental training data for machine learning applications (e.g. weather forecasting).



**We must continue to make the case for reanalysis as an operational service!**