The ERA5 reanalysis
An overview

Hans Hersbach

ERA reanalysis: Bill Bell, Paul Berrisford, Andras Horanyi, Julien Nicolas, Paul Poli, Raluca Radu, Joaquin Munoz Sabater, Cornel Soci, Dinand Schepers, Adrian Simmons, Adrien Oyono Owono, Roberto Ribas, Martin Suttie, Carlo Buontempo, Jean-Noel Thepaut

and many others inside and outside ECMWF!

Climate Change

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

Climate Change

Overview

- The concept of reanalysis
- The ERA5 reanalysis
  - Data assimilation system
  - Sub-daily observations
  - Gridded observations
- How accurate is ERA5?
- Towards Earth system reanalysis; ERA6 and beyond
- Summary

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

Climate Change

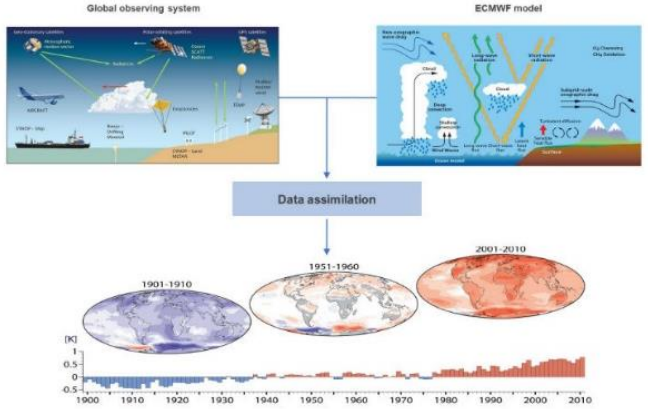
What (climate) reanalysis is and why it is important

Reconstruction of the past weather & climate:

- ✓ **Input:** integrator of all available 'sub-daily' observations, or gridded observations prepared as forcing
- ✓ Deal with inhomogeneities, relative biases, data formats, range of observables
- ✓ **Output:** complete, convenient, as consistent and accurate as possible
  - ✓ 'maps without gaps' of 3D atmosphere (+ other domains)

State-of-the-art:

- ✓ Redo historical weather using a modern but fixed NWP system
- ✓ For extended period back in time, but at lower resolution



Multiple classes of applications:

- ✓ Study of specific events or phenomena:
  - accurate (3D) synoptic situation; i.e., **the weather of the day**
- ✓ **Climate monitoring:**
  - Accurate recent synoptic situation + **consistent 30-year climate**
- ✓ **Climate applications:**
  - low-frequency variability of the **mean state**, extremes
- ✓ **Initialization, boundary conditions** and drive impact **models**
- ✓ **Training set for machine learning applications**

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

Climate Change

A consistent and complete picture of the past atmosphere or Earth system

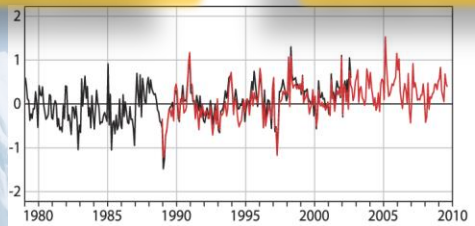
…in Time

…in the Horizontal

…across Atmospheric Parameters

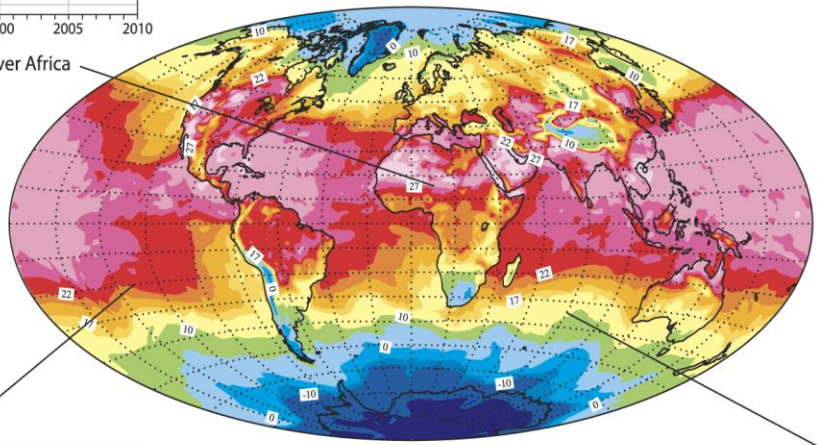
…in the Vertical

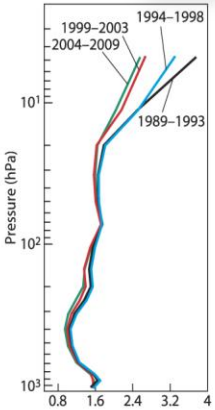
… across domains



2-metre temperature anomaly (°C) over Africa

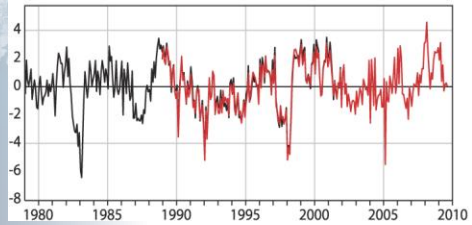
ERA-Interim 2-metre temperature (°C)
15 August 2003 03 UTC





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

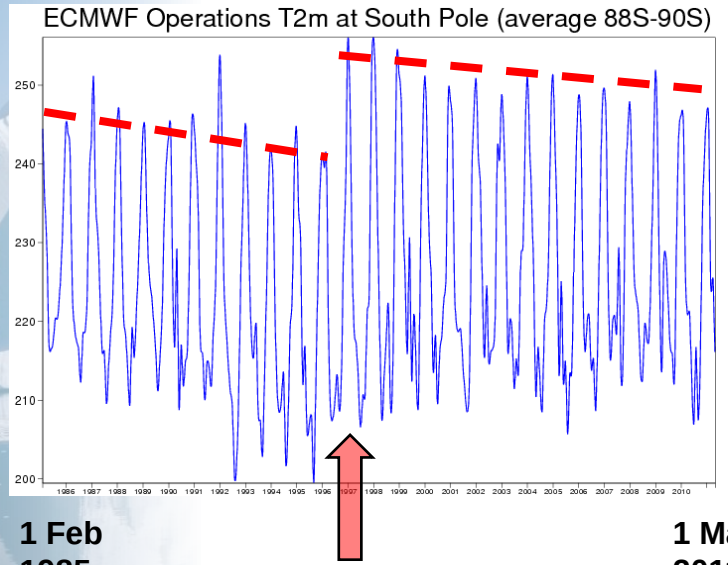
Southern Oscillation Index (hPa)



ECMWF

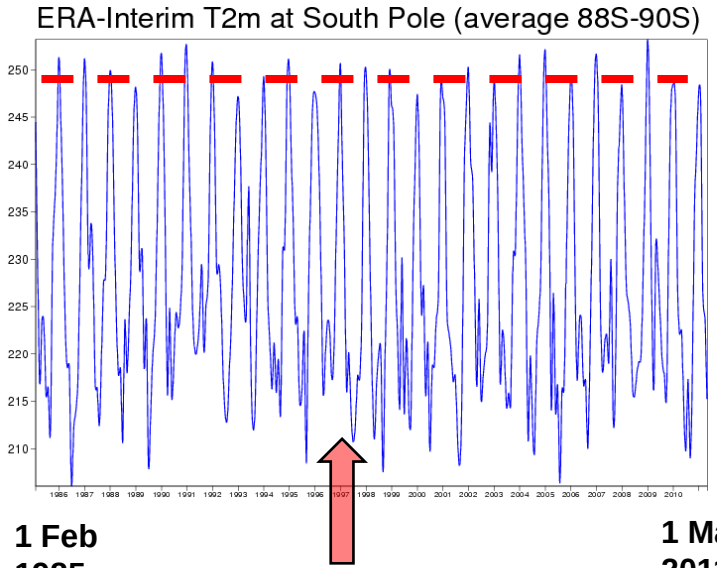
Climate Change

Why not simply use operational NWP?



1 Feb 1985

1 May 2011



1 Feb 1985

1 May 2011

The operational NWP system has evolved dramatically over time:

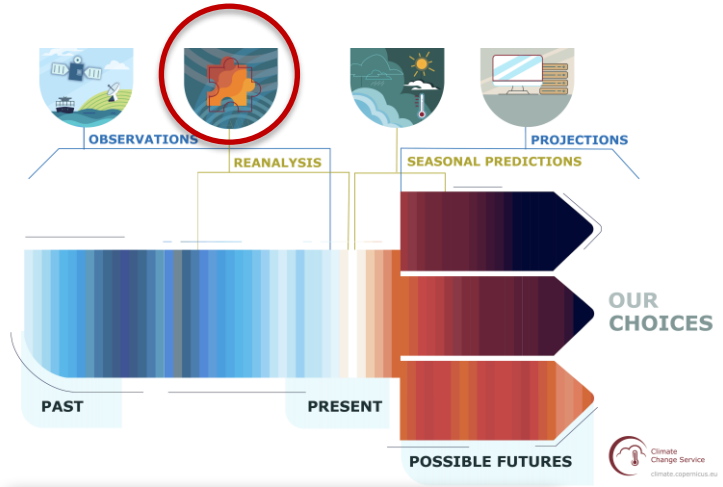
- Resolution
- Maturity of its NWP model and data-assimilation system

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

Climate Change

Overview

- The concept of reanalysis
- The ERA5 reanalysis
  - Data assimilation system
  - Sub-daily observations
  - Gridded observations
- How accurate is ERA5?
- Towards Earth system reanalysis; ERA6 and beyond
- Summary



Climate Change

The ERA5 global reanalysis

ERA5: *A full-observing-system global reanalysis for the atmosphere, land surface and ocean waves*

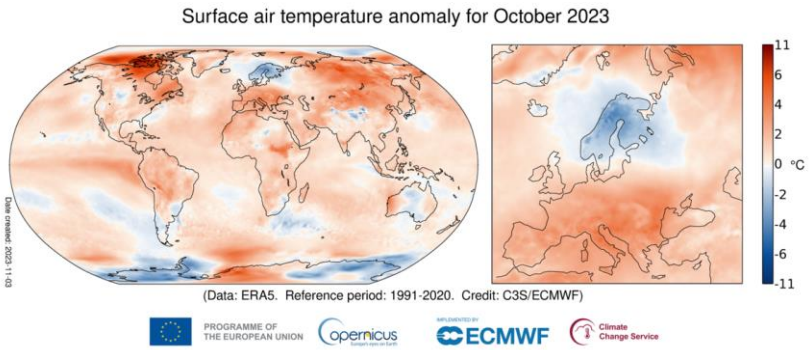
- Produced at ECMWF, by the **Copernicus Climate Change Service**
- 137,000 users to date, ~100 Tbyte of downloads per day

- Daily updates **5 days behind real time from 1940 onwards**

- **Hourly snapshots** at **31km resolution** up to about 80km height
- **Uncertainty estimate** from a 10-member ensemble at half resolution

- **ERA5-Land**: Dynamically downscaled land product at **9km** from 1950.

- Total dataset about 12 petabyte



Observation usage:

- Over 130 billion so far
- Many sources (in-situ, satellite) and observables

And usage of external (gridded) products 'as is':

opernicus Europe's eyes on Earth
European Commission
ECMWF

Climate Change

ERA5 CDS catalogue entries; pressure + single levels; hourly and monthly aggregates

ERA5 hourly data on pressure levels from 1940 to present

Overview | Download data | Quality assessment | Documentation

Clear all

Product type

- [x] Reanalysis
- [ ] Ensemble members
- [ ] Ensemble mean
- [ ] Ensemble spread

Select all Clear all

Variable

At least one selection must be made

- [ ] Divergence
- [ ] Geopotential
- [ ] Potential vorticity
- [ ] Specific cloud ice water content
- [ ] Specific humidity
- [ ] Specific snow water content
- [ ] U-component of wind
- [ ] Vertical velocity
- [ ] Fraction of cloud cover
- [ ] Ozone mass mixing ratio
- [ ] Relative humidity
- [ ] Specific cloud liquid water content
- [ ] Specific rain water content
- [ ] Temperature
- [ ] V-component of wind
- [ ] Vorticity (relative)

Select all

Pressure level

At least one selection must be made

- [ ] 1 hPa
- [ ] 2 hPa
- [ ] 3 hPa
- [ ] 5 hPa
- [ ] 7 hPa
- [ ] 10 hPa
- [ ] 20 hPa
- [ ] 30 hPa
- [ ] 50 hPa
- [ ] 70 hPa
- [ ] 100 hPa
- [ ] 125 hPa
- [ ] 150 hPa
- [ ] 175 hPa
- [ ] 200 hPa
- [ ] 225 hPa
- [ ] 250 hPa
- [ ] 300 hPa
- [ ] 350 hPa
- [ ] 400 hPa
- [ ] 450 hPa
- [ ] 500 hPa
- [ ] 550 hPa
- [ ] 600 hPa
- [ ] 650 hPa
- [ ] 700 hPa
- [ ] 750 hPa
- [ ] 775 hPa
- [ ] 800 hPa
- [ ] 825 hPa
- [ ] 850 hPa
- [ ] 875 hPa
- [ ] 900 hPa
- [ ] 925 hPa
- [ ] 950 hPa
- [ ] 975 hPa
- [ ] 1000 hPa

Select all

Year

At least one selection must be made

- [ ] 1940
- [ ] 1941
- [ ] 1942
- [ ] 1943
- [ ] 1944
- [ ] 1945
- [ ] 1946
- [ ] 1947
- [ ] 1948
- [ ] 1949
- [ ] 1950
- [ ] 1951
- [ ] 1952
- [ ] 1953
- [ ] 1954
- [ ] 1955
- [ ] 1956
- [ ] 1957

Help

Get help

Licence

Licence to use Copernicus Products

Publication date

2018-06-14

Resource updated

2023-08-22

References

Citation

Acknowledgement

DOI: 10.24381/cds.bd0915c6

Related data

Complete ERA5 global atmospheric reanalysis

ERA5 hourly data on pressure levels from 1950 to 1978 (preliminary version)(deprecated 2023-08-15)

ERA5 hourly data on single levels from 1940 to present

ERA5 hourly data on single levels from 1950 to 1978 (preliminary version)(deprecated 2023-08-15)

ERA5 monthly averaged data on pressure levels from 1940 to present

ERA5 monthly averaged data on pressure levels from 1950 to 1978 (preliminary version)(deprecated 2023-08-15)

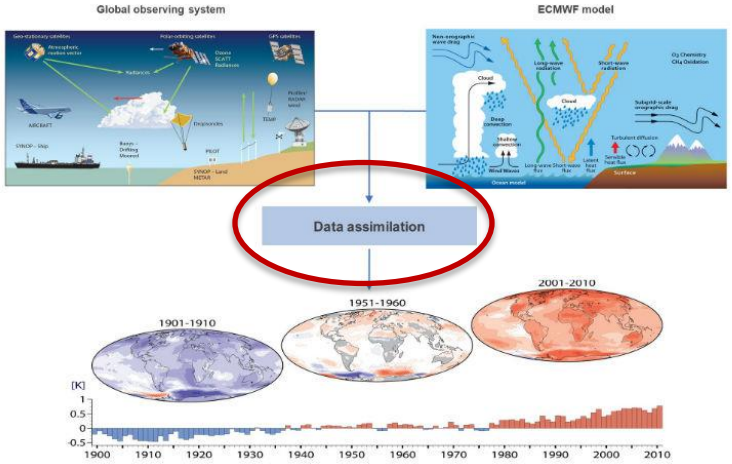
ERA5 monthly averaged data on single levels from 1940 to present

ECMWF

Climate Change

Overview

- The concept of reanalysis
- The ERA5 reanalysis
  - Data assimilation system
  - Sub-daily observations
  - Gridded observations
- How accurate is ERA5?
- Towards Earth system reanalysis; ERA6 and beyond
- Summary



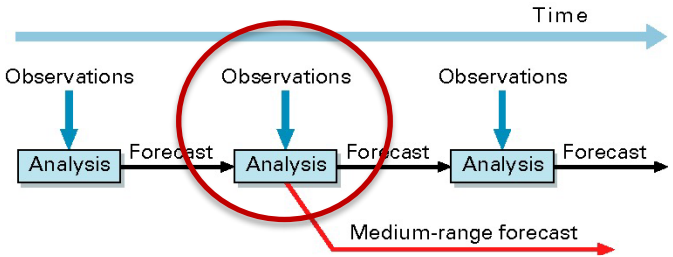
Copernicus Europe's eyes on Earth | European Commission | ECMWF

Climate Change

The ERA5 DA system and how does it differ from NWP?

It is good practice to base an operational reanalysis on a recent NWP system

✓ E.g., at ECMWF, ERA5 (2016) is based on Cy41r2



Differences:

✓ The focus is on the quality of the analysis, not the forecast

✓ Need to ensure that you have good and as many as possible historical *sub-daily* observations

  ✓ Reprocessing and data rescue

❖ The NWP system is well-tuned for the recent data-rich era
Ensure that it also works well for the data-sparser past, e.g.:

- Appropriate forcing fields
- Background errors
- Observation errors
- Quality control
- Systematic model and observation errors

The ERA5 Ensemble of Data Assimilations (EDA)

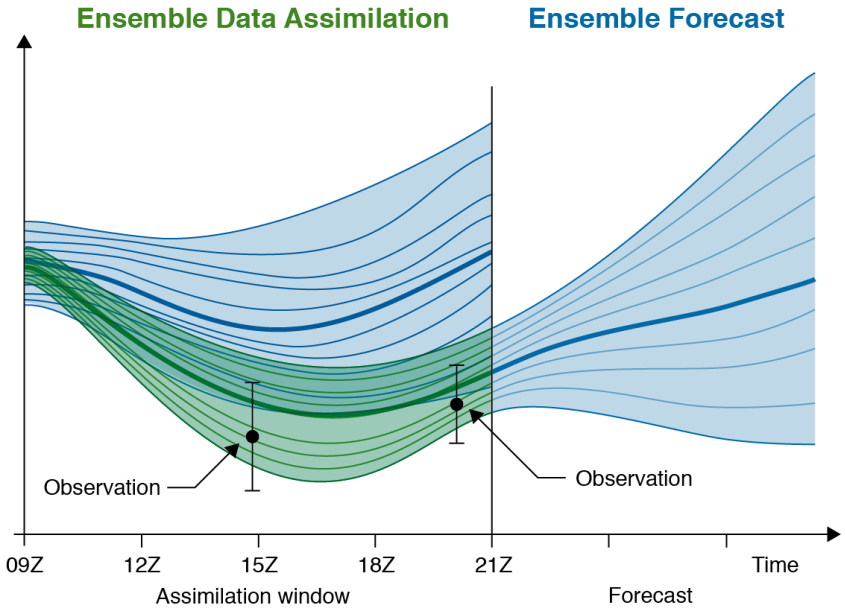
Climate Change

10 DA systems at half resolution. Per member:

- Perturb observations (including SST and sea ice)
- Perturb model in short forecasts linking analyses

From this we estimate:

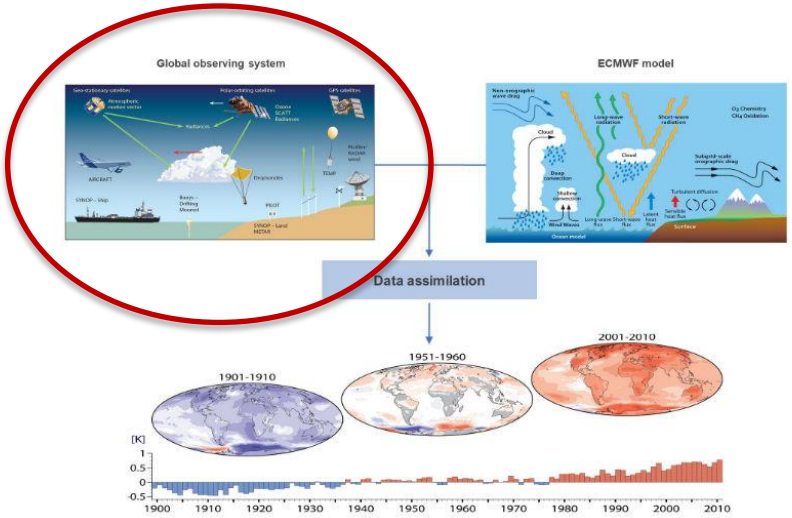
- a flow-dependent B matrix
- the quality of the synoptic situation from the ensemble spread



Climate Change

Overview

- The concept of reanalysis
- The ERA5 reanalysis
  - Data assimilation system
  - Sub-daily observations
  - Gridded observations
- How accurate is ERA5?
- Towards Earth system reanalysis; ERA6 and beyond
- Summary



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

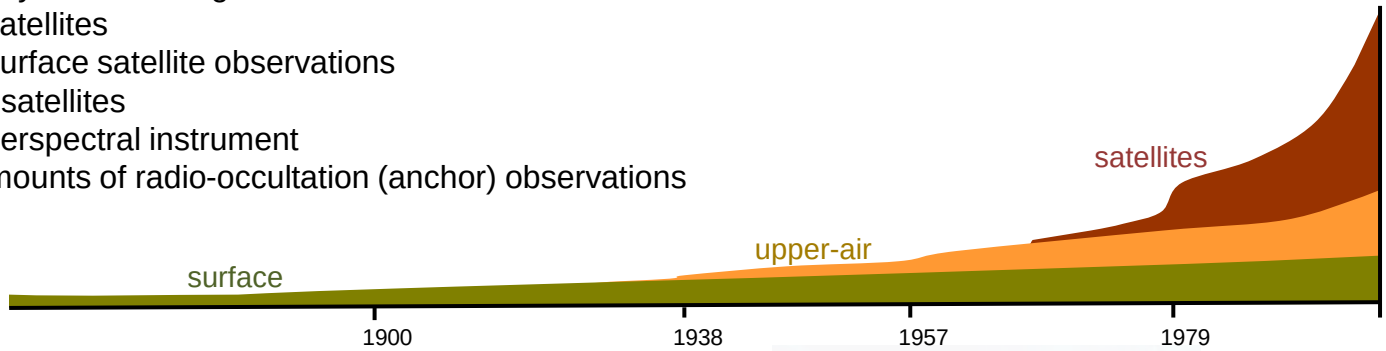
Climate Change

The evolving observing system

Data sources:
- many satellites
- surface observations
- weather balloons, aircraft, etc.

In the ERA5 reanalysis we daily use about:
- **17,000** obs in 1940, **25 Million** in 2022

There have been boosts in the observing system:
- Mid 1940s: start of upper-air observations
- 1957-1958: International Geophysical Year
- Mid 1970s: early satellites, e.g., VTPR
- 1979: TOVS satellites
- 1991: ocean surface satellite observations
- 1998: ATOVS satellites
- 2002: first hyperspectral instrument
- 2006: large amounts of radio-occultation (anchor) observations



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

Climate Change

Overview

- The concept of reanalysis
- The ERA5 reanalysis
  - Data assimilation system
  - Sub-daily observations
  - Gridded observations
- How accurate is ERA5?
- Towards Earth system reanalysis; ERA6 and beyond
- Summary

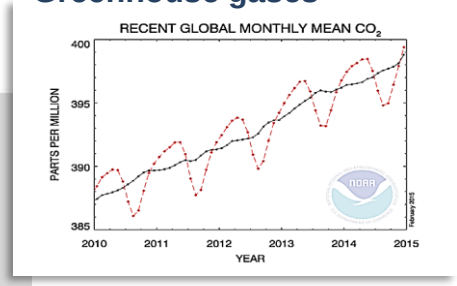
Climate Change

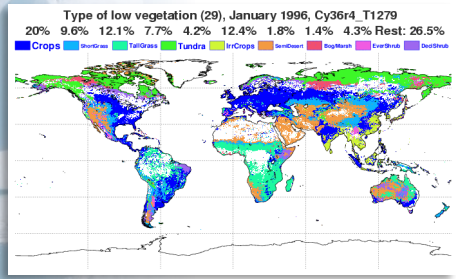
Observation-based (gridded) forcing and boundary conditions

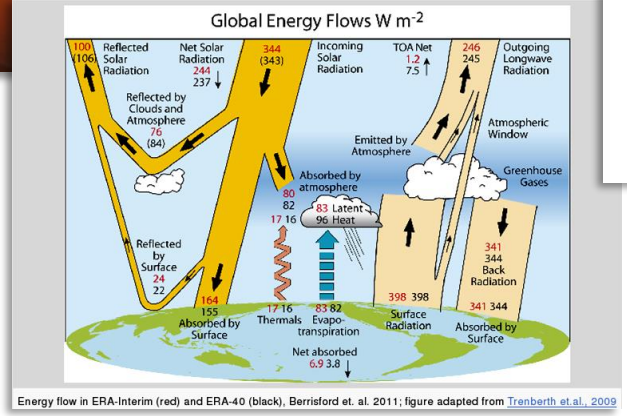
that reflect the 20th and 21st century evolution

Solar forcing

Greenhouse gases

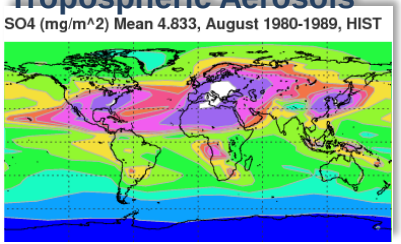




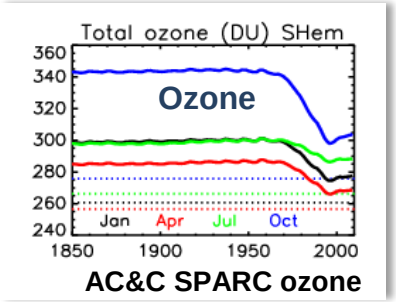


Energy flow in ERA-Interim (red) and ERA-40 (black), Berrisford et. al. 2011; figure adapted from Trenberth et.al., 2009

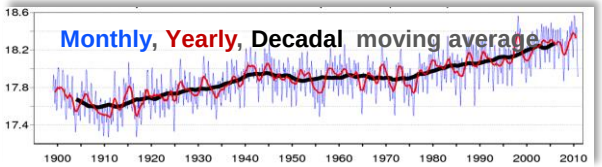
Tropospheric Aerosols



Volcanic eruptions



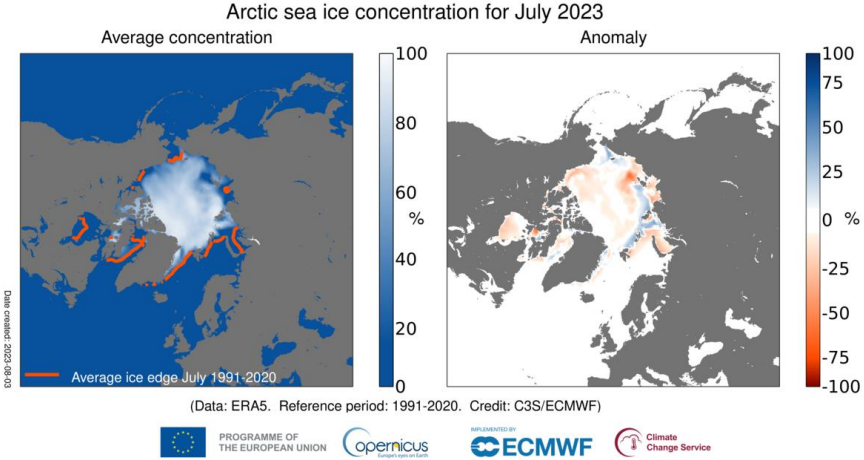
SST and sea ice

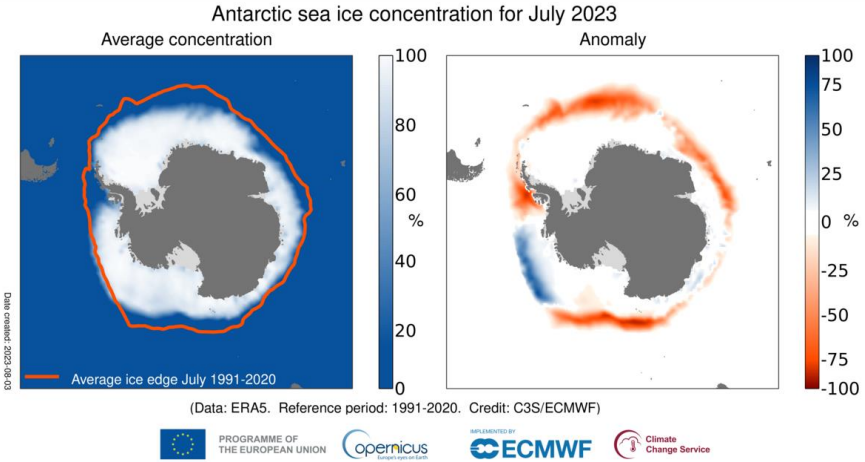


Copernicus Europe's eyes on Earth | European Commission | ECMWF

Climate Change

Need for temporally consistent datasets





European Commission

ECMWF

Climate Change

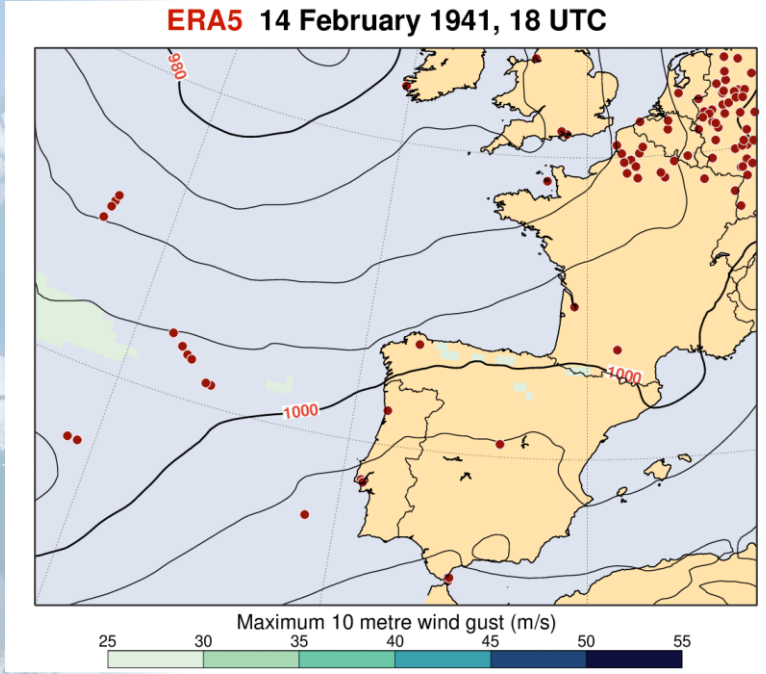
Overview

- The concept of reanalysis
- The ERA5 reanalysis
  - Data assimilation system
  - Sub-daily observations
  - Gridded observations
- How accurate is ERA5?
- Towards Earth system reanalysis; ERA6 and beyond
- Summary

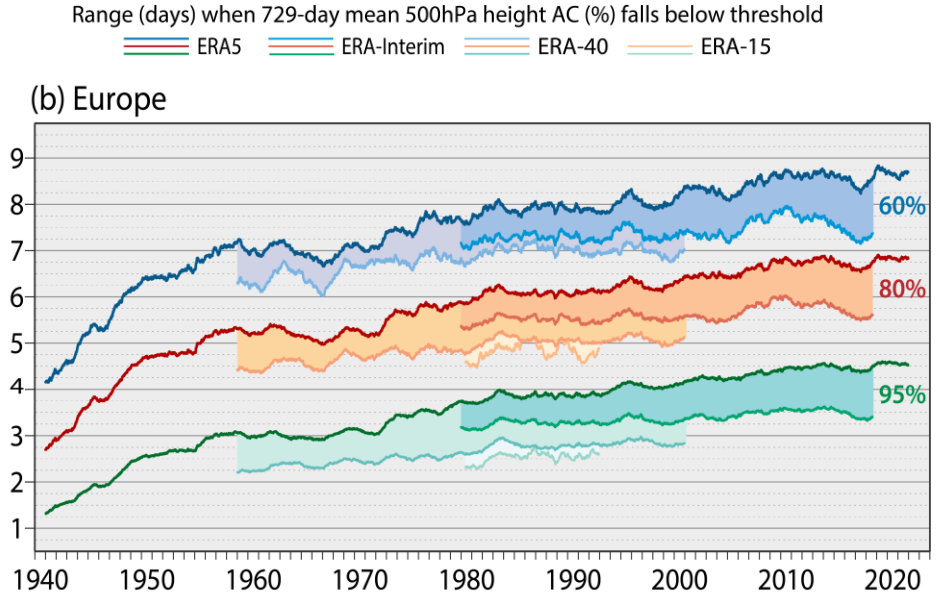
Copernicus Europe's eyes on Earth | European Commission | ECMWF

Climate Change

ERA5: hourly resolution from 1940 operational close to real time



Iberian storm case of 1941

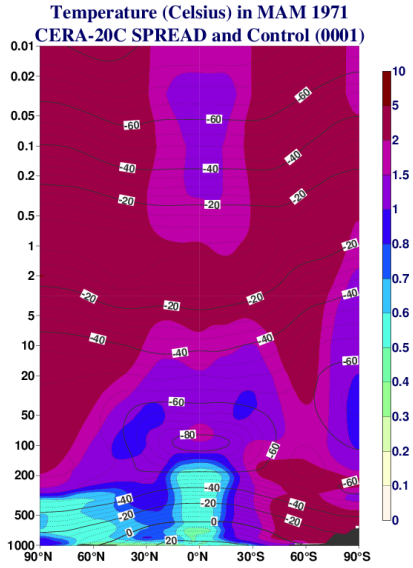


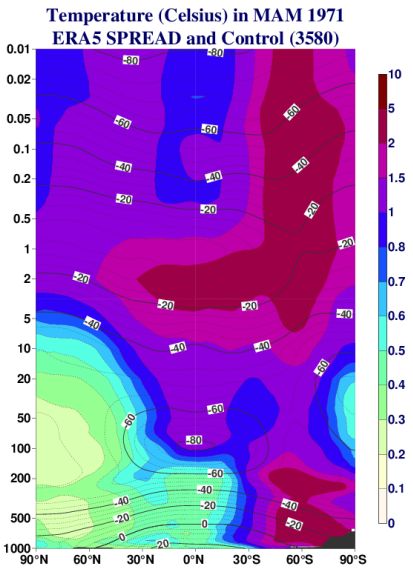
Skill of 10-day forecasts initialized from ERA against ERA at verification time
Note: over the Southern Hemisphere skill drops dramatically prior to 1979 due to the lack of satellite observations

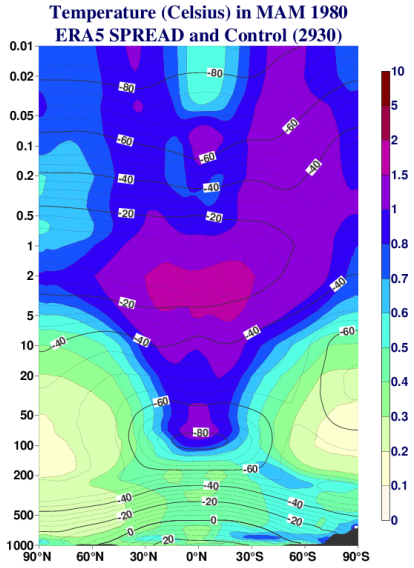
Copernicus Europe's eyes on Earth | European Commission | ECMWF

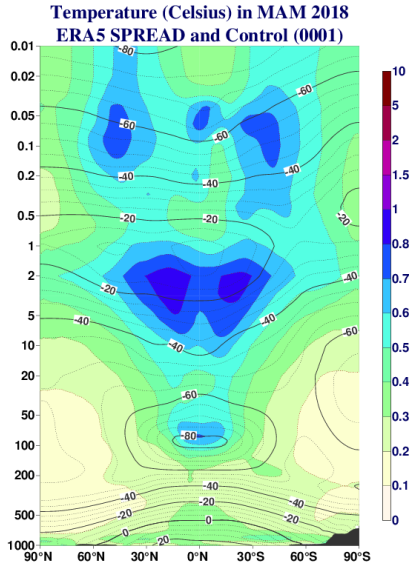
The evolution of ensemble spread; also proxy for synoptic uncertainty

Climate Change









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

1971 ERA5:
Upper-air data

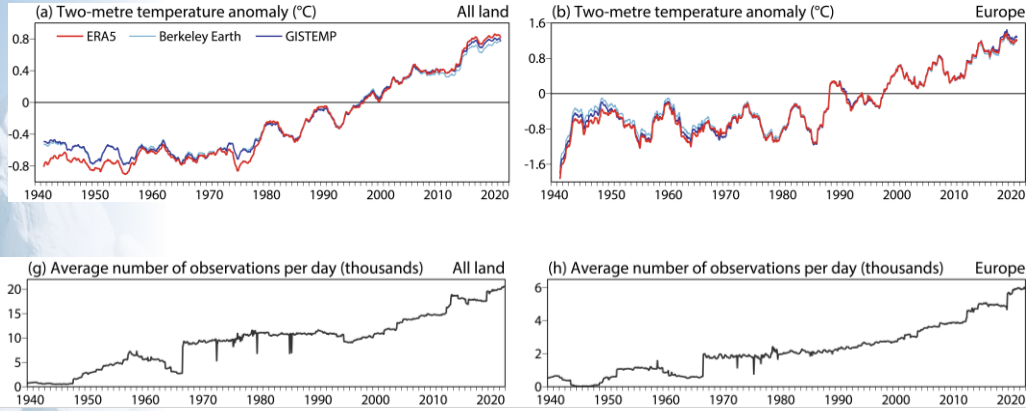
1980 ERA5:
Early-satellite era

2018 ERA5:
Recent observing system

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

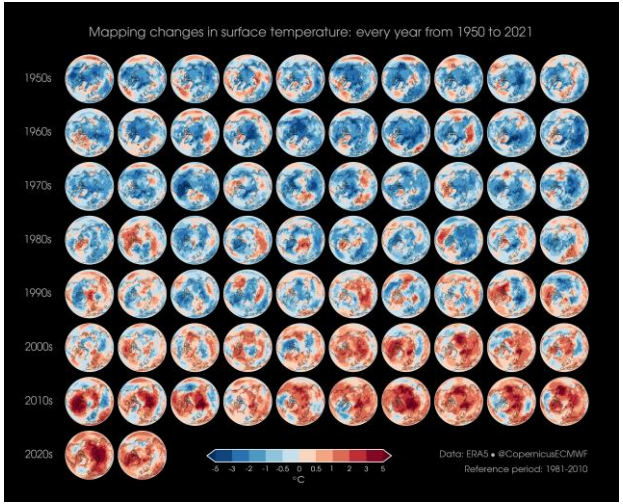
Climate change: evolution of 2m temperature and comparison with other datasets

Climate Change



Temperature trends:

- The global mean temperature shows little trend from 1940 to the mid 1970s.
- After that global warming becomes clearly visible and concerning



Courtesy: Ed Hawkins

Consistency between datasets:

reanalyses and more direct observation-based datasets:

- In general, quite good and reassuring
- However, there are some small discrepancies in certain periods and certain areas

Climate Change

Overview

- The concept of reanalysis
- The ERA5 reanalysis
  - Data assimilation system
  - Sub-daily observations
  - Gridded observations
- How accurate is ERA5?
- Towards Earth system reanalysis; ERA6 and beyond
- Summary

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

Climate Change

ECMWF has a long experience with reanalysis

Atmosphere/land *including ocean waves*

1) 1979 - 1981 FGGE	2) 1994 - 1996 ERA-15	3) 2001 - 2003 ERA-40	4) 2006 - 2019 ERA-Interim	5) 2016 - … ERA5

Ocean *+sea ice*

2004/2006 ORAS2/ORAS3	2010 - 2019 ORAS4	2016 - … ORAS5/OCEAN5

Centennial *Outer loop Coupling*

2013 - 2015 ERA-20CM/20C	2016 CERA-20C	2017 CERA-SAT

Enhanced land (from ERA atmosphere)

2012 ERA-Int/Land	2014 ERA-20C/Land	2018 - … ERA5L

Atmospheric composition

2008 - 2009 GEMS	2010 - 2011 MACC	2017 - … CAMS EAC4

Next generation

6) 2024 - … ERA6

2024 - … ORAS6/OCEAN6

2026 - … ERA6L

2024 - … CAMS EAC5

Climate Change

ERA systems specifications

	ERA4 (ERA-Interim)	ERA5	ERA6
IFS version (year)	cy31R2 (2006)	cy41R2 (2016)	cy49R2 (2024)
Hor. Resol.	79 km	31 km	14 or 18 km
Vert. Resol.	*60 model levels* 37 press. levels 10-metre wind	*137 model levels* 37 press. levels 100,10-metre wind	*137 model levels* 38 press. levels 11 height levels
Temp. Resol.	*1800 s* 3 or 6 h Monthly	*720 s* 1 h Monthly	*600 s* 1 h Daily Monthly
Ens. Hor. Resol.	-	63 km	28 km
Ocean SST Forcing	Daily	Daily	Hourly
Release Timeliness	> 1 month	5 days	TBC

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

Climate Change

Overview

- The concept of reanalysis
- The ERA5 reanalysis
  - Data assimilation system
  - Sub-daily observations
  - Gridded observations
- How accurate is ERA5?
- Towards Earth system reanalysis; ERA6 and beyond
- Summary

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

Climate Change

Summary and Final Remarks

The **ERA5** reanalysis provides hourly snapshots of the atmosphere, land surface and ocean waves for over 80 years

- Very popular dataset on the **CDS** (137,000 users): https://cds.climate.copernicus.eu/#!/home
- Compared to ERA-Interim: much higher resolution, in general better performance
- There are, of course several known issues (see ERA5 online documentation, or ERA5 paper)
- We closely monitor the production and quality of ERA5
- And we receive a lot of feedback from our users and listen to them: **we are user-driven**
- We have started the preparation of the next reanalysis: **ERA6**

User support:

Further reading:

- The ERA5 journal paper (Hersbach et. al, 2020)
- The ERA5 back extension (Bell et. al, 2021)
- Simmons et. al, 2020: Global stratospheric temperature bias and other stratospheric aspects of ERA5 and ERA5.1
- Simmons et. al, 2021: on ERA5 surface temperature and humidity
- Many, many journal papers.

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