C3S Earth System Reanalyses: progress and planned evolution

Hans Hersbach, C3S Reanalysis Team Leader

Climate Change

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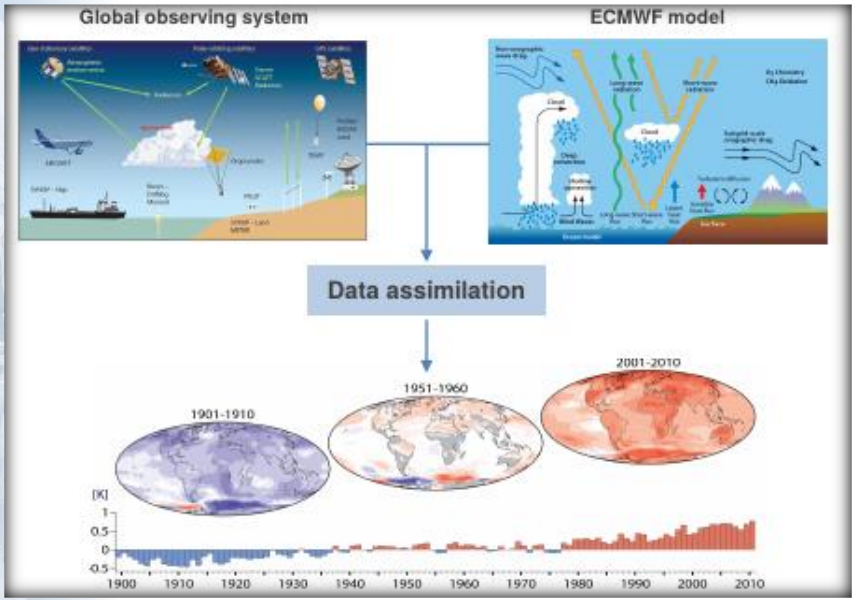
Reanalysis uses past observations with today's weather model

The data from reanalysis are widely used



- ✓ Complete: combining vast amounts of observations into (global) fields
- ✓ Consistent: use the same physical model and data assimilation system throughout
- ✓ Convenient: "maps without gaps", always available in the same way

- ❖ *Observations are absolutely key!!*
- ❖ *Plus gridded input datasets*

- ➢ provide an uncertainty estimate to reflect the evolution of the observing system

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Overview

- Overview of C3S
- Overview of ECMWF global reanalyses
- Observation-based gridded forcings and boundary conditions
- Evolution for C3S reanalysis

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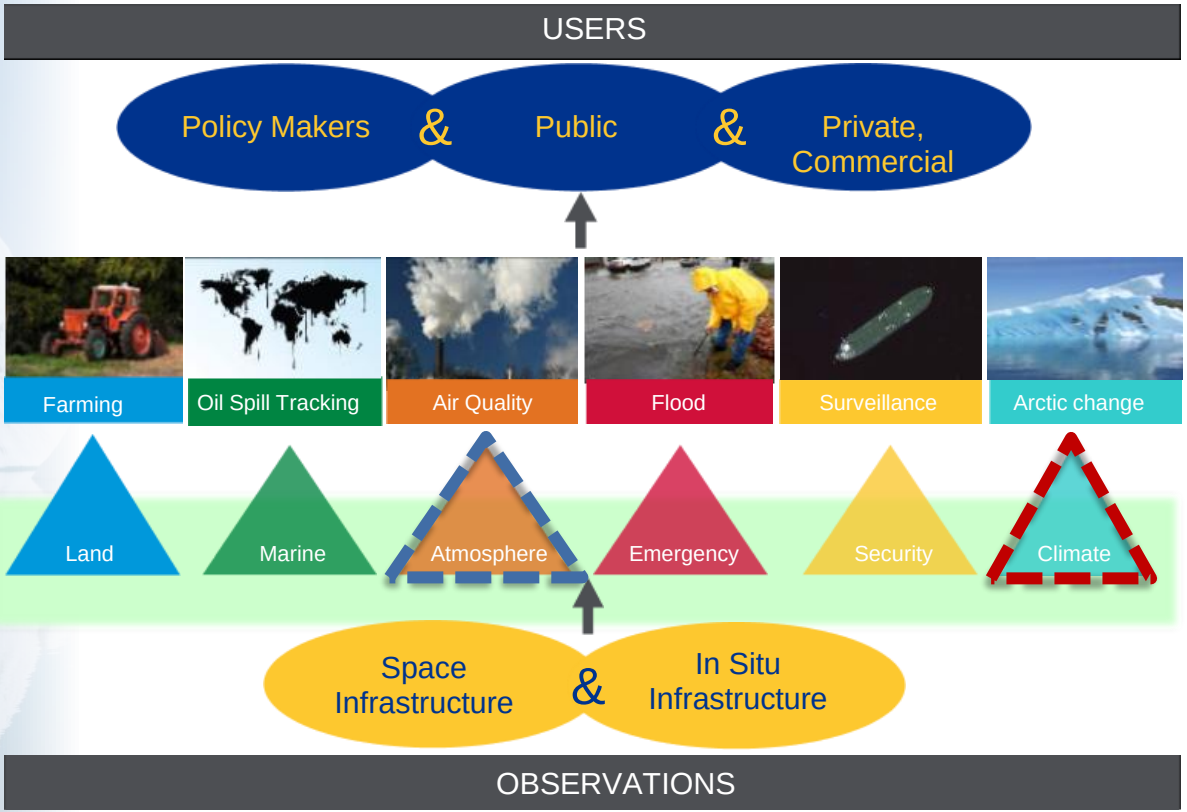
The Copernicus Climate Change Service



Different Needs

Examples of areas covered

6 Information Services

Sustainable observation capabilities

ECMWF operates the Copernicus Climate Change Service (C3S) and Copernicus Atmosphere Monitoring Service (CAMS) on behalf of the European Commission.

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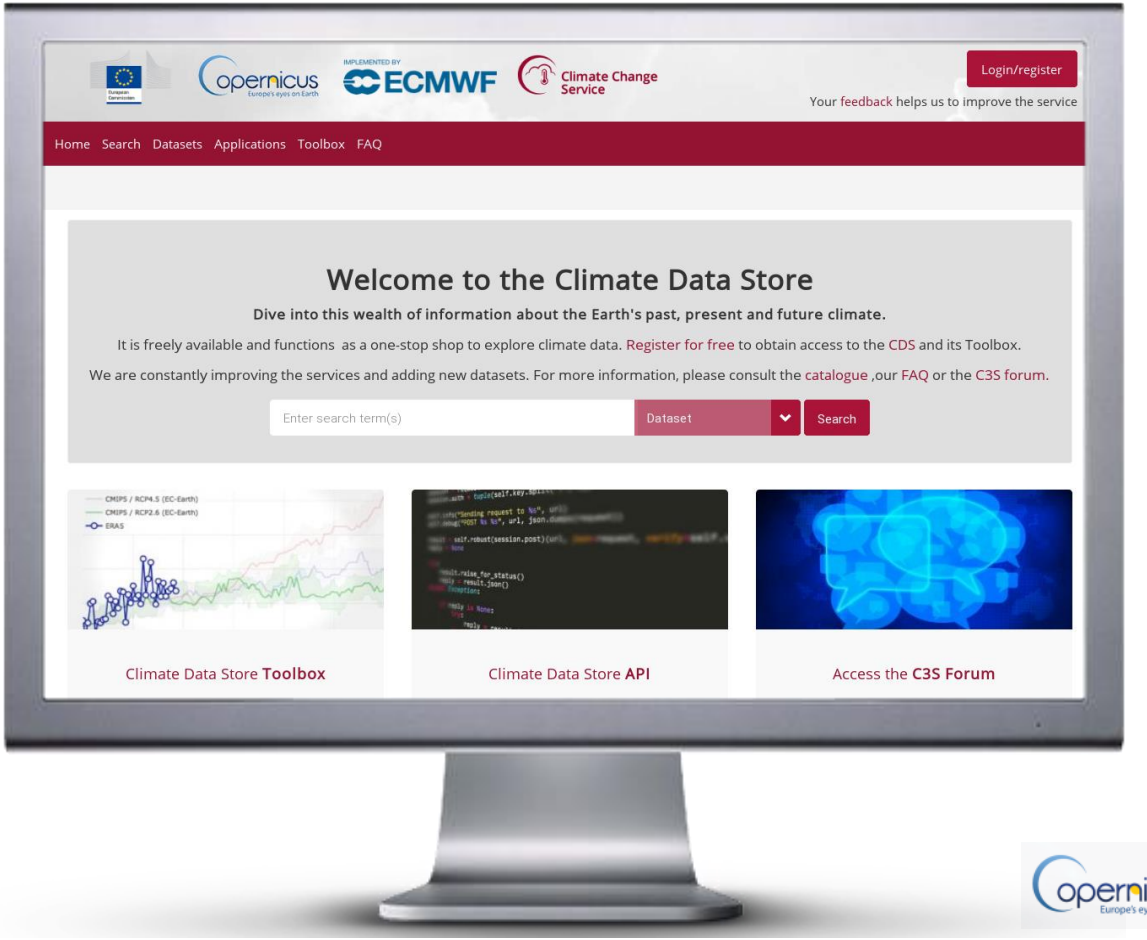
The Climate Data Store is the central entry point for C3S datasets



- ✓ Unified and free access to a large portfolio of climate data
- ✓ Direct downloading
- ✓ Cloud computing: CDS Toolbox
- ✓ Quality assurance reports
- ✓ User Support

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The Climate Data Store

One of the pillars of C3S

- One-stop shop for climate data
- Free access
- User support
- Includes CDS Tool Box
- Quality assessment (in steps)

Observations	Global estimates of ECVs from satellite and in-situ observations	Reprocessed CDRs, reference observations	Support for data rescue, climate data collections	Climate Indicators
Climate reanalysis	Global atmosphere, ocean, land	Regional reanalysis for Europe	Coupled climate reanalysis for 100 years	
Model output	Multi-model seasonal forecast products	Access to CMIP data and products (global and regional)	Reference set of climate projections for Europe	

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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 - … ERA-Interim	5) 2016 - … ERA5

Ocean *including sea ice*

2006 ORAS3	2010 - … ORAS4	2016 - … ORAS5

ERA CLIM / ERA CLIM2

Centennial *Coupled*

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

Enhanced land

2012 ERA-Int/Land	2014 ERA-20C/Land	2018 - … ERA5-Land

Atmospheric composition

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

ECMWF

C3S Global Reanalysis: ERA5 and its back extension

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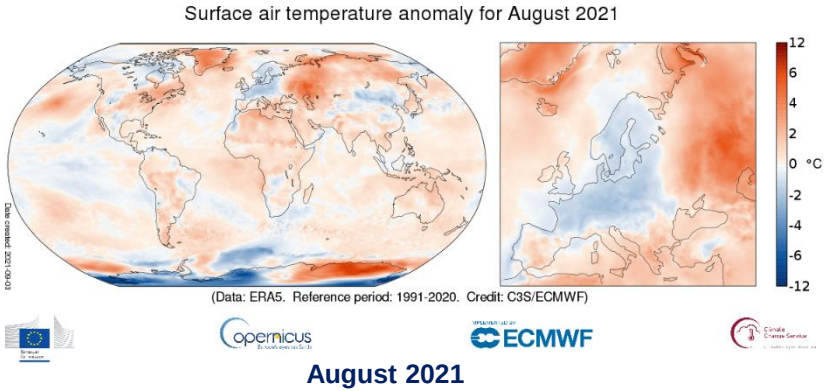
ERA5: *A full-observing-system global reanalysis for the atmosphere, land surface and ocean waves*

- Daily updates **5 days behind real time from 1979 onwards**
- **63,000 users; order of 400 Tb weekly downloads**
- Hourly snapshots at 31km resolution up to about 80km height
- Uncertainty estimate from a 10-member ensemble at 63km
- Over 100 billion observations have been used so far



ERA5.1: stratosphere 2000-2006

Improves on the mean state in the stratosphere

Access via the C3S Climate Data Store (CDS)

- **Fast:** on spinning disk (around 1.8 petabyte; not ERA5.1)
- **Slow:** ERA5-complete on tape (MARS, around 10 petabyte)

ERA5 Back extension: 1950 - 1978

Has in general good characteristics, suitable for many users
However sub-optimal for tropical cyclones (extremes)

Made available in the CDS as a separate, preliminary dataset
The production of the improved version is well underway, and will go back to 1940.

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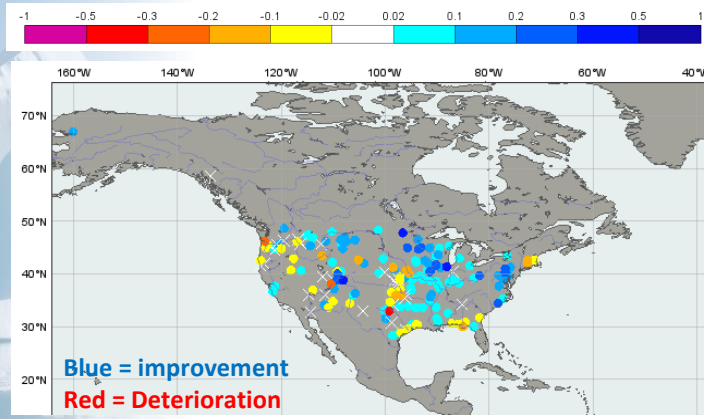
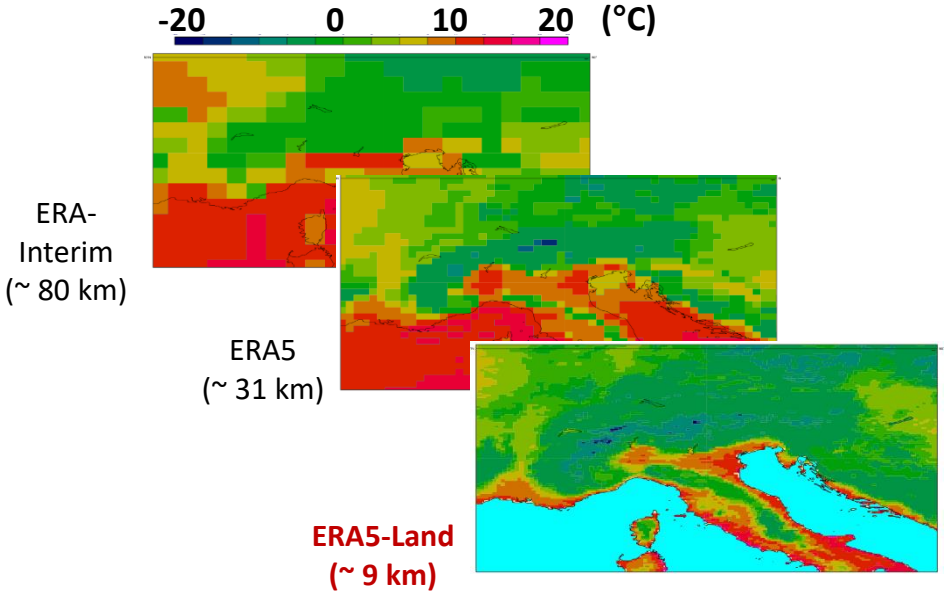
ERA5-Land, a high-resolution downscaling of the land-surface component



Discharge time series correlation difference ERA5-Land vs. ERA5



ERA5-Land is available from 1950 with a latency of 2-3 months

Joaquin Munoz-Sabater

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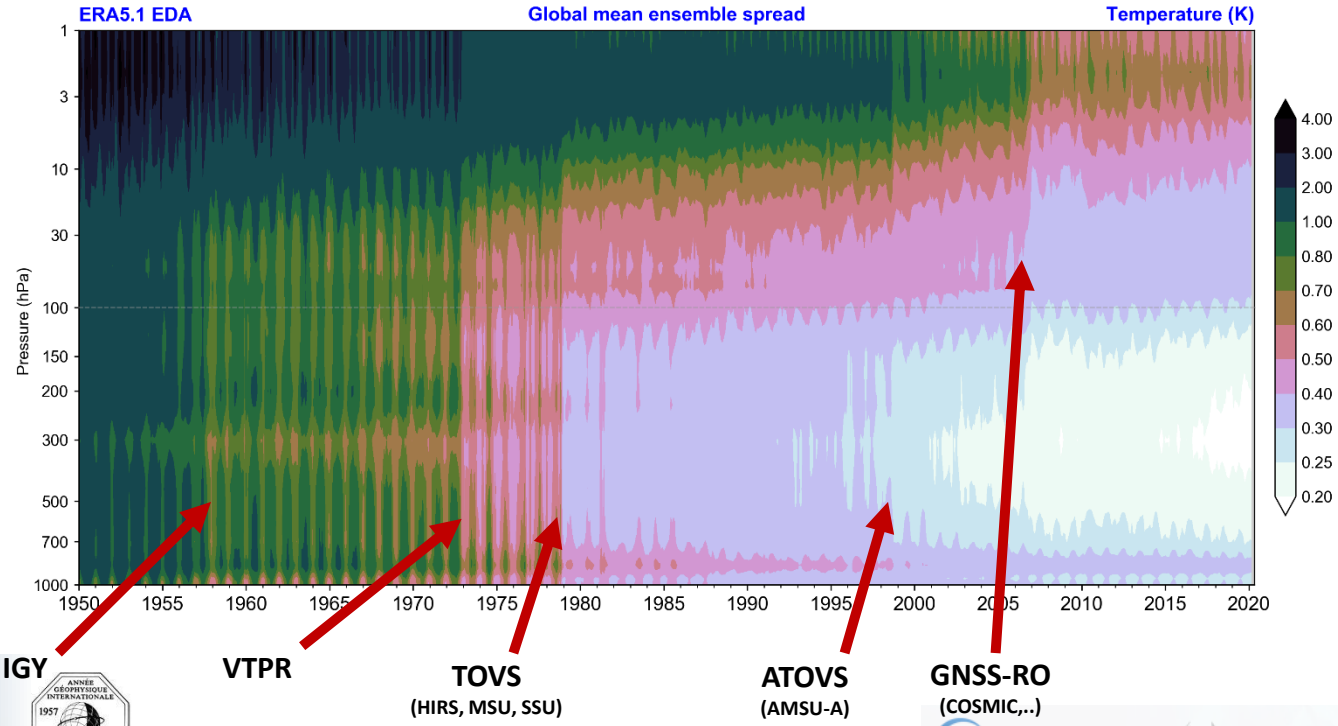
Ensemble spread as a measure for the *synoptic* ERA5 uncertainty

Spread decreases over time when more and more observations become available

Major changes in the observing system are clearly visible



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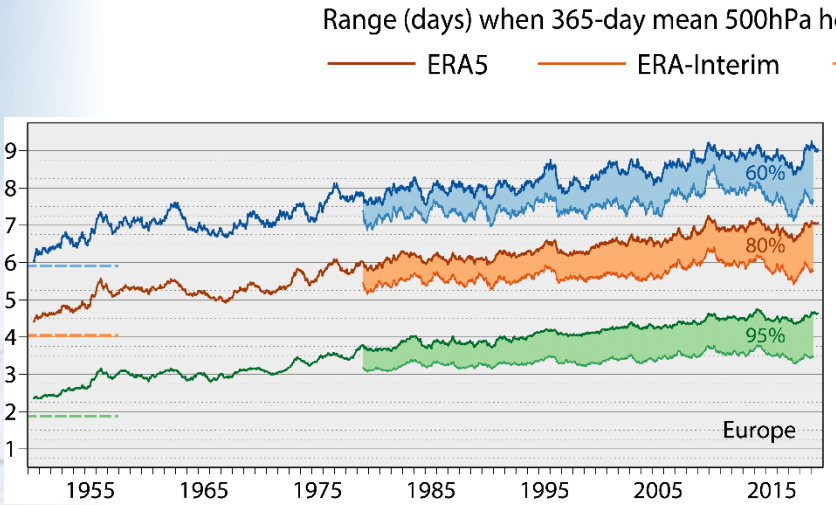
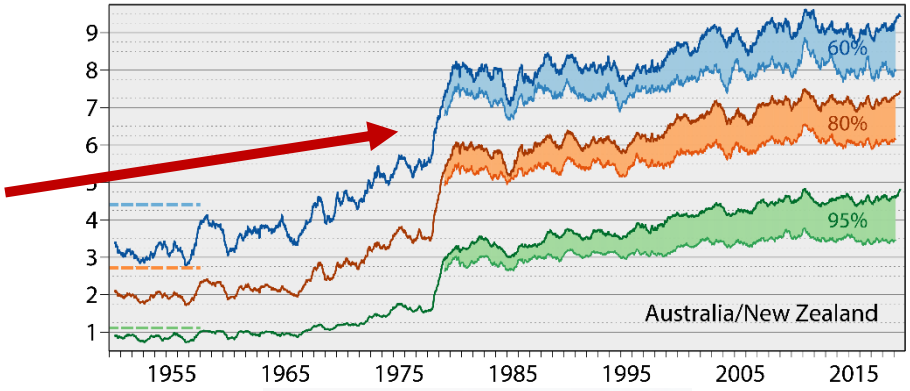
And the quality of re-forecasts issued from reanalysis evolves accordingly



ERA5 back extension:
NHEM (especially Europe) skill is promising, Thanks to radiosondes and many surface observations.

Over SHEM there is a dramatic improvement following the introduction of TOVS satellite data in late 1978.



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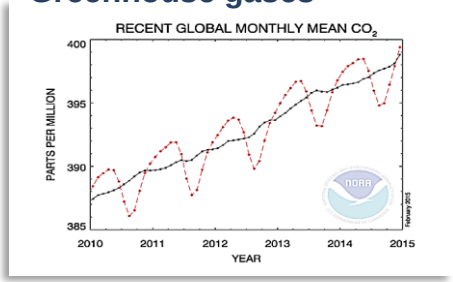
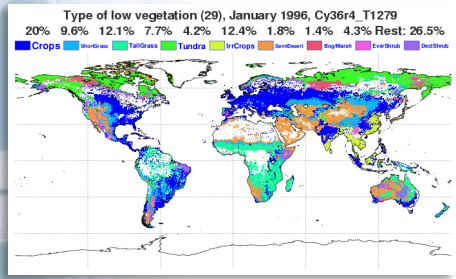
Observation-based (gridded) forcing and boundary conditions

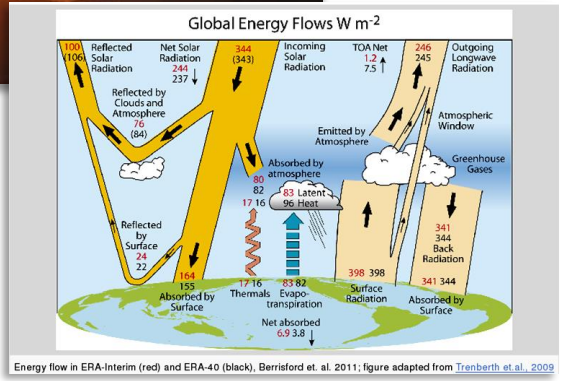
that reflect the 20th and 21st century evolution

Solar forcing

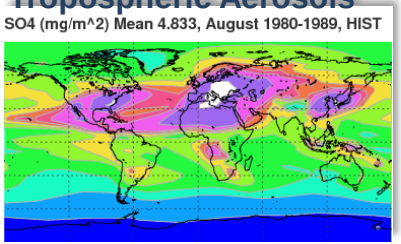
Greenhouse gases



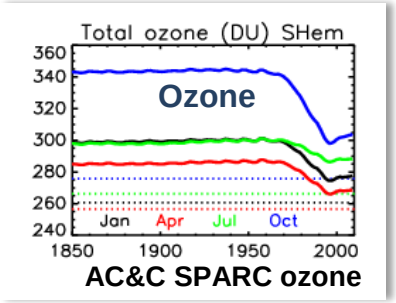




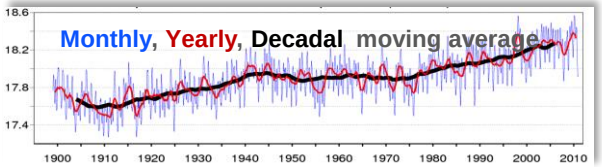
Tropospheric Aerosols



Volcanic eruptions



SST and sea ice



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Tropospheric aerosols

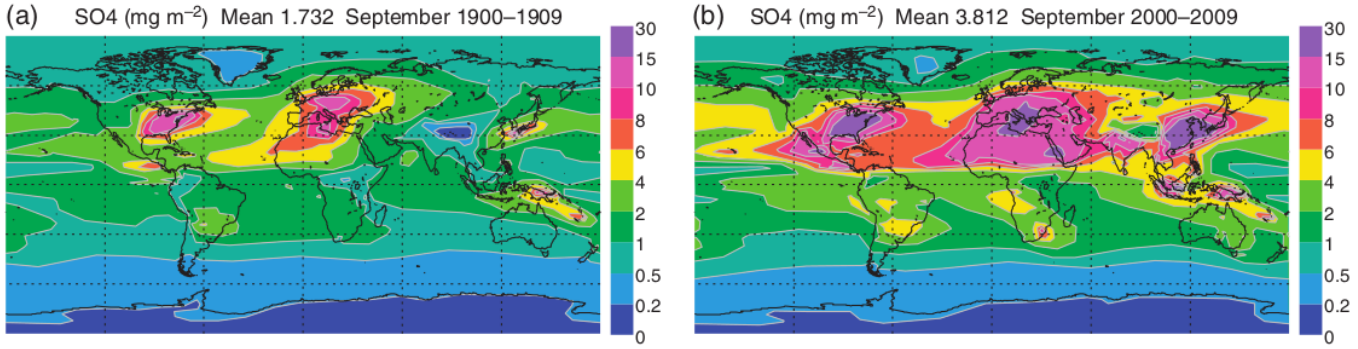

Figure 8. Total burden (10^{-6} kg m^{-2}) in September for sulphate from the CAM3.5 simulation for (a) the period 1900–1909 (mean 1.732) and (b) 2000–2009 (mean 3.812).

In ERA-Interim:

Monthly but no yearly variation:
- based on Tegen et al. 1997
- Optical depth for several species:
- Sea salt, dust, organic, black carbon, sulphate
- Redistributed in the vertical following empirical profiles

In ERA5:

For sulphate based on CMIP5 recommended decadal and monthly varying 3D fields from the NCAR Community Atmospheric Model CAM3.5.
However, converted to 2D fields for optical depth
Other species still followed Tegen et al. 1997

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Volcanic aerosols

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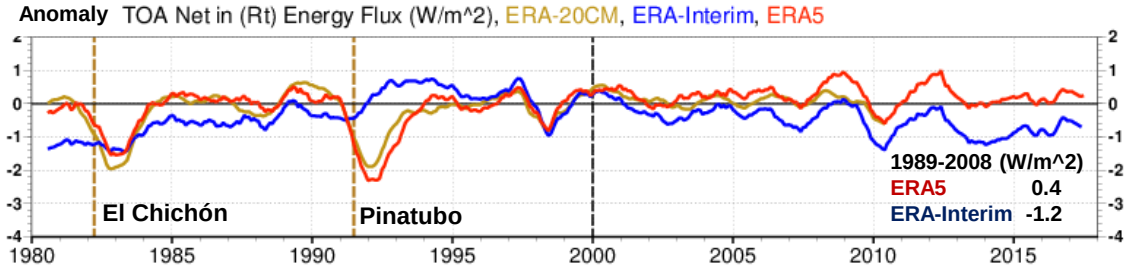
CMIP5 recommended data set

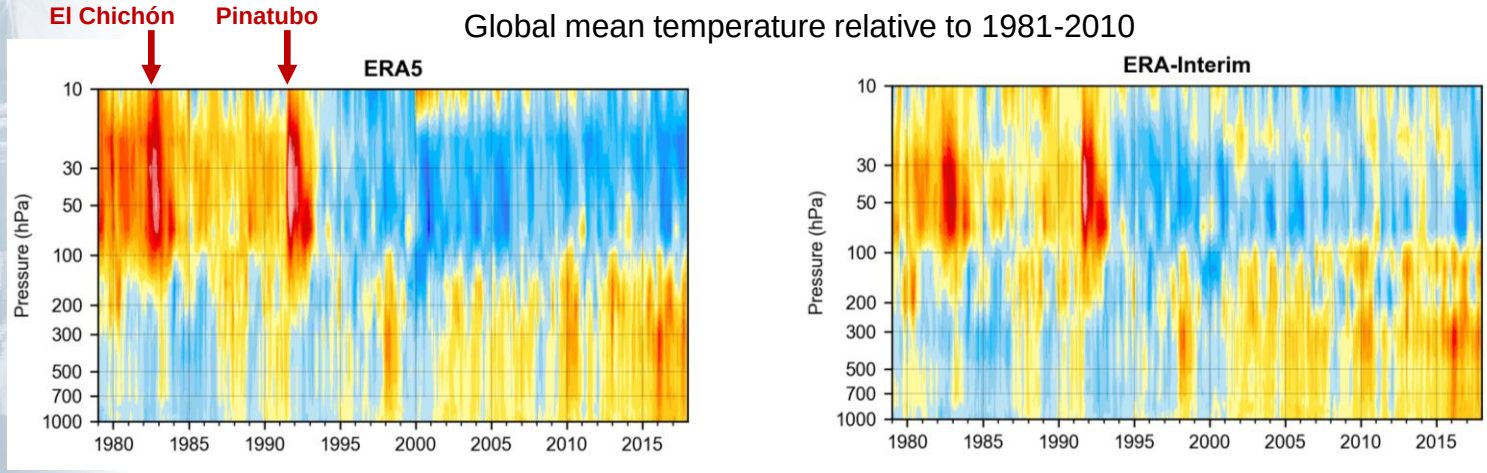
Based on Sato et al, 2010

Monthly zonal-mean optical depth

Zero from 2010 onwards



Global mean temperature relative to 1981-2010



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Land usage, vegetation and albedo

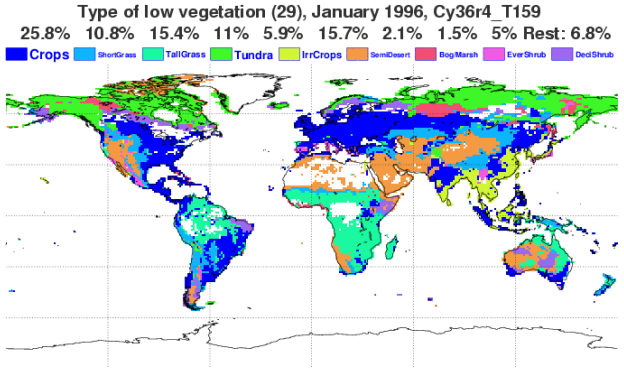
In ERA5 and previous reanalyses these have been static:

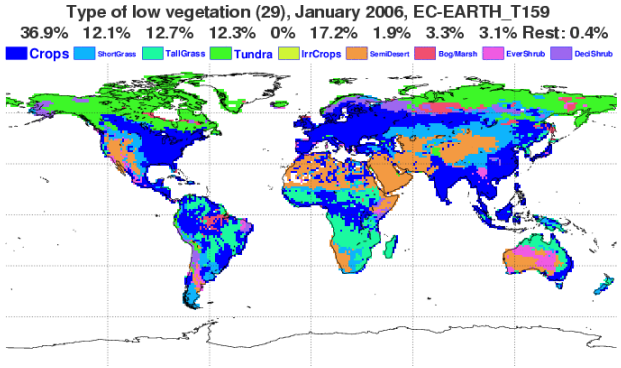
- Vegetation: constant during the year and between years
- Albedo and LAI: monthly, but no variation over years

For ERA-20CM a dataset produced by the EC-EARTH consortium (KNMI) had been considered:

- Merged Land-use Harmonization dataset with the GLCC database
- Decadal fields going back to 1850.

- However, for recent periods it was found to deviate from what is used in IFS,
- may require retuning of the IFS land-surface parametrization.
- How to interpolate decadal fields?
- So, it was decided not to use it





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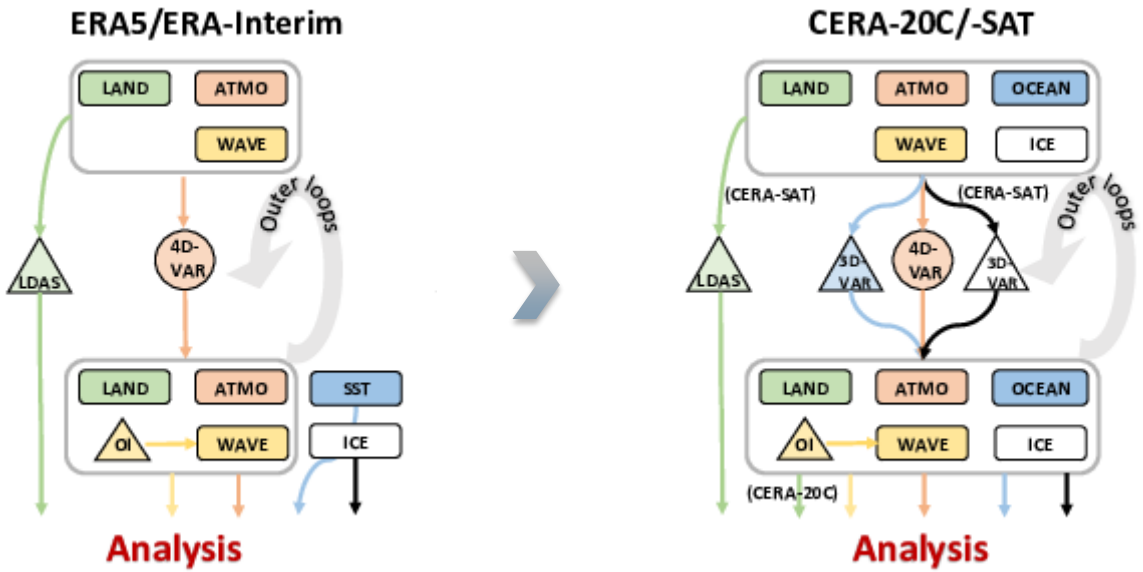
Make use of the work on coupled reanalysis in the ERA-CLIM2 project



The **ERA-CLIM2** project pioneered the development of an **outer-loop coupled** data-assimilation in climate reanalysis

- **CERA-20C:** centennial reanalysis using surface observations only
- **CERA-SAT:** proof of concept for a recent 9-year period using the full observing system at the ERA5 EDA resolution
- Land data assimilation (LDAS) remains **weakly-coupled**

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Coupled processes: tropical instability waves

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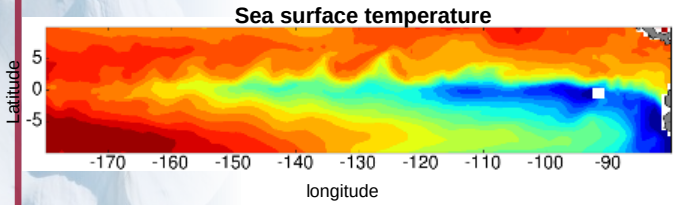
Tropical instability waves (TIW)

westward-propagating waves near the equator



ERA20C (Forced reanalysis)

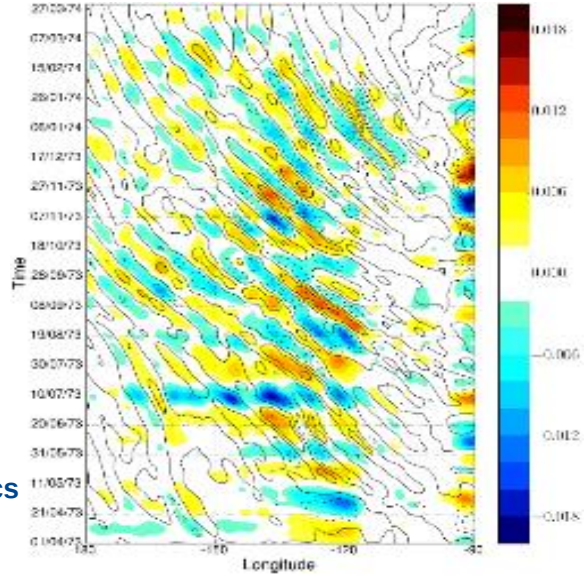
- no TIWs or wind stress signals (forced by 'monthly' SST)

CERA-20C (Coupled reanalysis)

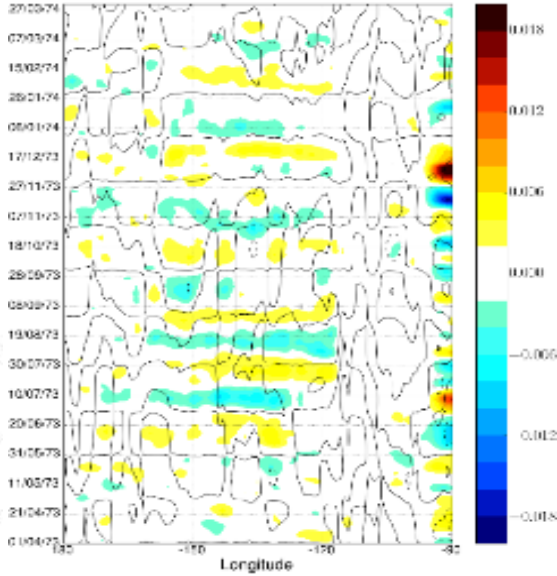
- represents TIWs thanks to the ocean dynamics
- atmosphere responds accordingly (surface wind stress is sensitive to the ocean TIW)

high-pass filtered SST (colour) and wind stress (contour)

CERA-20C



ERA-20C



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Preparations for ERA6

Start production of **ERA6** in 2024

- Higher resolution (Tco639, TBC), from 1950 or earlier
- Coupled with the ocean, based on the latest IFS cycle, likely 49r1:
  additional 8 years of ECMWF R&D like improved stratosphere, new ozone model, etc.
- Dedicated reanalysis developments like a better treatment of systematic biases and better representation of uncertainty.
- Improved observations, for a large part from our C3S providers:
  - Reprocessed (EUMETSAT) and newly-rescued satellite data
  - In-situ observations
- Improved (gridded) forcing and boundary conditions:
  - CMIP6 recommended datasets or better
  - Improved datasets for SST and sea ice
  - Ideally time-varying land usage, cover, LAI and lake cover.
    - However, this may become available too late for ERA5 where we need data prior to 1993 as well
    - To go back to 1940 or even 1925

An **ERA6-Land** downscaled product, which now will include land data assimilation, to start mid 2025

- Here we do target for time varying land conditions

Dedicated climate (coupled) integrations that allow for, e.g., a quick testing of new datasets for gridded forcing and boundary conditions

ERA5 is to be maintained into the late 2020s

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ERA6 time line

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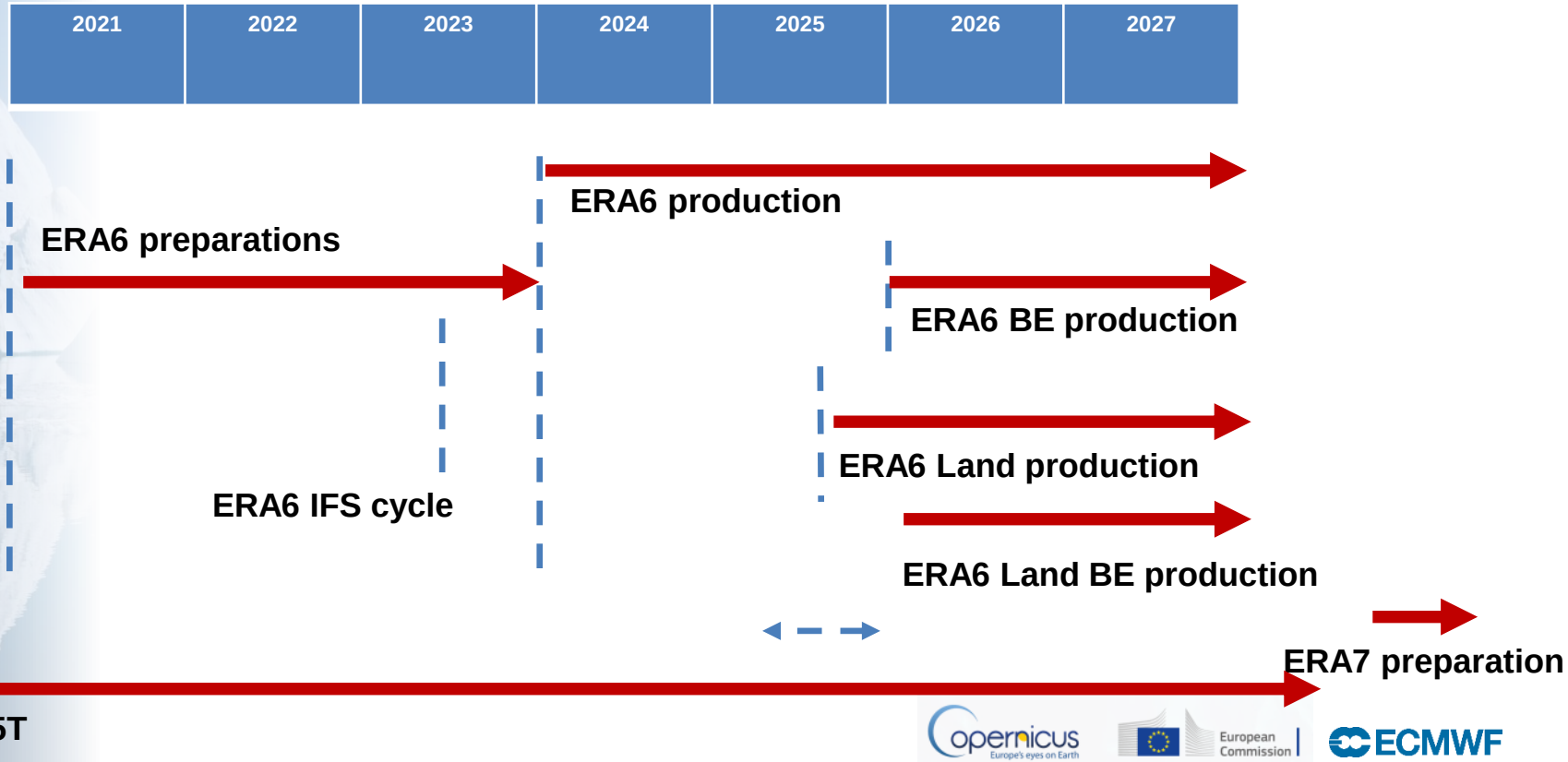

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Summary

ECMWF has a long experience with reanalysis

The **ERA5** and ERA5-Land reanalyses provide hourly snapshots of the atmosphere, land surface and ocean waves for over 70 years

In addition to billions of in-situ and satellite observations, reanalyses rely on

- Observation-based (gridded) forcing and boundary conditions
- In ERA5 part of the forcing data were based on CMIP5 recommendations and had a long-term evolution
- This was an improvement on ERA-Interim

The next C3S reanalysis, ERA6 will be coupled with the ocean

- Additional 8 years of ECMWF R&D plus dedicated reanalysis developments
- Forcing datasets should be based on at least CMIP6 recommendations and all have time variation
- Time varying surface conditions may come available too late for ERA6, but should be ingested for ERA6-Land

Further reading:

- The ERA-20CM paper: Hersbach et al., 2015 in QJRMS
- The ERA5 paper: Hersbach et. al 2020 in QJRMS
- The ERA5 back extension paper: Bell et al, 2021 in QJRMS
- The ERA5 online documentation
- Many, many journal papers.

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ERA5 configuration

	ERA-Interim	ERA5
Period	1979 – present	***1950 – present***, produced in 2 phases
Availability behind real time	2-3 months	2-3 months (final product) ***5 days*** (ERA5T)
Assimilation system	2006 (31r2), 4D-Var soil moisture: 1D-OI	***2016*** (41r2), ***4D-Var, hybrid EDA*** ***soil moisture: SEKF***
Model input (radiation and surface)	As in operations, *(inconsistent SST and sea ice)*	***Appropriate for climate***, e.g., evolution of greenhouse gases, volcanic eruptions, sea surface temperature and sea ice
Land-surface model	TESSEL	***HTESSEL***
Spatial resolution	79 km globally 60 levels to 10 Pa	***31 km globally*** 137 levels to 1 Pa
Uncertainty estimate		***from*** 10-member ***EDA at 63 km***
Output frequency	6-hourly Analysis fields	***Hourly*** (three-hourly for the ensemble), Extended list of parameters ~ 9 Peta Byte (1950 - timely updates)
Extra Observations	Mostly ERA-40, GTS	Various ***reprocessed CDRs***, ***latest instruments***
Variational Bias control Radiosondes	Satellite radiances, RAOBCORE	Also ozone, aircraft, surface pressure, RISE
Land downscaling product	ERA-Interim land, 79km	ERA5L, ***9km*** (forced by ERA5)