Prospects for Earth system reanalysis at ECMWF: ERA6 and beyond

Climate Change

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Ocean reanalysis: Hao Zuo, Philip Browne, Eric de Boisseson, Marcin Chrust

and many others !

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Overview

--------> **4-8 Sept 2023 ECMWF Annual Seminar on Earth System Reanalysis #AS2023** <--------

- Copernicus Climate Change Service (C3S) and ECMWF
- What reanalysis is and why it is important
- Status of the ERA5 reanalysis
- Overview of ECMWF reanalysis products
- Planning of ERA6
- Beyond ERA6: synergies with state-of-the-art DA at ECMWF
- Concluding remarks

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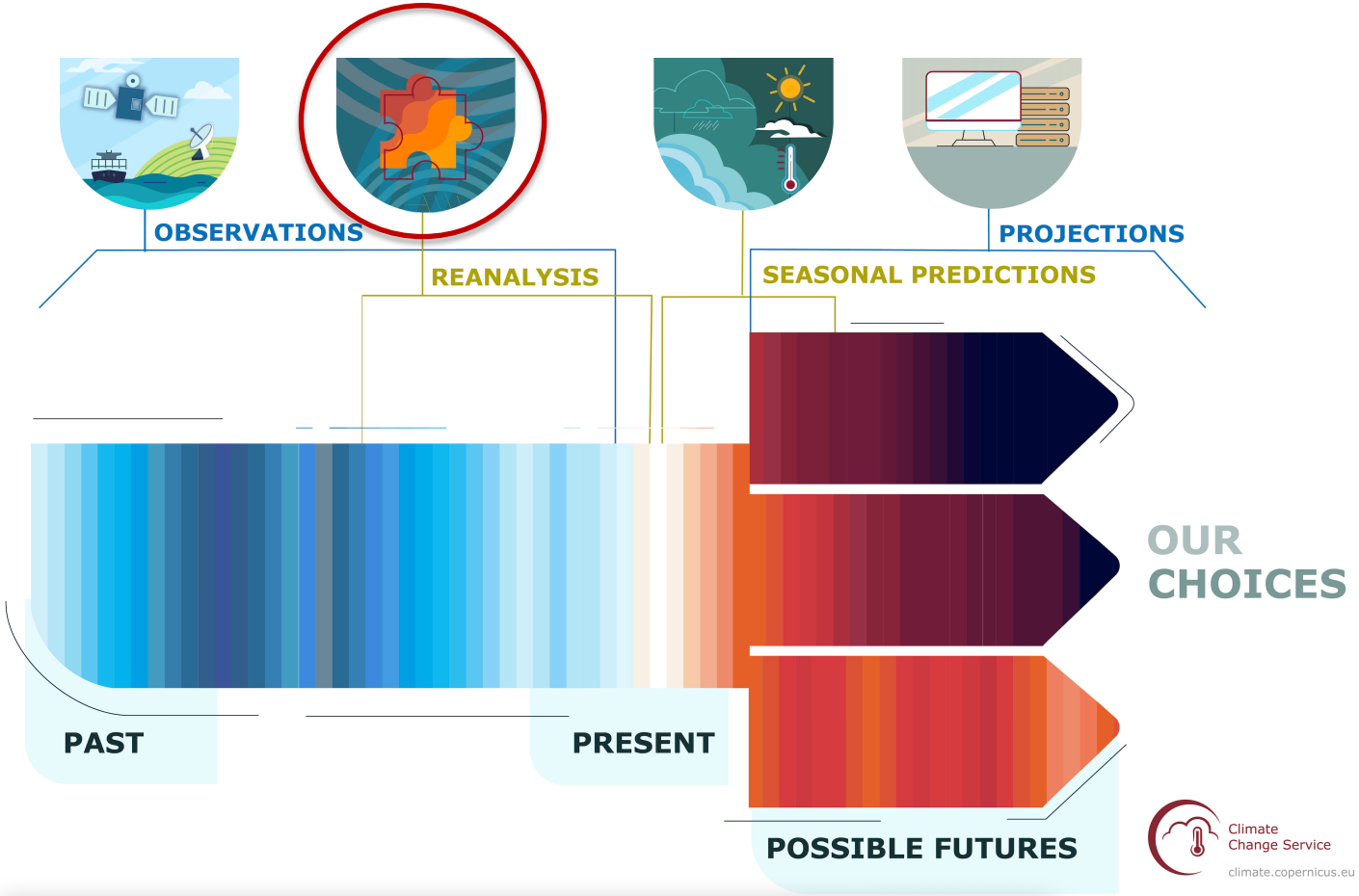
C3S and the Climate and Atmosphere Data Store (CADS)

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



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What reanalysis is and why it is important

Reconstruction of the past weather & climate:

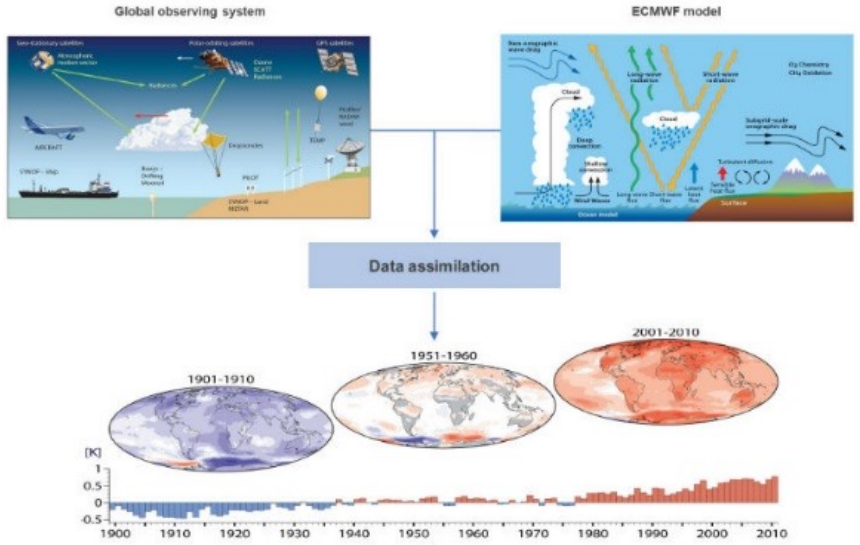
- ✓ **Input:** integrator of all available observations (level 1B, 2), some of them prepared as forcing (level 4)
- ✓ Deal with inhomogeneities, relative biases, data formats, range of observables
- ✓ **Output:** convenient and as accurate as possible ‘maps without gaps’ of 3D atmosphere (+ other domains)

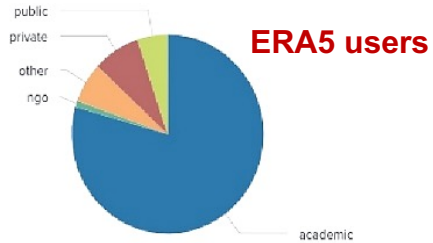
State-of-the-art:

- ✓ Redo historical weather using a modern but fixed NWP system
- ✓ For extended period back in time, but at lower resolution
- ✓ Maintained close to NRT (operational reanalysis)
- ✓ Made available to users in a convenient way (.e.g., CADS)

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**





ERA5 users

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Status of the ERA5 global reanalysis

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

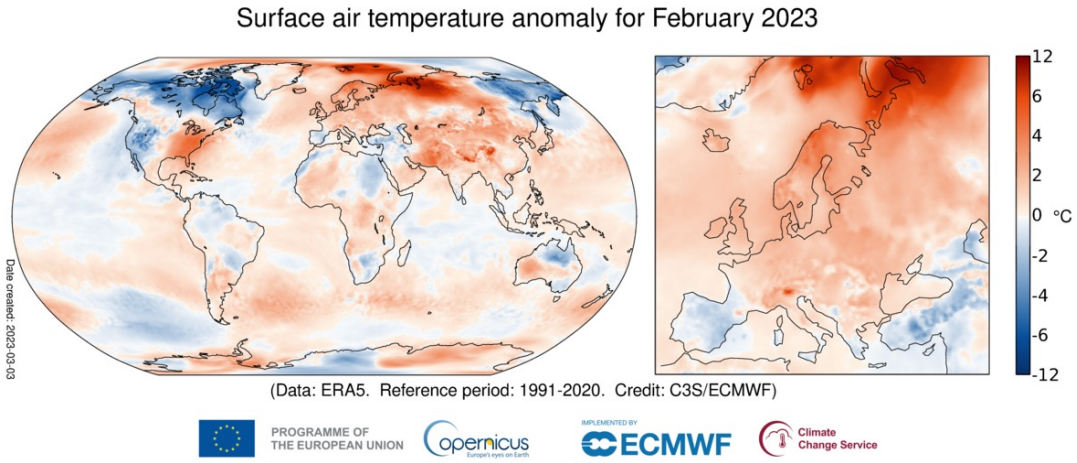
- Produced at ECMWF, by the **Copernicus Climate Change Service**
- Over 109,000 CADS users, ~700 Tbyte of downloads per week
- ERA5 Journal paper 2020 (doi.org/10.1002/qj.3803) > 7,500 citations

- 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**, 1950 onwards, 5 days behind real time.

- Total dataset is about 12 petabyte



Observation usage:

- Over 100 billion so far

Usage of external (gridded) products 'as is':

- SST and sea-ice cover
- GHGs, aerosols, TSI, (diagnostic) ozone

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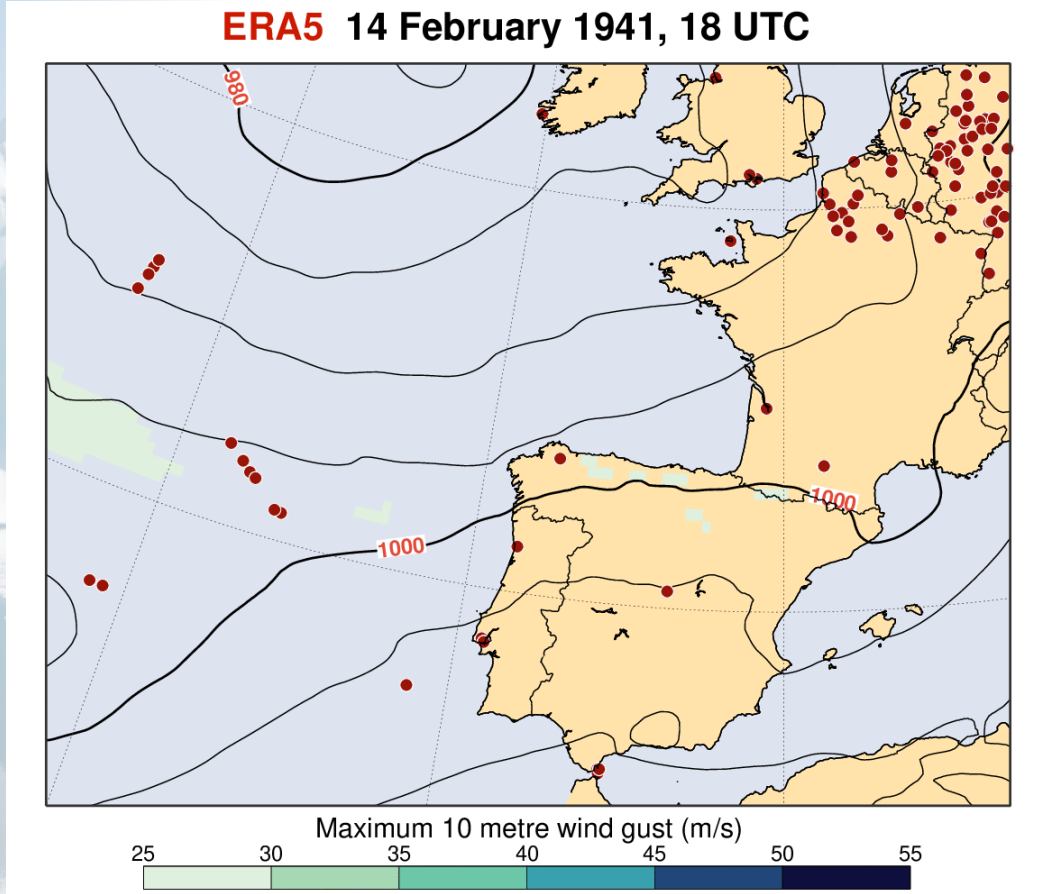
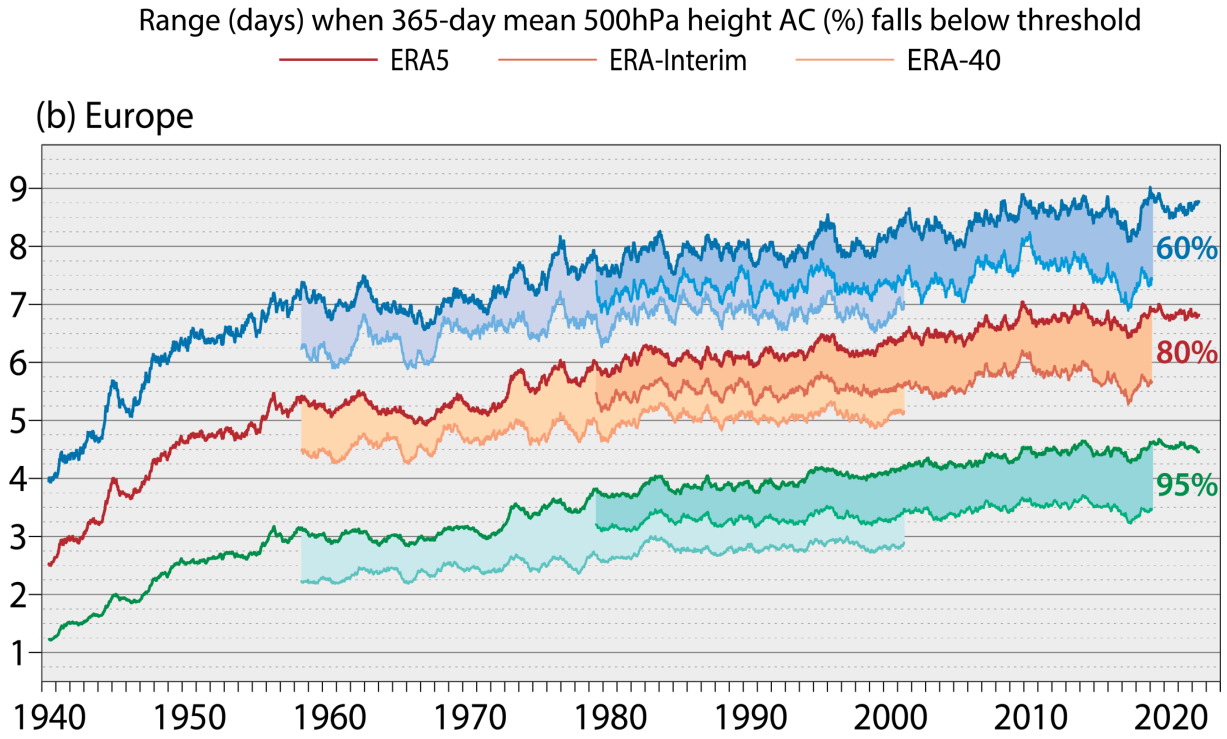
An extension back to 1940 was recently made available: over 83 years of hourly snapshots



Iberian storm case of 1941



Skill of 10-day forecasts initialized from ERA verified against ERA

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The ERA5 observing system

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53K (1950) – 26 Million (2021) obs per day
Over 200 types of reports

Satellite observations, mostly since 1979:

Microwave radiances:
- temperature and humidity sounders, imagers

Infrared sounder radiances
- multispectral, hyperspectral

Geostationary radiances
Atmospheric motion vectors
GNSS-RO bending angles
Scatterometer: ocean wind + land soil moisture
Ozone level 2 retrievals + level 1B
Altimeter wave height

Conventional observations

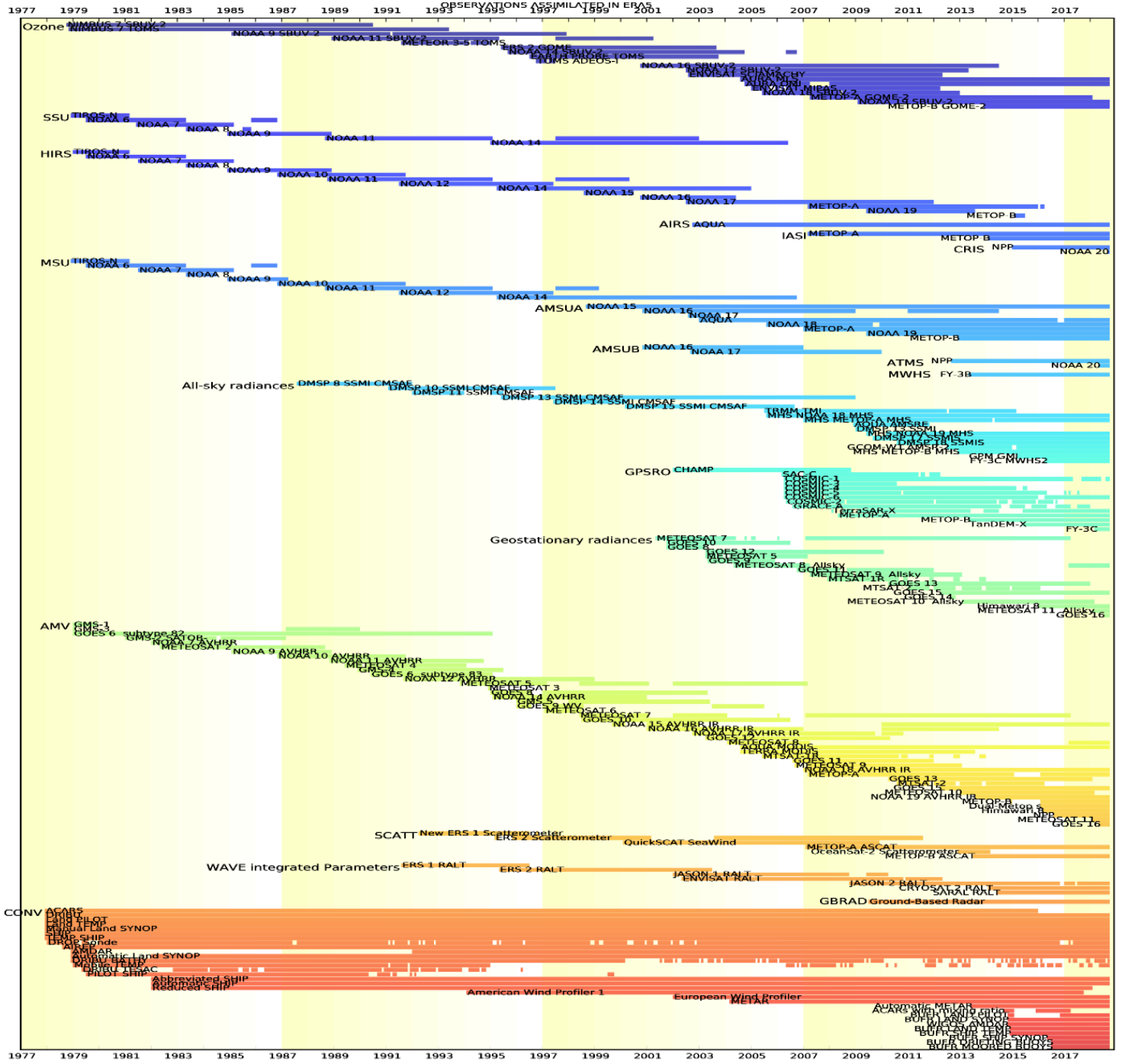
Surface: Land stations, buoys, ships
Upper-air: Balloons, dropsondes, aircraft, profilers

Latest instruments

TAMDAR, MODE-S, SPIRE, FY-3, ..

+ Reprocessed satellite observations

+ Rescued in situ observations



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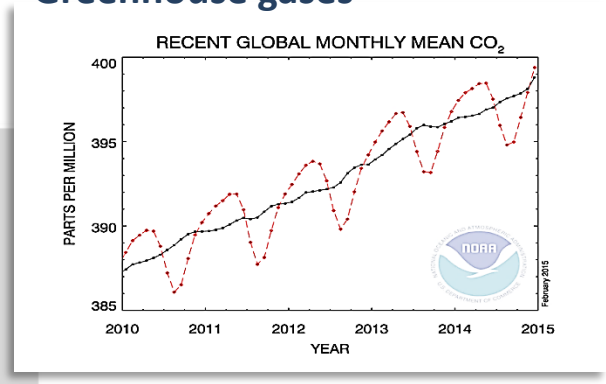
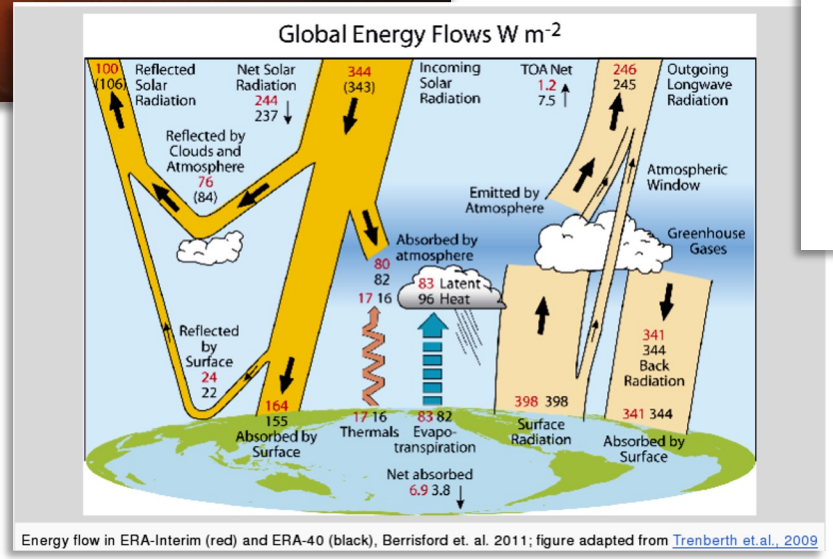
Observation-based (gridded) forcing and boundary conditions

that reflect the 20th and 21th century evolution

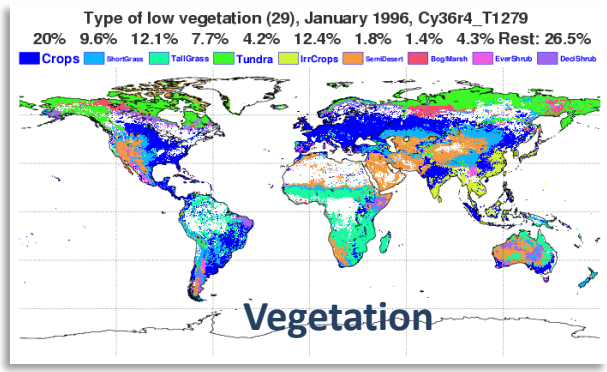
Solar forcing

Greenhouse gases

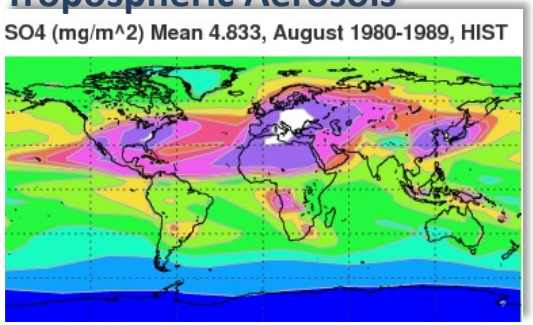




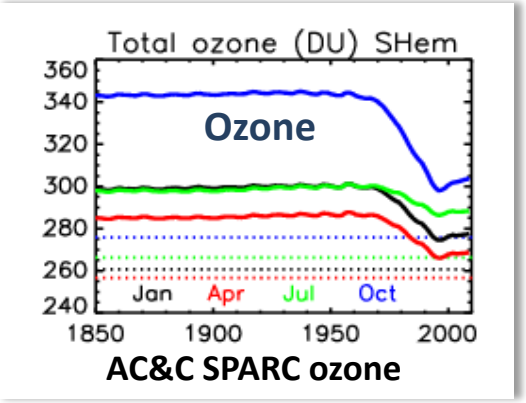
Energy flow in ERA-Interim (red) and ERA-40 (black), Berrisford et. al. 2011; figure adapted from Trenberth et.al., 2009



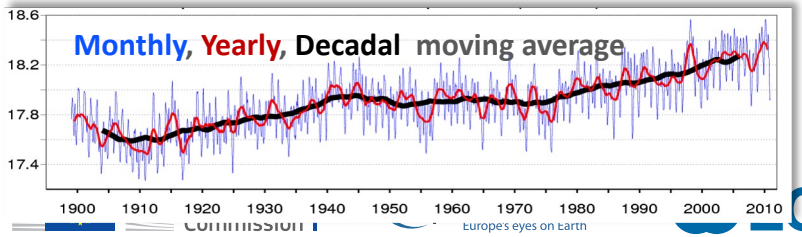
Tropospheric Aerosols



Volcanic eruptions



SST and sea ice



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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 - 2019 ERA-Interim	5) 2016 - … ERA5

Ocean *+sea ice*

2006 ORAS3	2010 - … ORAS4	2016 - … ORAS5/OCEAN5

ERA CLIM / ERA CLIM 2

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

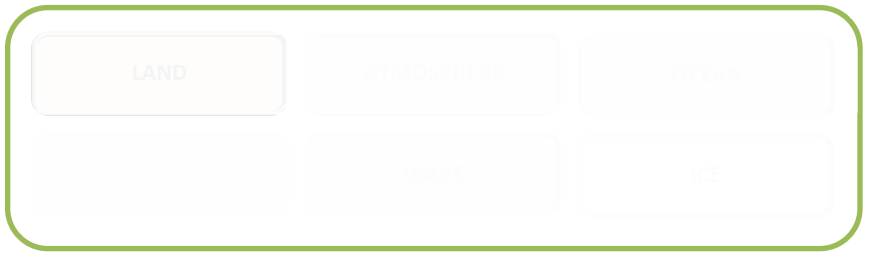
Next generation

6) 2024 - … ERA6

2023 - … ORAS6/OCEAN6

2026 - … ERA6L

2024 - … CAMS EAC5



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Planning towards ERA6: production to start in July 2024

From IFS Cy41r2 -> Cy49r1: ERA6 will benefit from an additional 8 years of R&D at ECMWF & improved compute capacity

Higher resolution: TCo639 (799) @ 18km (14km) vs 31km for ERA5

Ocean DA developments

- ERA6 is to use SST and sea ice fields that are enriched by the ORAS6 and OCEAN6 DA

4D-Var DA developments

- Better EDA that evolves the background error covariance matrix
- Weak constraint 4D-Var to handle systematic model error
- Evolution of VarBC for observations

Land DA developments

- Reduce biases in snow and improve assimilation of snow observations

Improved ocean wave physics

- At same resolution as the atmosphere (@18km or better)
- Improved drag for extreme situations

Improved atmosphere:

- New ozone model (HLO) and prognostic with radiation
- Improved gas optics and solar spectrum to reduce stratospheric biases

ERA6, more and better observations & better usage:

- Newly available at ECMWF since the ERA5 model cycle
- Potentially assimilate T2m observations in 4D-Var as well
- Reprocessed satellite observations (from EUMETSAT)
- Rescued data (satellite and in-situ)

Improved near-surface quantities and radiative forcing

- vegetation cover and type, LAI, lake cover and properties, urban tile
- New, and more species of, aerosols and GHG's

ORAS6/OCEAN6: to provide SST and sea ice cover to ERA6

- NEMOv4 + SI3 ocean and ice model
- Historical part driven by hourly ERA5 atmospheric forcing
- New ensemble-based variational ocean DA
- Flow-dependent background error variance and correlation scales, both are critical for better assimilation of sea surface observations
- SST assimilation rather than nudging
- Assimilation of L3 rather than L4 sea ice

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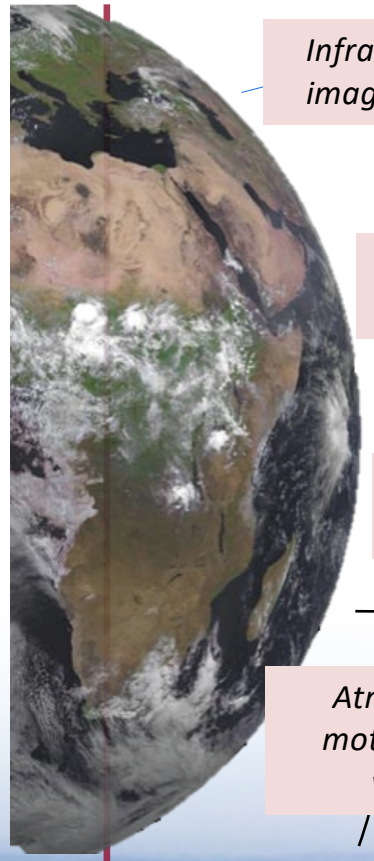
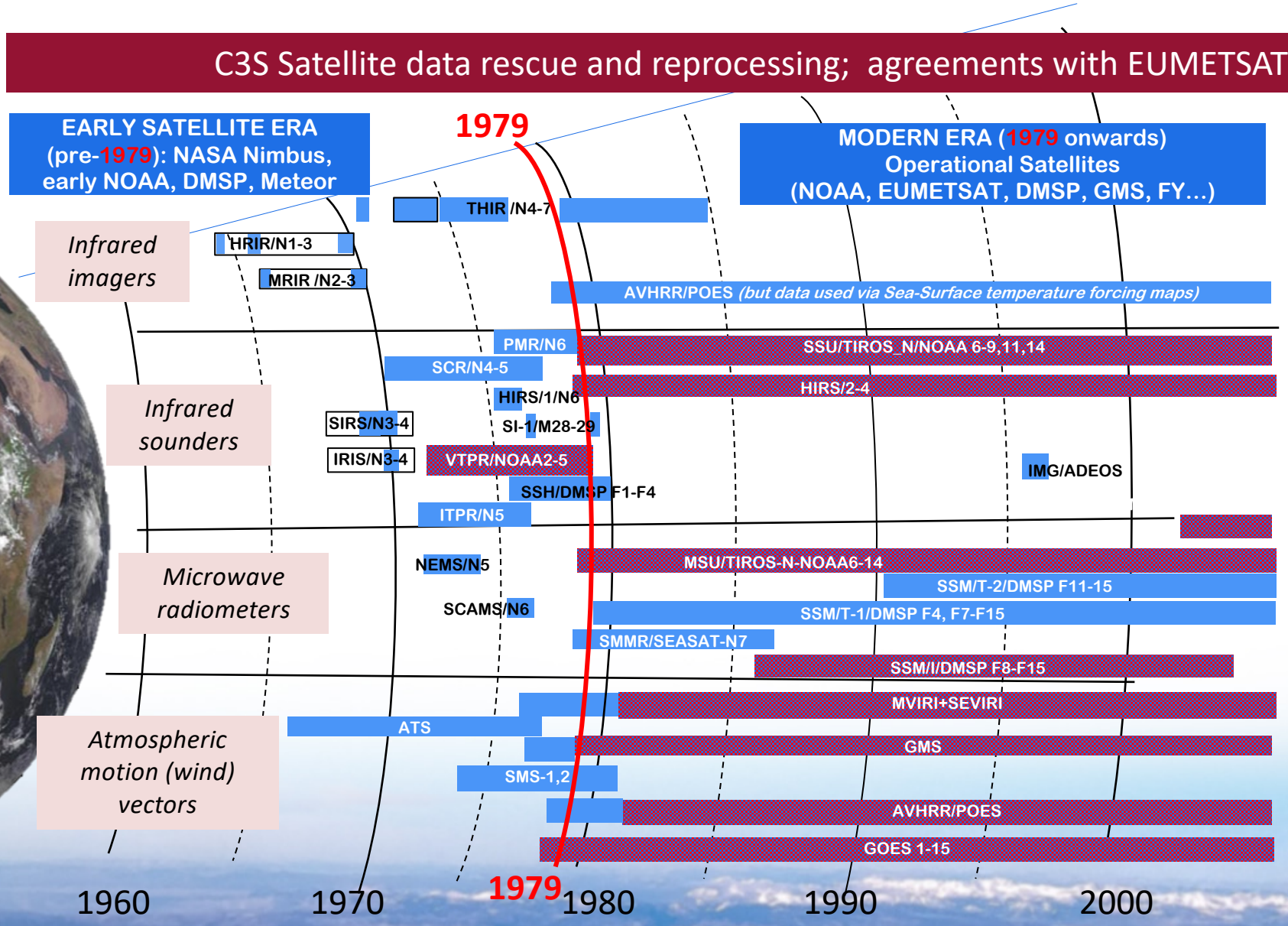
C3S Satellite data rescue and reprocessing; agreements with EUMETSAT and Spascia





Data Rescue (Spascia, C3S2_314): decoding original data, reformatting, archiving & QC

Reprocessing (EUMETSAT, C3S2_310): recalibration, navigation, quality assessment

Both activities aim to improve assimilation readiness of these datasets for ERA6 and high-resolution (regional) reanalyses, and also support ECV production

Recent progress includes :

- **Efficient collaboration** between rescue and reprocessing activities (*e.g.* Radiative transfer modelling, MSU reprocessing, polar AMVs from early rescued satellite radiances)
- **Assessment of COP1 datasets:** feedback from ECMWF in advance of ERA6, optimize processes to accelerate data readiness for ERA6
- **Inventory of early satellite data records:** intended for wider community use, discussed way forward towards publication

Data not yet assimilated in ERA

Original or earlier-reprocessed data version assimilated in ERA5

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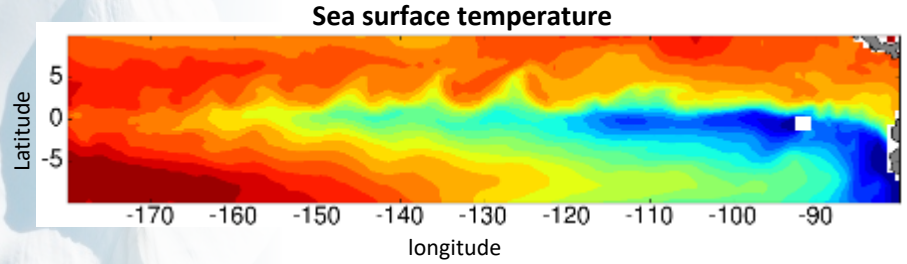
Expected impact from coupled processes: Experience from CERA-20C

Tropical instability waves (TIW)

westward-propagating waves near the equator



ERA20C (Forced reanalysis)

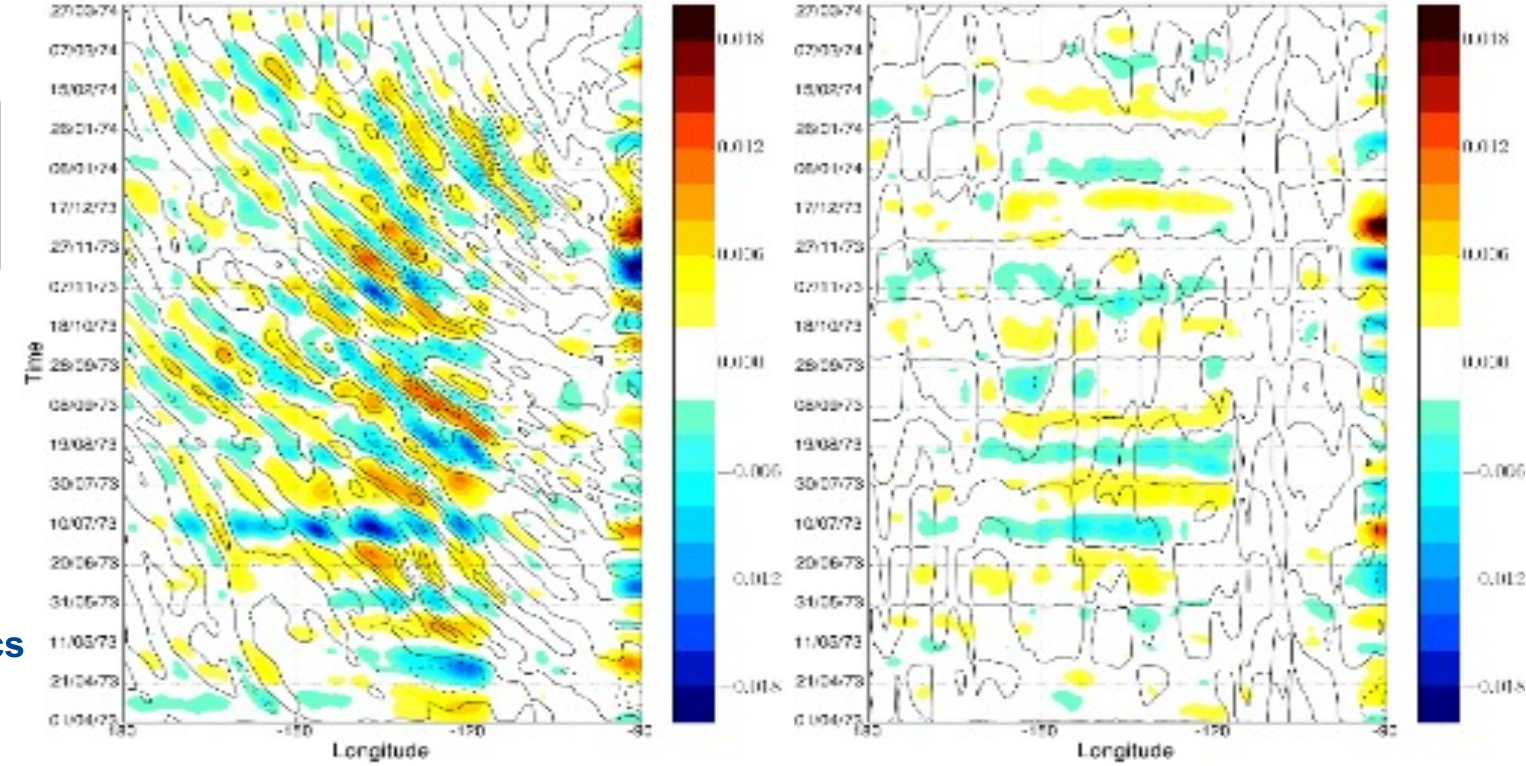
- no TIWs or wind stress signals (forced by 'monthly' SST)

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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Beyond ERA6: building on and synergy with R&D at ECMWF

Details described in: De Rosnay et al., 2022 (doi.org/10.1002/qj.4330)

A key focus of ECMWF R&D on DA is to identify an optimal degree of coupling across the Earth system components for the benefit of seamless NWP and reanalysis:

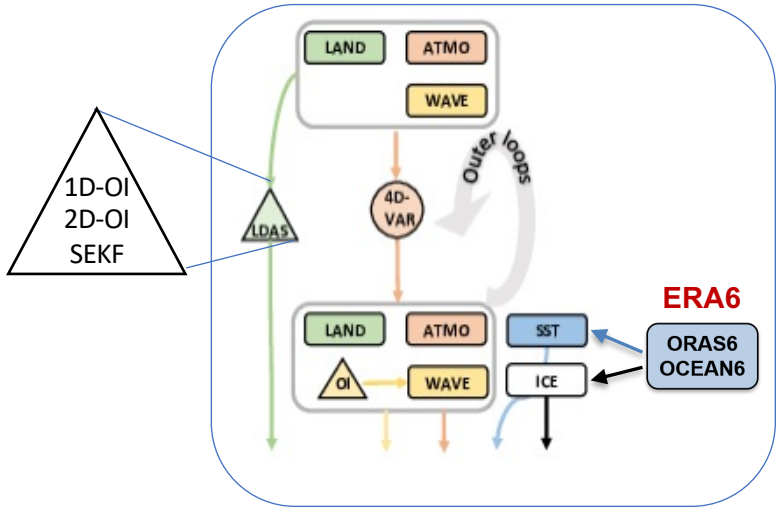
- **Enhance the consistency of individual components**
  Examples: an improved description of ocean covariances, evolution of the land DA into one, multivariate system.

- **Establish the optimal degree of coupling across components**
  Example: outer loop coupling where observations in each component have an influence on any other

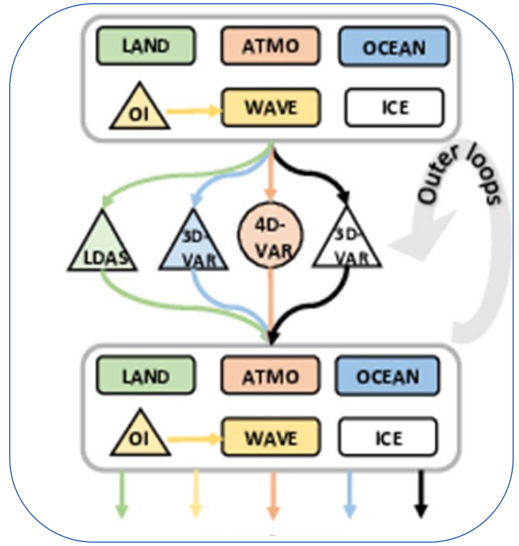
- **Enhance the exploitation of interface observations** that have sensitivity to more than one component.

Outcomes are expected to flow into ERA7.

ERA5 and ERA6



Target for ERA7



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Summary and Final Remarks

--------> **4-8 Sept 2023 ECMWF Annual Seminar on Earth System Reanalysis #AS2023** <--------

The **ERA5** reanalysis provides **hourly snapshots** of the atmosphere, land surface and ocean waves for **over 83 years**

- Very popular dataset on the **CADS**: https://cds.climate.copernicus.eu/#!/home

We have started preparations for ERA6

- Higher resolution and based on an additional 8 years of R&D and state-of-the-art at ECMWF
- Better and more observations; together with C3S contractors
- Improved realism of boundary conditions and forcing
- Address ERA5 challenges:
  - counter-act systematic model error
  - improve the uncertainty estimate

Future Earth System Reanalysis will continue to be aligned with R&D at ECMWF

- Towards enhanced and stronger coupling of components
- Also with help of external funding, such as
  - the concept of outer loop coupling (ESA CERA, EU-FP7 ERACLIM-2),
  - Multivariate LDAS and its outer loop coupling (EU-HE CERISE)

We receive a lot of feedback from our users and listen to them: **we are user-driven**

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