Prospects for Earth system reanalysis at ECMWF: ERA6 and beyond

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

and many others!
Overview

• 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
ECMWF operates the Copernicus Climate Change Service (C3S) and Copernicus Atmosphere Monitoring Service (CAMS) on behalf of the European Commission.
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: 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
An extension back to 1940 was recently made available: over 83 years of hourly snapshots.

Iberian storm case of 1941
The ERA5 observing system

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
Observation-based (gridded) forcing and boundary conditions that reflect the 20th and 21st century evolution.
ECMWF has a long experience with reanalysis:

- **Atmosphere/land**
  - 1) 1979 - 1981 FGGE
  - 2) 1994 - 1996 ERA-15

- **including ocean waves**
  - 3) 2001 - 2003 ERA-40
  - 4) 2006 - 2019 ERA-Interim
  - 5) 2016 - ... ERA5

- **Ocean**
  - 2006 ORAS3
  - 2010 - ... ORAS4
  - 2016 - ... ORAS5/ OCEAN5

- **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 - ... ORAS5/OCEAN5

- **Centennial**
  - 2013 - 2015 ERA-20CM/20C

- **Outer loop Coupling**
  - 2016 CERA-20C
  - 2017 CERA-SAT

- **2006 - 2009 GEMS**
  - 2010 - 2011 MACC
  - 2017 - ... CAMS EAC4
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
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

**MODERN ERA (1979 onwards)**
- Operational Satellites (NOAA, EUMETSAT, DMSP, GMS, FY...)

**EARLY SATELLITE ERA** (pre-1979): NASA Nimbus, early NOAA, DMSP, Meteor

**Infrared imagers**
- HRIR/N1
- MRIR /N2
- MODERN ERA (1979 onwards)
- Operational Satellites (NOAA, EUMETSAT, DMSP, GMS, FY...)

**Infrared sounders**
- HIRS/N1-3
- SIRS/N3-4
- IRIS/N3-4
- THIR/N4-7

**Microwave radiometers**
- SMS-1,2
- MVIRI+SEVIRI
- GMS
- SSU/TIROS_N/NOAA 6,9,11,14
- SSU/NOAA6-14
- SSMT-2/DMSP F11-15
- SSMT-1/DMSP F4, F7-F15
- SSMR/SEASAT-N7
- SSM/I/DMSP F8-F15
- SMMR/SEASAT
- AVHRR/POES
- GOES 1-15

**Atmospheric motion (wind) vectors**
- ATS
- NEMS/N5
- SCAMS/NL
- SSH/DMSP F1-F4
- VTPR/NOAA2-5
- PMR/N6
- SCR/N4-5
- HIRS/1/N6
- SI-RM2B-2B

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- MSU/TIROS
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**Data not yet assimilated in ERA**

**Original or earlier-reprocessed data version assimilated in ERA5**
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)
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.
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](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**