Coupled reanalysis at ECMWF

Dinand Schepers,
Eric de Boisseson, Roberto Buizza, Giovanna De-Chiara,
Dick Dee, Reima Eresmaa, Hans Hersbach, Patrick Laloyaux,
Cristina Lupu, Patricia de Rosnay

Dinand.Schepers@ecmwf.int
Reanalysis

Reanalysis offers a detailed overview of the past atmosphere Earth system

- **Complete**: combining vast amounts of observations into (global) fields
- **Consistent**: use the same physical model and DA system throughout
- **State-of-the-art**: use the best available observations and model at highest feasible resolution

Reanalysis allows for a close monitoring of the Earth’s climate system also where direct observations are sparse.
Reanalysis (II)

Reanalyses of the modern observing period (~30-50 years):

- Produce the best state estimate at any given time (as for NWP)
- Use as many observations as possible, including from satellites
- Closely tied to forecast system development and evaluation
- Can support product updates in near-real time

Extended climate reanalyses (~100-200 years):

- As far back as the instrumental record allows
- Pioneered by NOAA-CIRES 20th-Century Reanalysis Project
- Long perspective needed to assess current changes
- Main focus is on consistency, low-frequency variability
- Use only a restricted set of observations
Reanalysis (III) – The ECMWF reanalysis landscape

<table>
<thead>
<tr>
<th>Atmosphere/land</th>
<th>including ocean waves</th>
<th>including sea ice</th>
</tr>
</thead>
<tbody>
<tr>
<td>4) 2006 - ... ERA-Interim</td>
<td>5) 2016 - ... ERA5</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ocean</th>
<th>Centennial</th>
<th>Coupled</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010 - ... ORAS4</td>
<td></td>
<td>2017 CERA-SAT</td>
</tr>
<tr>
<td>2016 - ... ORAS5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Enhanced land</th>
<th>Atmospheric composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012 ERA-Int/Land</td>
<td>2008 - 2009 GEMS</td>
</tr>
<tr>
<td>2014 ERA-20C/Land</td>
<td>2010 - 2011 MACC</td>
</tr>
<tr>
<td>2018 - ... ERA5L</td>
<td>2017 - ... CAMS</td>
</tr>
</tbody>
</table>
Outline - Coupled reanalysis at ECMWF

• Reanalysis – An introduction

• A quick recap – how did we get where we are now?
  • Pioneering work done in the ERA-CLIM and ERA-CLIM2 projects

• A pilot for coupled reanalysis in the satellite era: CERA-SAT
  • Assimilation approach and system setup
  • Preliminary assessment of performance

• Current reanalysis (and related) activities at ECMWF
  • ERA5
  • Copernicus Climate Change Service (C3S)
Goal: Preparing input observations, model data, and data assimilation systems for a global atmospheric reanalysis of the 20th century

Main components:
- Data rescue (in-situ upper-air and satellite observations)
- Incremental development of new 20C reanalysis products
- Use of reanalysis feedback to improve the historic data record
- Access to reanalysis data and observation quality information
Although there are certainly model biases:

- **ERA-20CM** gives good reference of low-frequency variability
- Well suited to project global warming and major events onto other geophysical quantities not directly provided in the forcing data

**Radiative forcing**

**HadISST2 SST and sea ice**
Century-long climate reanalysis using surface observations only

ISPD 3.2.6 and ICOADS 2.5.1 pressure observations assimilated in ERA-20C

1899

ERA-CLIM project – ERA-20C

Published: February 16, 1899
Copyright © The New York Times

TERRIFIC STORMS AT SEA
Steamships from All Quarters Report Extremely Rough Voyages.

ALL MORE OR LESS BATTERED
Vessels Sighted in Distress and Abandoned — Blinding Snow and Waves Like Mountains.

All the steamers that came in yesterday were covered with ice from the tops of the masts down to the water line, and all had passed through storms of blinding snow and mountainous waves. The British steamer Ethelenda, from Bristol and Boston, which left the latter port on Jan.

1) Poli et al. J. Climate 2016 ; ERA-20C Observation Feedback Archive available at www.ecmwf.int/research
Goal: Production of a consistent 20th-century reanalysis of the coupled Earth-system: atmosphere, land surface, ocean, sea-ice, and the carbon cycle

Main components:
- Production of coupled reanalyses, for 20C and the modern era
- Research and development in coupled data assimilation
- Earth system observations for extended climate reanalyses
- Evaluation of uncertainties in observations and reanalyses
Century-long climate reanalysis using surface observations only (like ERA-20C), but coupled with the ocean and sea ice

Example: Tropical instability waves (westward-propagating waves near the equator)

CERA-20C
- represents TIWs thanks to the ocean dynamics
- atmosphere responds accordingly (surface wind stress is sensitive to the ocean TIW)

ERA20C
- no TIWs or wind stress signals (forced by monthly SST)

Courtesy of Eric de Boisseson
A pilot for coupled reanalysis of the satellite era, using a higher resolution ocean component and the full, modern observing system

“Whilst Earth system modelling is already in its early stages, its application to data assimilation is very novel and results could be ground-breaking”
ERA-CLIM2 project – CERA-SAT

**Atmosphere/Land**
- **Model:** IFS (CY42R1, April 2016)
- **Atmosphere Resolution:** TL319 (~60 Km); 137 levels
- **Assimilation:** 24-hour window 4D-Var
- **Full observing system:** ERA5 observing system
- **Land surface analysis:** Dedicated; Weakly coupled

**Ocean/Sea ice**
- **Model:** NEMO / LIM2 (CY42r1)
- **Resolution** (1/4 degree; ORCA025) ~30 km; 75 levels
- **Assimilation:** 24-hour window 3D-Var FGAT
- **Observations:** salinity and temperature profiles, SSH, SI analysis (OSTIA L4)

**Wave**
- **Model:** WAM (CY42R1)
- **Resolution:** 0.5 degree
- **Assimilation:** 24-hour window
- **Observation:** ERA5 observing system
CERA – Outer loop coupled assimilation

Full observing system
- SYNOP, radiosondes, radiances, scatterometer, etc.
- Screen level, snow depth and cover, soil moisture, etc.

Salinity and Temperature
- Subsurface profiles of salinity and temperature
- EN4.1.1 dataset
- Sea surface height

SST and sea ice analysis
- OSTIA 0.05° product
  sea ice concentration (L4)

SST nudging
CERA-SAT – A pilot for satellite era coupled reanalysis

- 10-member ensemble of data assimilations (EDA)
- Available between 2008 and 2016 (produced in 4 streams)
- Uncoupled CTRL for assessment studies
CERA-SAT – Improved fit to observations

Control-normalized standard deviation of background departure
- Global, 1-year sample (1 Sept 2015 – 31 Aug 2016)
- Improvements in
  - Temperature btw 300—1000 hPa
  - Wind btw 100—300 hPa

Bars indicate 95% confidence intervals

CTRL: Uncoupled, atmosphere/land/wave analysis and forecasts

Courtesy: Reima Eresmaa Cristina Lupu
CERA-SAT – Improved fit to observations

Control-normalized standard deviation of background departure

- global 1-year sample (1 Sept 2015 – 31 Aug 2016)
- Improvements in
  - AMSU-A microwave radiance channels 9—14
  - Microwave humidity sounder radiances
  - Radio occultation data btw 15—35 km

Bars indicate 95% confidence intervals

CTRL: Uncoupled, atmosphere/land/wave analysis and forecasts

Courtesy: Reima Eresmaa, Cristina Lupu
CERA-SAT – Improved fit to observations (in the Tropics)

Courtesy: Reima Eresmaa, Cristina Lupu

EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS
CERA-SAT – Improved forecast performance

Forecast improvements at Day+5 in Tropical regions - against own analysis

Reduction of forecast error standard deviation

- Temperature: 1.5% - 3%
- Relative humidity: 1% - 2%
- Vector winds: 4% - 5%

CTRL: Uncoupled, atmosphere/land/wave analysis and forecasts

Difference in standard deviation of error
(May 2015 – Aug 2016, own analysis)

Courtesy: Reima Eresmaa, Cristina Lupu
CERA-SAT – Improved forecast performance

Forecast improvements at Day+5 in Tropical regions - against own analysis
Reduction of forecast error standard deviation

- Tropics pressure about 5 - 10 %
- Tropics Z500 about 5 - 10 %

CTRL: Uncoupled, atmosphere/land/wave analysis and forecasts

Difference in standard deviation of error (May 2015 – Aug 2016, own analysis)

Courtesy: Reima Eresmaa, Cristina Lupu
Coupled assimilation – Scatterometer denial experiments

Assimilation of scatterometer winds benefits ocean salinity
Reduction of salinity background and analysis departures

Courtesy: Giovanna De-Chiara

- RANGE WEATHER FORECASTS
CERA-SAT – Global ocean heat budget

Global ocean heat budget decomposition - Comparing CERA-SAT and ORAS5

- Total global heat content rate of change (Black) very similar
- Although contributions from individual sources differ significantly

![Graph showing global ocean heat budget decomposition]

Courtesy of Eric de Boisseson
Forecast performance for Europe - compared to operational ECMWF reanalyses

Number of days after which AC (%) falls below threshold

- CERA-SAT outperforms ERA-Interim
- CERA-SAT underperforms w.r.t. ERA5
- Note the temporal variations

500 hPa geopotential height

Two-metre temperature
CERA-SAT vs. ERA5

State-of-the-art, operational reanalysis

- High resolution (TL639)
- 12-hour assimilation window
- ‘Uncoupled’ – atmosphere/land/wave only

Experimental, pilot reanalysis

- Moderate resolution (TL319)
- 24-hour assimilation window
- Outer loop coupled
ERA5 – State of the art reanalysis

Hourly data throughout and more parameters

Uncertainty estimate

Spread in Surface Pressure (hPa)

January 1979

July 2014
**ERA5 – State of the art reanalysis**

<table>
<thead>
<tr>
<th></th>
<th>ERA-Interim</th>
<th>ERA5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Period</strong></td>
<td>1979 – present</td>
<td>Initially 1979 – present, later addition 1950-1978</td>
</tr>
<tr>
<td><strong>Streams</strong></td>
<td>1979-1989, 1989-present</td>
<td>Parallel streams, one/two per decade</td>
</tr>
<tr>
<td><strong>Assimilation system</strong></td>
<td>2006, 4D-Var</td>
<td>2016 ECMWF model cycle (41r2), 4D-Var</td>
</tr>
<tr>
<td><strong>Model input</strong></td>
<td>As in operations, <em>(inconsistent sea surface temperature)</em></td>
<td><em>Appropriate for climate</em>, e.g., evolution greenhouse gases, volcanic eruptions, sea surface temperature and sea ice</td>
</tr>
<tr>
<td><strong>Spatial resolution</strong></td>
<td>79 km globally 60 levels to 10 Pa</td>
<td>31 km globally 137 levels to 1 Pa</td>
</tr>
<tr>
<td><strong>Uncertainty estimate</strong></td>
<td></td>
<td>Based on a 10-member <em>4D-Var ensemble</em> at 62 km</td>
</tr>
<tr>
<td><strong>Land Component</strong></td>
<td>79km</td>
<td>ERA5L, 9km (separate, forced by ERA5)</td>
</tr>
<tr>
<td><strong>Output frequency</strong></td>
<td>6-hourly Analysis fields</td>
<td><em>Hourly</em> (three-hourly for the ensemble), <em>Extended list of parameters</em></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~ 9 Peta Byte <em>(1950 - timely updates)</em></td>
</tr>
<tr>
<td><strong>Extra Observations</strong></td>
<td>Mostly ERA-40, GTS</td>
<td>Various <em>reprocessed CDRs, latest instruments</em></td>
</tr>
<tr>
<td><strong>Variational Bias correction</strong></td>
<td>Satellite radiances, radiosondes predetermined</td>
<td>Also ozone, aircraft, surface pressure, newly predetermined for radiosondes.</td>
</tr>
</tbody>
</table>
ERA5 – State of the art reanalysis

Forecast performance for Northern / Southern hemisphere - compared to ERA-Interim
Number of days after which AC (%) falls below threshold
C3S – Climate data store

Scientific basis:
- Essential Climate Variables as defined by GCOS
- GCOS Status Report and Implementation Plan
- IPCC, CMIP

Observations
- Global estimates of ECVs from satellite and in-situ observations
- Reprocessed CDRs, reference observations
- Support for data rescue, climate data collections

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

Climate Indicators
## C3S – Climate indicators

<table>
<thead>
<tr>
<th>Climate Indicators</th>
<th>Trend</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface temperature</td>
<td>↑</td>
</tr>
<tr>
<td>Greenhouse gases</td>
<td>↑</td>
</tr>
<tr>
<td>Rain</td>
<td>─</td>
</tr>
<tr>
<td>Sea Ice</td>
<td>↓</td>
</tr>
<tr>
<td>Glaciers</td>
<td>↓</td>
</tr>
<tr>
<td>Sea Level</td>
<td>↑</td>
</tr>
<tr>
<td>Soil Moisture</td>
<td>↓</td>
</tr>
</tbody>
</table>

*Credit: Victor & Kennel, Nature Climate Change, 2014.*
The CDS contains observations, global and regional climate reanalyses, global and regional climate projections and seasonal forecasts. It also contains generic and sectoral climate indicators.

The CDS is designed as a distributed system, providing improved access to existing datasets through a unified web interface.

cds.climate.copernicus.eu
Where next?

C3A provides for operational production of reanalyses, envisioning a regular upgrade cycle

- Centennial reanalyses based on limited historical observations
- Reanalyses of the modern era
- Based on ECMWF operational models (following operational drive towards coupling)
Final remarks

Reanalysis activities at ECMWF have produced a sizable body of experience—and data sets—regarding Earth system assimilation in the context of limited, historical observations systems (CERA-20C) as well as for modern-day assimilation scenarios (CERA-SAT).

State of the art—uncoupled—operational reanalysis production is now undertaken at ECMWF by the Copernicus Climate Change Service (C3S). Future, coupled reanalyses are envisioned within C3S, leveraging operational model developments towards Earth system assimilation as well as external reprocessing and data rescue efforts.

For now, the vanguard of coupled reanalysis at ECMWF is represented by CERA-SAT, publicly available through MARS.
Thank you
10-member ensemble spread for Temperature

- Lower ensemble spread in coupled experiment
- June 2015 – May 2016
- Signal consistent in time (no apparent seasonality or change in time)

Hypothesis: Nudging to external SST analysis in coupled setup is stricter (too strict?) than SST perturbation in uncoupled.