Modern reanalysis:
A framework for paleoclimate data assimilation?

Dick Dee, ECMWF
DAPS2017, Louvain-la-Neuve, 29 May 2017

Global Temperature Relative to 1800-1900 (°C)
Modern reanalysis:
A framework for paleoclimate data assimilation?

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DAPS2017, Louvain-la-Neuve, 29 May 2017

• Reanalysis at ECMWF
• Centennial reanalysis: ERA-CLIM
• A few thoughts on the title
Numerical weather prediction and climate reanalysis

Weather prediction (real time)

Observations → Analysis → Forecast → Analysis → Forecast

Reanalysis (past time)

Observations → Analysis → Forecast → Analysis → Forecast

Anomaly correlation of 500hPa height forecasts

- Northern hemisphere
- Southern hemisphere

ERA-interim
Operations


D+3 D+5 D+7 D+10

30 40 50 60 70 80 90 95 98
A brief history of atmospheric reanalysis productions at ECMWF

- The FGGE analyses provided the first global atmospheric dataset for scientific research
- Numerous seminal studies on atmospheric circulation
- Many case studies performed at ECMWF
- **FGGE** = First GARP Global Experiment
- **GARP** = Global Atmospheric Research Program

**FGGE**

1980

Atmosphere/land

1990

ERA-15

Atmosphere/land/waves

2000

ERA-40

2010

ERA-Interim

ERA5

Kanamitsu 1980

Julian 1980
A brief history of atmospheric reanalysis productions at ECMWF

- **ERA-40**: Reanalysis data for 1957-2002
- Includes analyses of ocean wave height
- Use of radiance observations from satellites
- Improved SST and sea-ice data
**A brief history of atmospheric reanalysis productions at ECMWF**

<table>
<thead>
<tr>
<th>1980</th>
<th>1990</th>
<th>2000</th>
<th>2010</th>
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<tbody>
<tr>
<td>FGGE</td>
<td>ERA-15</td>
<td>ERA-40</td>
<td>ERA-Interim</td>
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**Atmosphere/land**

- **ERA-Interim**: Data from 1979 onward
- Continuously updated close to real time
- 4D-Variational data assimilation
- Improved use of satellite data
- Increasingly important for ECMWF research and operations
- ERA-Interim has a major role in Copernicus Services development
ERA5: The latest ECMWF reanalysis is now in production

- Atmosphere/land/wave parameters
- 31 km global resolution, 137 levels
- Hourly output from 1979 onward
- Based on IFS Cy41r2 (March 2016)
- Using improved input observations
- Ensemble data assimilation
- Providing uncertainty estimates

Public release plan:

<table>
<thead>
<tr>
<th>Month</th>
<th>Release Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov 2016</td>
<td>Test data (Jan-Feb 2016)</td>
</tr>
<tr>
<td>July 2017</td>
<td>Hourly data from 2010 - 2016</td>
</tr>
<tr>
<td>Aug 2017</td>
<td>Daily updates at short delay</td>
</tr>
<tr>
<td>Apr 2018</td>
<td>Complete from 1979 onward</td>
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</tbody>
</table>

ERA5 hourly temperatures for January 2016
Why does ECMWF invest in reanalysis?

**Reanalysis provides an excellent testbed for data assimilation**

- It reveals a great deal about the quality of the forecast model
- It leads to new ways to make better use of observations
- It exposes bugs and other technical problems in the Integrated Forecast System (IFS)

**Reanalysis data are essential for ECMWF research and development**

- It provides a comprehensive verification dataset for testing new model developments
- It allows development of new forecast products that rely on climatologies
- It is needed for calibration of monthly and seasonal forecasts

**Reanalysis data are extremely popular with external users**

- Global datasets for research and education
- Input for downstream models and systems
- Essential data for services development
Use of reanalysis data to evaluate forecast performance

• Evolution of skill in operational forecasts is due to
  • model upgrades
  • changes in the observing system
  • atmospheric predictability
• ERA-Interim re-forecasts are produced using a fixed version of the IFS
• Forecast skill relative to ERA-Interim re-forecasts isolates the impact of specific model upgrades
Global EFI - multiple parameters

Anomalous weather predicted by EPS: Wednesday 30 November 2016 0000 UTC
1000 hPa Z ensemble mean (Wednesday 30 November 2016 1200 UTC)
and EFI values for Total precipitation, maximum 10m wind gust and mean 2m temperature (all 24h)
valid for 24 hours from Wednesday 30 November 2016 0000 UTC to Thursday 01 December 2016 0000 UTC
Toward a reanalysis of the coupled Earth system

1980

FGGE
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ERA-Interim

ERA5

Ocean

Ocean/sea ice

Global ocean, using NEMO ocean model

Atmospheric composition, using satellite data from 2003

Century-long reanalyses, using IFS coupled with NEMO

ORAS3
ORAS4
ORAS5

GEMS
MACC
CAMS

ERA-20C
ORA-20C
CERA-20C

Atmosphere/land/waves/ocean/sea ice

ECMWF
Development of century-long reanalyses (FP-7 funding)

Weather observations have been collected systematically since the 18th century. Can we develop a reanalysis extending back to the beginning of the instrumental record? Where do we get the data? How accurate are the observations?
Making the best of early 20th-century weather observations

Two modern analyses of NH geopotential height at 500hPa

Using all available observations

Using surface pressure observations only

Whitaker, Compo, and Thépaut 2009
European collaborative research: The ERA-CLIM projects (2011-2017)

Development of global climate reanalyses spanning the 20th century

Coordinated by ECMWF and involving many institutes across Europe

- Work on input observations and model data
- Data rescue for \textit{in situ} and satellite observations
- Incremental development of new 20C reanalysis products
- Research in coupled data assimilation
- Progress toward a reanalysis of the coupled Earth system
ERA-20C: Reanalysis of an Atlantic storm

3 February 1899

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 coated 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 Ethelinda, from Bristol and Swansea, which left the latter port on Jan. 19, ran into a gale of hurricane force, and seas swept her decks repeatedly. So fierce was the wind that the boat drifted before the gales and was barely able to keep steerage way. She anchored outside the bar late Sunday afternoon. The cable parted and she lost her anchor, together with 100 fathoms of chain. Then the great snow-storm drove her 170 miles off the shore. She succeeded in getting back late on Tuesday night.

The French liner La Bretagne, from Havre, came in a little before noon yesterday, with 58 cabin and 225 steerage passengers. She left Havre on Feb. 4, and two days later she encountered a fierce gale, which soon raised tremendous seas. This lasted until Feb. 12, and during this time the vessel had to be slowed down. The following day heavy head seas were encountered, but the steamer proved herself a
CERA-20C: ECMWF’s first centennial coupled reanalysis

**Model:** IFS/NEMO/LIM2 (CY41R2, March 2016)
**Forcing:** HADISST2 for SST (nudged)
**Observations:** surface conventional, salinity and temperature profiles
**Assimilation:** new CERA system (10-member ensemble coupled DA)
**Resolution:** T159L91/ORCA1 Z42
**Period:** 1901-2010
What do we mean by “Modern reanalysis”?

- Multi-decadal output of a forecast (climate) model constrained by observations
- Can be formulated as a maximum-likelihood problem:
  \[
  J(x) = (x_b - x)^T B^{-1} (x_b - x) + [y - h(x)]^T R^{-1} [y - h(x)]
  \]
  \( J_b \): background constraint
  \( J_o \): observation constraint

- Background constraint: Short model predictions
- Observation constraint: Observations (or proxies)
- Need prior information on errors: B, R (Q, …)
- Other constraints and parameters can be added
Difficult problems with the use of “old” data in modern reanalyses

Data sparsity
- Spatial/co-variate impact of observations is largely determined by assumptions on background errors (B)
- Temporal impact dissipates rapidly (weather scales)
- Quality control and bias correction is very difficult

\[ x^a - x^b = B \left( \frac{\partial h}{\partial x} \bigg|_{x=x^a} \right)^T R^{-1} \{ y - h(x^a) \} \]
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Model biases
- Are not sufficiently constrained by observations
- Changes in observing system result in false trends and variability
- Some work has been done on correcting model biases during data assimilation

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Accurate modelling of observations
- Not enough metadata
- Representativity issues: can the model represent what was measured?
Conclusions Questions

Modern reanalysis
• Developed in NWP context
• Data and models are compatible in terms of representing weather scales
• Is the methodology useful for paleoclimate reconstruction?

Model biases
• Biases in coupled climate models are considerable
• Should the data assimilation problem be re-formulated to constrain model bias parameters first of all?

Accurate modelling of observations
• Are current-generation climate models good enough to accurately simulate available proxy data?
ERA-20CM: Annual and decadal temperature change (ensemble mean)

ERA-20CM data available at www.ecmwf.int/research

Hersbach et al, QJ 2015
Data rescue: Early 20th-century upper-air weather observations

Stickler et al, BAMS 2014
Initial conditions from previous ocean runs based on different configurations were used to sample the uncertainty of the ocean state in 1900.

60°S - 60°N heat-content anomalies for the upper ocean with respect to the EN4OA average for 1970-2000.

E. de Boisseson et al. (2016) An ensemble of 20th century ocean reanalyses for providing ocean initial conditions for CERA-20C coupled. ERA Report Series, 24
Diversification: MACC, ORAS and ERA/Land