The importance of GNSS Radio Occultation data in the ERA5 global reanalysis

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C3S Reanalysis Team, Copernicus Department, ECMWF
Overview

• Copernicus services
• ERA5 configuration and performance
• The usage of GNSS-RO data
• Importance of GNSS-RO data
• Final remarks
The Copernicus Climate Change Service

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

- Copernicus services
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The ERA5 global reanalysis

**ERA5 is in production at ECMWF for C3S**
Atmosphere, land, ocean waves

**ERA5 has replaced ERA-Interim**
(ERA-I was stopped end August 2019)

**Improvements compared to ERA-Interim:**
- Benefit from 10 years model development (2006 to 2016)
- Much higher resolution; **31km** versus 80km
- More and better input data
- **Hourly output**
- 10-member EDA-based **uncertainty estimate** (at 63km)
  - Perturbations to: SST, model tendencies & obs
  - Will reach further back in time (1950 versus 1979)

**Climate Data Store public release plan:**
- **Published to date:** Jan 1979 – June 2019
- **End 2019:** updates 2-5 days behind real time: **ERA5T**
- **Q2 2020:** 1950-1978.
Better model, more and better observations, higher resolution, hourly output
Breakup southern polar vortex in September-October 2002

Water vapour (colours), Montgomery potential on 850K isentropic surface

ERA5 shows finer details
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The ERA5 observing system

0.75 (1979) – 24 Million (2019) obs per day
Over 200 types of reports

Reprocessed data sets
Radiances: SSM/I brightness temp from CM-SAF
MSG from EUMETSAT
Atmospheric motion vector winds: METEOSAT, GMS/GOES-9/MTSAT,
GOES-8 to 15, AVHRR METOP and NOAA
Scatterometers: ASCAT-A (EUMETSAT),
ERS 1/2 soil moisture (ESA)
Radio Occultation: COSMIC, CHAMP, GRACE, SAC-C, TERRASAR-x (UCAR)
Ozone: NIMBUS-7, EP TOMS, ERS-2 GOME, ENVISAT SCIAMACHY, Aura
MLS, OMI, MIPAS, SBUV
Wave Height: ERS-1, ERS-2, Envisat, Jason

Latest instruments
IASI, ASCAT, ATMS, CrIS, MWHS, Himawari, ...

Improved data usage
all-sky vs clear-sky assimilation,
latest radiative transfer function, corrections,
extended variational bias control

Courtesy: Paul Poli
GNSS-RO observations assimilated in ERA5

Reprocessed (from UCAR):
CHAMP, GRACE-A, SAC-C
TerraSAR-X, COSMIC 1-6

Operational product:
METOP-A and B
TanDEM-X
FY-3C
KompSAT-5 (from end July 2019)
**ERA5 data usage** has increased from 0.75 (1979) to 24 million/day (2019).

87 Billion observations assimilated (1979 - 2019)

*Number of used observations per day (log₁₀ scale) for ERA5 and ERA-Interim*

- **Radiances:** Largest volume
- **Conventional:** Radiosondes, aircraft
- **GNSS-RO:** Initially low numbers
  Counts ~ conventional
  Some recent decline
Assimilation of GNSS-RO data in ERA5

Observation operator for bending angle:
- 2-Dimensional
- Sensitive to both temperature and humidity
- Accounts for tangent drift point

Assimilation:
- Increased weight compared to ERA-Interim
- Use between 2-50 km

Anchor measurements
- Do not bias correct
- Note: radiosonde temperatures are subject to prescribed corrections (e.g., RICH)
The merits of variational bias correction

Like ERA-Interim, ERA5 has a dynamic way of estimating biases in the observing system:

- time-evolving biases (both gradual and abrupt)
- relative biases between different components

- Note: need anchors.

The bias parameters are included in the variational control:

\[ J(x, \beta) = (x_b - x)^T B^{-1} (x_b - x) + \left[y - h(x, \beta)\right]^T R^{-1} \left[y - h(x, \beta)\right] \]

On-board warm target variations for MSU NOAA-14: (Dee and Uppala 2009)

Resulting bias estimates also provide a path to more homogeneous observational records
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Ensemble spread as a measure for the *synoptic* ERA5 uncertainty

(a)

**AMSU-A**

**COSMIC?**

Temperature

![Diagram of pressure and temperature over time with color-coded zones indicating ensemble spread and uncertainty.](image-url)
Inter-comparison of global reanalyses: convergence from 2006 (COSMIC)
Between 2000-2006 the ERA5 temperature mean state has a problem in the stratosphere

- ERA5 model is more biased than ERA-Interim
  - Cold in lower stratosphere
  - Warm above 20 hPa
- background-error covariance matrix with shorter correlation lengths
- Weight radiosonde temperatures reduced
- Insufficient RO observations to anchor model bias
  - Bias estimates of satellite data alias model error

Solution:
- Use more appropriate background-error covariance matrix, as from 1979-1999
- **ERA5.1**: to be made available early 2020
- 2000 until advent of COSMIC in 2006
ERA5 anomalies compared to 1981-2010
ERA5.1 anomalies compared to 1981-2010

Monthly mean anomalies wrt. 1981-2010 - Global

Temperature (K)

Monthly mean analysis increments - Global

Temperature (K)
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The ERA5 Global Reanalysis

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- Submitted September 2019 to QJRMS
- In the meantime, see: Hersbach et al 2018, Operational global reanalysis: progress, future directions and synergies with NWP (from https://www.ecmwf.int/en/publications/)
- For ERA5 data from the C3S Climate Data store: https://cds.climate.copernicus.eu
Final remarks and outlook

**ERA5 is available from 1979 and has replaced ERA-Interim.**
- Produced at ECMWF by C3S
- Much higher resolution, better model, better and more observations
- The ensemble provides information on the evolving confidence of its products
- 1950-1978 to come, as well as ERA5.1

**Although ERA5 uses VarBC, anchor observations are essential**
- To guarantee the temporal consistency of the reanalysis mean state
- To avoid the aliasing of model bias into satellite observation bias estimates

**Sufficient amounts of GNSS-RO observations from 2006 onwards are important**
- To estimate the large-scale model bias, by using e.g., weak-constraint 4D-Var (*Patrick Laloyaux, Monday 23 Sept.*)
- which may be mapped back in time as forcing term to also improve the mean state before 2006

**Future C3S reanalysis will build on better observations and models:**
- satellite reprocessing (EUMETSAT), data rescue, consolidation of historical datasets
- DMI, Orsted occultations (1999)
Back-up slides
### What is new in ERA5?

<table>
<thead>
<tr>
<th>Feature</th>
<th>ERA-Interim</th>
<th>ERA5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Period</strong></td>
<td>1979 – present</td>
<td><strong>1950 – present</strong>, produced in 2 phases</td>
</tr>
<tr>
<td><strong>Availability behind real time</strong></td>
<td>2-3 months</td>
<td>2-3 months (final product)</td>
</tr>
<tr>
<td><strong>Assimilation system</strong></td>
<td>2006 (31r2), 4D-Var</td>
<td>2016 (41r2), <strong>4D-Var, hybrid EDA providing B</strong></td>
</tr>
<tr>
<td><strong>Model input (radiation and surface)</strong></td>
<td>As in operations, <em>(inconsistent SST and sea ice)</em></td>
<td>Appropriate for climate, 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>
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<td><strong>Uncertainty estimate</strong></td>
<td></td>
<td>from 10-member <strong>EDA at 62 km</strong></td>
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<tr>
<td><strong>Output frequency</strong></td>
<td>6-hourly Analysis fields</td>
<td><strong>Hourly</strong> (three-hourly for the ensemble), Extended list of parameters ~ 9 Peta Byte (1950 - timely updates)</td>
</tr>
<tr>
<td><strong>Extra Observations</strong></td>
<td>Mostly ERA-40, GTS</td>
<td>Various <strong>reprocessed CDRs, latest instruments</strong></td>
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<tr>
<td><strong>Variational Bias control radiosondes</strong></td>
<td>Satellite radiances, RAOBCORE</td>
<td>Also ozone, aircraft, surface pressure, RISE</td>
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<tr>
<td><strong>Land downscaling product</strong></td>
<td>ERA-Interim land, 79km</td>
<td><strong>ERA5L, 9km</strong> (forced by ERA5)</td>
</tr>
</tbody>
</table>

*ERA-Interim and ERA5 are climate reanalysis products. ERA5 provides updated model input, improved spatial resolution, and increased availability behind real time.*
Numerical Weather Prediction and Climate Reanalysis

- NWP is primarily concerned with prediction (the Medium Range Forecast)
  - NWP models are upgraded every 6-12 months
  - Observations lose (most of their) value after ~0.5 day

- Reanalysis is concerned with the retrospective analysis of the atmosphere, in a consistent way, over many decades
  - Uses state-of-the-art NWP systems (but using a fixed configuration over decades)
  - Observations (esp. reprocessed/ recalibrated) continue to have value
  - Reanalyses updated every 5-10 years (ERA5 is the 5th generation ECMWF reanalysis)
Welcome to the Climate Data Store

Dive into this wealth of information about the Earth’s past, present and future climate.

It is freely available and functions as a one-stop shop to explore climate data. Register for free to obtain access to the CDS and its Toolbox.

We are constantly improving the services and adding new datasets. For more information, please consult the catalogue, our FAQ or the C35 forum.
ERA5 user uptake

C3S ERA5: total number of data users

C3S ERA5 downloads (TB)