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

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Overview

- **Copernicus services**
- ERA5 configuration and performance
- The usage of GNSS-RO data
- Importance of GNSS-RO data
- Final remarks

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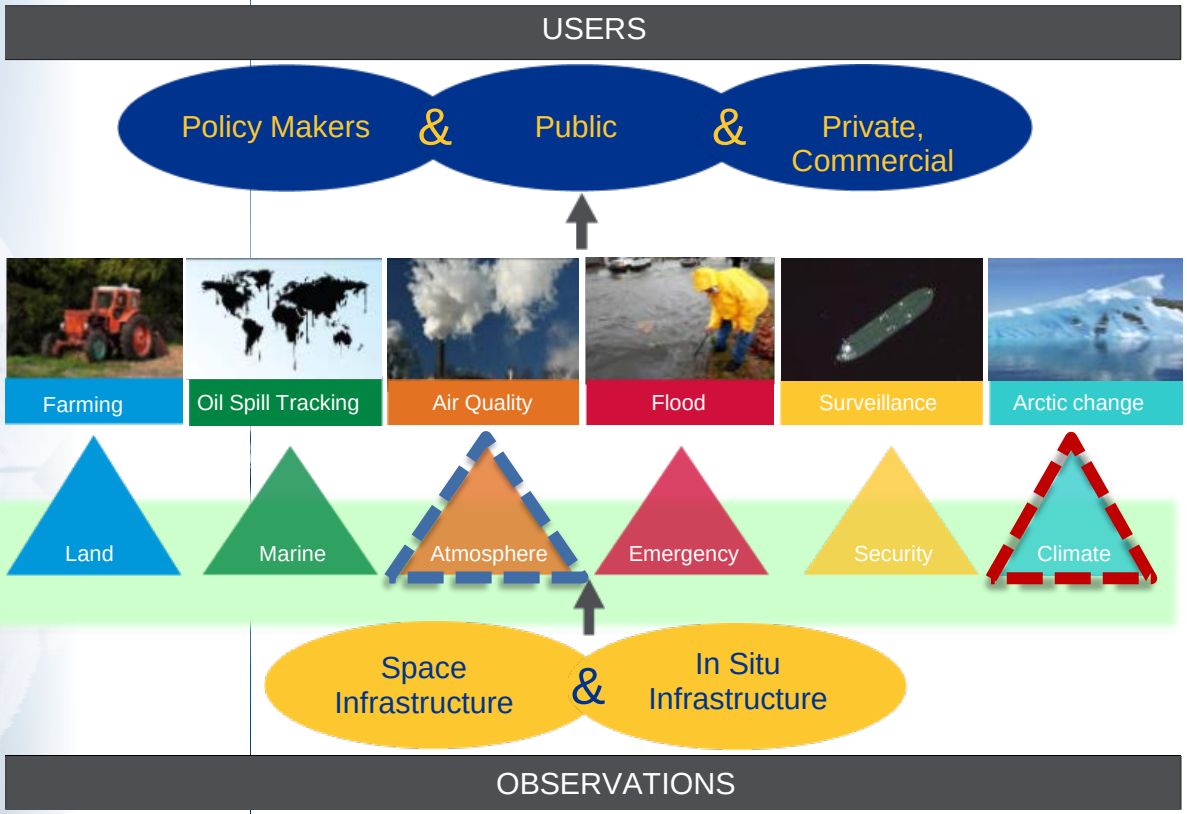
The Copernicus Climate Change Service



Different Needs

Examples of areas covered

6 Information Services

Sustainable observation capabilities

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

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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

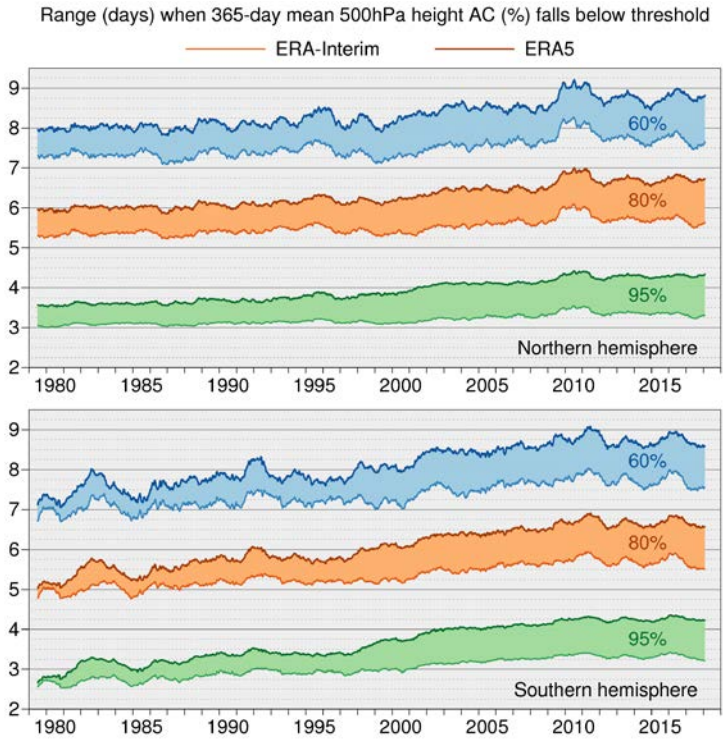
(ERA-I was stopped end August 2019)

Improvements compared to ERA-Interim:

- Benefit from 10 years model development (2006 to 201
- 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**.



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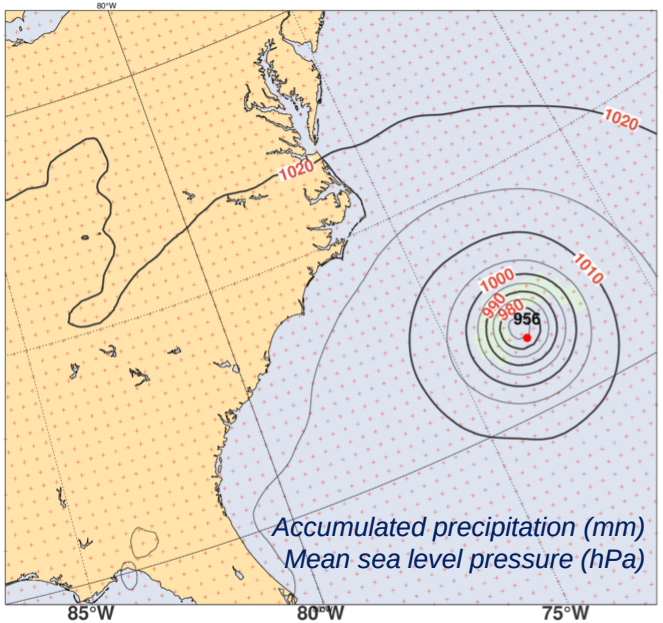
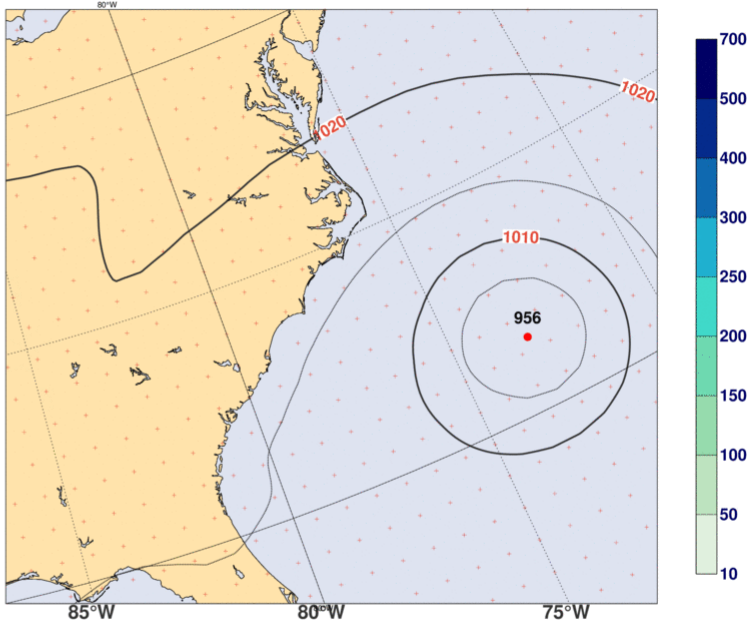
Better model, more and better observations, higher resolution, hourly output



ERA5



ERA-Interim

Freja Vamborg, Hans H

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Climate Change Service climate.copernicus.eu

IMPLEMENTED BY ECMWF

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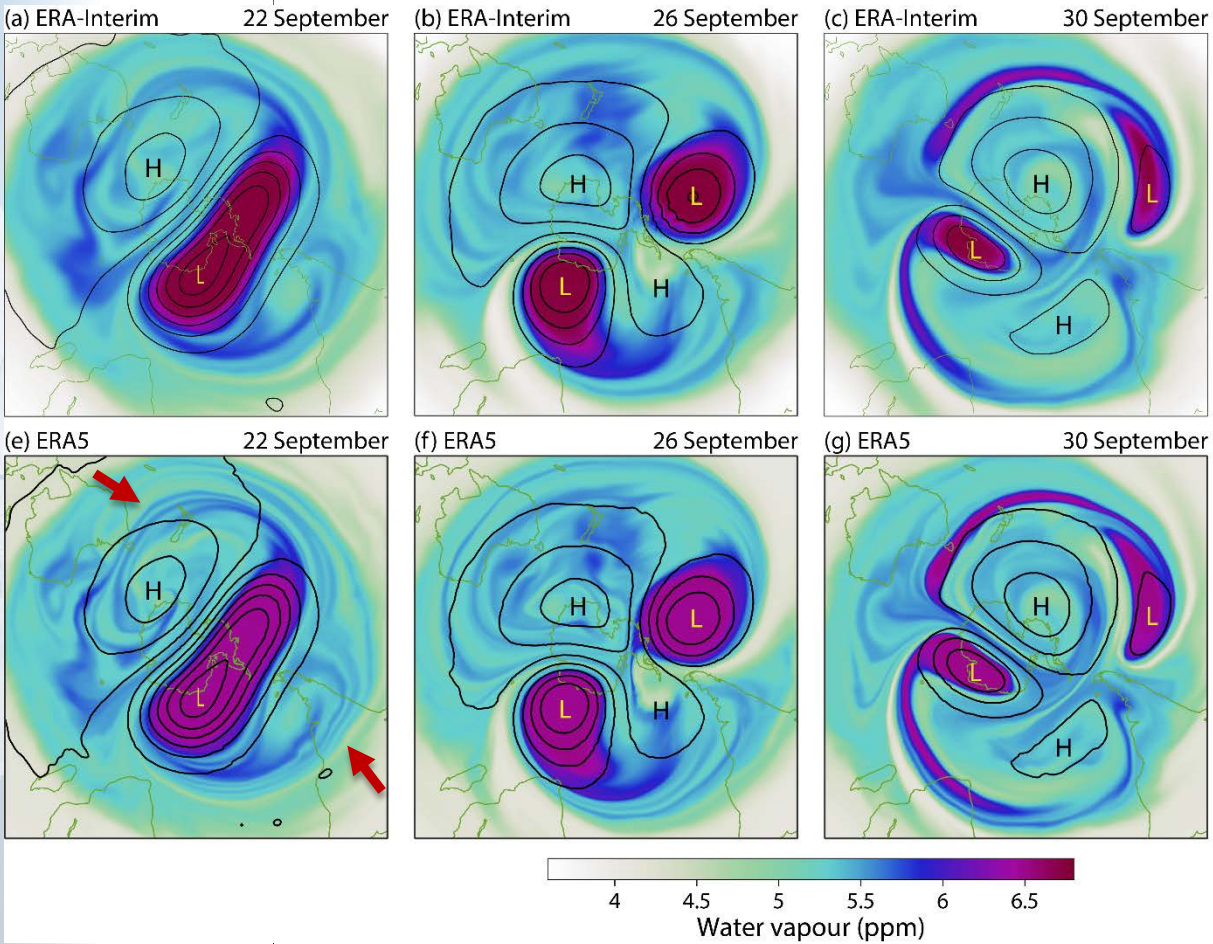
Breakup southern polar vortex in September-October 2002



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

ERA5 shows finer details

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The ERA5 observing system

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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

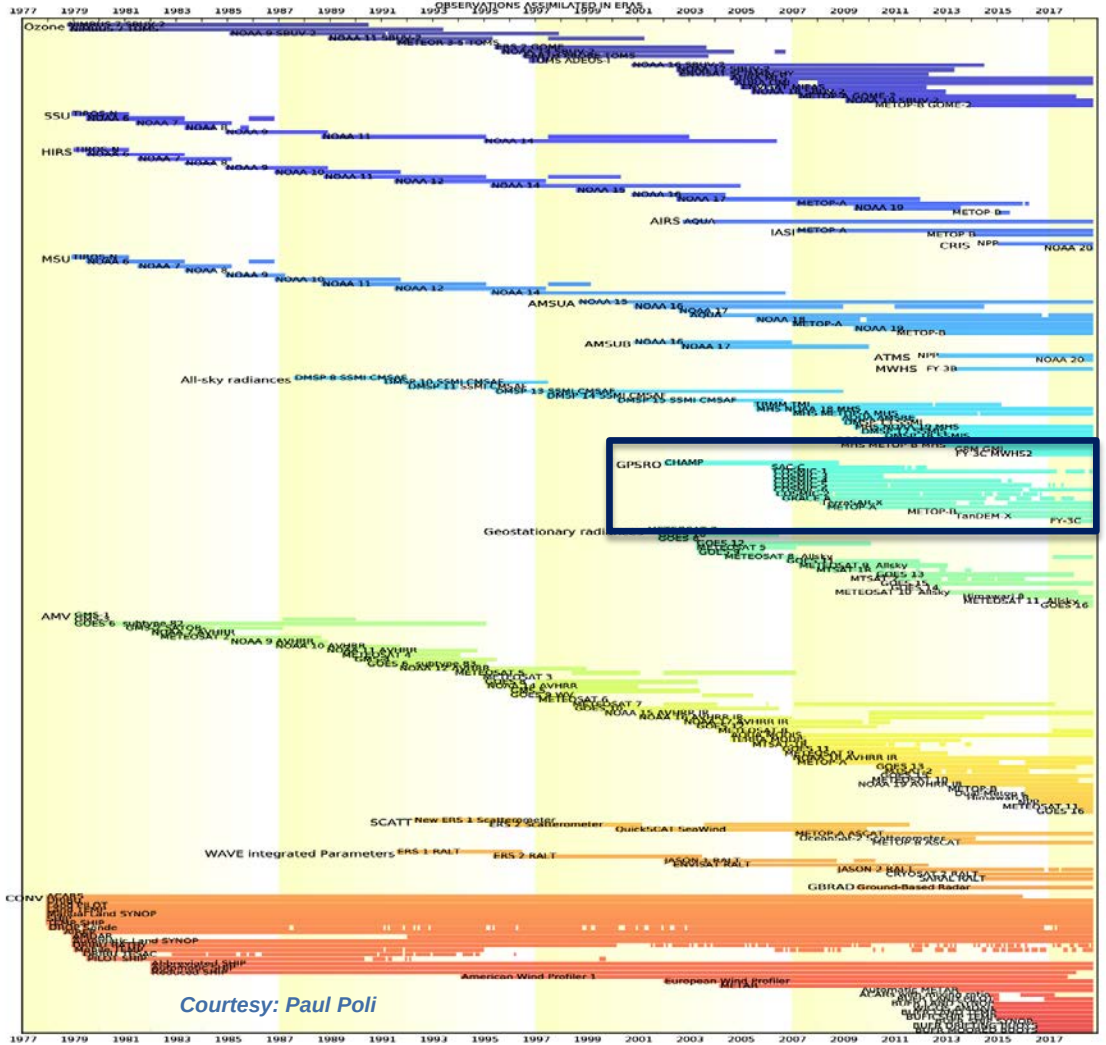
Wave Height: ERS-1,ERS-2, Envisat, Jason

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



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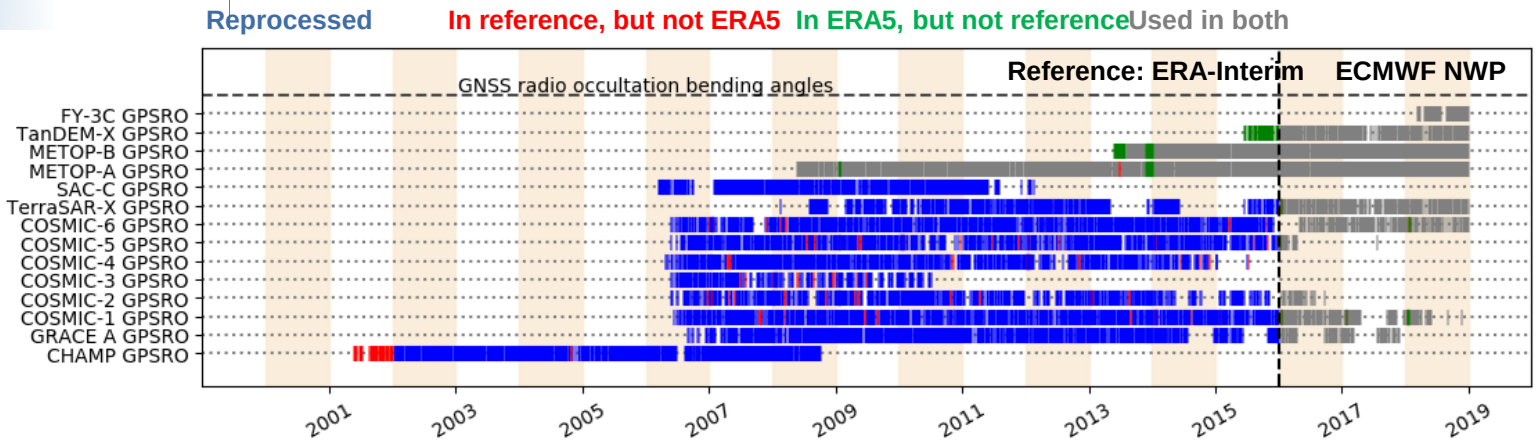
GNSS-RO observations assimilated in ERA5



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)

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ERA5 data counts

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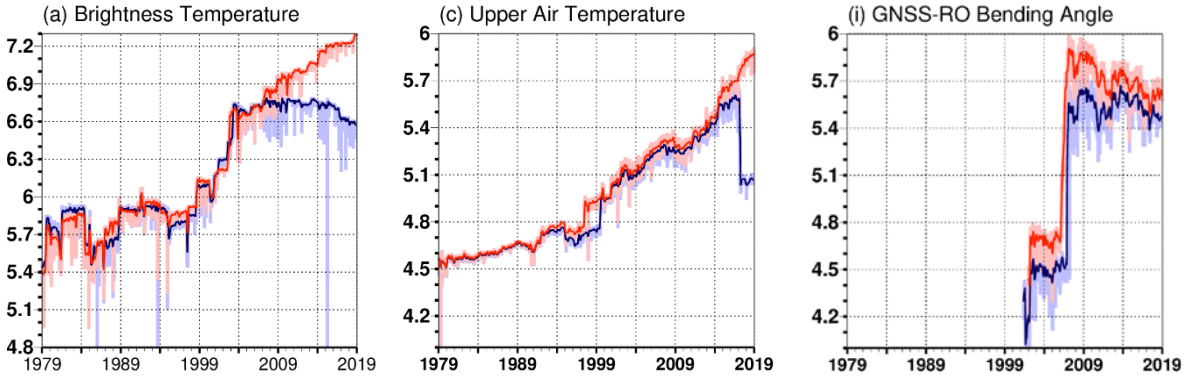
ERA5 data usage has increased from 0.75 (1979) to 24 million/day (2019).

87 Billion observations assimilated (1979 - 2019)

*Number of used observations per day (log_{10} scale) for **ERA5** and **ERA-Interim***



Radiances:
Largest volume

Conventional:
Radiosondes, aircraft

GNSS-RO:
Initially low numbers
Counts ~ conventional
Some recent decline

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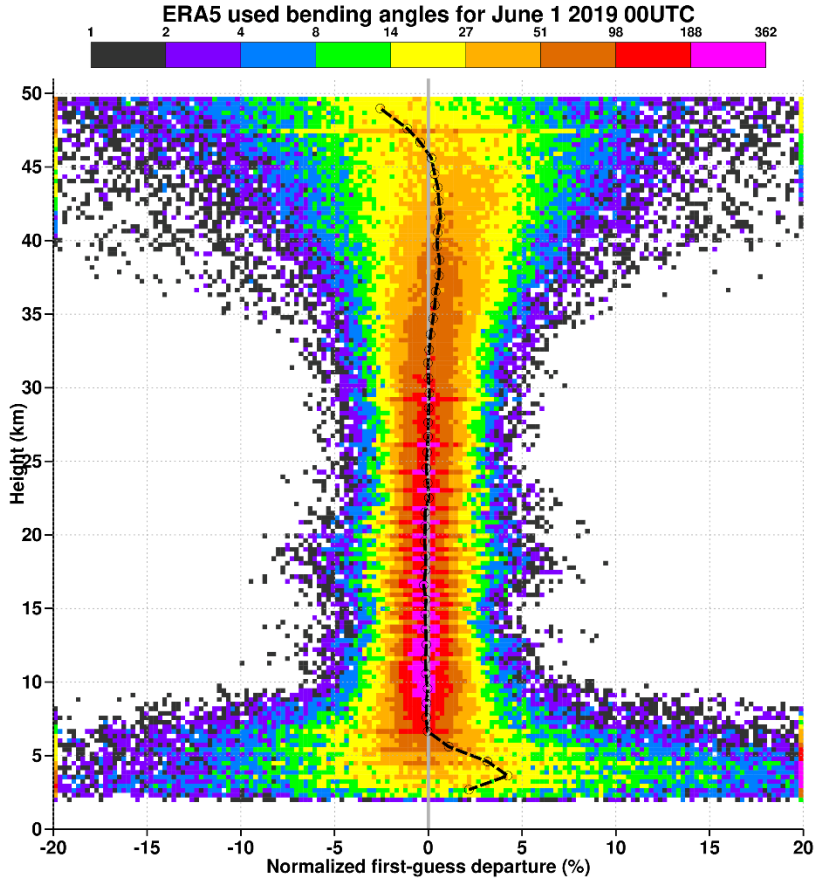
Assimilation of GNSS-RO data in ERA5



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)

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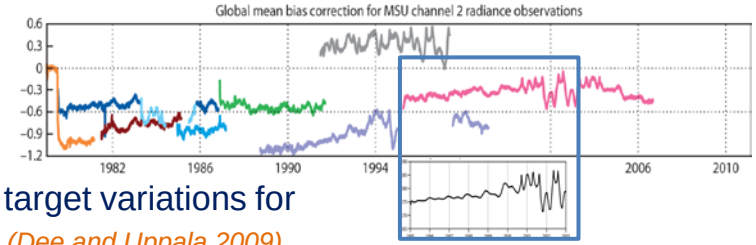
The merits of variational bias correction

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:

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



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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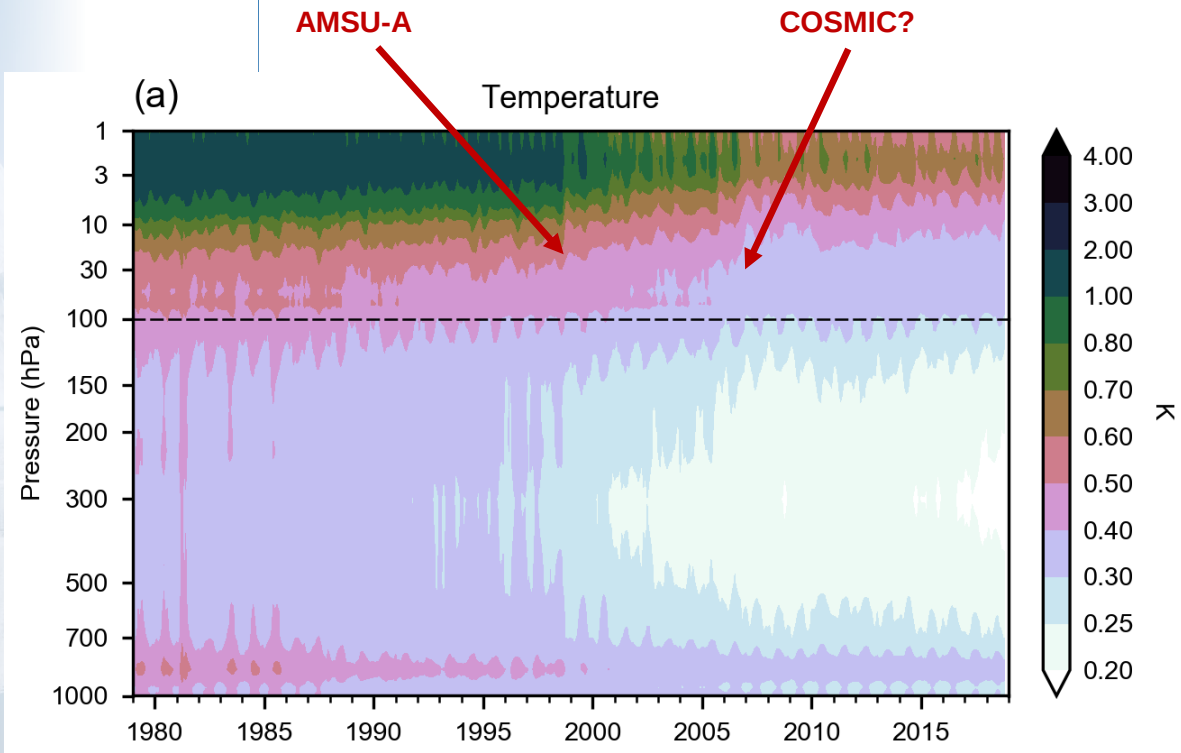
Ensemble spread as a measure for the *synoptic* ERA5 uncertainty



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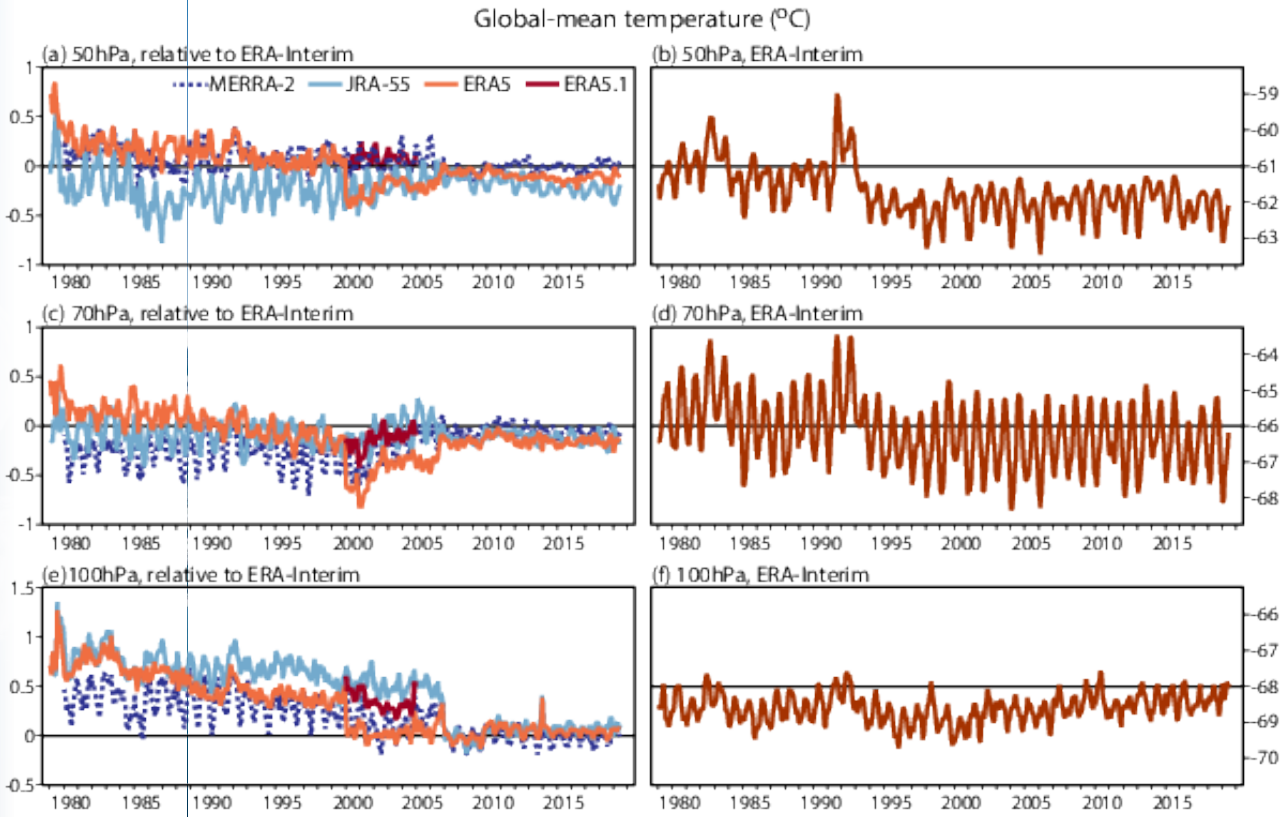
Inter-comparison of global reanalyses: convergence from 2006 (COSMIC)



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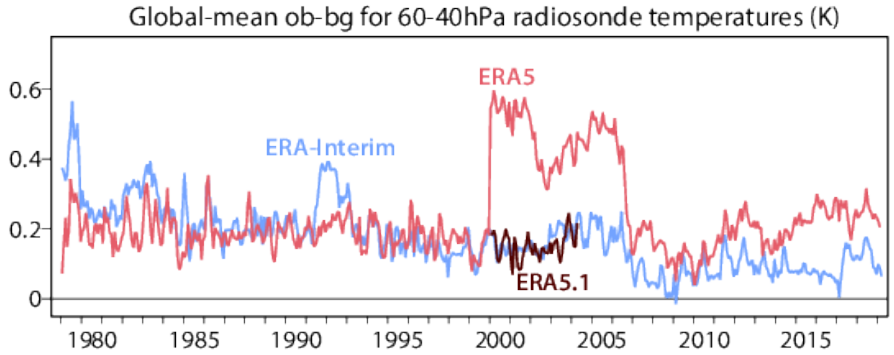
Radiosonde first-guess departure statistics

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

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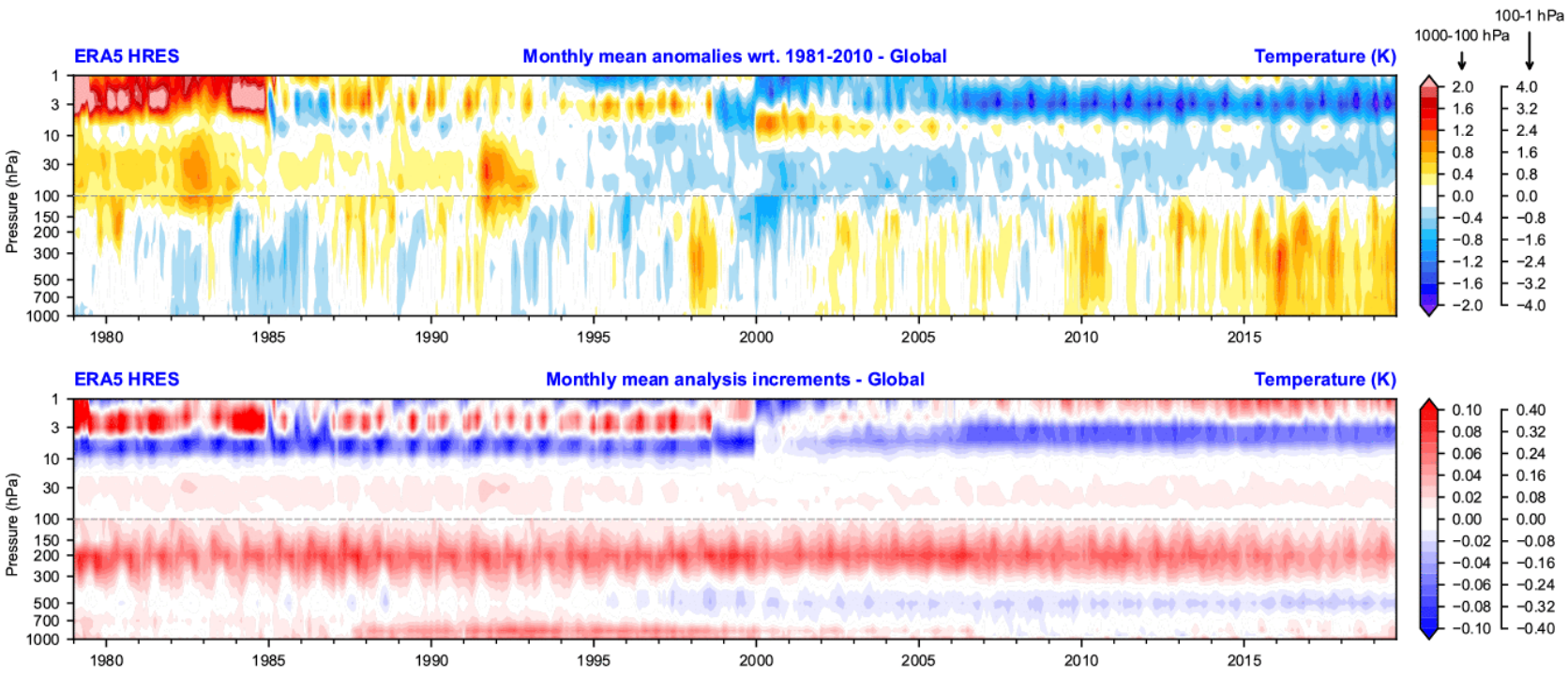
ERA5 anomalies compared to 1981-2010



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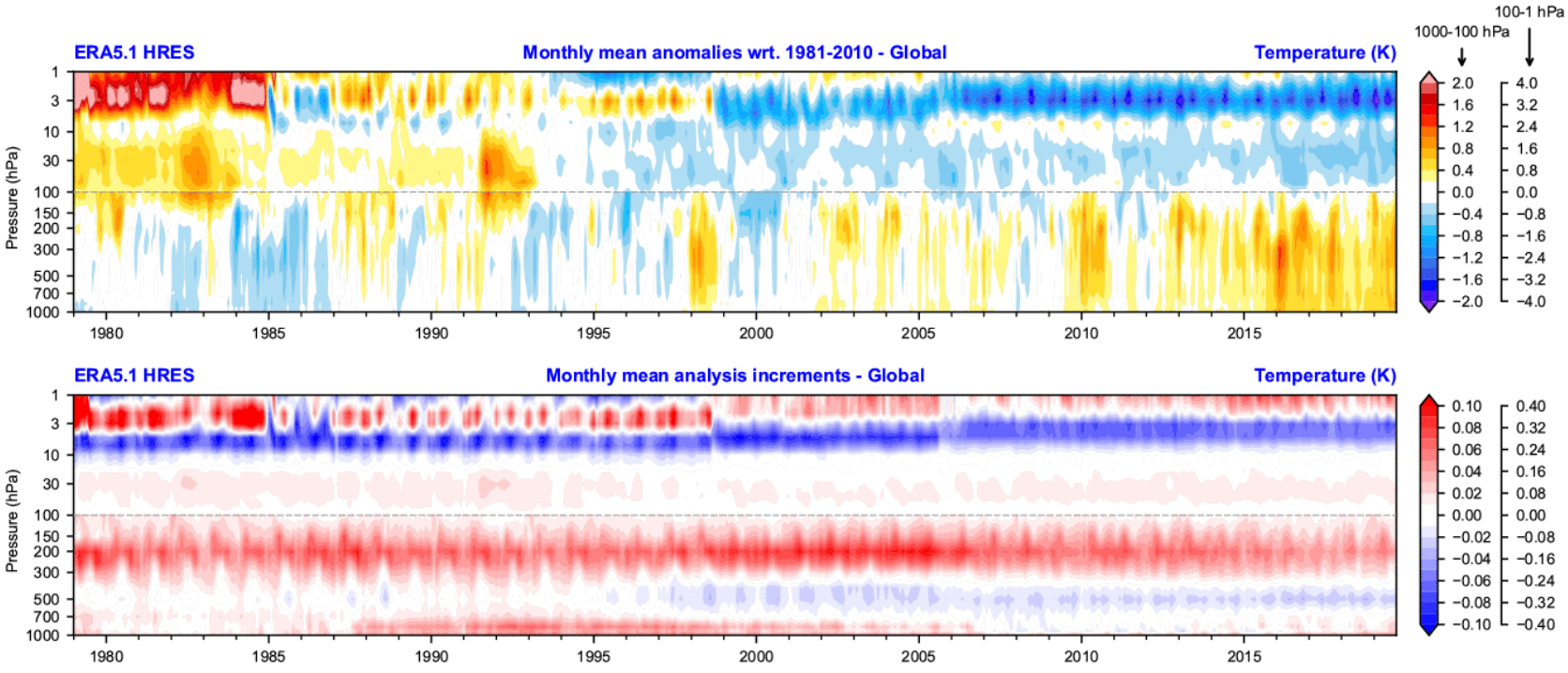
ERA5.1 anomalies compared to 1981-2010



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More information

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

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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

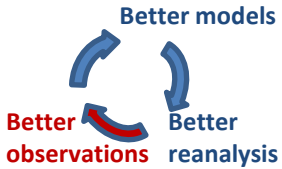
- To guarantee the temporal consistency of the reanalysis mean state
- To avoid the aliasing of model bias into satellite observation bias estimates

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)



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Back-up slides

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What is new in ERA5?

	ERA-Interim	ERA5
Period	1979 – present	***1950 – present***, produced in 2 phases
Availability behind real time	2-3 months	2-3 months (final product) ***2-5 days*** (ERA5T)
Assimilation system	2006 (31r2), 4D-Var	***2016*** (41r2), ***4D-Var, hybrid EDA providing B***
Model input (radiation and surface)	As in operations, *(inconsistent SST and sea ice)*	***Appropriate for climate***, e.g., evolution greenhouse gases, volcanic eruptions, sea surface temperature and sea ice
Spatial resolution	79 km globally 60 levels to 10 Pa	***31 km globally*** 137 levels to 1 Pa
Uncertainty estimate		***from*** 10-member ***EDA at 62 km***
Output frequency	6-hourly Analysis fields	***Hourly*** (three-hourly for the ensemble), Extended list of parameters ~ 9 Peta Byte (1950 - timely updates)
Extra Observations	Mostly ERA-40, GTS	Various ***reprocessed CDRs***, ***latest instruments***
Variational Bias control radiosondes	Satellite radiances, RAOBCORE	Also ozone, aircraft, surface pressure, RISE
Land downscaling product	ERA-Interim land, 79km	ERA5L, ***9km*** (forced by ERA5)

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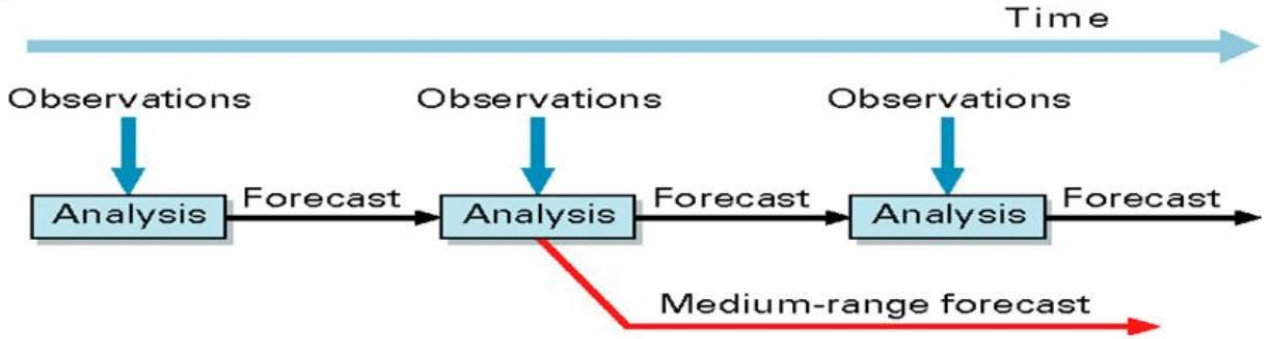
Numerical Weather Prediction and Climate Reanalysis



- 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 (ERA**5** is the **5**th generation ECMWF reanalysis)

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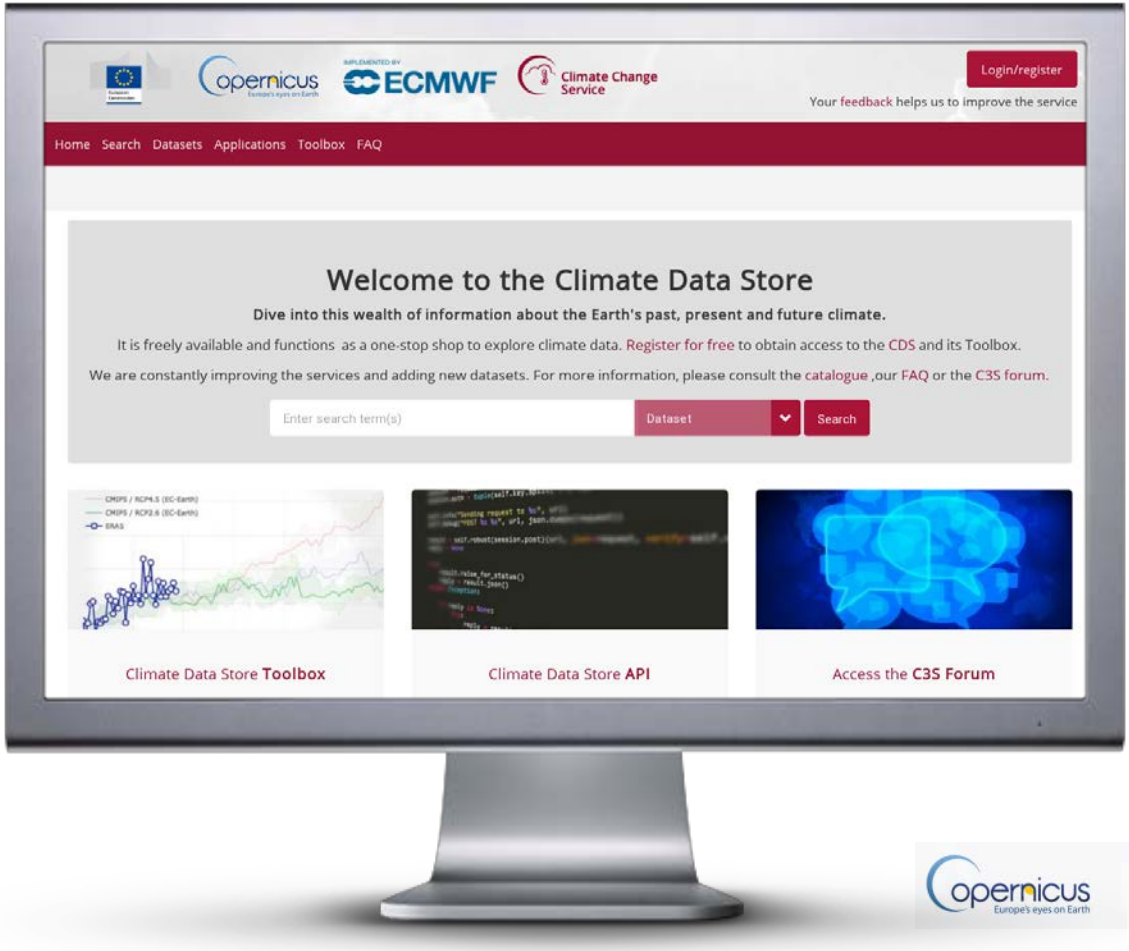
ERA5 in the Climate Data Store



ERA5 user uptake

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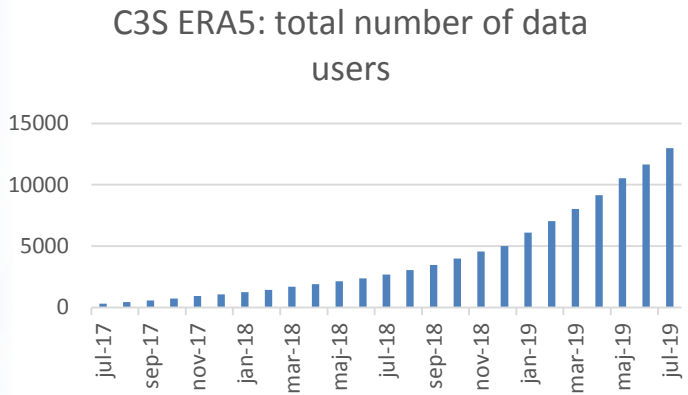

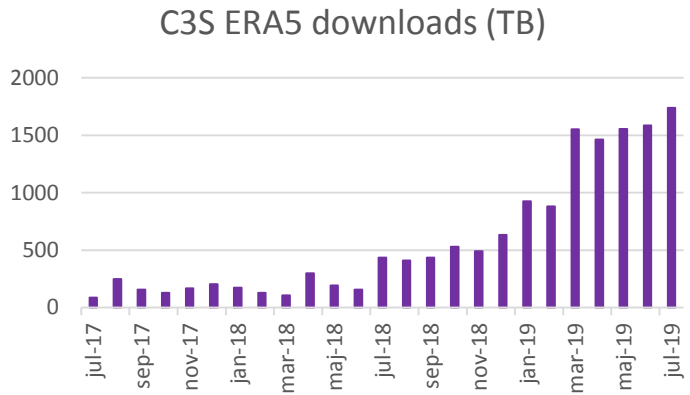

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