Climate Change

The ERA5 Global Reanalysis: achieving a detailed record of the climate and weather for the past 70 years.

Hans Hersbach, Bill Bell, Paul Berrisford, Per Dahlgren, András Horányi, Joaquín Muñoz-Sabater, Julien Nicolas, Raluca Radu, Dinand Schepers, Adrian Simmons, and Cornel Soci.

Overview

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- Introduction, overview of ERA5 products
- ERA5 configuration (1979 onwards) and some diagnostics
- ERA5.1 (2000-2006); the importance of the weight of the background
- Preliminary results on the ERA5 back-extension (1950-1978)
- Final remarks and outlook

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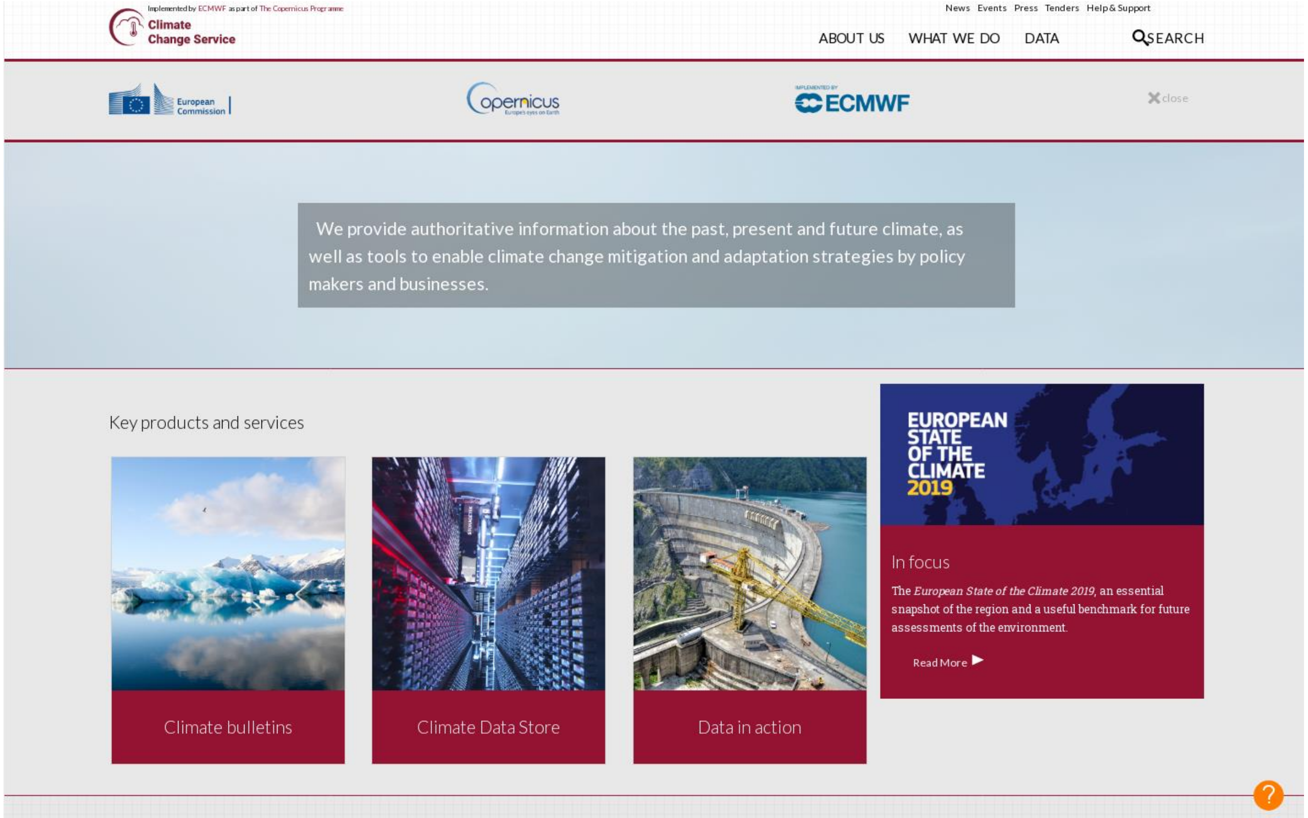
ERA5 is produced within the Copernicus Climate Change Service



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

The ERA5 Global Reanalysis, available from the C3S climate data store.

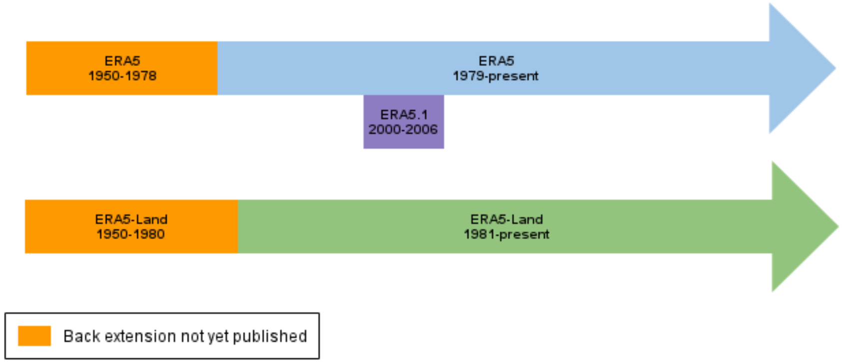
A full-observing-system global reanalysis for the atmosphere, land and ocean waves.

ERA5 replaced ERA-Interim (end date 31 August 2019)

To date ERA5 is publicly available from 1979 onwards, with daily updates 5 days behind real time.

ERA5-Land (9km downscaled) is available from 1981 (2 months behind real time)

ERA5 Family Timeline



Improvements compared to ERA-Interim:

- Benefit from 10 more years of model development
- Much higher resolution; **31km** versus 79km
- More and better input data
- Hourly output
- Uncertainty estimate (at 63km)

Updates in 2020:

- **New:** ERA5.1 (2000-2006) now available
- **Q2/Q3:** ERA5 back extension (1950-1978)
- **Q3:** updates 5 days behind real time for ERA5-Land and 'ERA5-complete'
- **Q4:** ERA5-Land back extension (1950-1980)

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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) ***5 days*** (ERA5T)
Assimilation system	2006 (31r2), 4D-Var soil moisture: 1D-OI	***2016*** (41r2), ***4D-Var, hybrid EDA*** ***soil moisture: SEKF***
Model input (radiation and surface)	As in operations, *(inconsistent SST and sea ice)*	***Appropriate for climate***, e.g., evolution of greenhouse gases, volcanic eruptions, sea surface temperature and sea ice
Land-surface model	TESSEL	***HTESSEL***
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 63 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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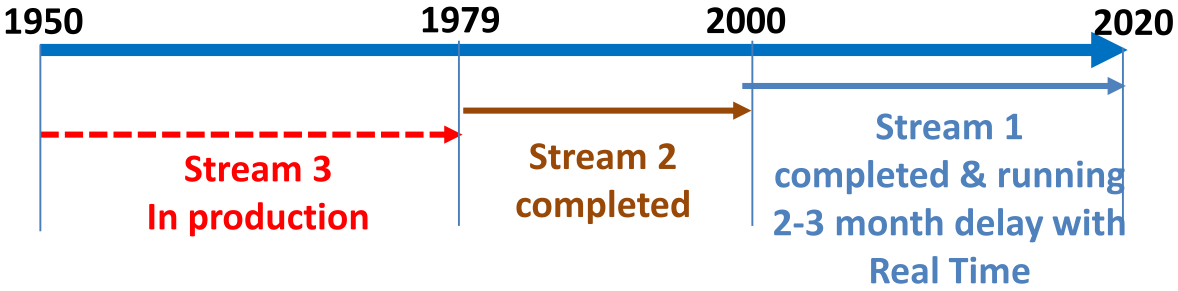
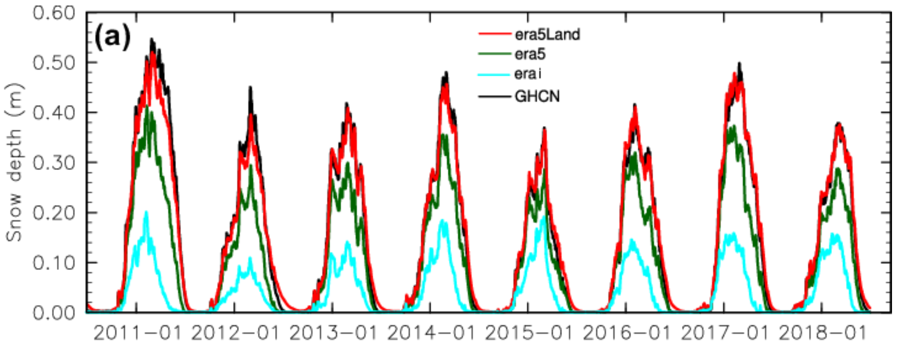
ERA5-Land: An improved version of the land-surface component



- **Global**, spatial res. **9 km**, temporal res. **hourly**
- **Availability** in the CDS: **Jan-1981 to Feb-2020**
- 1950-1980 in production
- **NRT** capacity (5 days behind RT) **by Q3-2020**
- Preliminary validation against in-situ data & comparison with ECMWF reanalysis
  - → positive impact on the hydrological cycle
  - → neutral impact on the energy cycle.



Comparison of North-America snow depth observations from the Global Historical Climatological Network for different ECMWF reanalysis

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ERA5 forcing appropriate for climate

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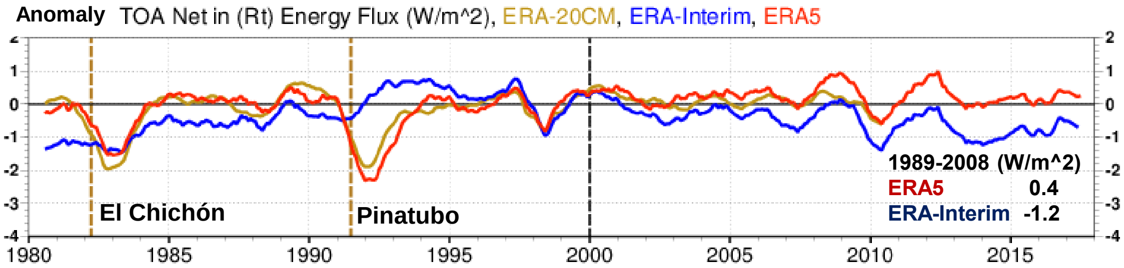
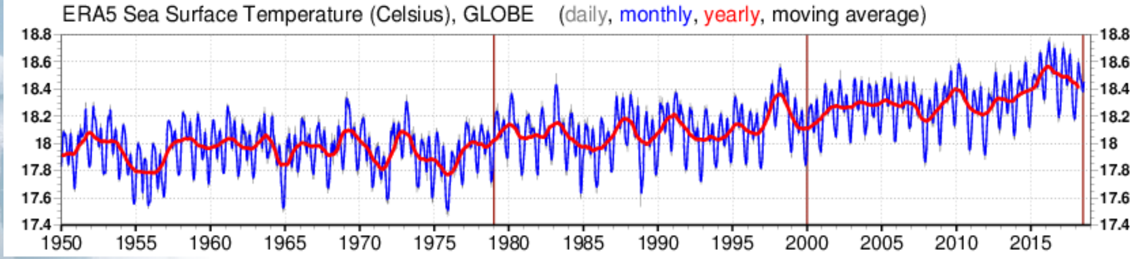
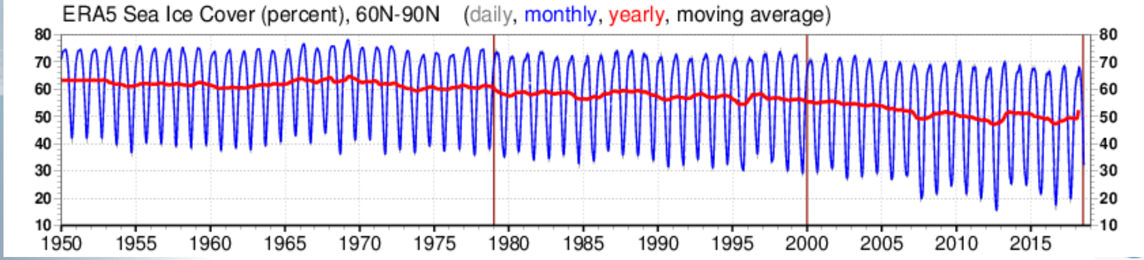
CMIP5 recommended data sets

Total solar irradiance, greenhouse gases, ozone, aerosols (including volcanic)

*(Prepared in the ERA-CLIM project, ERA-20CM, **Hersbach et. al., 2015**)*







SST and sea ice cover

Carefully selected from OSTIA, OSI-SAF and HadISST2 (Hadley Centre, *ERA-CLIM*)

(Hirahara et. al., 2016)

The ERA5 observing system

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Over 200 types of reports, using 96 billion observations from 1979-2019

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

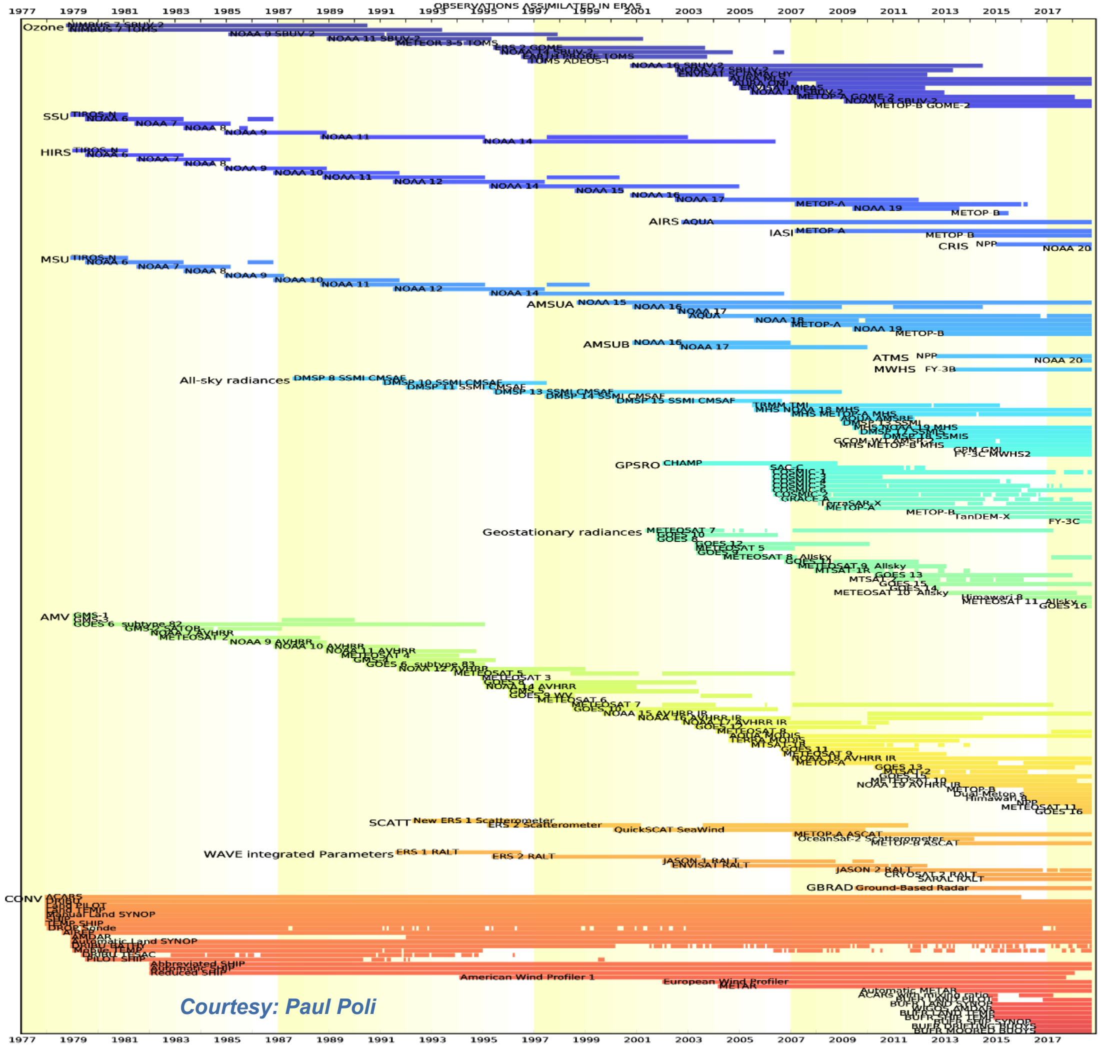
Wave Height: ERS-1,ERS-2, Envisat, Jason

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



Diagnostics: fit to observations prior to assimilation

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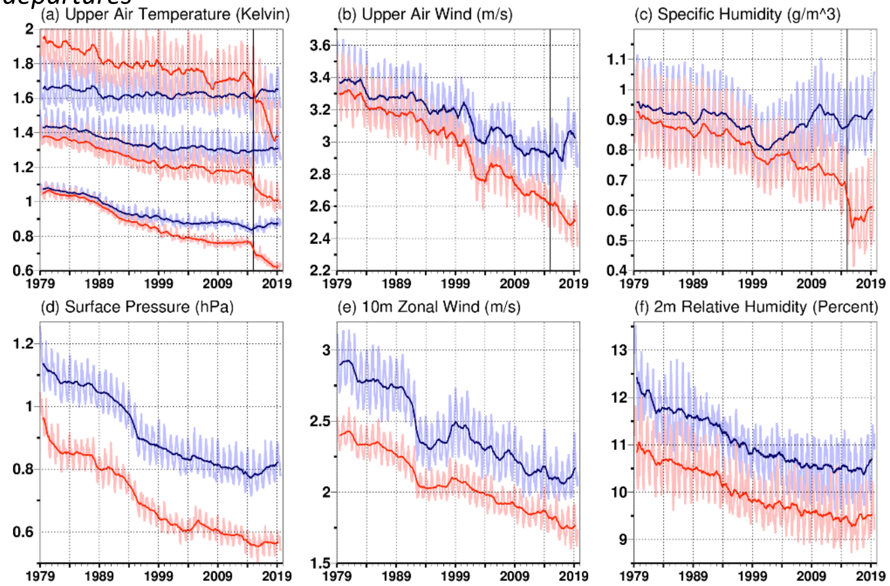
Hersbach, H. et al., 2020 (in press), doi:10.1002/qj.3803

In the troposphere ERA5 has a much Improved fit to observations. However, in the stratosphere the fit is worse for temperature due to a larger model bias.

Standard deviation of ***ERA5 (red)*** *and* ***ERA-Interim (blue)*** *first-guess departures*



(a) upper-air temperature from radiosondes (from top to bottom in the panel) within ±25 hPa of 50 hPa, 850 hPa and 400 hPa, (b) upper-air zonal wind from radiosondes, dropsondes and PILOTs, (c) upper-air humidity from radiosondes and dropsondes, (d) surface pressure from SYNOP, buoys, ships and METAR, (e) 10m zonal wind from buoys, ships, radiosondes, PILOT and SYNOP, (f) 2m relative humidity from SYNOP. The vertical black line marks the start date of the usage of BUFR TEMP data in ERA5 from 1 January 2015.

Inter-comparison of global mean temperature relative to 1981-2010

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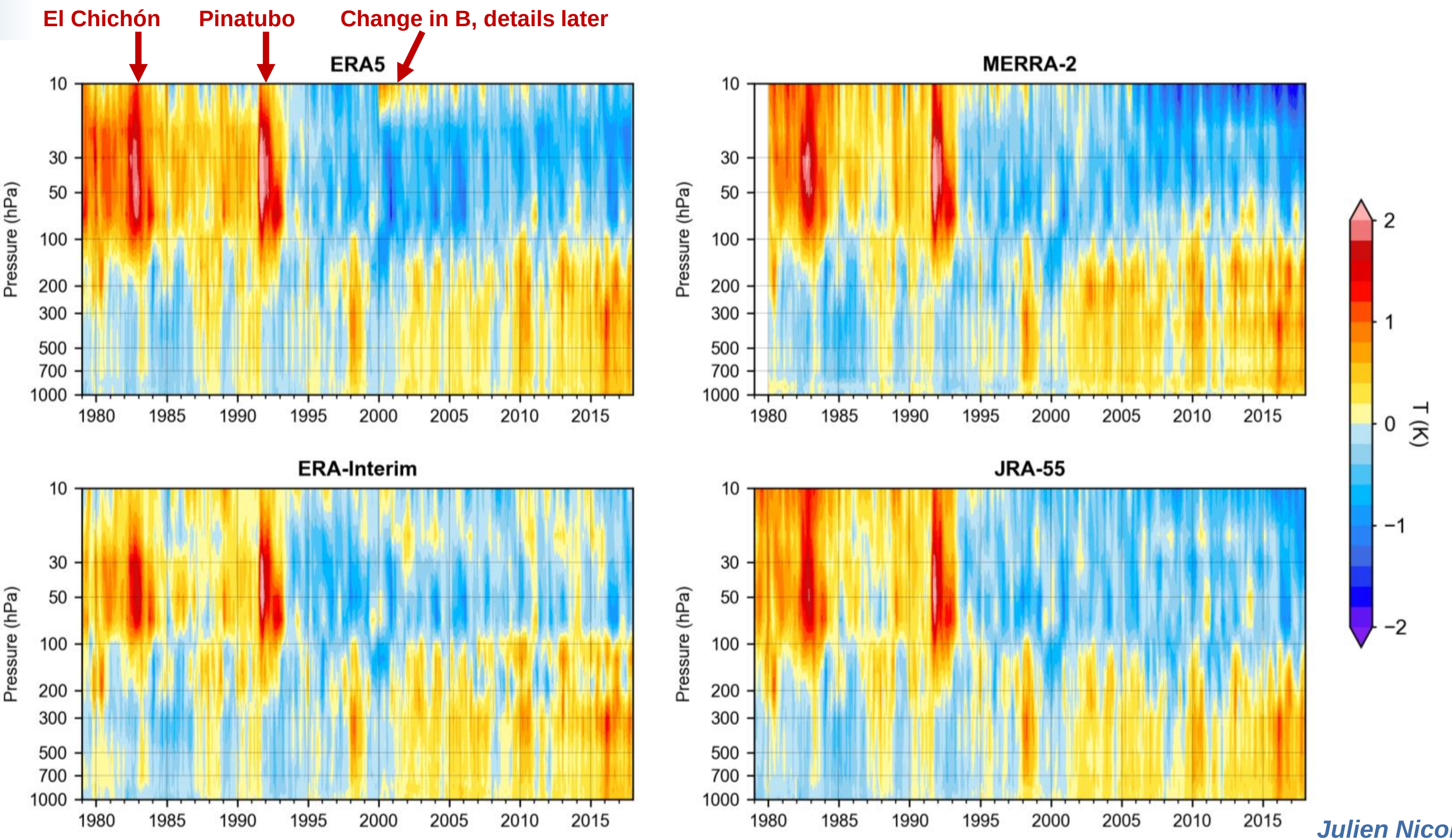

Julien Nicolas

The advantage of hourly output (soon from 1950 onwards) for December 1999 storm Lothar

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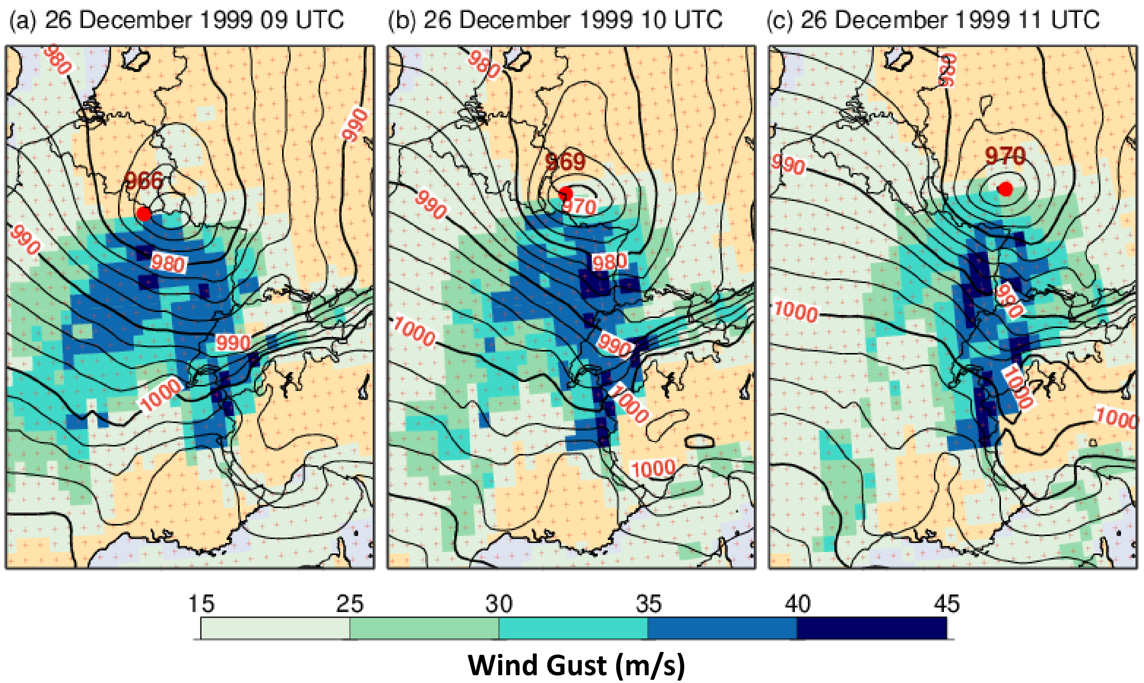
The ERA5 hourly resolution presents a detailed view of this rapidly evolving storm.

Although at 9 UTC the ERA5 minimum pressure is about 5 hPa higher (ensemble spread 2.1 hPa) than the reported minimum (Hewson and Neu 2015) (which also has an associated uncertainty) and also somewhat misplaced, the match is within one hPa at 10 and 11 UTC (spread 0.5 hPa at 12 UTC), and the analysed position is highly accurate at 11 UTC.

ERA5 provides a detailed view of wind gust with maximum values up to 42 m/s in the Black Forest and French Alpine area. Maximum observed gusts in the Black Forest area were 59 m/s (DWD 2000).



ERA5 analysis of mean sea level pressure and wind gusts within the preceding hour for Lothar on 26 December 1999 at (a) 09, (b) 10, and (c) 11 UTC. Red dots and values mark the position and pressure (hPa) of the reported low. Red plusses indicate the ERA5 native grid.

Hersbach, H. et al., 2020 (in press), doi:10.1002/qj.3803

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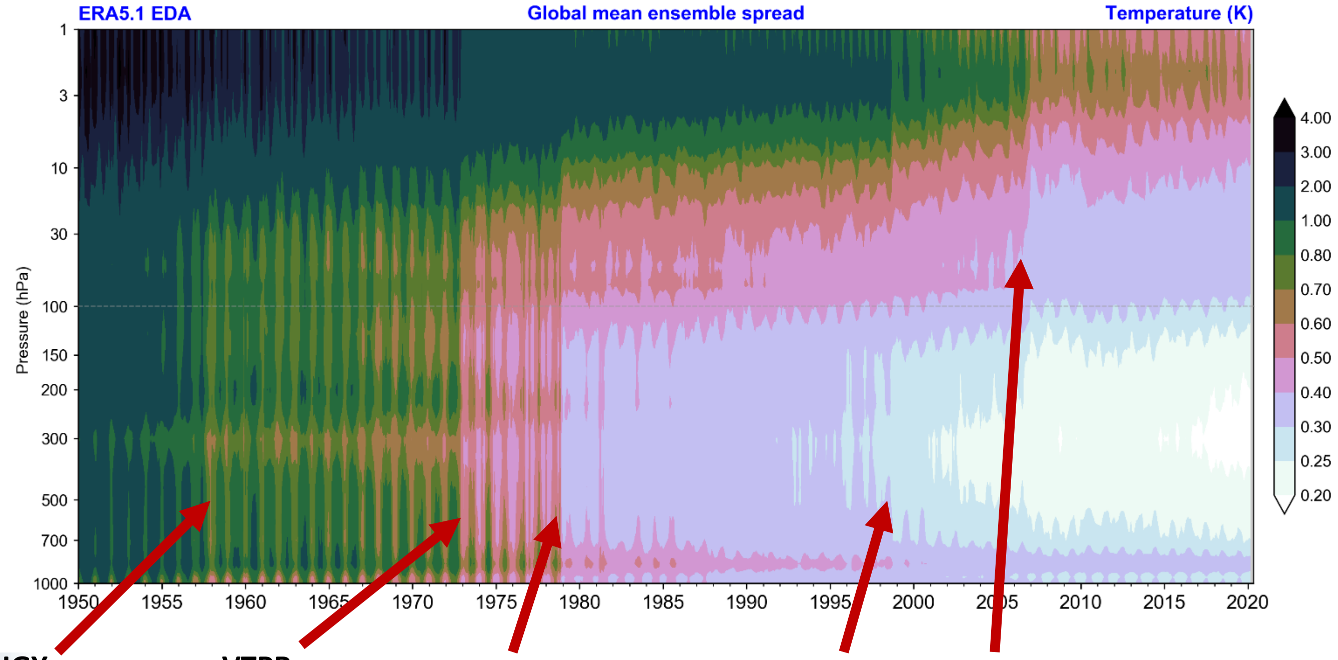
Ensemble spread as a measure for the *synoptic* ERA5 uncertainty

Spread decreases over time when more and more observations become available

Major changes in the observing system are clearly visible



IGY

VTPR

TOVS
(HIRS, MSU, SSU)

ATOVS
(AMSU-A)

GNSS-RO
(COSMIC,..)

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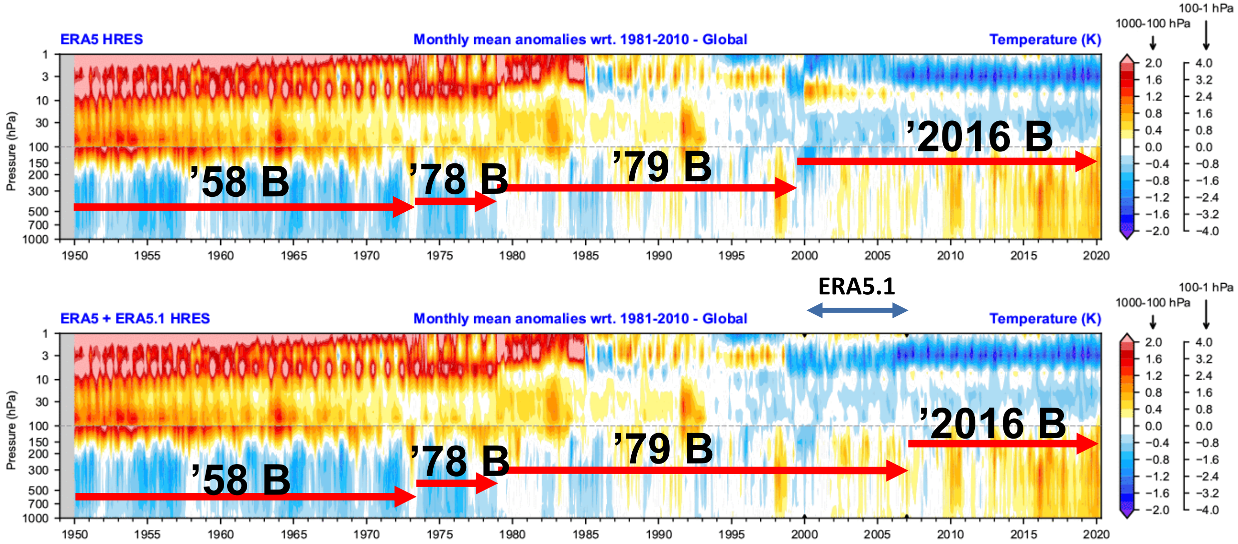
The effect of the background error covariance matrix on the mean state



In ERA5 the 10-member ensemble of data assimilation systems (EDA) also provides a flow-dependent background error covariance matrix **B**:

$$B(t) = (1-\alpha)B_{cli} + \alpha B_{EDA}(t)$$

It relies partly on a static component **Bcli**, which should evolve slowly with the observing system: In ERA5 **Bcli** was changed with the introduction of major changes in the observing system. However, too short correlations in **'2016 Bcli** could not counteract a model cold bias in the lower stratosphere. This was improved by a rerun for 2000-2006 (ERA5.1) using the longer correlations from **Bcli** tuned for 1979. From 2007 onwards such bias is resolved by GNSS-RO observations.

The improved mean state for stratospheric temperature in ERA5.1

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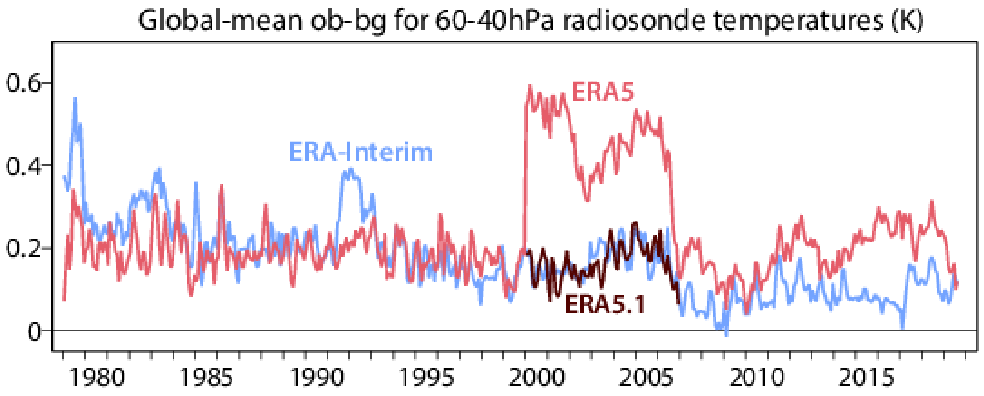
ERA5.1 provides an improved mean state for stratospheric temperature.

In the troposphere the difference between ERA5 and ERA5.1 is very small.

In the CDS ERA5.1 **is now available** as: ‘era5.1-complete’:
https://confluence.ecmwf.int/display/CKB/How+to+download+ERA5



Monthly average observation-background differences from 1979 onwards for all assimilated bias-adjusted radiosonde temperature data (K) between 40 and 60 hPa, for ERA-Interim, ERA5 (based on 1979-Bcli before 2000 and 41r2-B cli afterwards) and ERA5.1 (using 1979-Bcli from 2000-2006).

Hersbach, H. et al., 2020 (in press), doi:10.1002/qj.3803

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ERA5 back extension uses VTPR ('72-'79), BUV ('70-'77) and additional in situ observations

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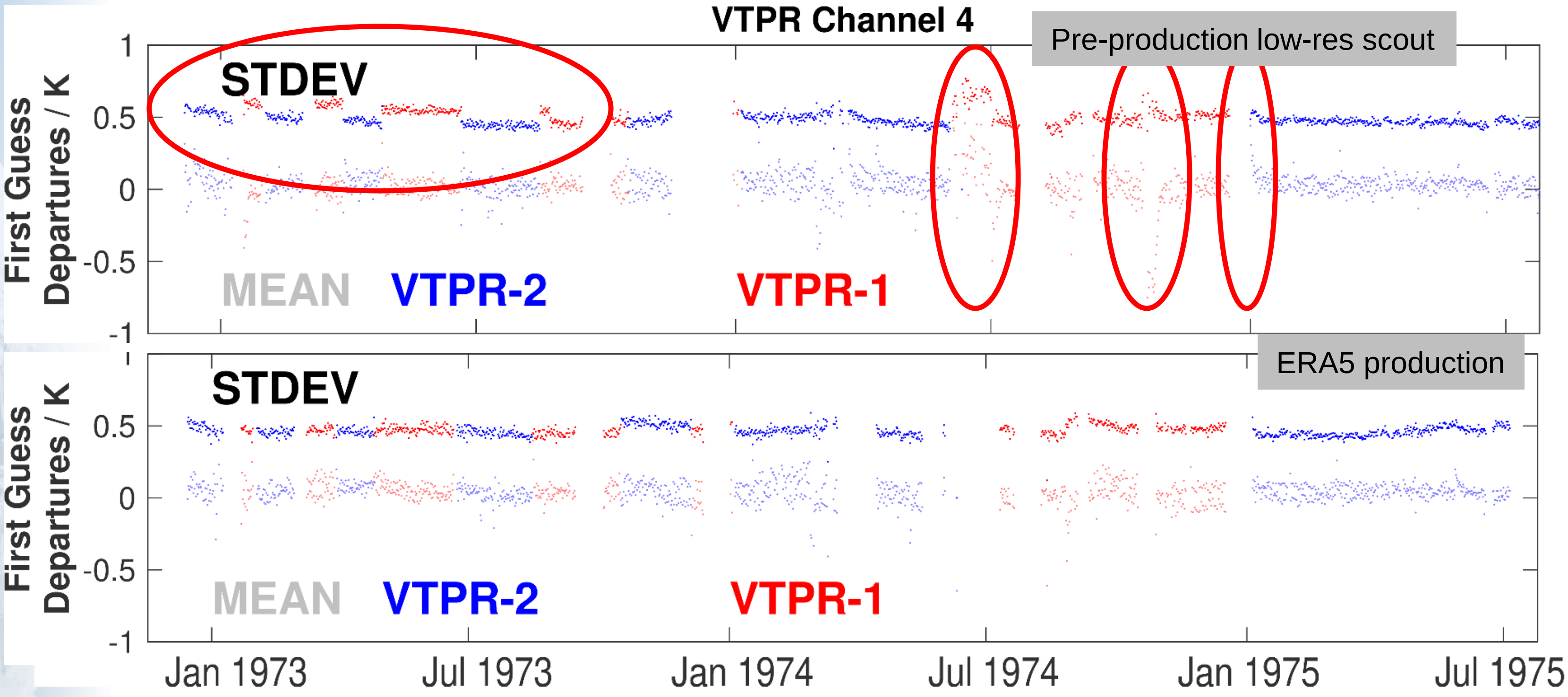

Relative to ERA-40

- New cloud detection scheme
- RT coefficient optimisation
- Blacklisting periods of degraded data quality
- Observation error tuning (Desroziers , reduced obs errors)

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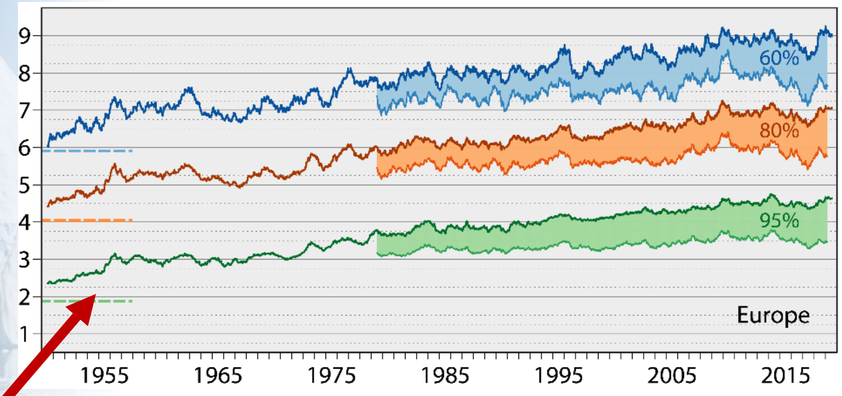
Skill from re-forecasts as a measure for the accuracy of reanalysis products

Range (days) when 365-day mean 500hPa height AC (%) falls below threshold

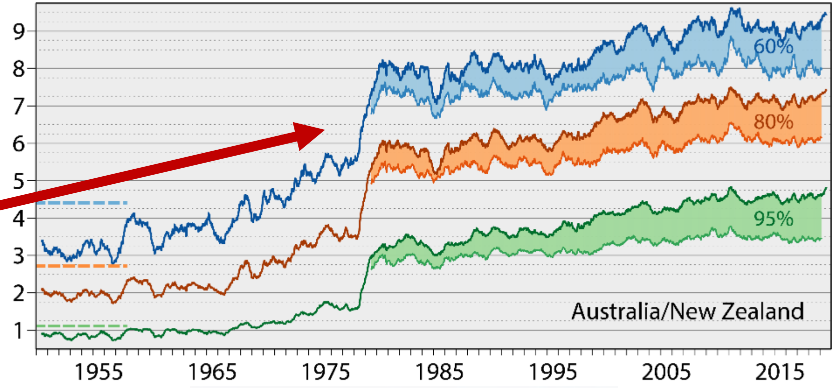
ERA5 — ERA-Interim — ECMWF operations 1981



ERA5 1979 onwards:
Re-forecasts from ERA5 are up to 1 day more skilful than ERA-Interim

ERA5 back extension:
NHEM (especially Europe) skill is rather robust, but declines prior to the IGY in 1957-1958

Over SHEM there is a dramatic improvement following the introduction of TOVS satellite data in late 1978.



Inter-comparison of global 2m temperature anomalies

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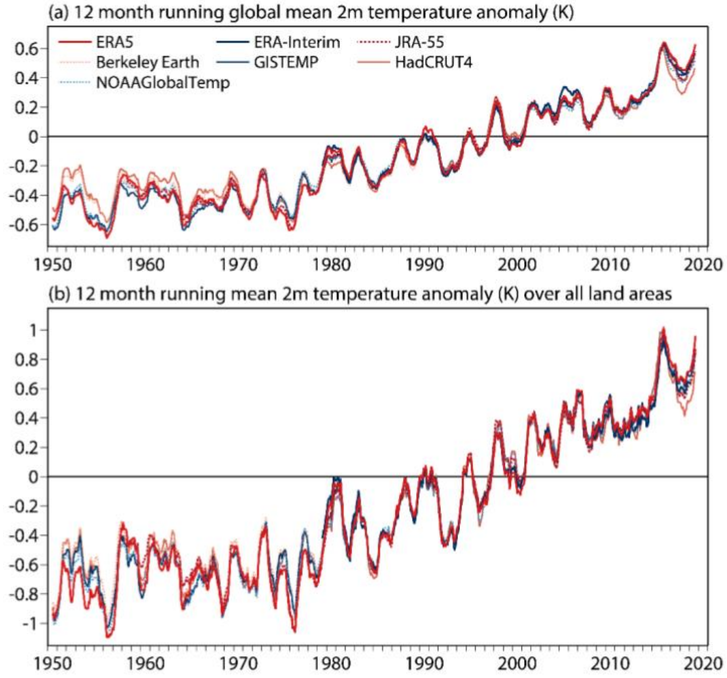
Simmons, A. et al., 2020 (in preparation):

In general there is a good agreement between datasets.

Each dataset shows considerable warming over the period shown, with a peak early in 2016 associated with a strong El Niño event and generally high values over the past six years. ERA5 and ERA-Interim are the datasets with the largest anomalies since 2016, but not the datasets with the largest trends over the period since 1979.

Trends from ordinary least squares fits to monthly values for the forty years 1979 to 2018 are 0.182K/decade for ERA5, 0.183K/decade for ERA-Interim, 0.180K/decade for JRA-55 and otherwise range from 0.171K/decade for NOAAGlobalTemp to 0.188K/decade for Berkeley Earth.

The reanalyses are colder prior to 1970.



Time series of monthly values from 1950 to 2020. (a) Twelve-month running averages of the global average two-metre temperature (K) anomaly with respect to 1981-2010 from ERA5, ERA-Interim, JRA-55, Berkeley Earth, GISTEMP, HadCRUT4 and NOAAGlobalTemp. (b) As (a), but for averages over land only.

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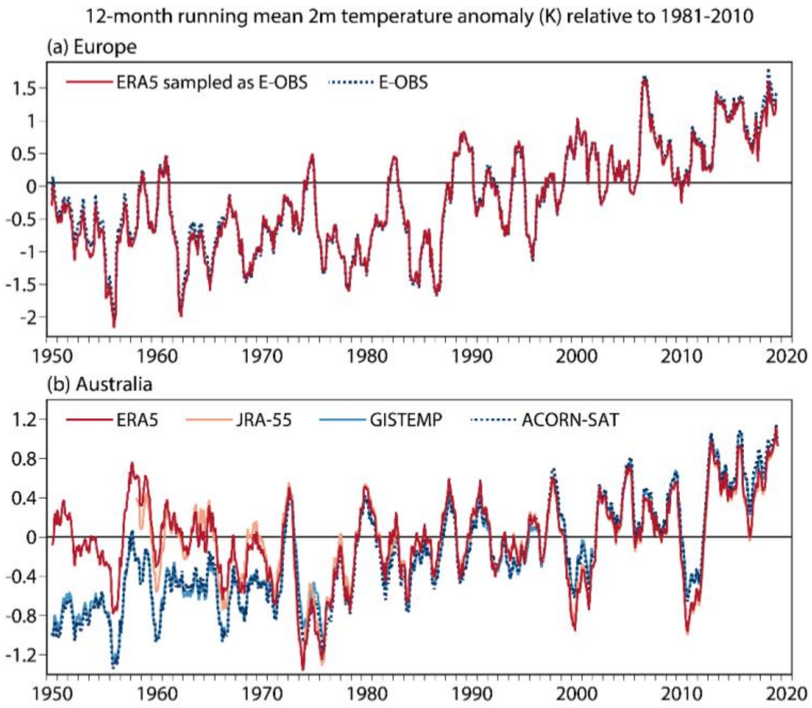
Inter-comparison of 2m temperature anomalies for sub areas

Simmons, A. et al., 2020 (in preparation)

ERA5 agrees very well with the E-OBS gridded-observation data set.

However,

- The reanalyses are quite warmer over Australia before 1970 than more direct observational datasets.



Time series from 1950 to 2020 of twelve-month running means of two-metre temperature anomalies (K) relative to 1981-2010 for (a) Europe from ERA5 (red, solid) and E-OBS (version 20.0e; dark blue, dotted), with ERA5 sampled to match the E-OBS data coverage, and (b) Australia from ERA5 (red, solid), JRA-55 (orange, solid), GISTEMP (blue, solid) and ACORN-SAT (dark blue, dotted).

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Summary of products and pointers to further reading

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ERA5 data availability
– 1979-present available in the Climate Data Store (hourly data and monthly means)
– Preliminary version of ERA5 (ERA5T) available with 5-day delay behind real-time
– ERA5 has replaced ERA-Interim

Reference paper about ERA5
– Hersbach, H. *et al.*, 2020: The ERA5 Reanalysis. *Quart. J. Roy. Meteorol. Soc.*, doi:10.1002/qj.3803, accepted.

ERA5 back-extension (1950-1978)
– Production has completed, to be available early Q3.
– Later: possible extension of ERA5 to 1940 (low-hanging fruit but lower skill expected)

ERA5.1 (2000-2006)
– Rerun of ERA5 to improve stratospheric temperatures, now available
– Detailed description in Simmons, A., *et al.*, 2020: Global stratospheric temperature bias and other stratospheric aspects of ERA5 and ERA5.1. ECMWF Technical Memorandum number 859, 40 pp., doi:10.21957/rcxqfmg0.

ERA5-Land
– High-resolution (9km) land product forced by ERA5 (no data assimilation)
– 1981-present currently available in the Climate Data Store
– Production of back-extension (1950-1978) is ongoing

Final remarks and outlook

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The ongoing production of ERA5 is undertaken within the Copernicus C3S framework at ECMWF as part of the C3S operational service.

Many reanalysis-related tasks are being carried out by C3S providers:
– satellite reprocessing (EUMETSAT), data rescue, consolidation of historical datasets
– the production of two high-resolution regional reanalyses, for Europe and the Arctic

ECMWF's vision for C3S post-2020 continues to allocate a high priority to reanalysis:

High-resolution climate integrations back to 1850 or earlier
– Coupled with the ocean if possible, but constrained by SST and sea ice cover (nudging)
– Ensemble, CMIP6 forcings
– Test-bed for non-DA areas relevant for next reanalysis
– Production to start around 2021

Next full-observing-system coupled reanalysis (ERA6)
– State-of-the-art NWP system, coupled with the ocean
– Boundary conditions: similar concept to what was used for the climate integrations (see above)
– Production to start around 2023