The ERA6 Reanalysis

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ECMWF Research Department

ECMWF Forecasts and Services Department

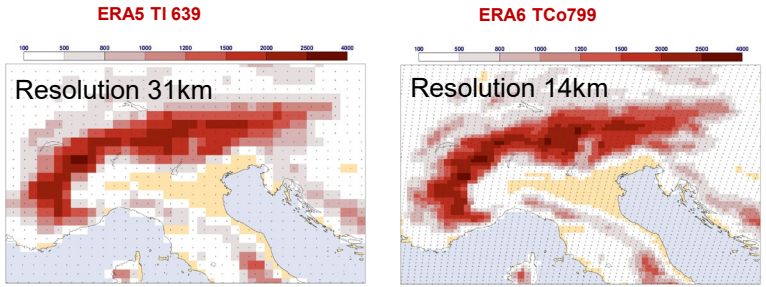
C3S Partners & Contractors

Climate Change

Overview

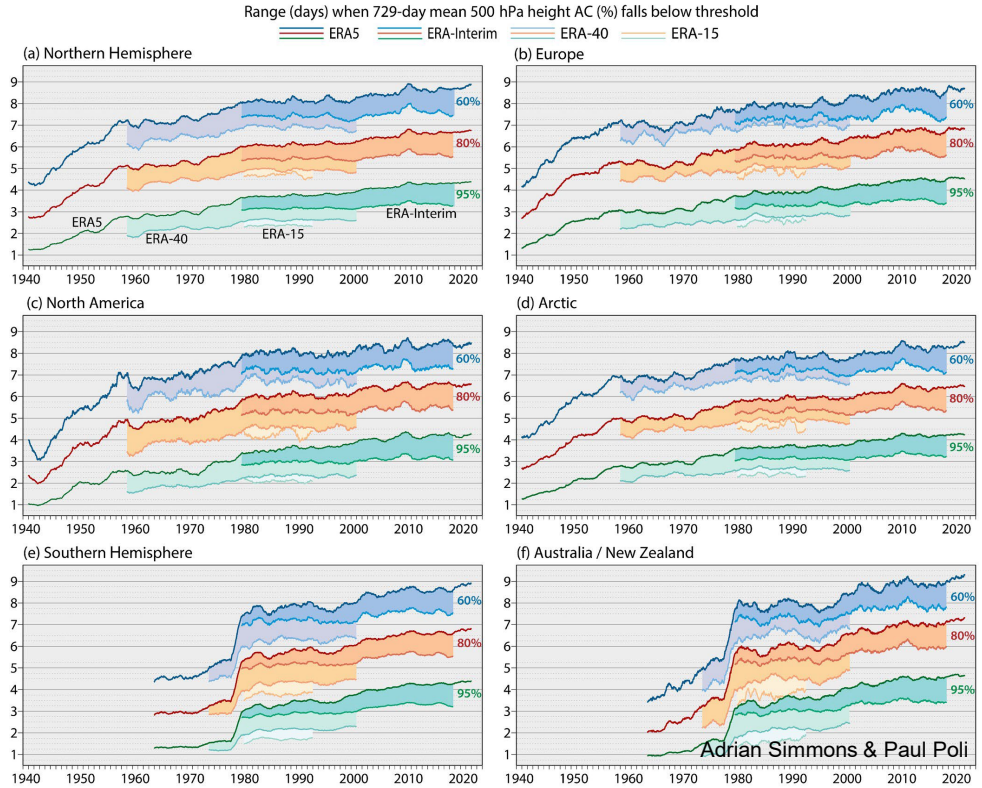
- Recap: previous ECMWF reanalyses
- ‘ *What do we get from ERA6 ?* ’ – enhanced performance from **many** developments !
- Some specific themes :
  - improved stratosphere / T2m / tropical cyclones / ocean-atmosphere coupling
  - observations (rescued and reprocessed, satellite and conventional)
- Initial indications of expected performance
- Summary & concluding remarks

Horizontal grid



ECMWF

ECMWF atmospheric reanalyses



- **Most recent is ERA5, started in 2016, still runs in NRT**:
  - part of the EU's Copernicus Climate Change Service (C3S)
  - 31km horizontal resolution
  - hourly state estimates, 1940 – NRT
- **A popular ECMWF product !**
  - > 20 000 citations (Hersbach et al, 2020)
  - user base > 200 000 since 2018
- **Supports a very wide range of applications, including, for example:**
  - climate trend assessments
  - studies of extreme events
  - training datasets for ML forecast models

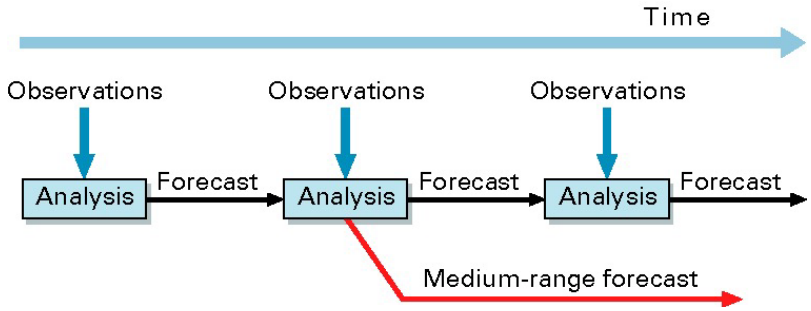
For more detail on applications, see:

- Wed 14:00: Carlo Buontempo & Laurence Rouil, *Serving Society through CAMS and C3S*
- Thurs. 14:00: Simon Lang, *Machine learned weather forecasting with AIFS*
- Friday am: *Session on Scoping the future of forecasting*

For more details on ERA5:

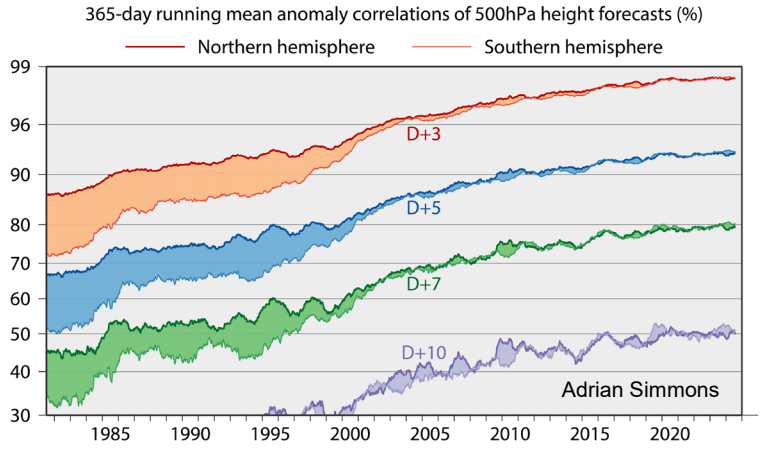
- Hersbach *et al*, QJ, 2020
- Bell *et al*, QJ, 2021
- Soci *et al*, QJ, 2024

Reanalysis



- Reanalysis uses the latest versions of the assimilation system and forecast model → benefits from continuous improvement in the IFS between successive generations of reanalyses, as well as enhanced computing power (largest drivers of improvements)
- Free from the constraint of NRT operations, we can exploit observations never used in NWP
- In addition, we can iteratively improve the input observational datasets & rescue observations which have never been assimilated before

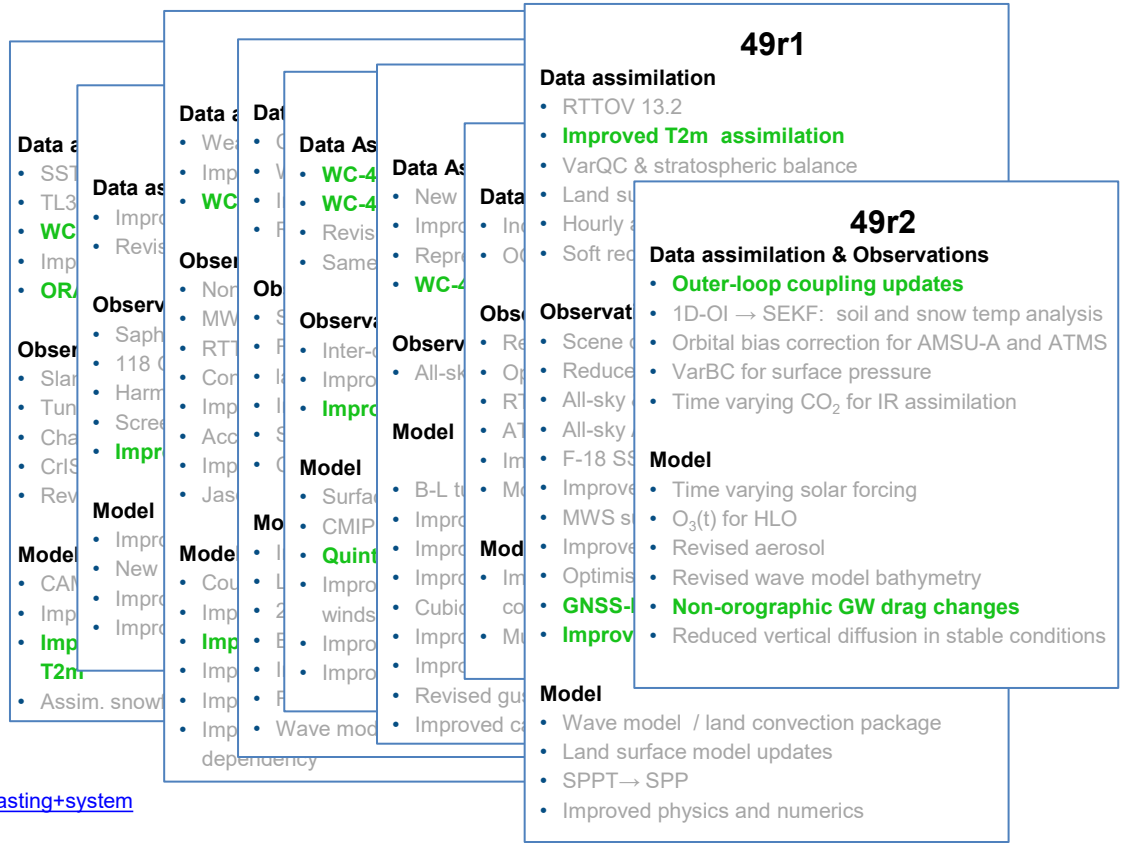
"Why not use operational analyses ?"



OK for very recent past, for *some* applications, but :

- performance & resolution of operational model declines as we go back in time (resolution in 1985: T106, ~100km)
- What do we use pre-NWP (1st August 1979 for ECMWF) ?
- Model updated 1-2 times per year, each change potentially resulting in discontinuities

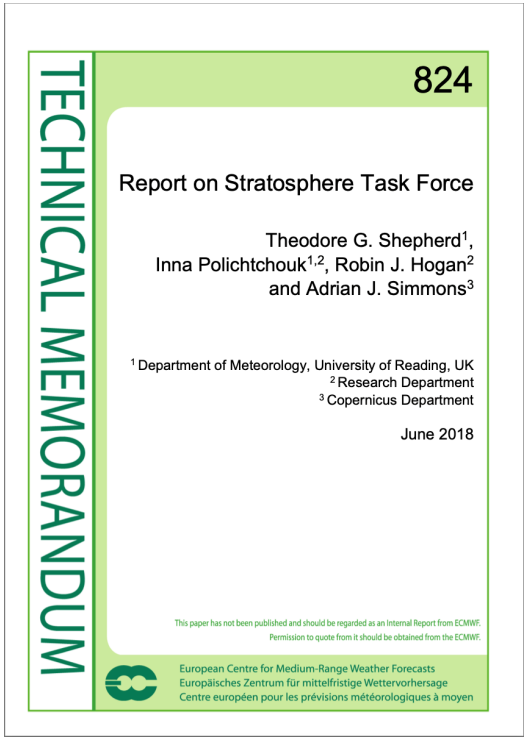
‘ *What do we get from ERA6 ? ’*
Integrated Forecasting System (IFS) upgrades since ERA5

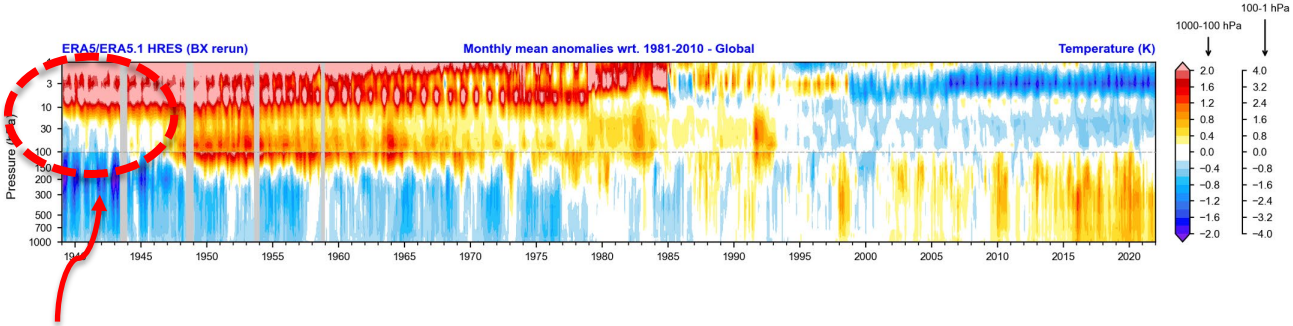


https://confluence.ecmwf.int/display/FCST/Changes+to+the+forecasting+system

+ analogous technical developments, incl. HPC upgrade

Improvements in the representation of the stratosphere since ERA5





- **Model cold bias in the lower stratosphere** (and warm bias in upper stratosphere) exposed in the earliest 5 years of ERA5, at the very beginning of the upper air observing system.
- **Post-2006 (GNSS-RO era) -** analysis relatively free of discontinuities and bias.
- Combination of **model improvements** & **weak-constraint 4D-Var** (WC 4D-Var) will improve these aspects (see next slide) in ERA6

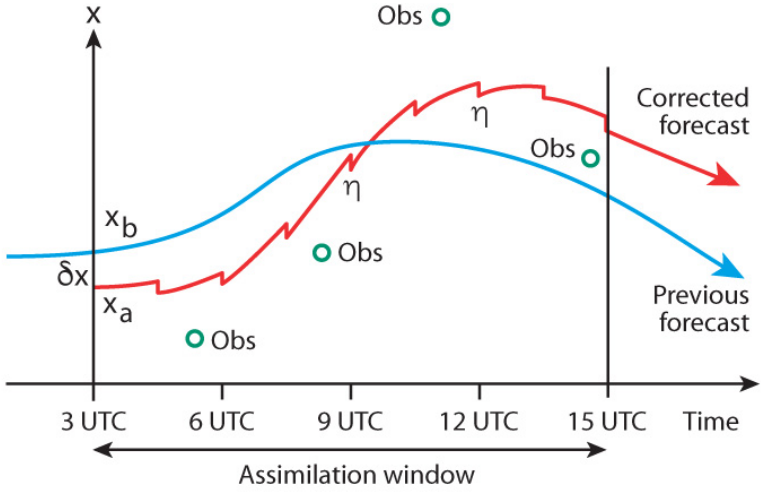
https://www.ecmwf.int/en/elibrary/80609-report-stratosphere-task-force

Weak-constraint 4D-Var formulation

We assume that the model is not perfect, adding an error term η in the model equation

$$x_k = \mathcal{M}_k(x_{k-1}) + \eta \quad \text{for } k = 1, 2, \cdots, K$$

The model error estimate η contains 3 physical fields (temperature, vorticity and divergence)



➔ Introduce additional degrees of freedom to fit background and observations

➔ A model trajectory is entirely determined by its initial condition and the model error forcing

Laloyaux et al., Exploring the potential and limitations of weak-constraint 4D-Var, QJRMS, 2020

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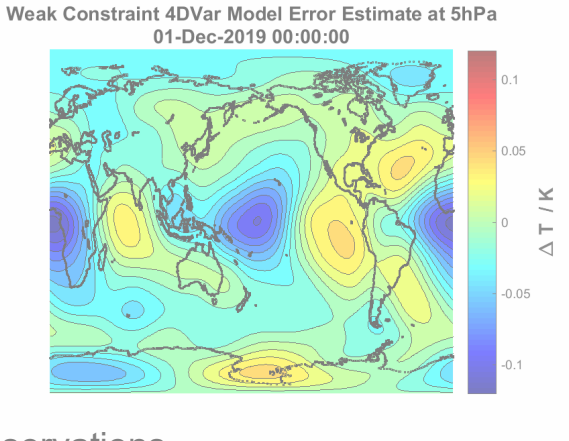
$$J(x_0, \eta) = \frac{1}{2}(x_0 - x_b)^T \mathbf{B}^{-1}(x_0 - x_b)$$
$$+ \frac{1}{2}\sum_{k=0}^{K}[y_k - \mathcal{H}(x_k)]^T \mathbf{R}_k^{-1}[y_k - \mathcal{H}(x_k)]$$
$$+ \frac{1}{2}(\eta - \eta_b)^T \mathbf{Q}^{-1}(\eta - \eta_b)$$

Model initial condition

Model bias correction



➔ Introduce additional degrees of freedom to fit background and observations

➔ A model trajectory is entirely determined by its initial condition and the model error forcing

➔ ERA6 will use WC 4D-Var 2006 → (GNSS-RO obs provide a good analysis in the stratosphere)

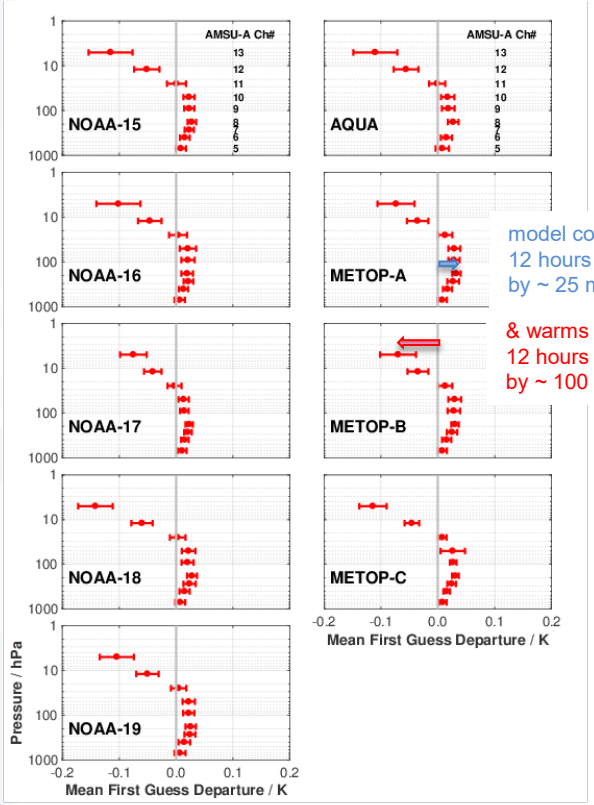
➔ Use the estimated model error forcing for earlier periods (1950-2006)

Laloyaux et al., Exploring the potential and limitations of weak-constraint 4D-Var, QJRMS, 2020

Bonavita & Laloyaux, Machine Learning for Model Error Inference & Correction, JAMES, 2020

Climate Change

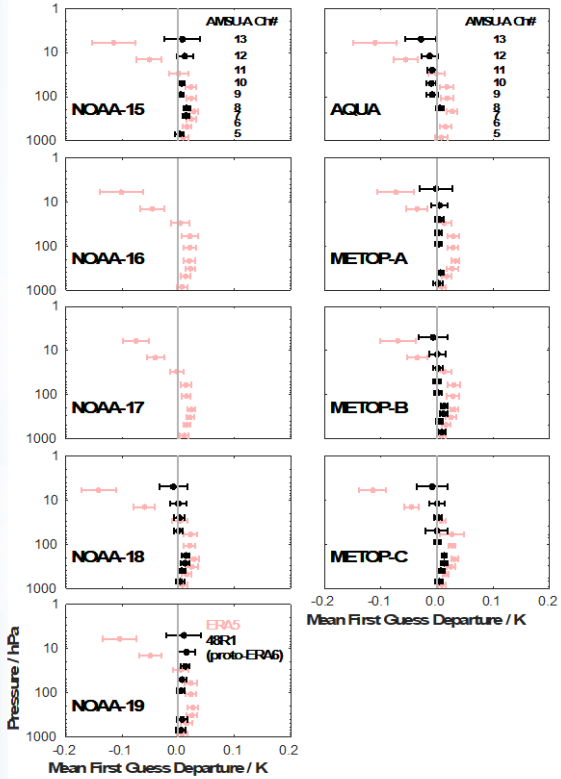
Biases in the stratosphere: background departures for AMSU-A from ERA5



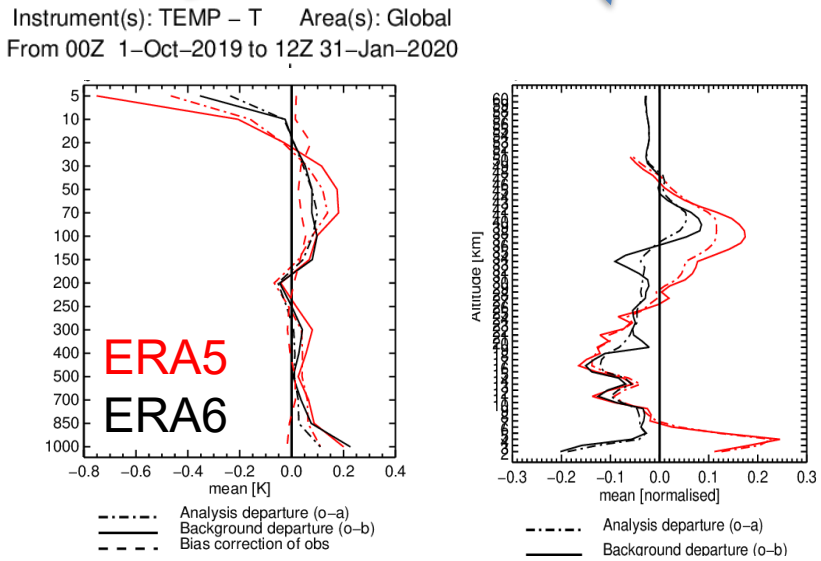
- DA diagnostics are a very sensitive indicator of model biases
- Coherent across all AMSU-A instruments,
  and consistent in time over mission lifetimes for ERA5

Climate Change

Biases in the stratosphere: background departures for AMSU-A & Temp-T from ERA5 & pre-ERA6 tests

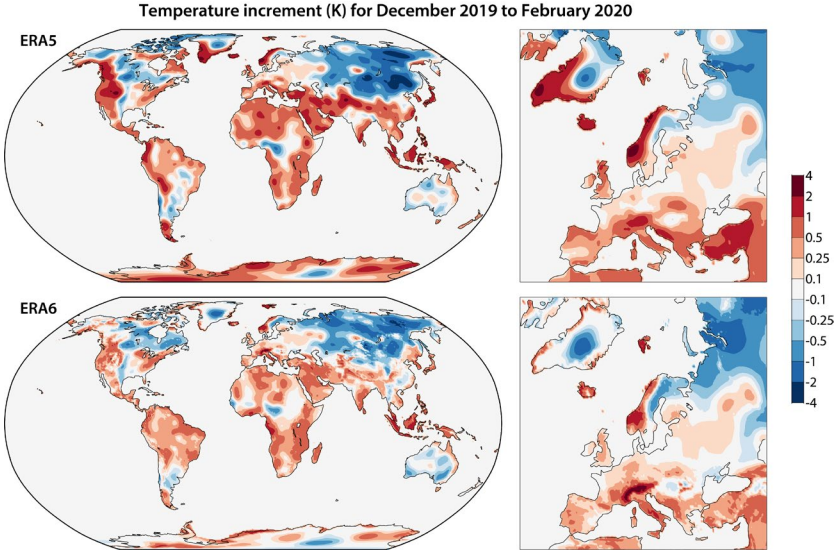


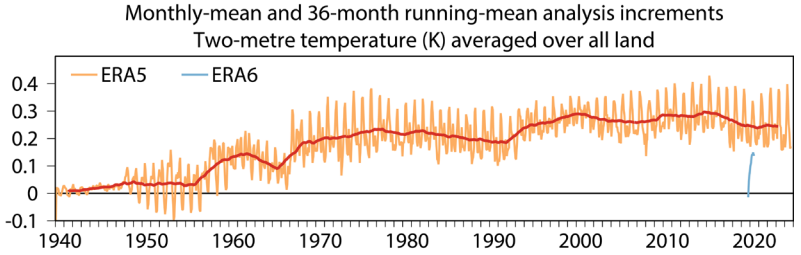
- Due to model improvements & WC-4DVar, ERA6 analyses and backgrounds are less biased
- Improvements evident for :
  AMSU-A ; Radiosonde temperatures & GNSS-RO obs



'… but how well does it work in the earliest epochs of the reanalysis ? '
- we'll come back to that later

Improvements in the analysis of T2m in ERA6

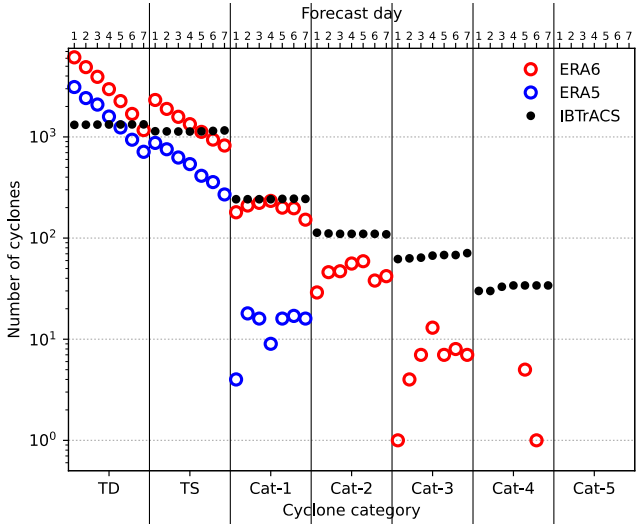




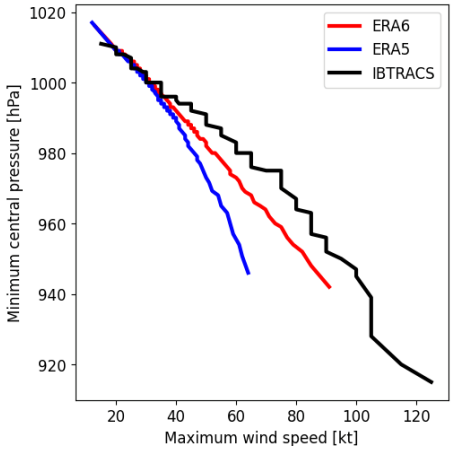
Verification of 12-month ERA6-like experiment
Adrian Simmons

- Increments in two-metre temperature from the surface analysis are generally smaller for the ERA6 prototype than for ERA5, both locally and in all-land averages.
- Background fits to observations are generally closer for the ERA6 prototype than for ERA5.

Improvements in the representation of tropical cyclones in ERA6



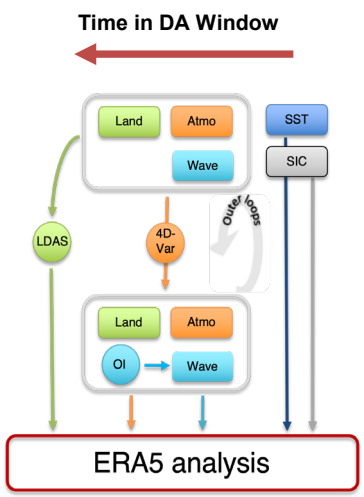
Logarithmic scale of the y axes to highlight differences in the stronger intensity categories.

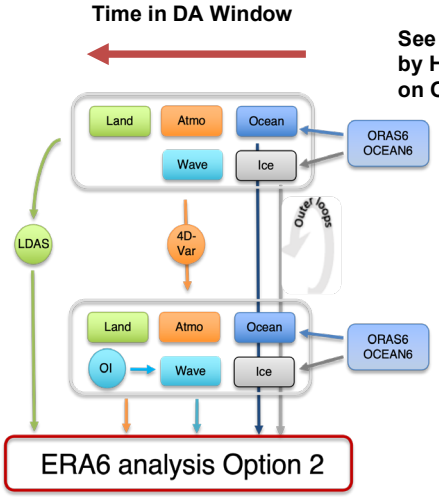


Verification of 12-month ERA6-like experiment
Michael Maier-Gerber

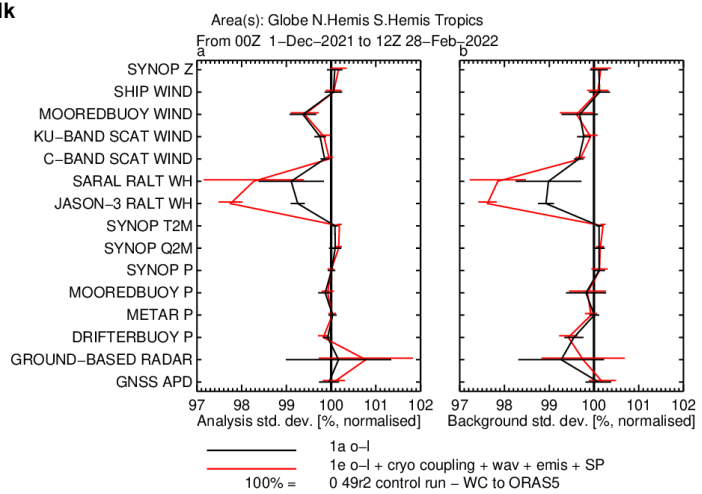
- Forecasted numbers of Cat-1 hurricanes now fit well to observed numbers.
- ERA6 captures Cat-2 to Cat-4 hurricanes, which were missing in ERA5.
- TC track errors reduced by almost 1 day at lead times larger than 2 days.
- Deeper core pressure and higher wind speeds on average
- ERA6 features smaller TCs compared to ERA5 (smaller average maximum wind radii)
- Pressure-wind relationship is also more consistent with observations, now qualitatively similar to the operational IFS
- AI forecast models inherit the deficiencies in ERA5. ERA6 will offer improvements in this regard.

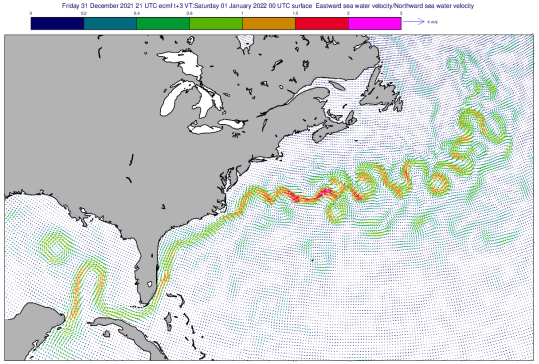
ERA6 is coupled with the ocean, with the ocean initial state from ORAS6





See next talk by Hao on ORAS6



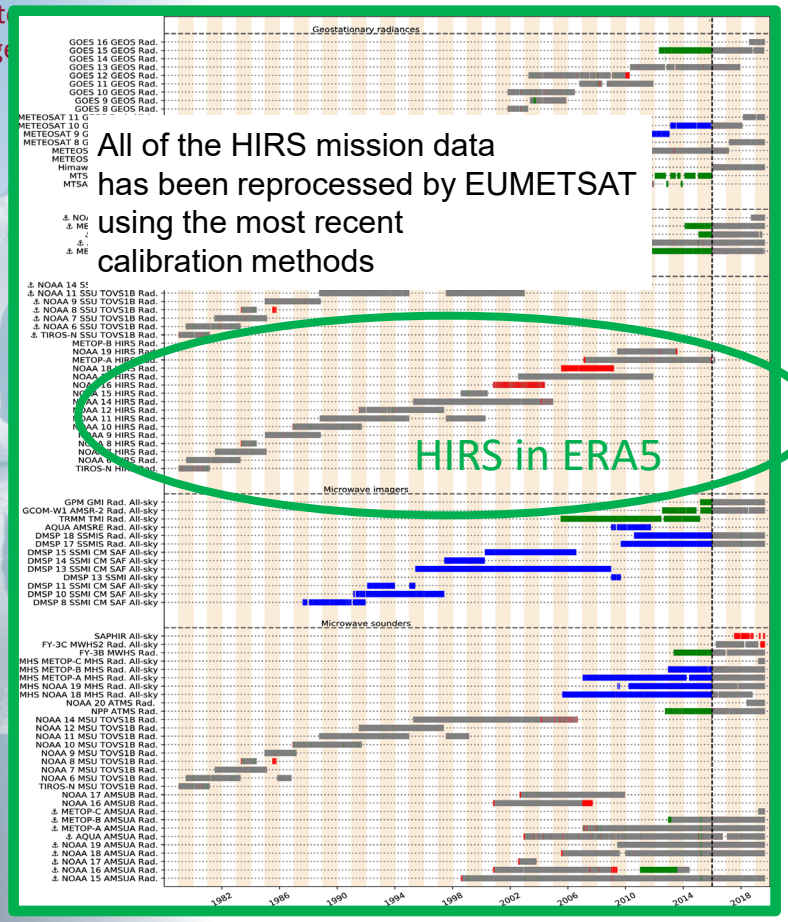


Positive impact where you expect it:

- near the surface, improved ocean wave forecasts (account for ocean currents)
- better fit to near ocean surface observations (scatt wind and alt Hs)
- SST/SIC evolving hourly rather than daily in ERA5, ocean currents

Impact of reprocessed HIRS data on reanalysis and re-forecast quality
pre-ERA6 production tests

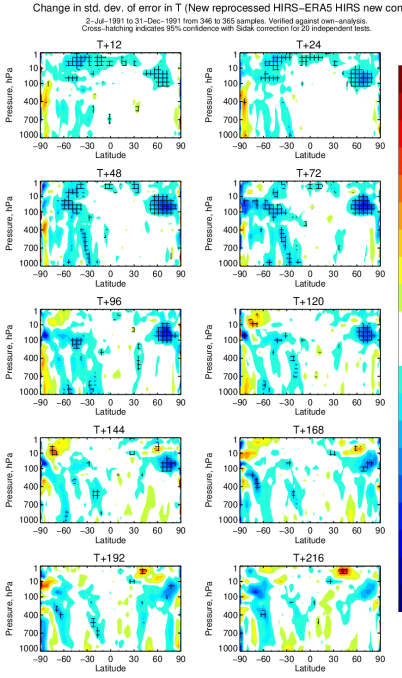
Climat
Change



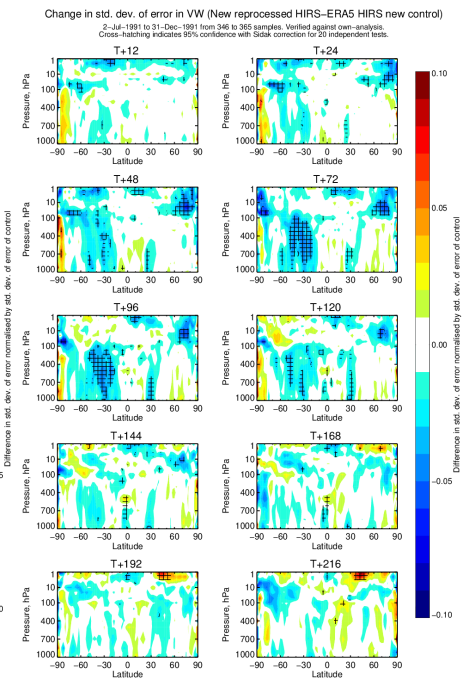
Improved analyses and forecasts
Using EUMETSAT reprocessed HIRS data

(blue areas below represent smaller errors for the test with reprocessed HIRS, relative to a control using HIRS data assimilated in ERA5)

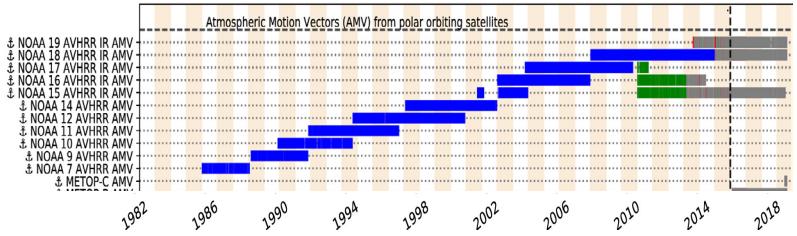
Temperature



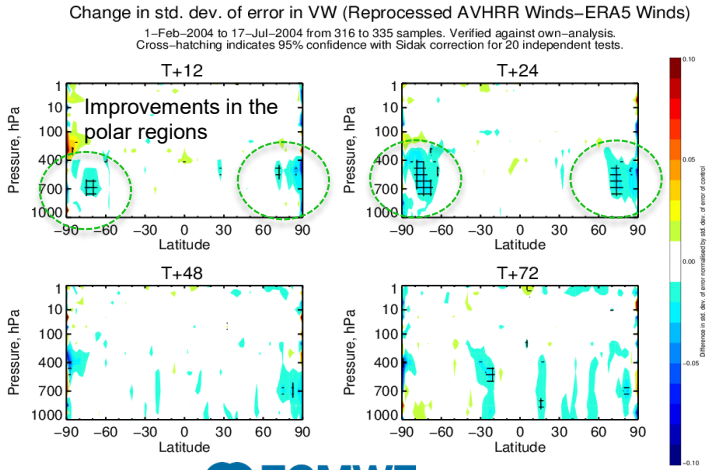
Winds

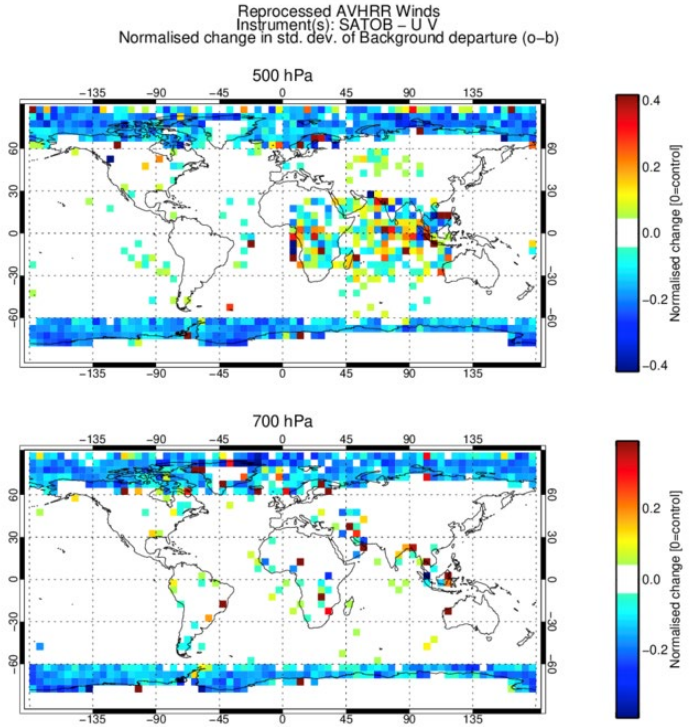


Reprocessed AVHRR Polar Winds



- Winds derived from sequences of images from polar orbiters.
- Reprocessed by EUMETSAT using latest methods applied to entire AVHRR mission





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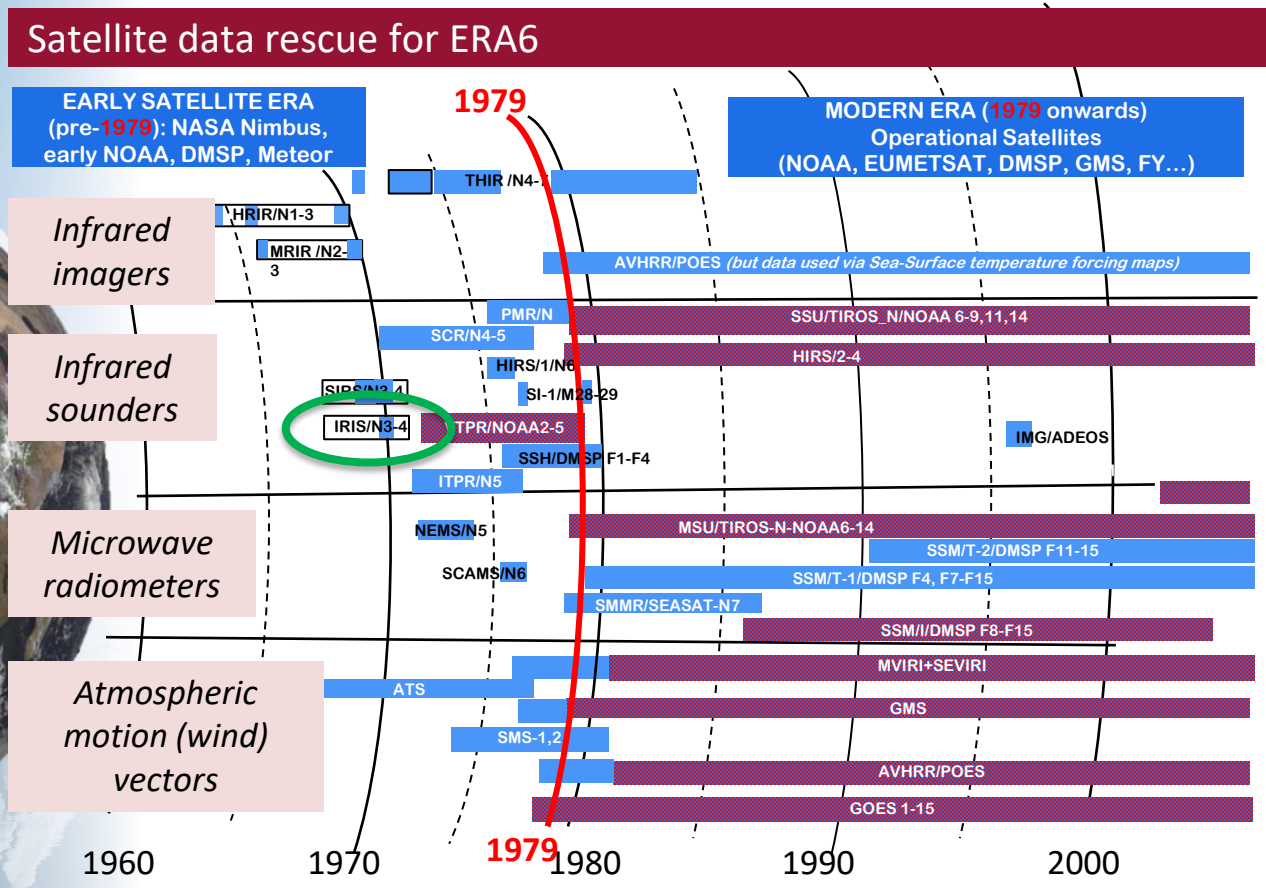
Satellite data rescue for ERA6



Preparations for ERA6 include:

- **Rescue and Assessment** of radiance observation from pre-1979 sensors
- Aim is to improve the '***assimilation readiness***' of the data
- Example of the impact of **Nimbus-4 IRIS** shown in the following slides

Data not yet assimilated in ERA

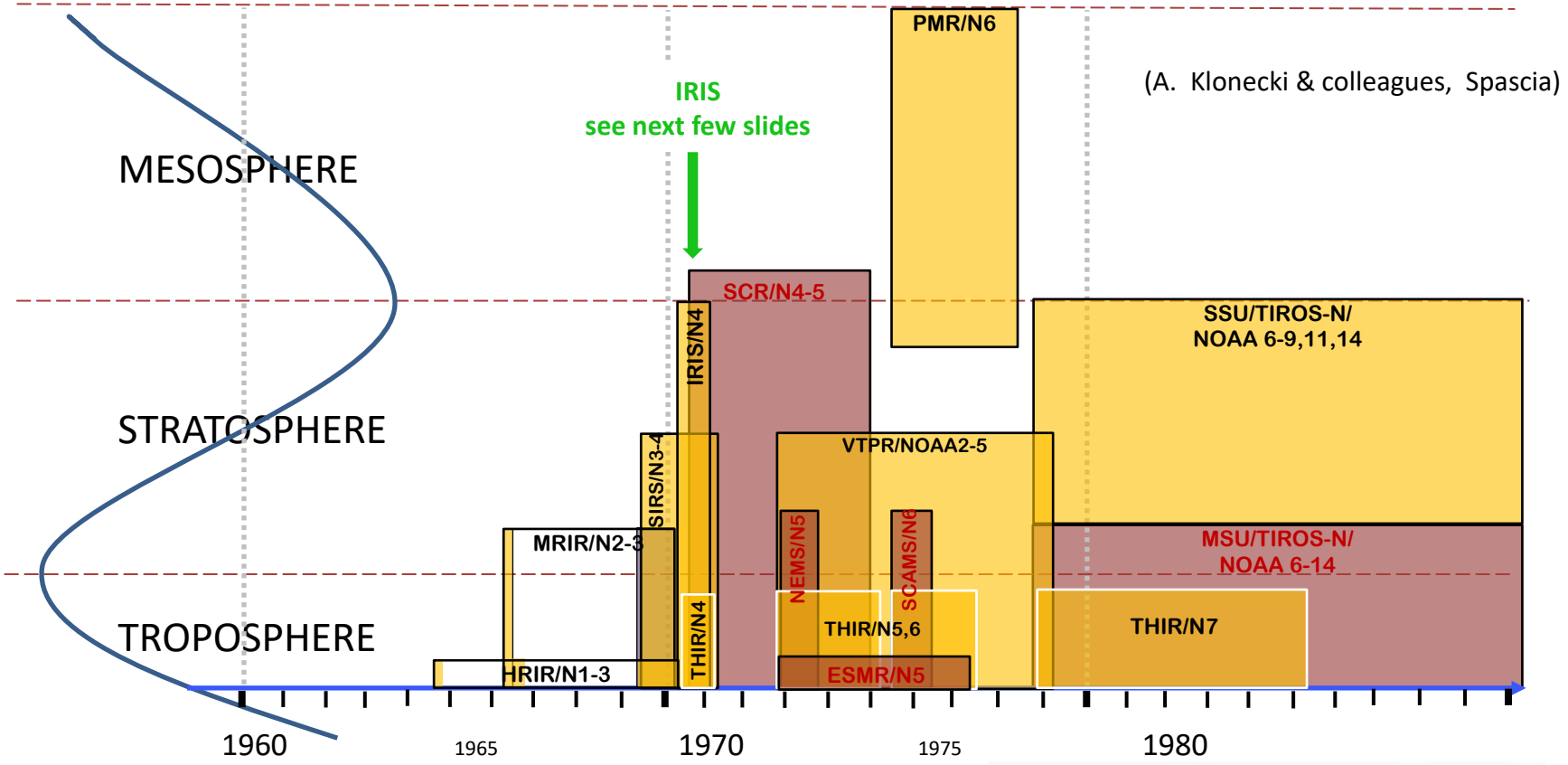
Original or earlier reprocessed data version assimilated in ERA5

(A. Klonecki & colleagues, Spascia)

Copernicus Europe's eyes on Earth | European Commission | ECMWF

Temporal coverage and vertical sensitivity of the data from early satellite data records

Climate Change



SPASCIA · University of Reading · Icare · cnrm · Met Office · absiskey · ECMWF · Copernicus Europe's eyes on Earth · European Commission

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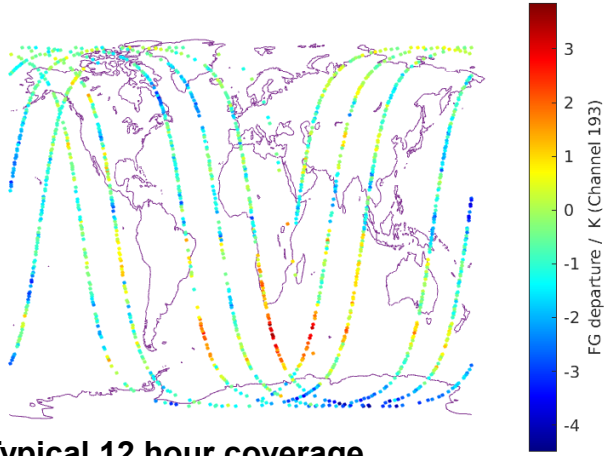
Assimilating Nimbus-4 IRIS Observations

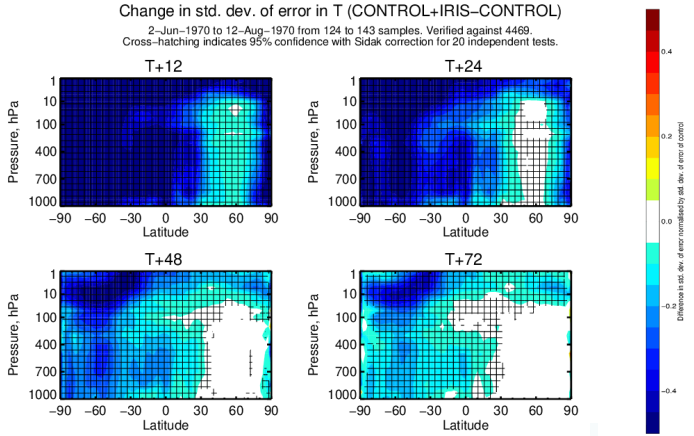


Typical 12 hour coverage

- Data evaluated & prepared by C3S partners, Spascia (A. Klonecki and colleagues)
- Interferometric IR sounder, operated on Nimbus-4, from **April 1970 – January 1971** (preceded Metop-A IASI **by 36 years** !)
- Nadir only observations. Spectral range 400 - 1600 cm^{-1}
- Resolution: 2.53 cm^{-1} to 2.69 cm^{-1}, 94 km footprint

For more details on IRIS see Poli & Brunel, Advances in Space Research , 2018.

- **Control:** CY48R1 / **Experiment** assimilated IRIS data
- Background error covariances from ERA5 (so appropriate for 1970)
- 12Z 1st June 1970 – 00Z 12th August 1970
- **Significant improvements in southern hemisphere and stratosphere**
- **Improved background (and analysis) fits** to radiosonde temperatures and winds (~5%) and surface pressure obs (7%)



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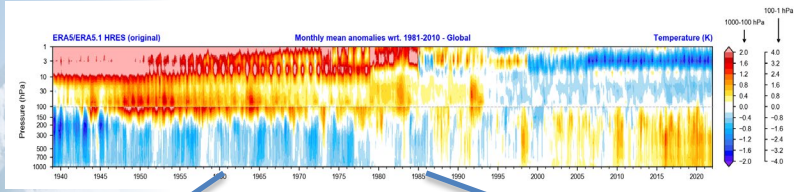
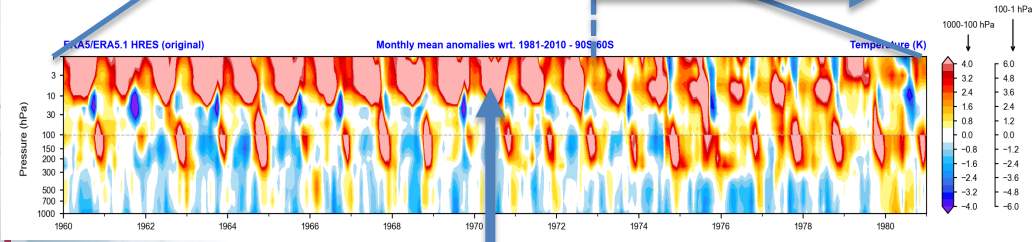
Upper stratospheric biases in ERA5. Using IRIS observations to assess the performance of model error forcing (derived from WC 4D-Var) in ERA6 during S. polar winter 1970

Global statistics 1940 - 2022



Southern polar statistics 1960 - 1980

VTPR assimilated



IRIS mission covered this winter

biases reduced using model error forcing

Fit to IRIS upper stratospheric observations improved

- Particularly large biases evident in southern polar winter (>> 6K in the plot shown). Repeatable year-to-year
- Reduced following the assimilation of VTPR data (Nov 1972 - Jan 1979)

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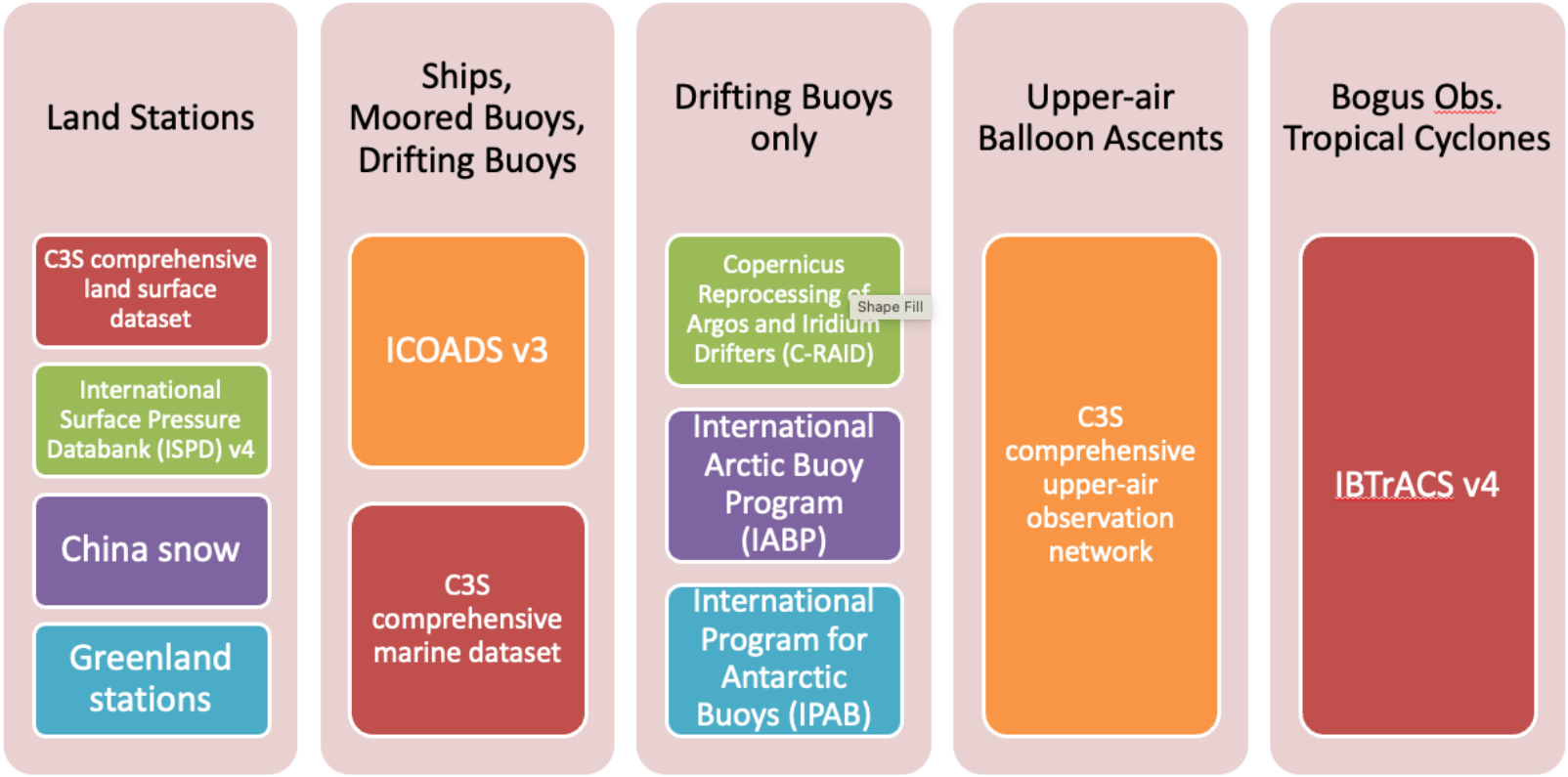
Changes in conventional observation input for ERA6



(Paul Poli)

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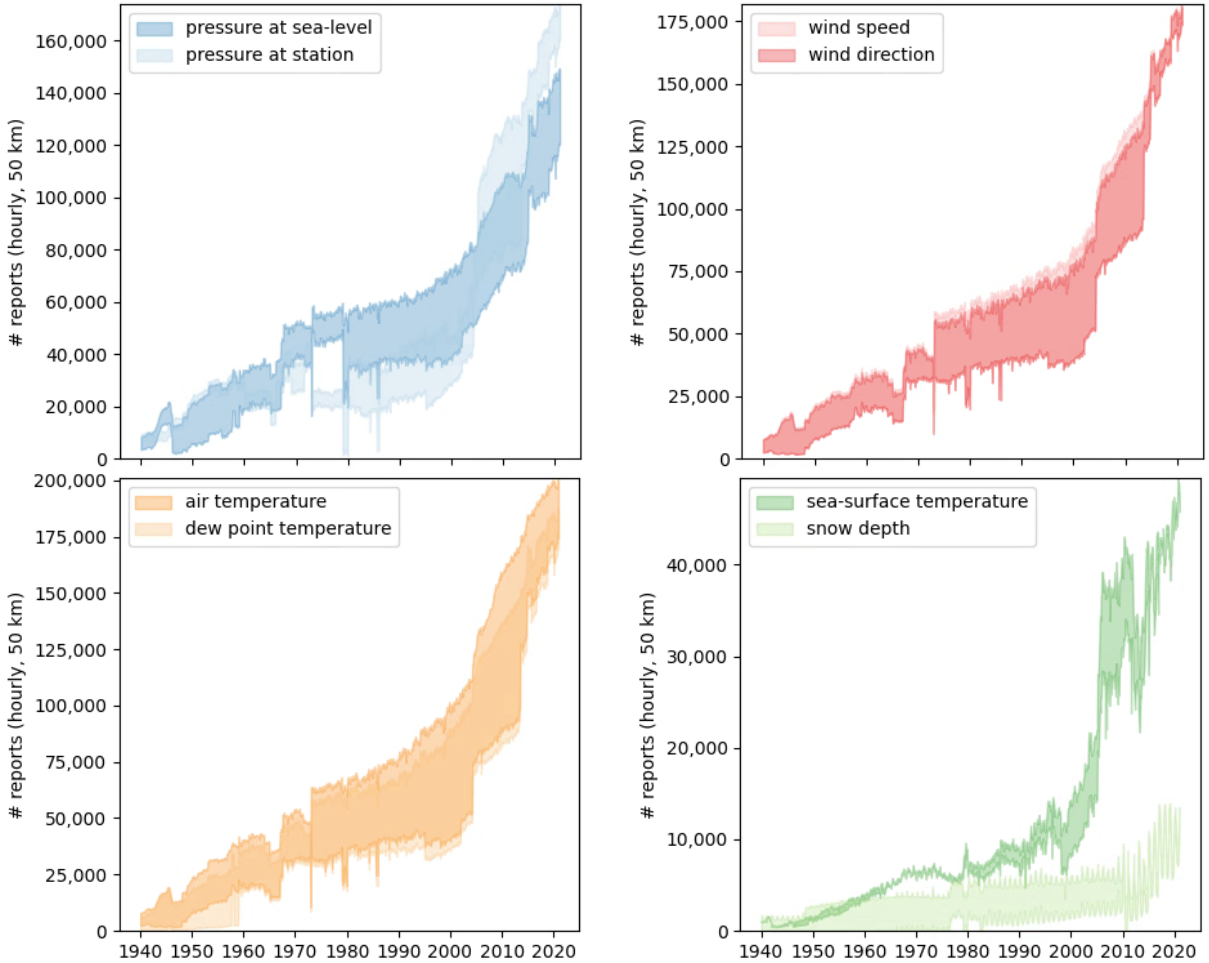
In-situ observations: Additional reports in ERA6, as compared to ERA5



- Bottom curves show **numbers of reports available to ERA5, at hourly, 50-km equal-area grid resolution**.
- Top curves show **numbers of reports available to ERA6**.
- Shading shows the additional reports, between +50% to more than doubling, for key variables.
- Final counts of data used will only be known after ERA6 is produced!

(Paul Poli)

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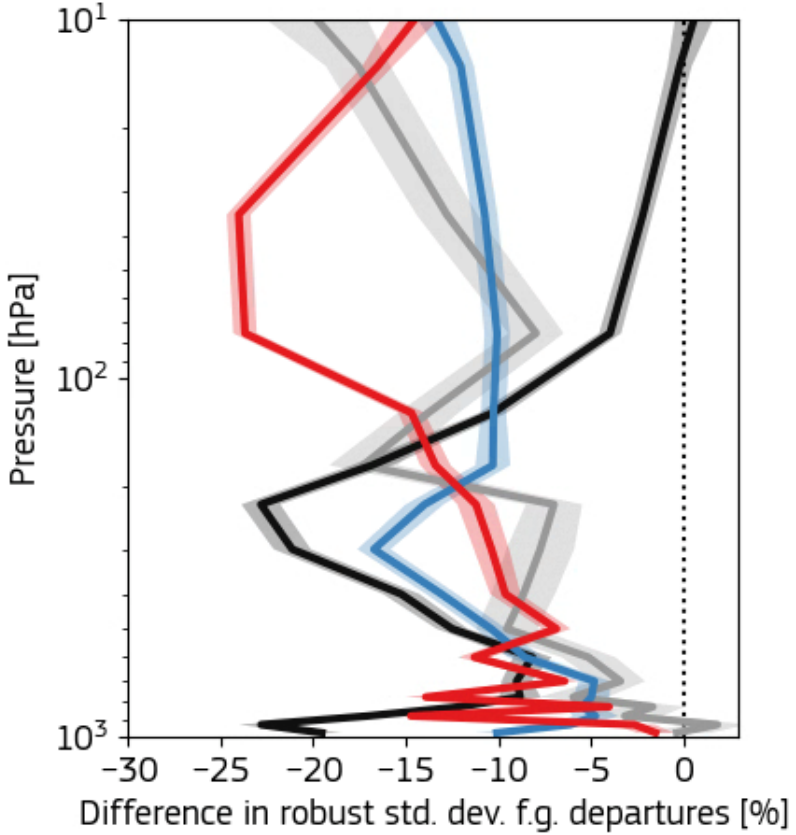
What difference do the rescued/reprocessed in-situ obs. make?

Impact of rescued/reprocessed in-situ obs. in ERA6 system (red), and successive improvements between ERA generations:

6 ↑ 5 ↑ 4 ↑ 3

- From GTS to In-Situ obs. for ERA6 (2006)
- From ERA5 to Pre-ERA6 (2020)
- From ERA-Interim to ERA5 (2006)
- From ERA-40 to ERA-Interim (2000)



Each pair of experiments:

- Radiosonde temperature observations assimilated
- 15 July to 15 August
- Year indicated in legend

Blue: "Pre-ERA6" is the **second** pre-ERA6 prototype test dataset (https://doi.org/10.21957/1qyd-ep25)

Red: Last pair of experiments is at standard IFS "research" resolution (Tco399)

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Performance of ERA6 test experiments

NH Z500 (Oct 2019 – Jan 2020)

anomaly correlation

+12 hrs

ERA5
ERA6

By this metric (remember slide 3) improvements from ERA5 to ERA6 are in-line with those achieved in previous generations of reanalyses

Summary and concluding remarks

- **It's coming!** 9 years on from the start of ERA5, production of ERA6 will commence soon, building on IFS developments from across ECMWF. It's impossible to do justice to those developments in 25 minutes ! ... or 25 hours … but we've looked at a few strands of work (the stratosphere, tropical cyclones, surface temperature & coupling)

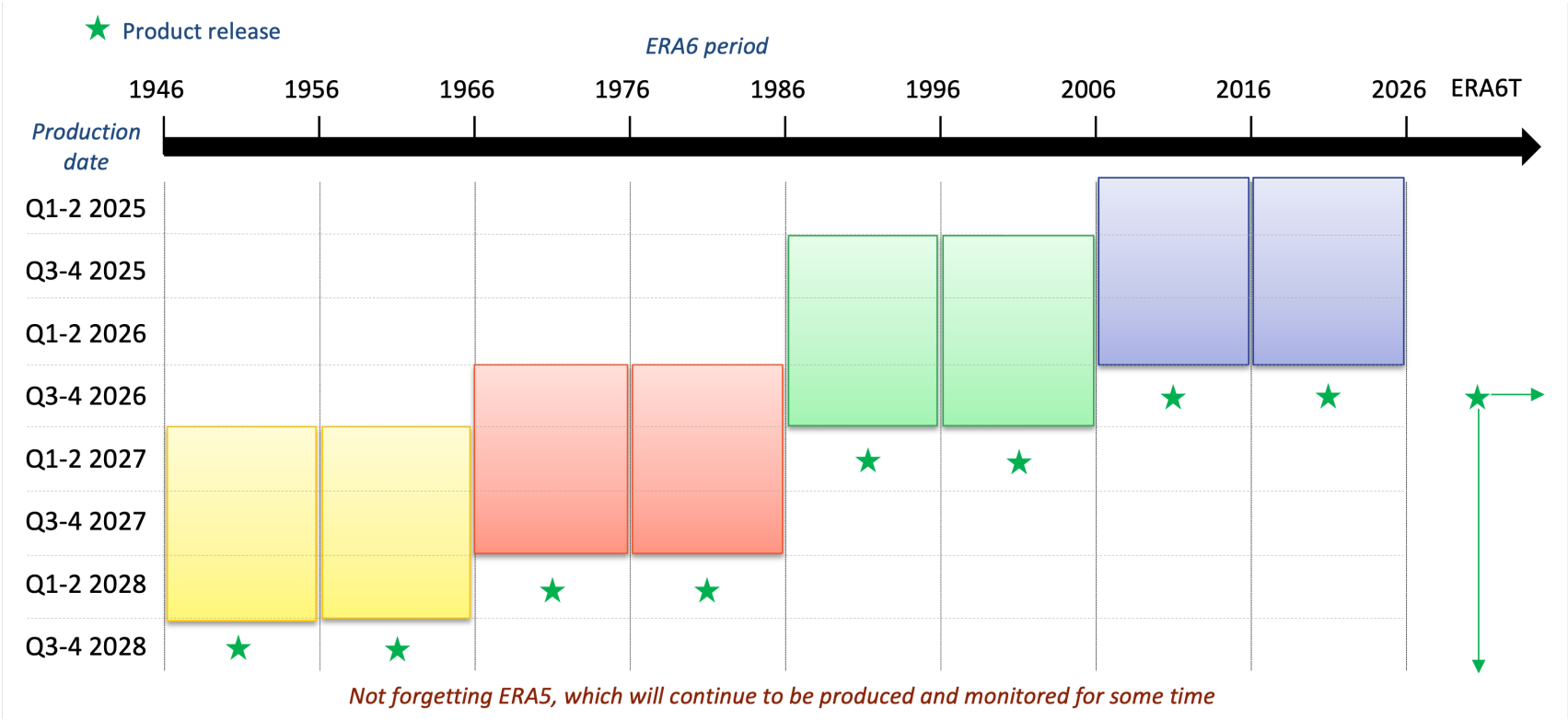
- **Observations.** Unlike NWP, observations have a ***long shelf life*** in reanalysis. C3S has enabled us to support the rescue and reprocessing of conventional and satellite observations & these are demonstrably improving the performance of ERA6 (and subsequent generations of reanalyses)

- **Performance.** Based on re-forecast verification, latest tests indicate a similar improvement in quality to that achieved in previous reanalyses.

Thanks for your time !

EXTRA SLIDES

ERA6 preliminary production plan

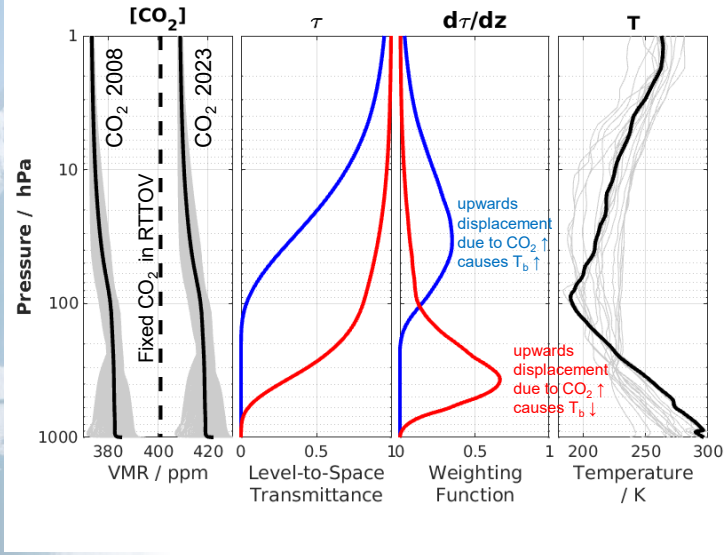


Not forgetting ERA5, which will continue to be produced and monitored for some time

ECMWF

Climate Change

The treatment of CO_2 in the assimilation of advanced IR sounder observations in ERA5



Two effects of changing $[CO_2]$ – when a fixed $[CO_2]$ profile is assumed in RTTOV :

1. **Long-term drift in biases** (analysed by VarBC) due to upwards drift in weighting functions in time
2. **Complex state-dependent biases** (due to $[CO_2]$(time, space) **<u>and</u>** T(time, space))

Expect to **improve (1)** & **reduce the impact of (2)** by using a more realistic CO_2 climatology (CO_2 (latitude, z, time))

(Marco Matricardi & Robin Hogan)

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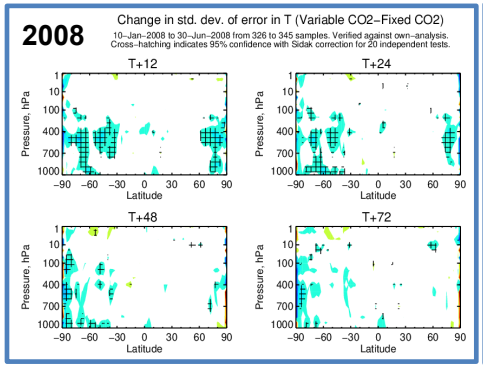
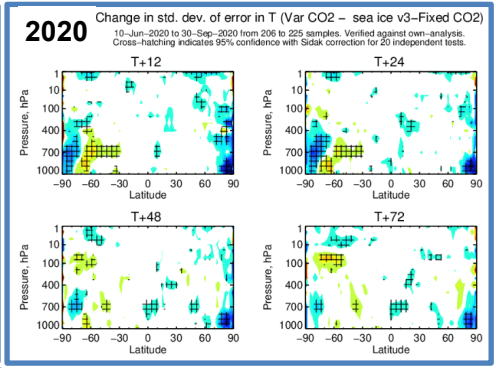
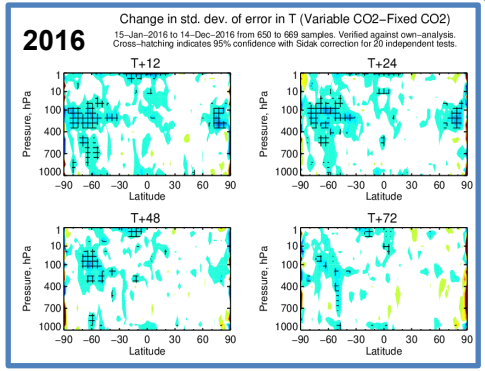
Climate Change

Performance of the variable CO_2 scheme in ERA6 pre-production testing: Impact on bias corrections & temperature analysis







- Temperature analyses and reforecasts improved for all periods tested (2008 - 2023)

- Biases more stable in time for hyperspectral-IR sensors
- Intersatellite biases (AIRS / IASI / CrIS) reduced

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