

Reanalysis methods at ECMWF

Data assimilation training course 2026

Bill Bell,

(Based on DA course 2025 lecture by Hans Hersbach)

The Climate Reanalysis Team and many others

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Overview

- **What is reanalysis and why do we produce it?**
- A walk through ERA5: an example of global reanalysis
 - Data assimilation system
 - The evolving observing system
 - Background errors
 - Systematic model error: symptoms and solutions
 - Ensemble spread as a proxy for synoptic quality
 - Long-term forcing fields
- ERA6: a step towards a coupled Earth system reanalysis
- Summary

What is reanalysis and why are we doing this?

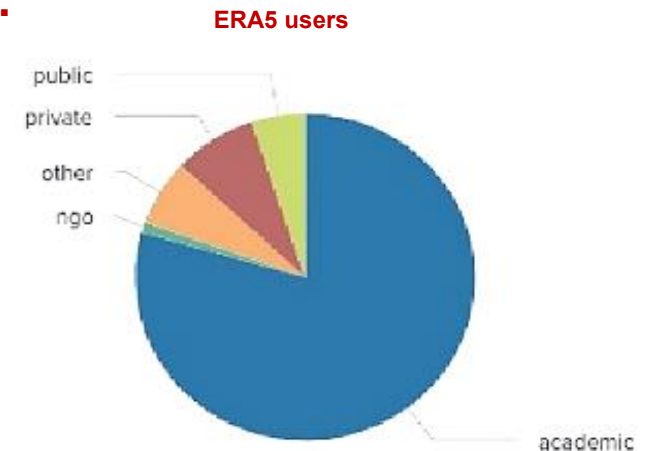
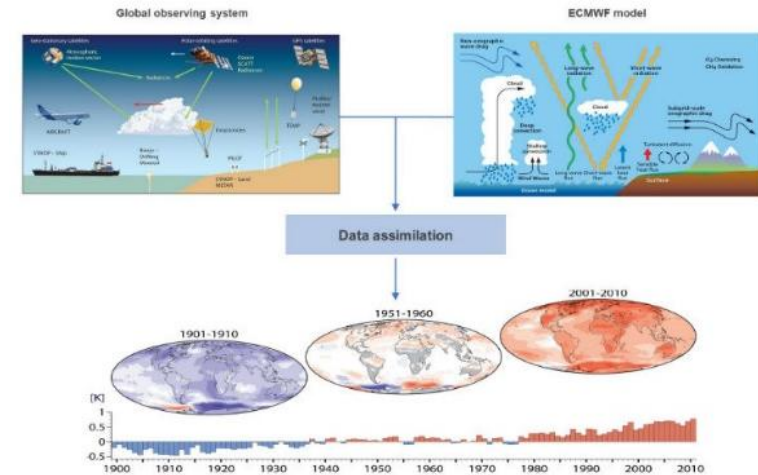
Goal: Estimate past weather & climate, over multi-year timescales:

- ✓ **Input:** all available observations + forcings + weather model
- ✓ **Challenge:** deal with inhomogeneities, biases, range of observables
- ✓ **Output:** convenient and as accurate as possible
'maps without gaps' of 3D atmosphere (+ other domains)
using 4D-Var, land and ocean-wave assimilation

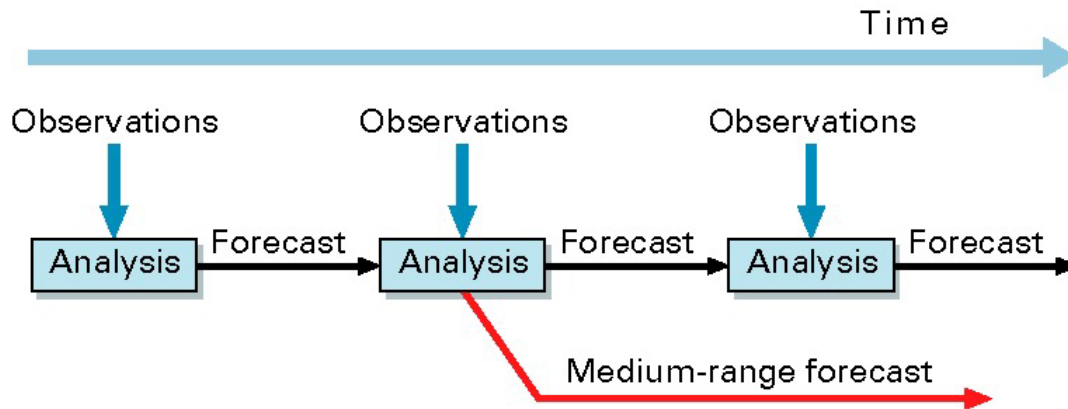
How: use a recent DA system but at lower resolution, for affordability

Reanalyses are very popular and used for many applications, such as:

- ✓ **Study of specific events or phenomena:**
 - accurate (3D) synoptic situation; i.e., **the weather of the day**
- ✓ **Climate monitoring:**
 - Accurate recent synoptic situation + **consistent 30-year climate**
- ✓ **Climate applications:**
 - low-frequency variability of the **mean state**, extremes
- ✓ **Initialization, boundary conditions** and drive impact **models**
- ✓ **Training set for machine learning applications**

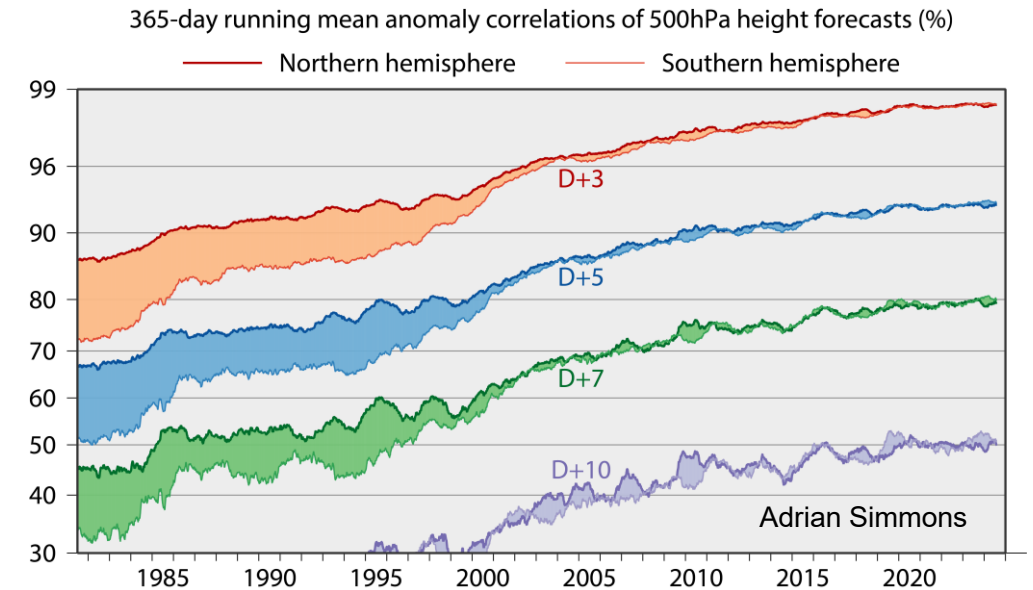


What is reanalysis and why are we doing this?



- 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 timeliness constraints 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

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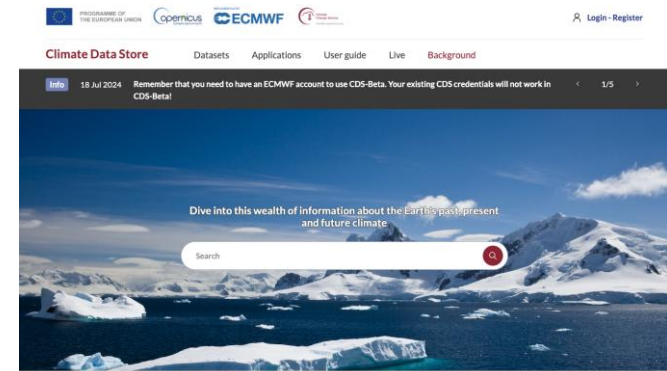
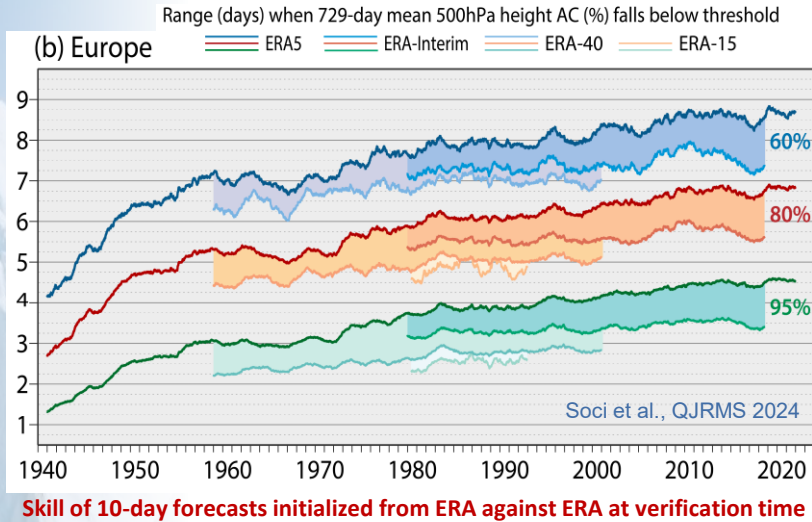


ERA5: Global reanalysis, 31km, hourly from 1940 to 5 days behind time, operationally

Climate Change

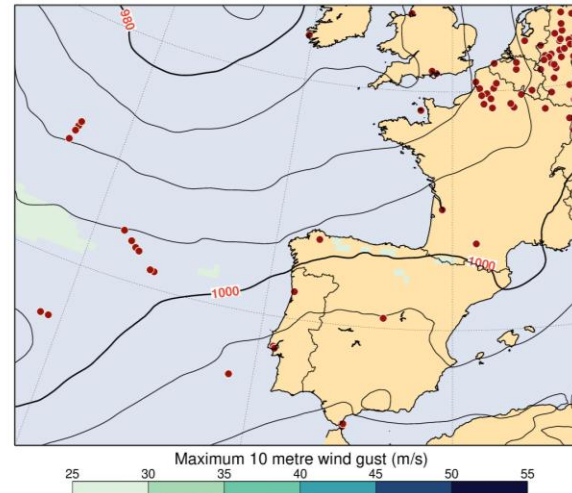
ERA5 was built on the shoulders of other ECMWF reanalyses

ERA5 has over **200,000 users**, providing **petabytes** of climate data

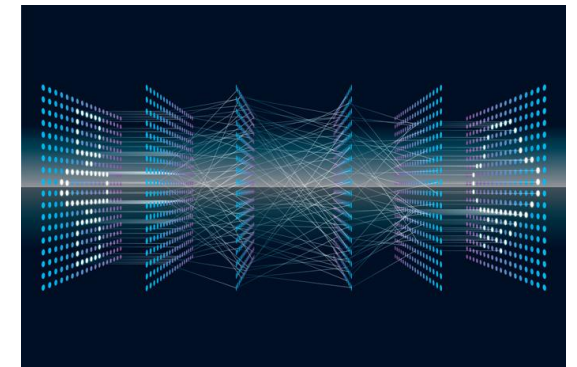


.. to historical extreme cases ..

ERA5 14 February 1941, 18 UTC



.. and leading training set for data-driven weather forecasting and much more ...



From accurate timely climate monitoring, ..



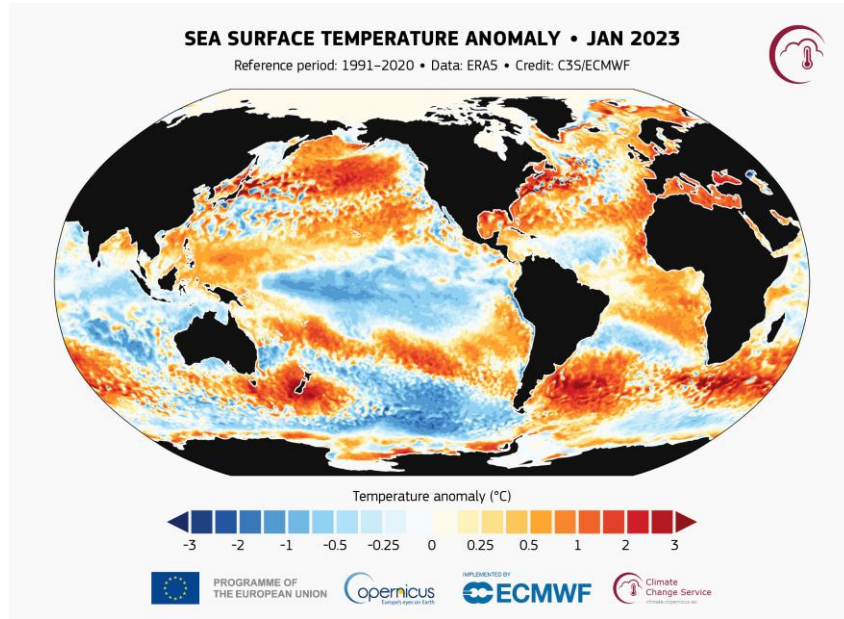
1. The first year warmer than 1.5°C above the pre-industrial average
2. Record number of days above 1.5°C in 2024



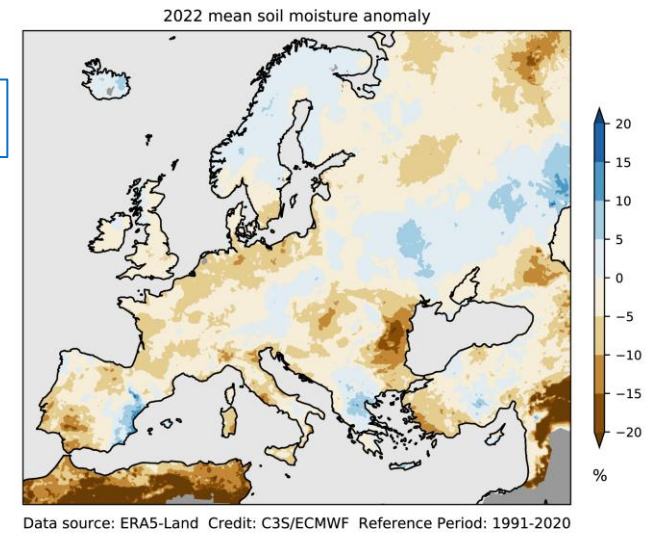


Overview of C3S reanalysis products

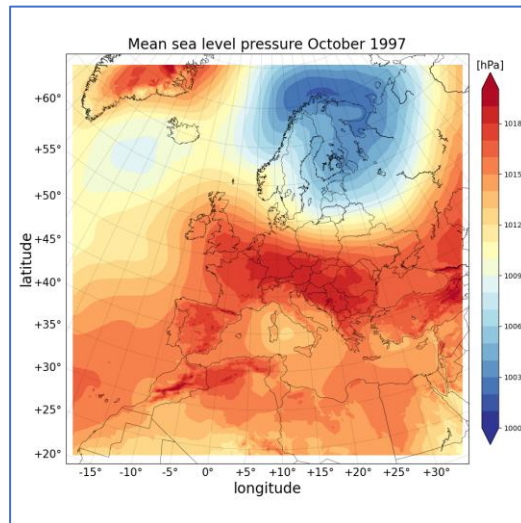
ERA5



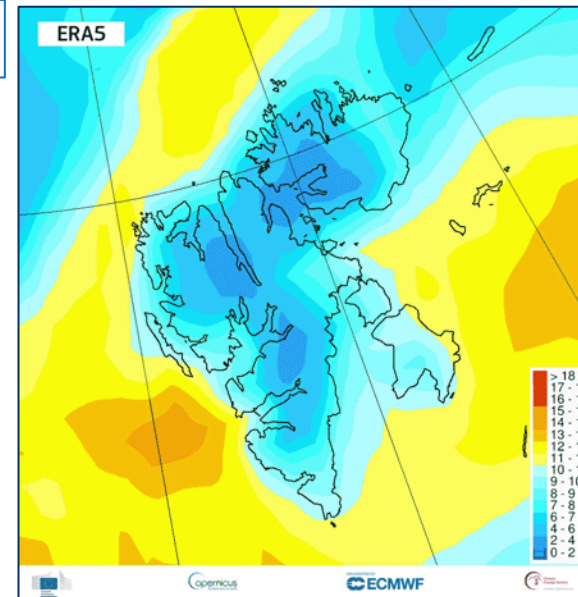
ERA5-Land



CERRA



CARRA



PROGRAMME OF THE EUROPEAN UNION



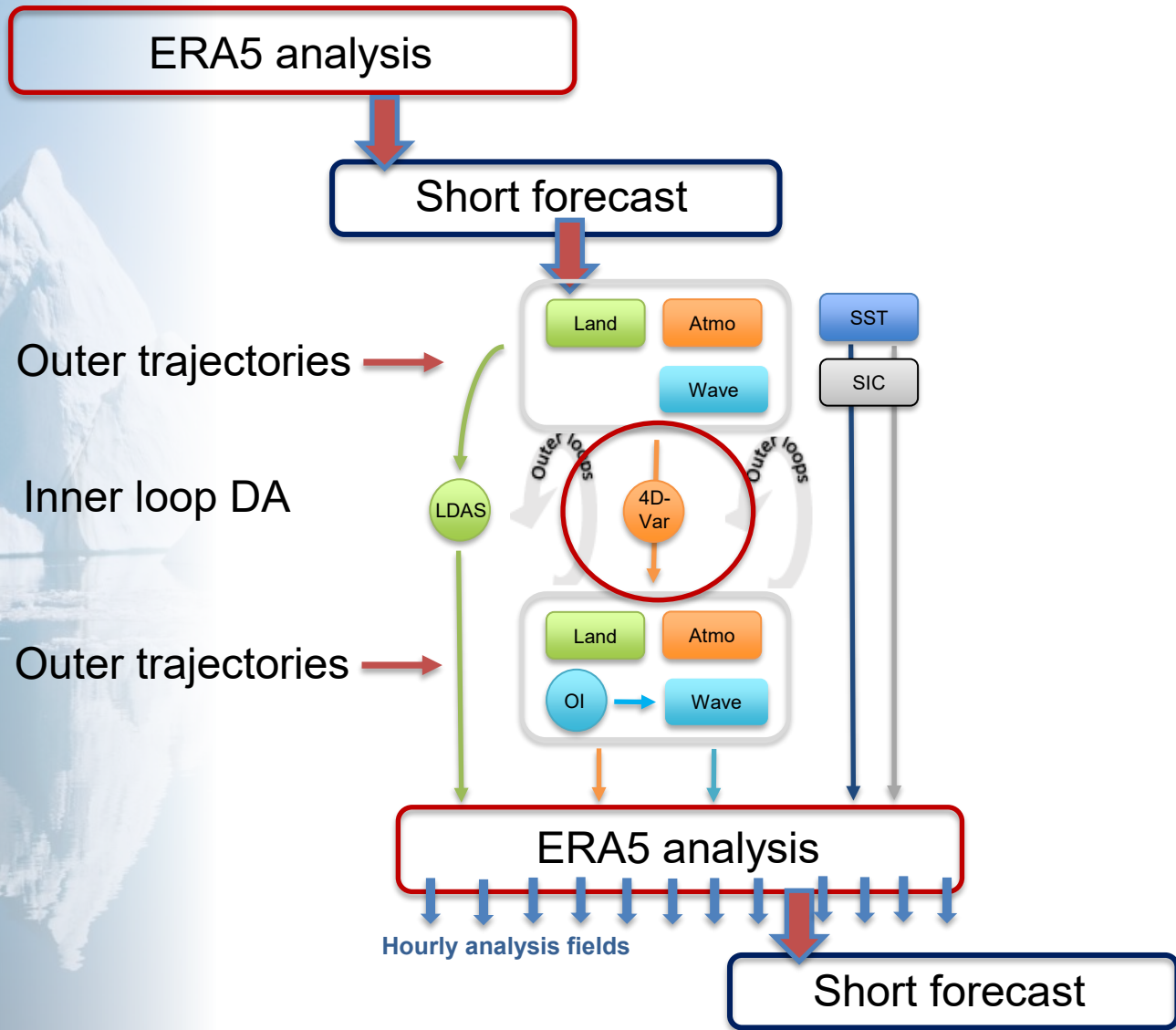
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The ERA5 assimilation system for atmosphere, land and ocean waves



4D-Var for atmosphere: assimilate observations

- solve in an incremental way to better deal with non-linearities
- all upper-air variables plus a number of surface parameters

Ocean wave analysis:

- Altimeter wave height using optimal interpolation (OI)
- 2D-wave spectrum plus large set of integrated parameters

Land data assimilation (LDAS):

- sum of univariate OI for t2m, rh2m, snow, soil+snow temperature,
- Plus, Simplified Extended Kalman Filter (SEKF) for soil moisture

Sea surface temperature (SST) and sea ice cover:

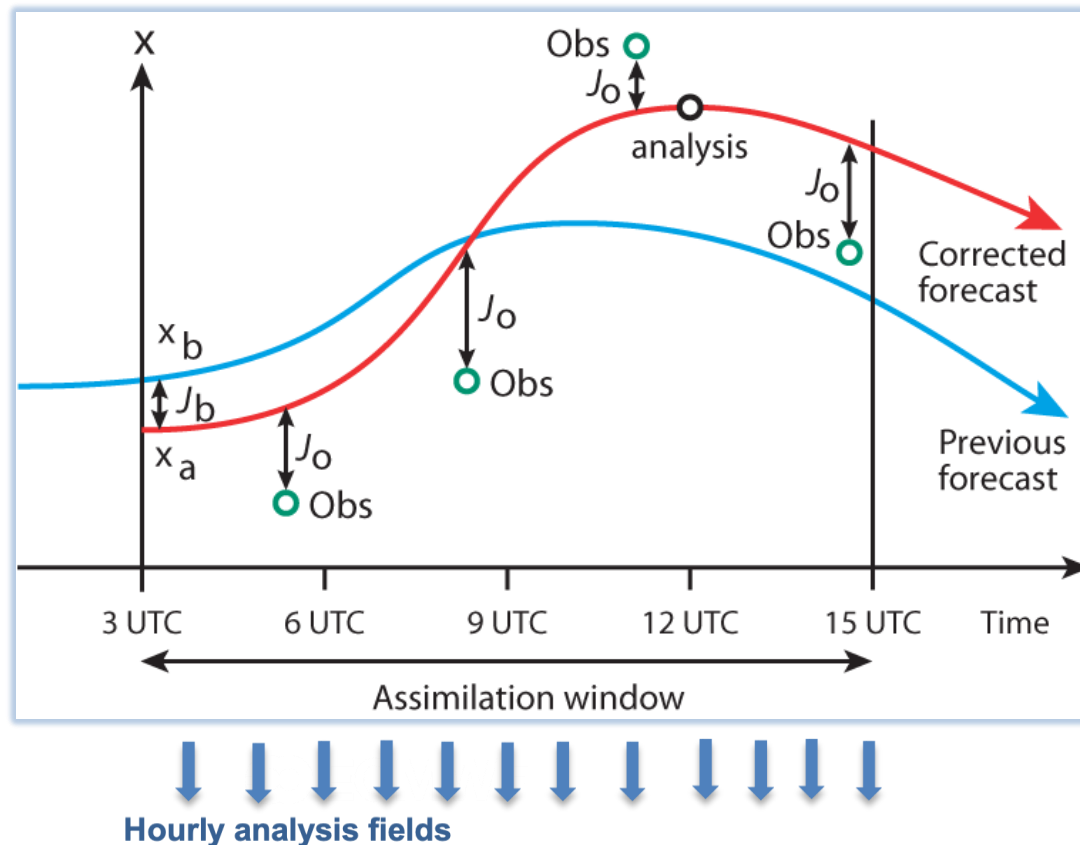
- ingested from external source (OSTIA, HadISST2, OSI SAF)

4D-Var data assimilation: using observations to correct the first guess

background constraint (J_b) observational constraint (J_o)

Minimise
$$\mathbf{J}(\mathbf{z}) = (\mathbf{z}_b - \mathbf{z})^T \mathbf{B}_z^{-1} (\mathbf{z}_b - \mathbf{z}) + [\mathbf{y} - \tilde{\mathbf{h}}(\mathbf{z})]^T \mathbf{R}^{-1} [\mathbf{y} - \tilde{\mathbf{h}}(\mathbf{z})]$$

$\mathbf{z}^T = [\mathbf{x}^T \boldsymbol{\beta}^T]$ $\tilde{\mathbf{h}}(\mathbf{z}) = \mathbf{h}(\mathbf{x}) + \mathbf{b}(\mathbf{x}, \boldsymbol{\beta})$



Method:

- Start with a **first guess** $\mathbf{x}_b, \boldsymbol{\beta}_b$ from the previous analysis
- Compare with **observations** \mathbf{y}
- Calculate the misfit: the cost \mathbf{J}
- Change the first guess such that **the fit is optimal**

Result depends on:

- The confidence in your first guess: \mathbf{B} matrix
- The confidence in your observations: \mathbf{R} matrix
- How you compare the model to observations: $\mathbf{h}(\mathbf{x})$
- The choice of the observation bias model $\mathbf{b}(\mathbf{x}, \boldsymbol{\beta})$

Result:

- The **reanalysis** $\mathbf{x}_a, \boldsymbol{\beta}_a$
- used to provide first guess for next analysis

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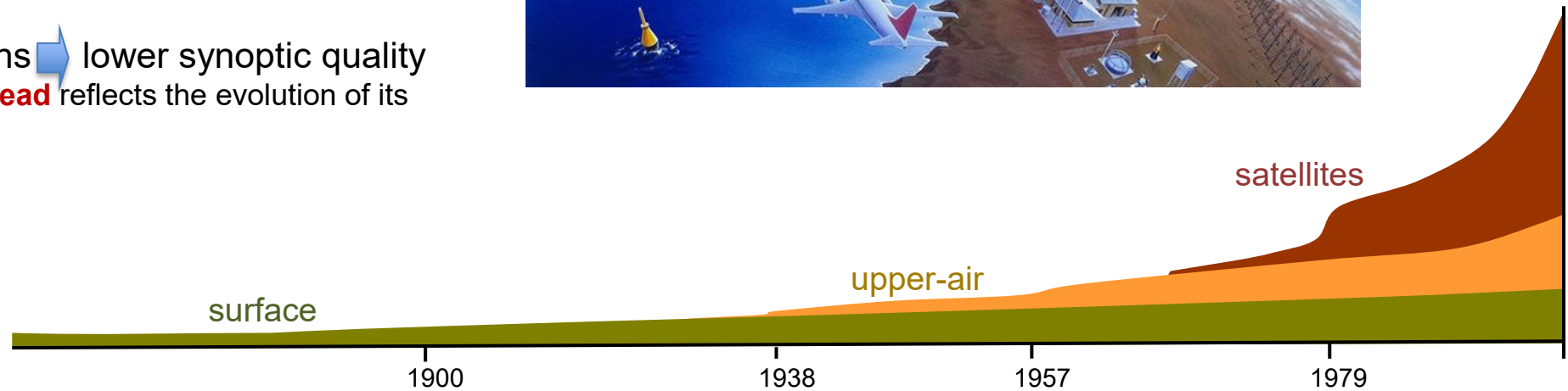
The evolving observing system and the ERA5 ensemble

Data sources:

- many satellites
- surface observations
- weather balloons, aircraft, etc.

In the ERA5 reanalysis we daily use about:

- **17,000** observations in 1940
 - and **26 million** in 2021
 - Over 130 billion in total, so far
 - evolved heavily over time
-
- Fewer observations → lower synoptic quality
 - **ERA5 ensemble spread** reflects the evolution of its synoptic quality



The historical observing system is a 'zoo'

Satellite observations, mostly since 1979:

Microwave radiances:

- temperature and humidity sounders, imagers

Infrared sounder radiances

- multispectral, hyperspectral

Geostationary radiances

Atmospheric motion vectors

GNSS-RO bending angles

Scatterometer: ocean wind + land soil moisture

Ozone level 2 retrievals + level 1B

Altimeter wave height

Conventional observations

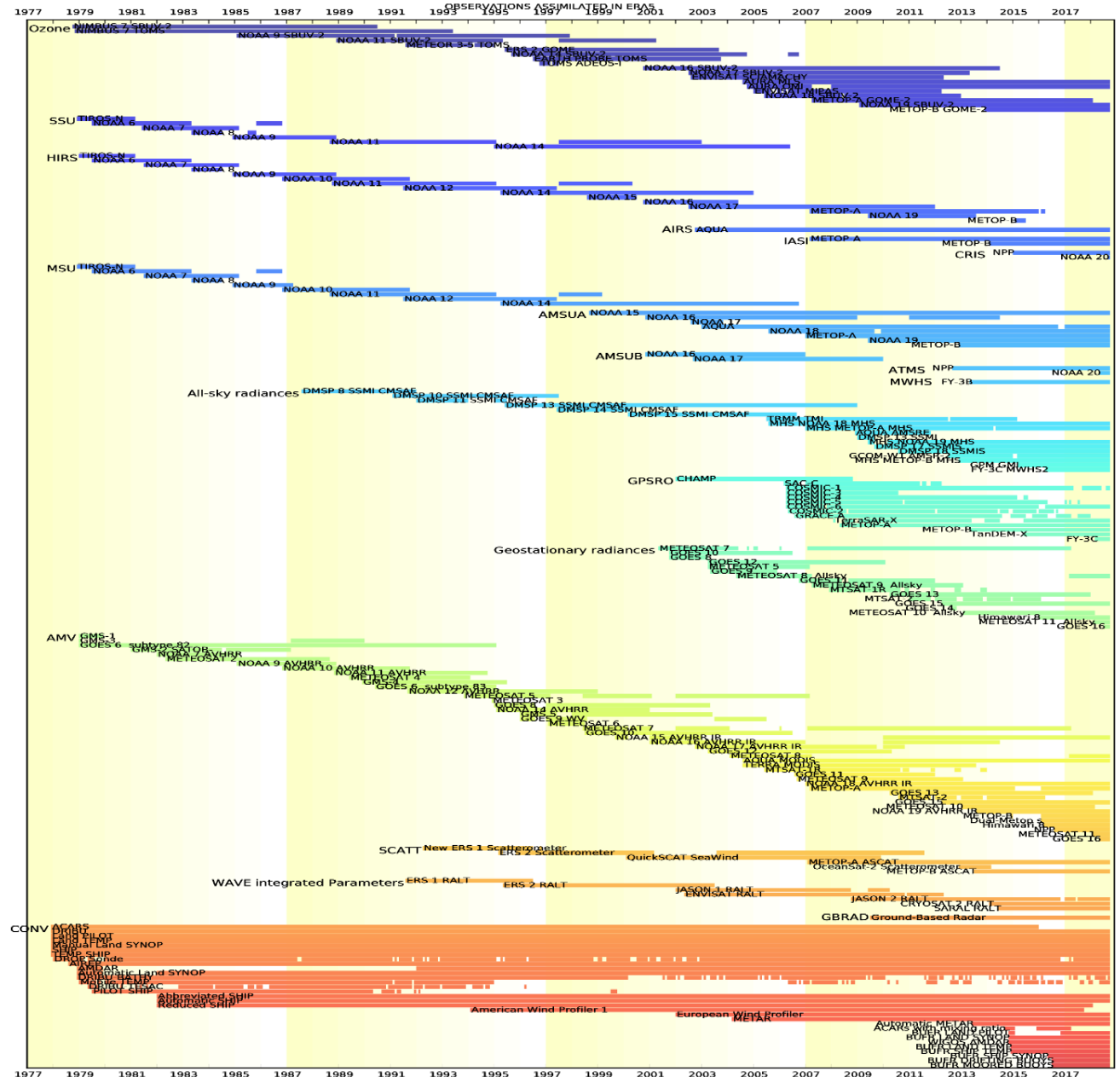
Surface: Land stations, buoys, ships

Upper-air: Balloons, dropsondes, aircraft, profilers

+ Reprocessed satellite observations

+ Rescued in situ observations

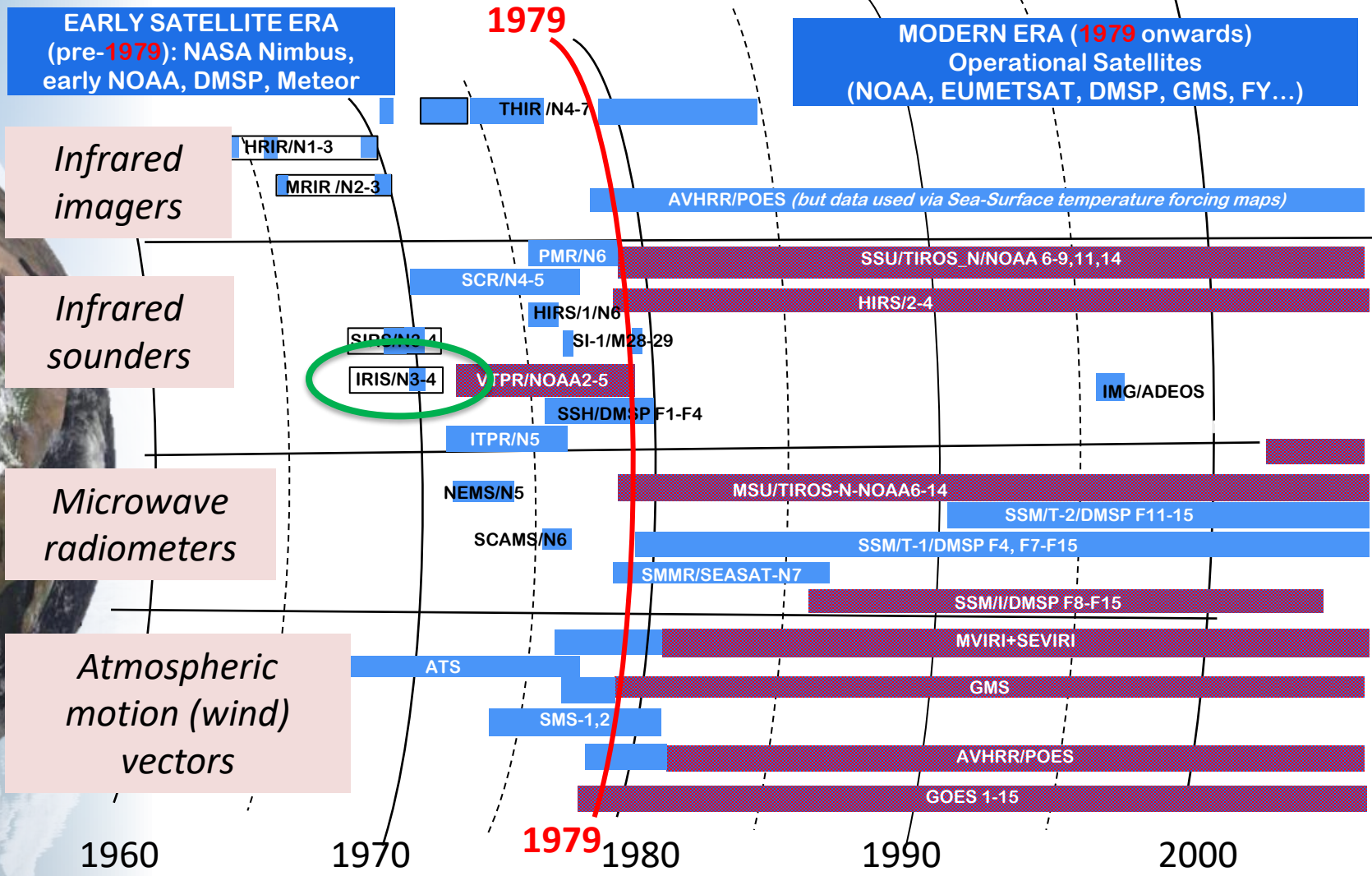
- All need to be monitored during production!
- VarBC is very effective at dealing with the challenges of bias correction





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Satellite data rescue for ERA6



Preparations for ERA6 include:

- **Rescue and Assessment** of radiance observation from pre-1979 sensors
- Example of the impact of **Nimbus-4 IRIS** shown in the following slides
- Recent experiments have shown significant benefit from assimilating **SIRS, IRIS, NEMS, SCAMS, SSH, SSM/T- 1 and SSM/T-2**

Data not yet assimilated in ERA

Original or earlier-reprocessed data version assimilated in ERA5

(A. Klonecki & colleagues, Spascia)

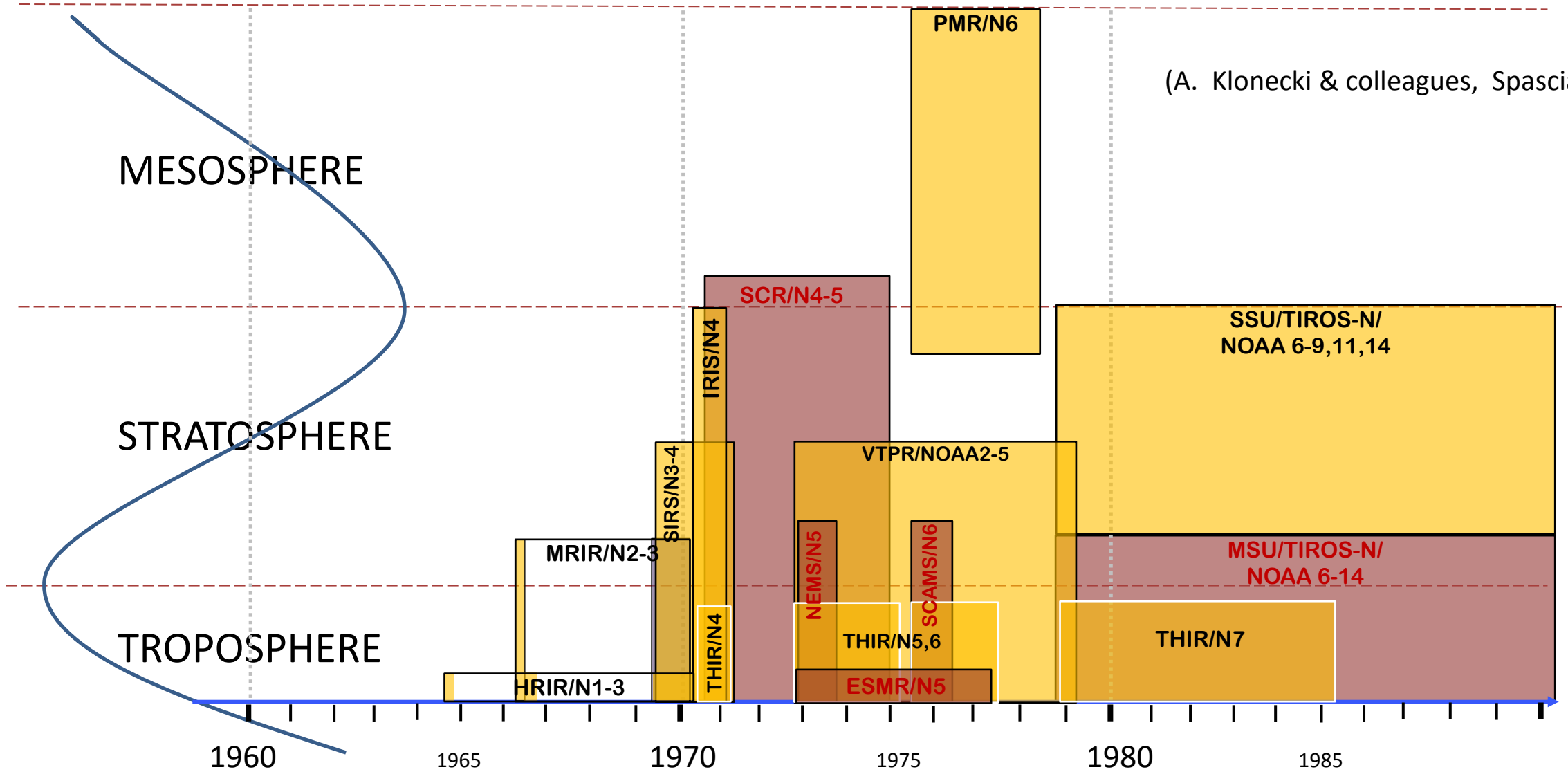




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Temporal coverage and vertical sensitivity of the data from early satellite data records

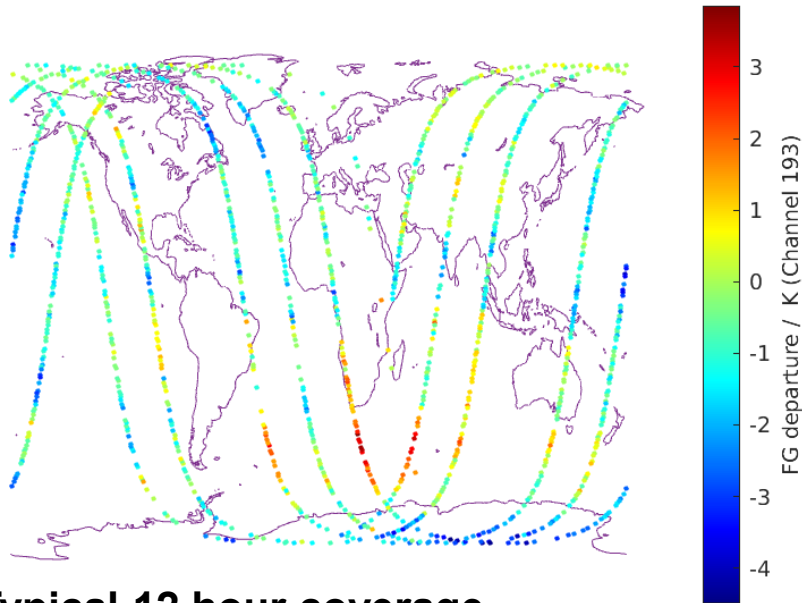
(A. Klonecki & colleagues, Spascia)





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Assimilating Nimbus-4 IRIS Observations



Typical 12 hour coverage

- Interferometric IR sounder, operated on Nimbus-4, from **April 1970 – January 1971** (preceded Metop-A IASI by **36 years** !)

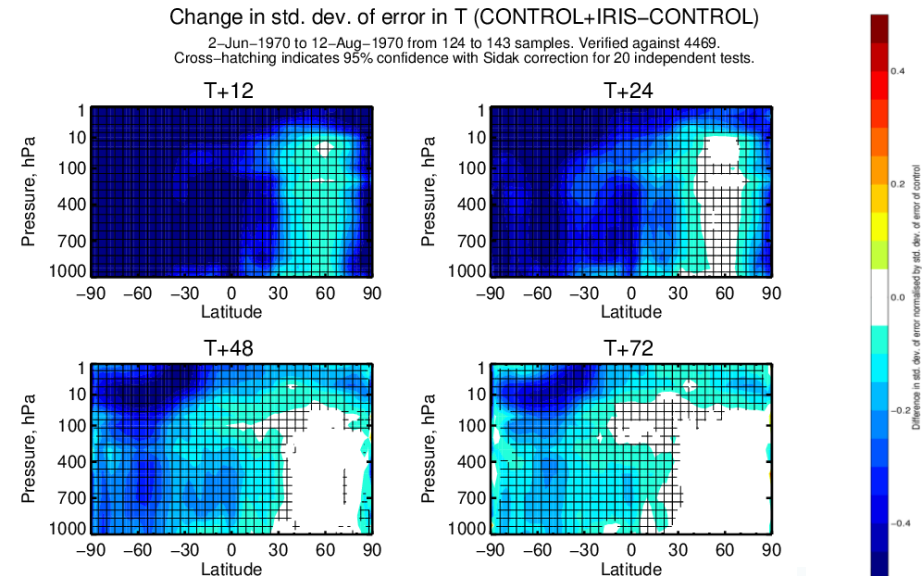
- Nadir only observations. Spectral range $400 - 1600 \text{ cm}^{-1}$

- 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.)

- Similarly significant benefits realised recently from SIRS, NEMS, SCAMS, SSH (1969-1980)

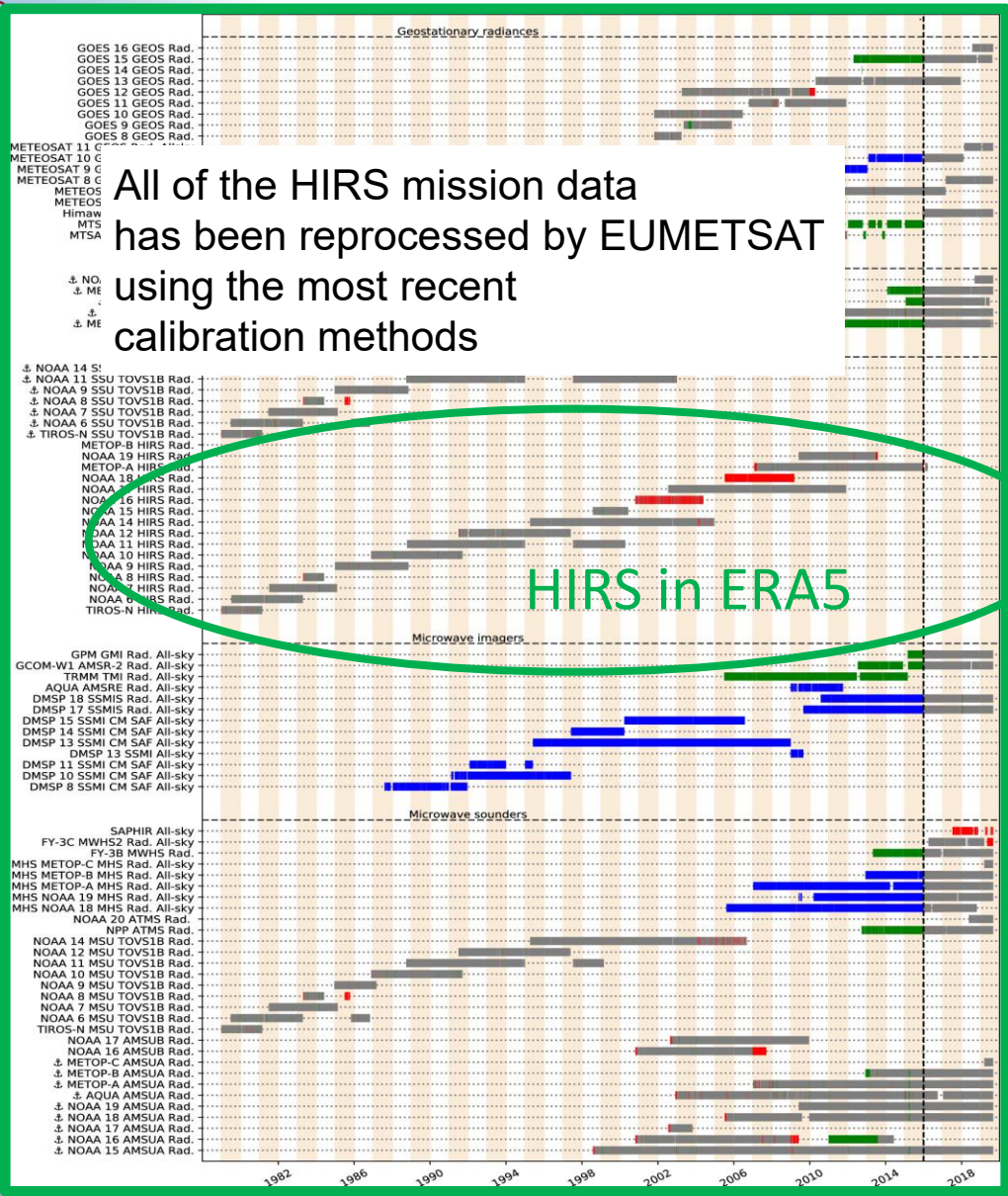
- **Control:** CY48R1 / **Experiment** assimilated IRIS data
- Background error covariances from ERA5 (so appropriate for 1970)
- 12Z 1st June 1970 – 00Z 12th August 1970
- **Significant improvements in southern hemisphere and stratosphere**





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



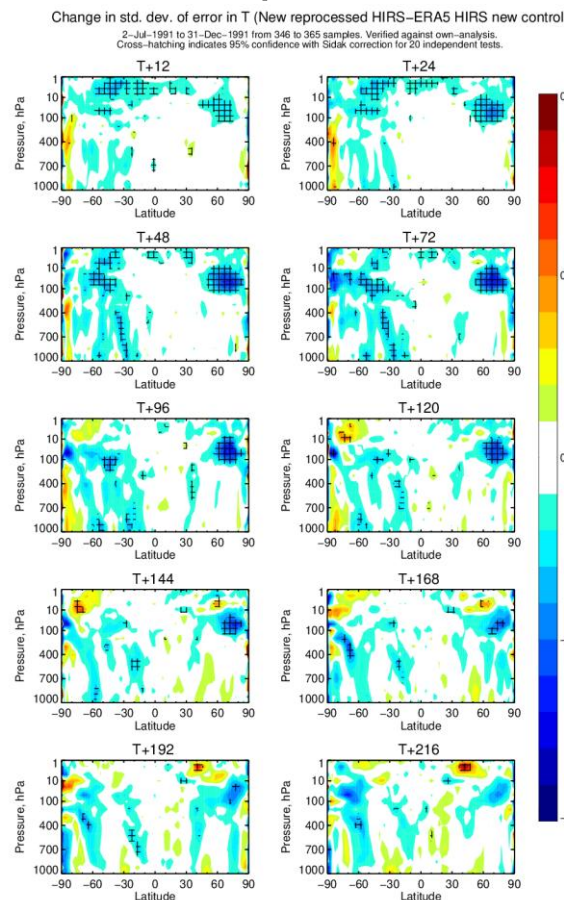
All of the HIRS mission data has been reprocessed by EUMETSAT using the most recent calibration methods

HIRS in ERA5

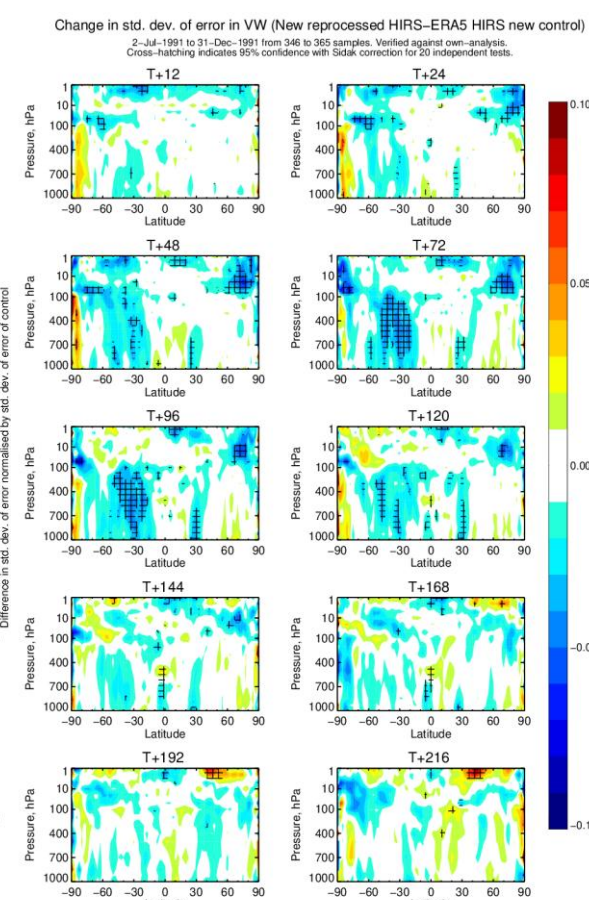
Improved analyses and forecasts Using EUMETSAT reprocessed HIRS data

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

Temperature



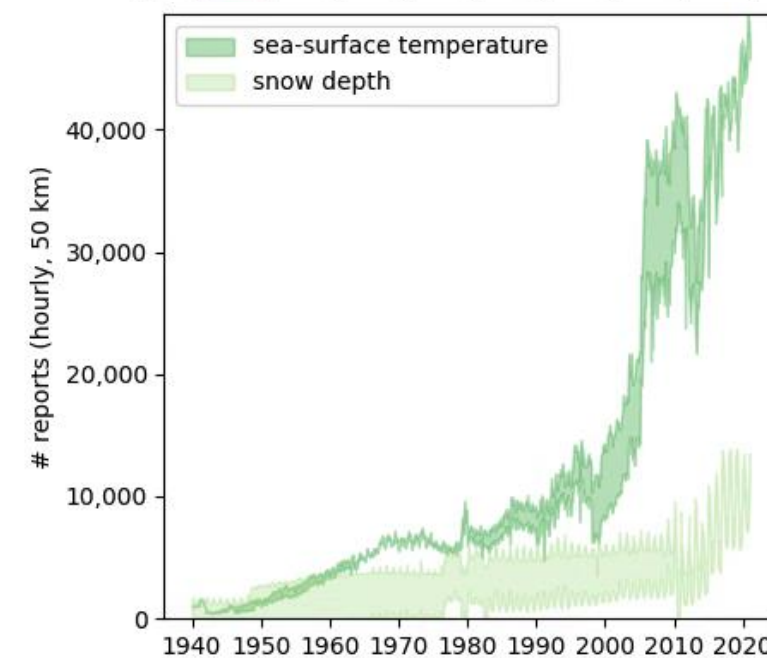
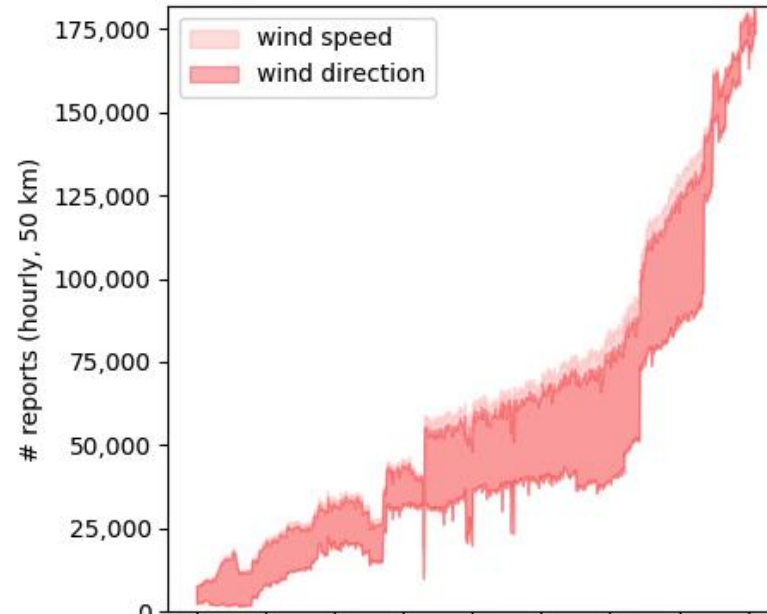
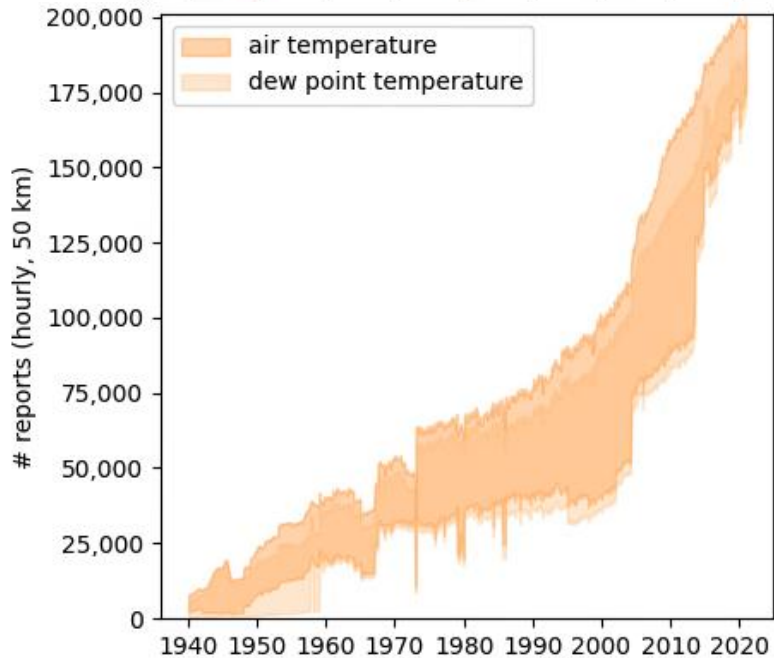
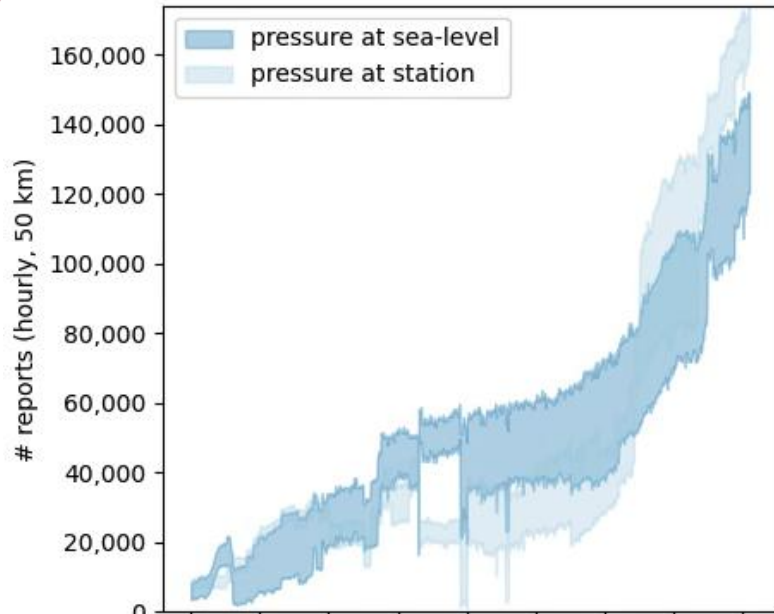
Winds





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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)

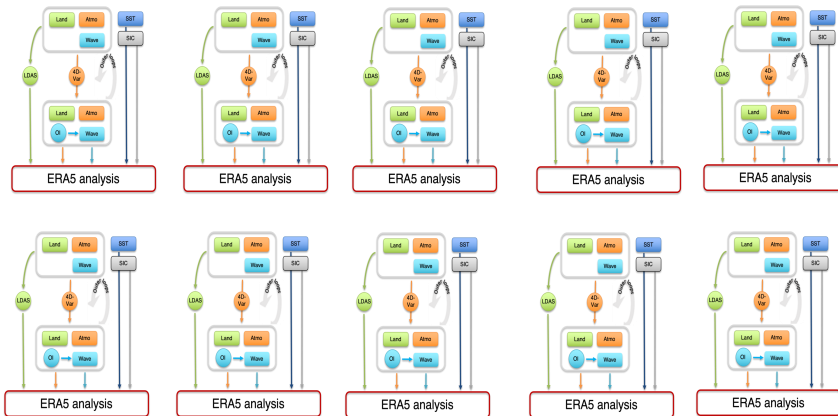
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The ERA5 Ensemble of Data Assimilations (EDA)

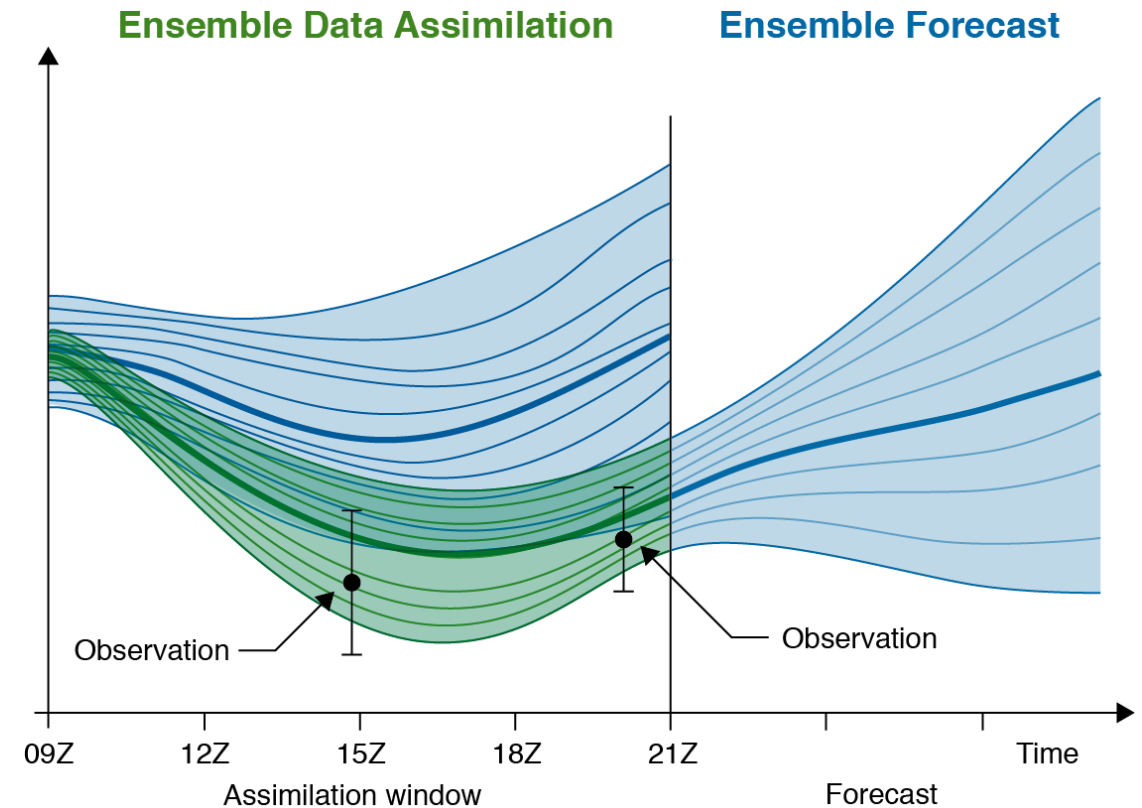
10 DA systems at half resolution. Per member:

- Perturb observations; plus SST and sea ice
- Perturb model in short forecasts linking analyses



From this we estimate:

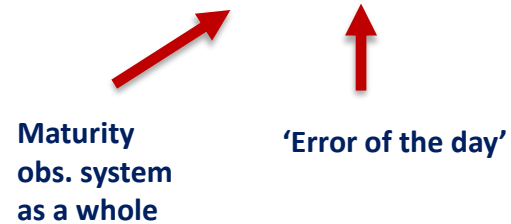
- a flow-dependent B matrix required for DA
- info on quality of the synoptic situation



Long-term evolution of the background error covariance matrix

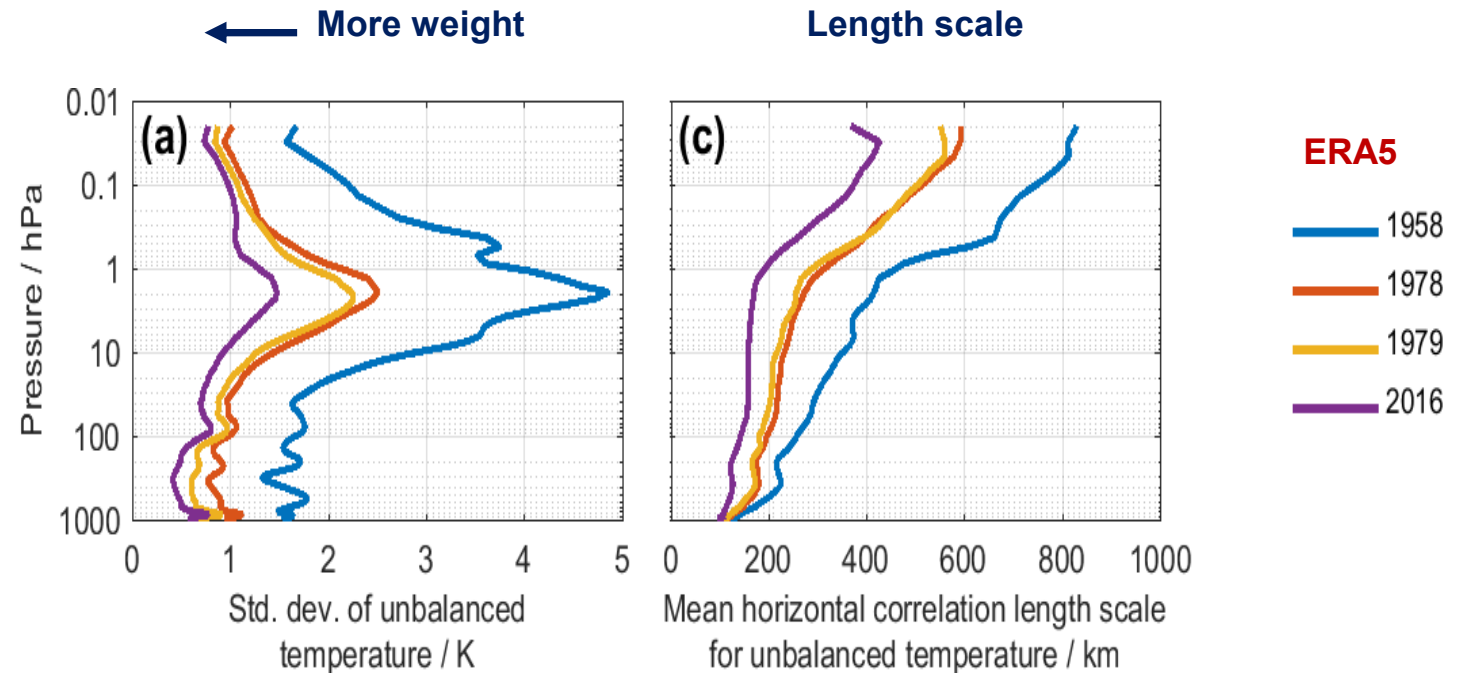
Besides a flow-dependent part, **B** also relies on climatology:

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



B_{cli} needs retuning for large changes in the observing system

- Before 1979: hardly satellite data -> B_{cli} 1958
- 1979-1999: TOVS, early satellites -> B_{cli} 1978
- 2000-onwards: ATOVS -> B_{cli} 2016
- 2006 - .. : RO, hyperspectral, ... -> B_{cli} 2016



Over time smaller and more local increments are required

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How to handle the undesired effect of systematic model error

One of the roles of B is to spread out information from the observations into the model analysis

Choice of B_{cli} needed extra care between 2000-2006

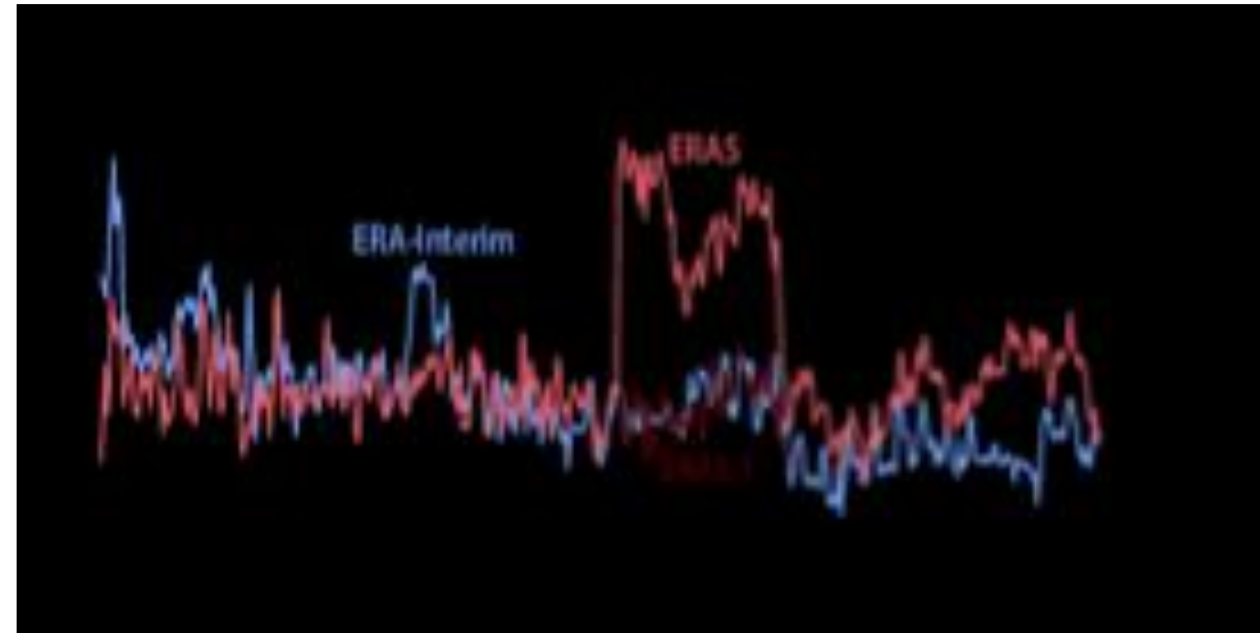
From 2000: ATOVS satellites → Use new B_{cli} !

- B more weight + shorter correlation lengths
- Smaller increments over smaller areas

However, in the lower stratosphere:

- **model cold bias** +
- lack of sufficient RO anchor observations
- VarBC 'happily' aliases systematic model bias into observation bias
- 0.4K may seem small, but for the mean state it is not.

- ERA5.1: use of pre-ATOVS B_{cli} until 2006!
- Basically using another B_{cli} to do something for what it was not designed (managing systematic model error)



Improvements in the representation of the stratosphere since ERA5

TECHNICAL MEMORANDUM 824

Report on Stratosphere Task Force

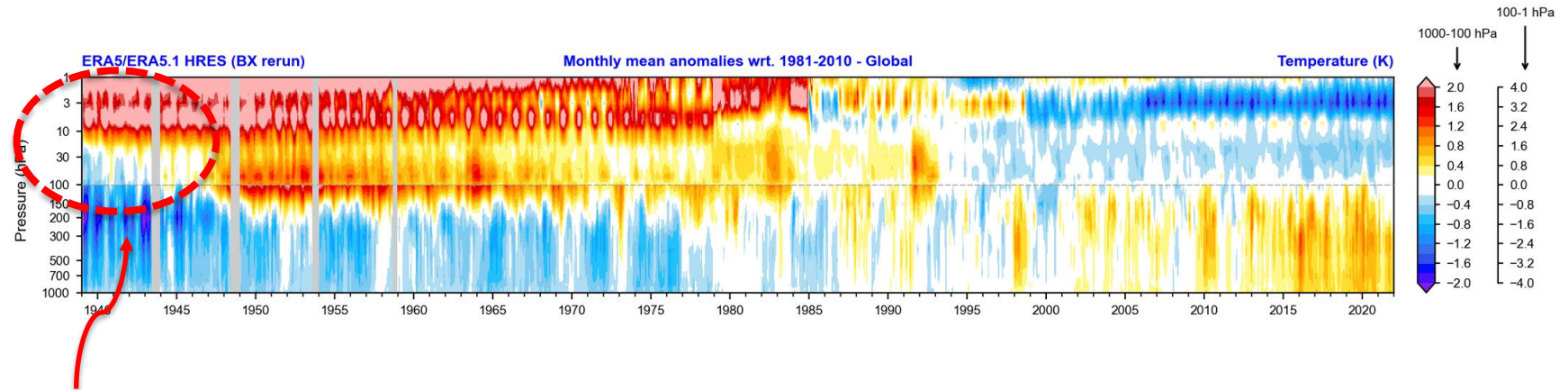
Theodore G. Shepherd¹,
Inna Polichtchouk^{1,2}, Robin J. Hogan²
and Adrian J. Simmons³

¹ Department of Meteorology, University of Reading, UK
² Research Department
³ Copernicus Department

June 2018

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Centre européen pour les prévisions météorologiques à moyen



- **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

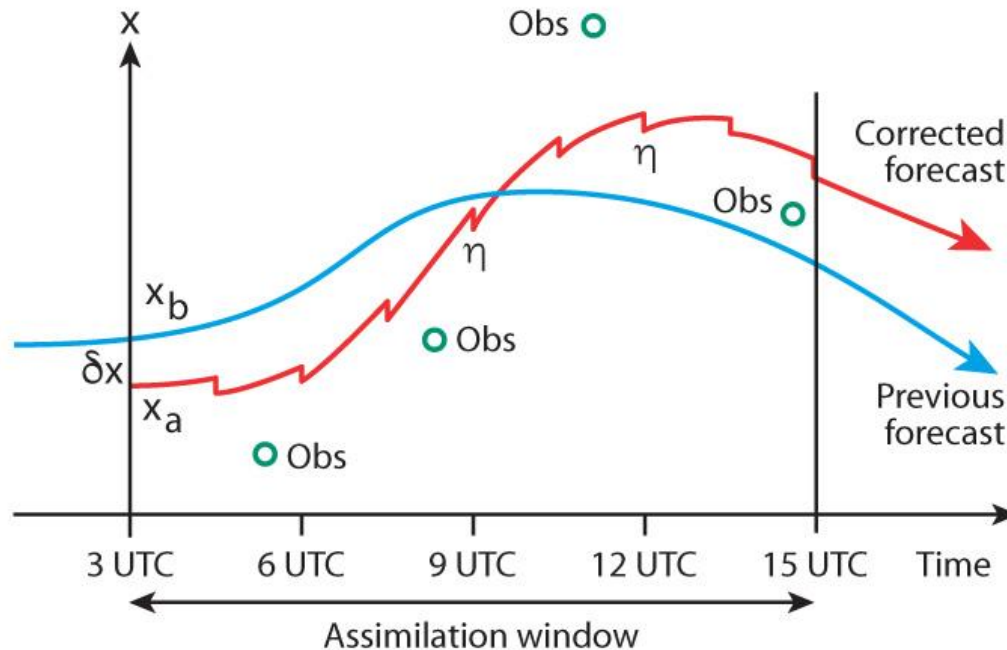
<https://www.ecmwf.int/en/elibrary/80609-report-stratosphere-task-force>

Weak-constraint 4D-Var formulation

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

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

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

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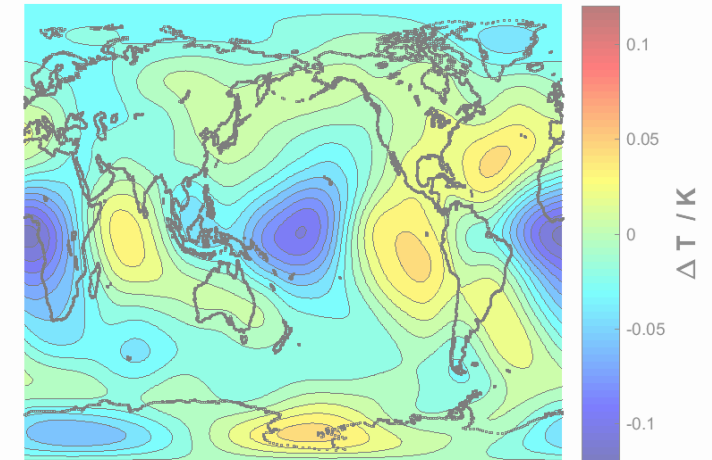
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Model initial condition \uparrow

Model bias correction \uparrow

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

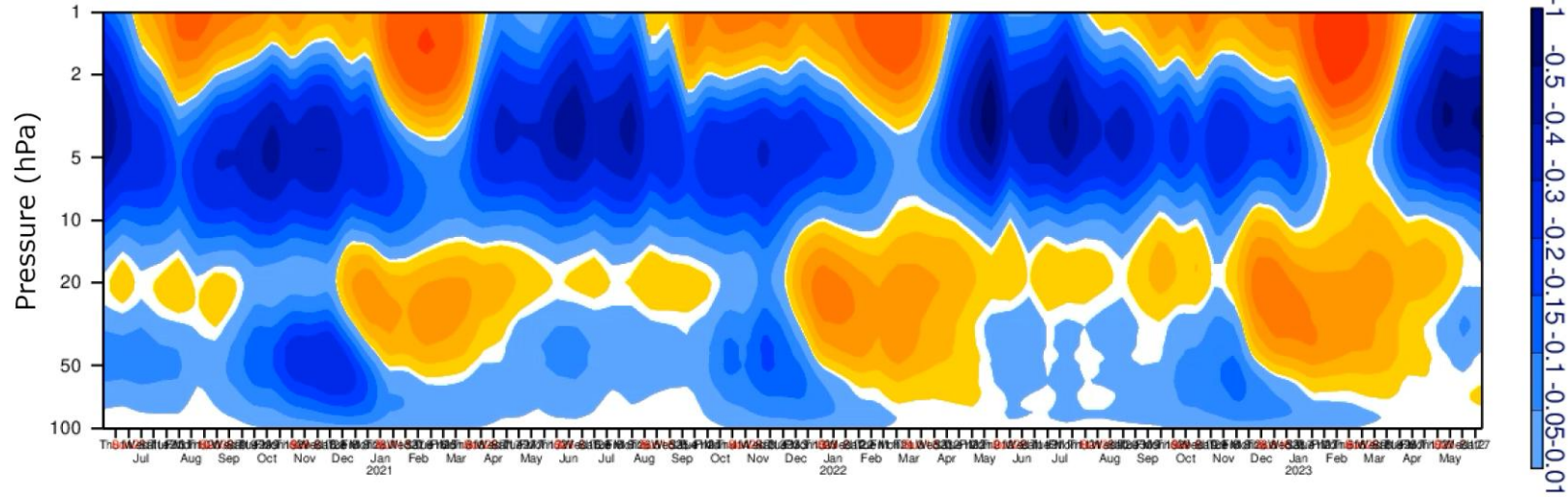
Weak Constraint 4DVar Model Error Estimate at 5hPa
01-Dec-2019 00:00:00



- ➔ 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)

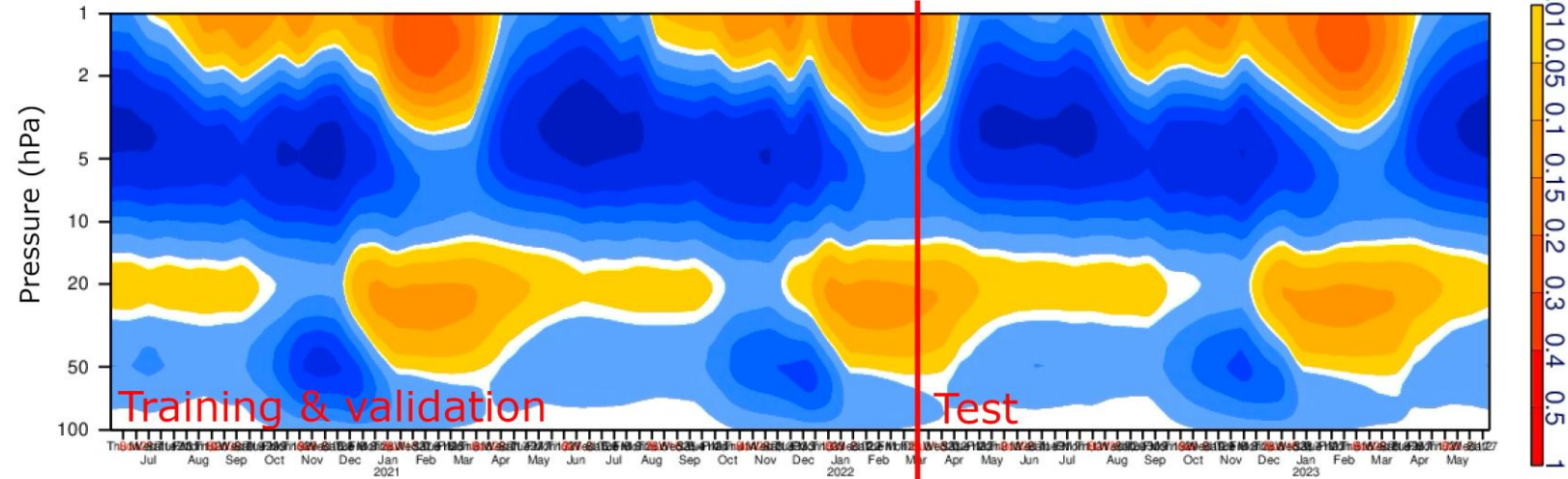
Emulate weak-constraint 4D-Var at Tco1279

Model error correction from weak-constraint 4D-Var



Patrick Laloyaux

Model error correction from Neural Network

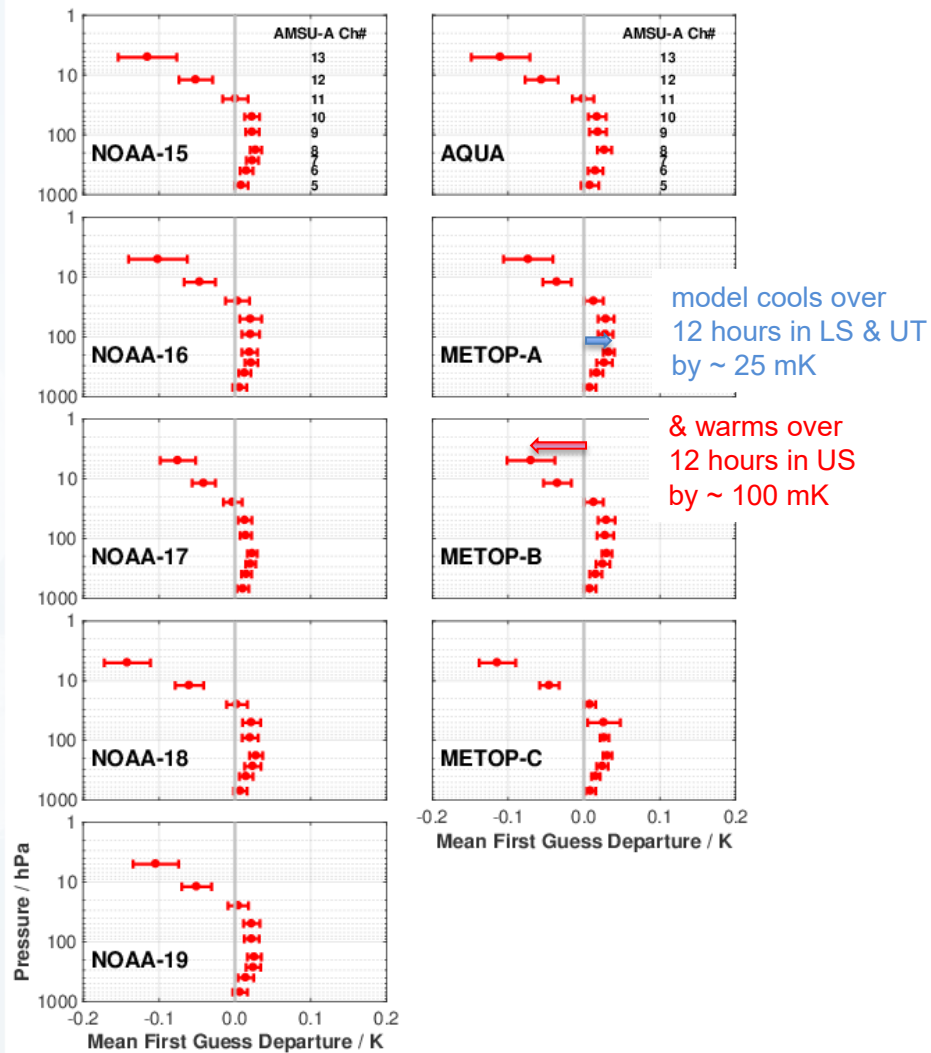


Timeseries are averaged between 70S and 90S. The emulator represents the model error (from WC 4D-Var) well. **Predictors:** Model state + time of the year + ..



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

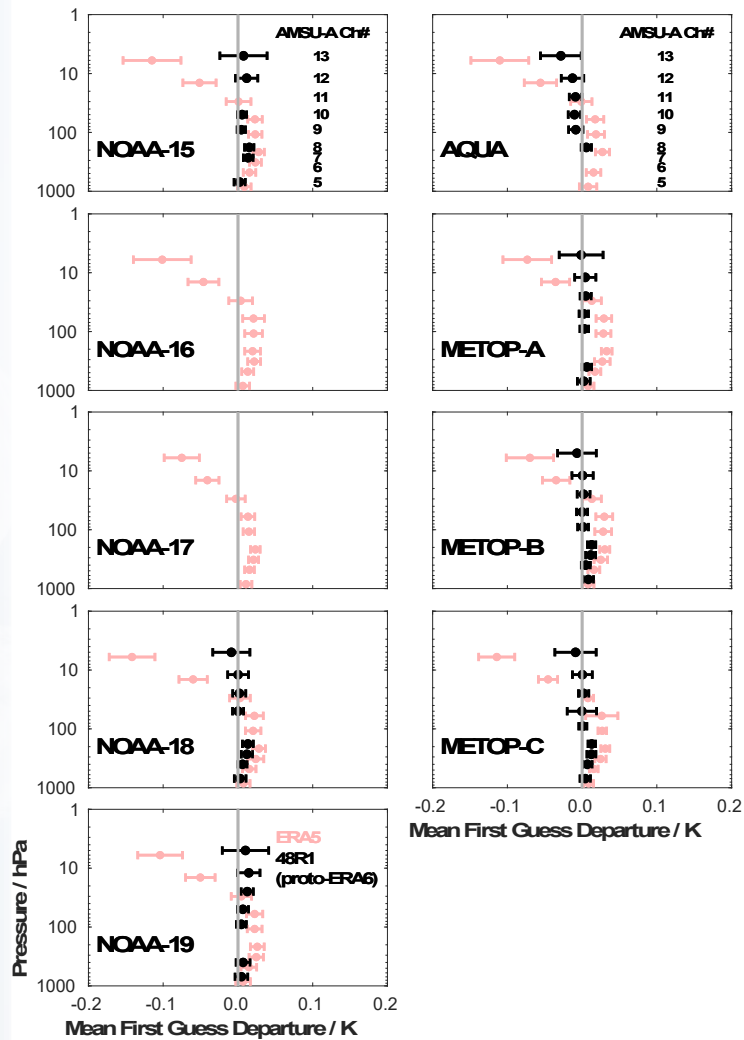


- DA diagnostics are a very sensitive indicator of model biases
- Coherent across all AMSU-A instruments, and consistent in time over mission lifetimes for ERA5



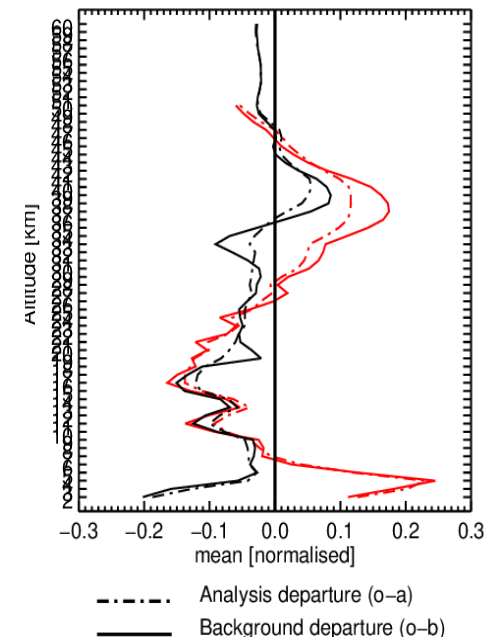
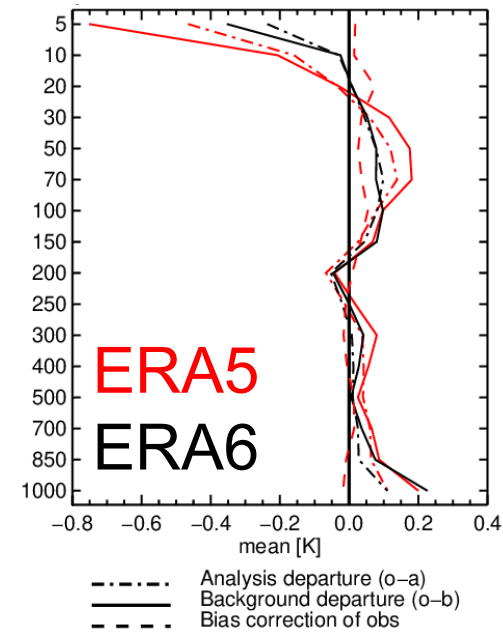
Climate Change

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

Instrument(s): TEMP - T Area(s): Global
From 00Z 1-Oct-2019 to 12Z 31-Jan-2020



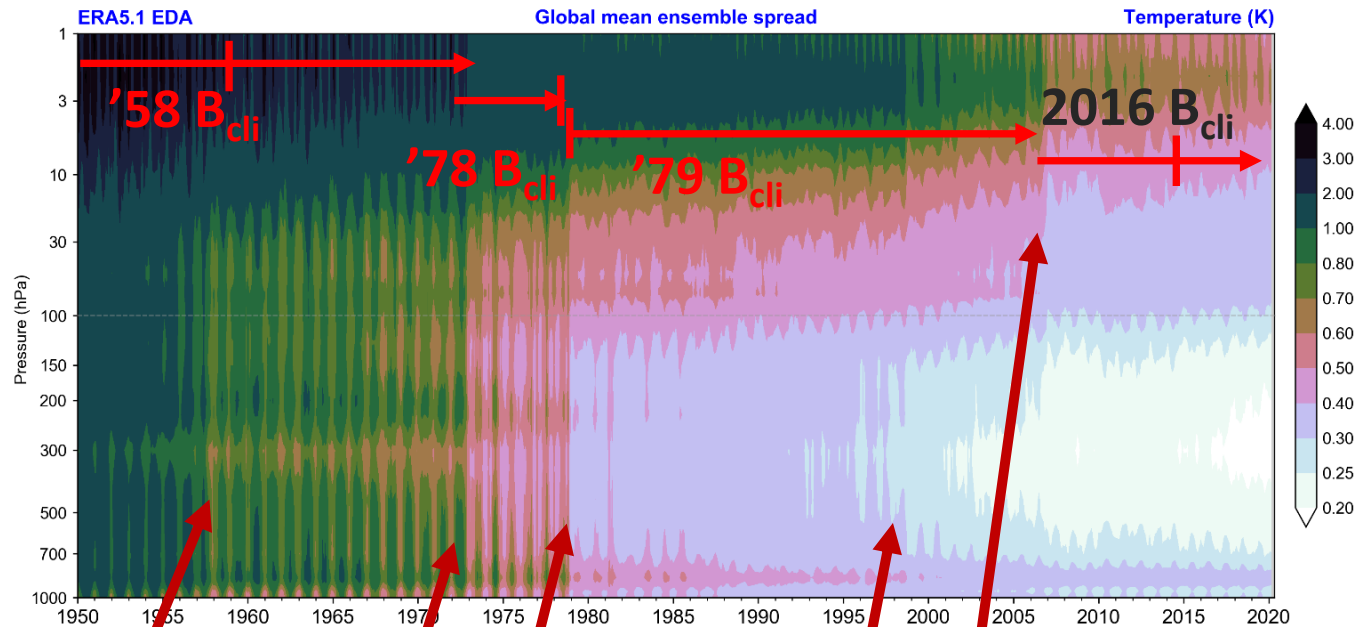
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EDA Ensemble spread as a measure for the synoptic ERA5 uncertainty

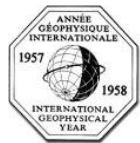
Spread decreases over time as more observations become available

Major changes in the observing system are clearly visible



Flow-dependent B matrix:

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



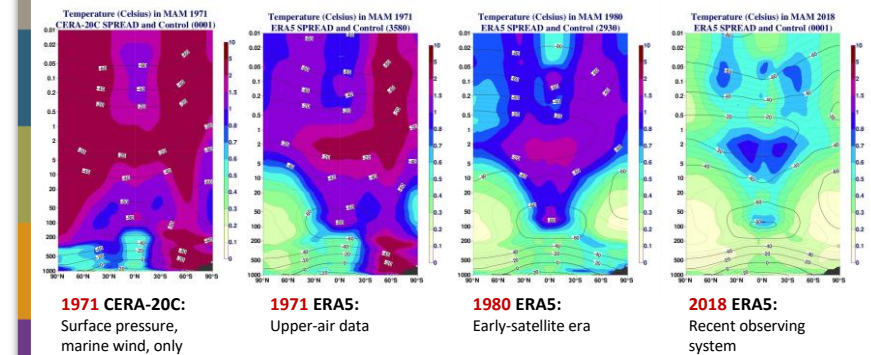
International Geophysical Year (1957/58)

VTPR TOVS (HIRS, MSU, SSU)

ATOVS (AMSU-A)

GNSS-RO (COSMIC,..)

The evolution of ensemble spread; also proxy for synoptic uncertainty



1971 CERA-20C: Surface pressure, marine wind, only

1971 ERA5: Upper-air data

1980 ERA5: Early-satellite era

2018 ERA5: Recent observing system

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 - **Input from long-term forcing fields**
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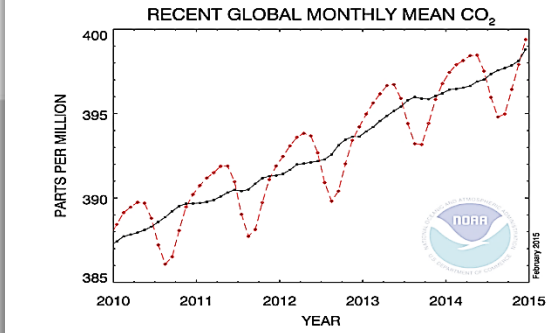
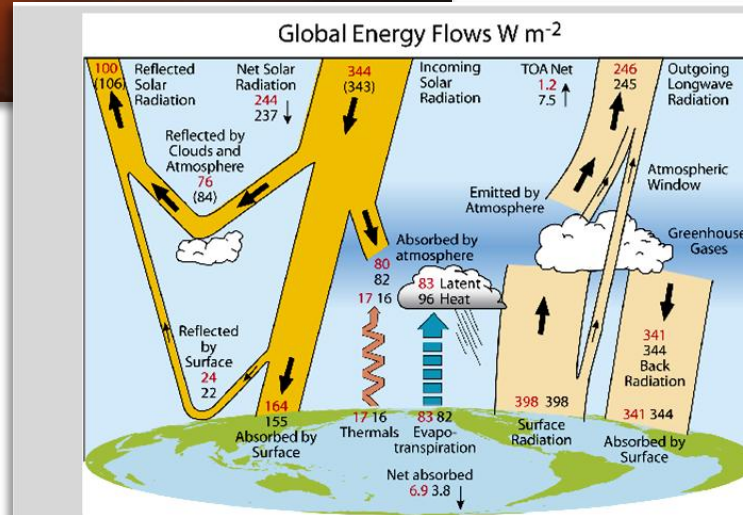
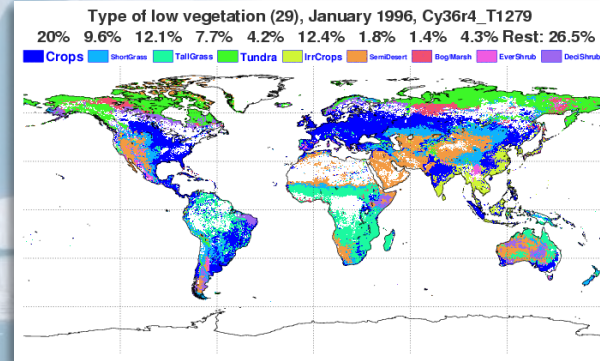
Climate Change

Evolution of observation-based (gridded) forcing and boundary conditions

that reflect the 20th and 21th century evolution

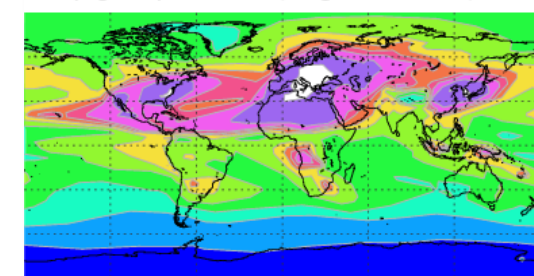


Greenhouse gases

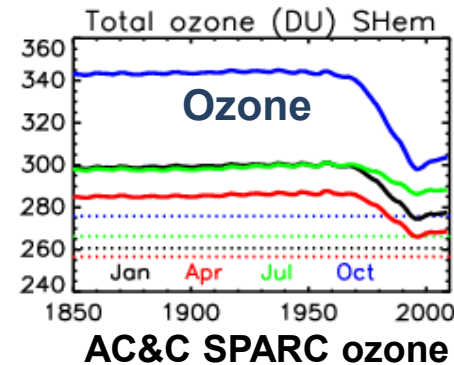


Tropospheric Aerosols

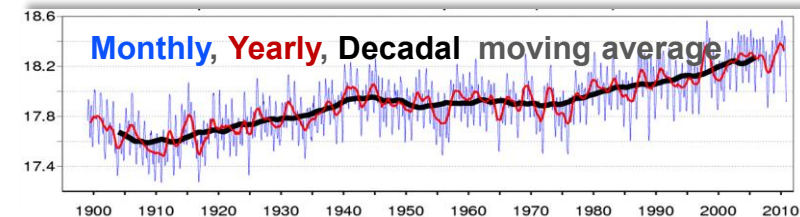
SO₄ (mg/m²) Mean 4.833, August 1980-1989, HIST



Volcanic eruptions



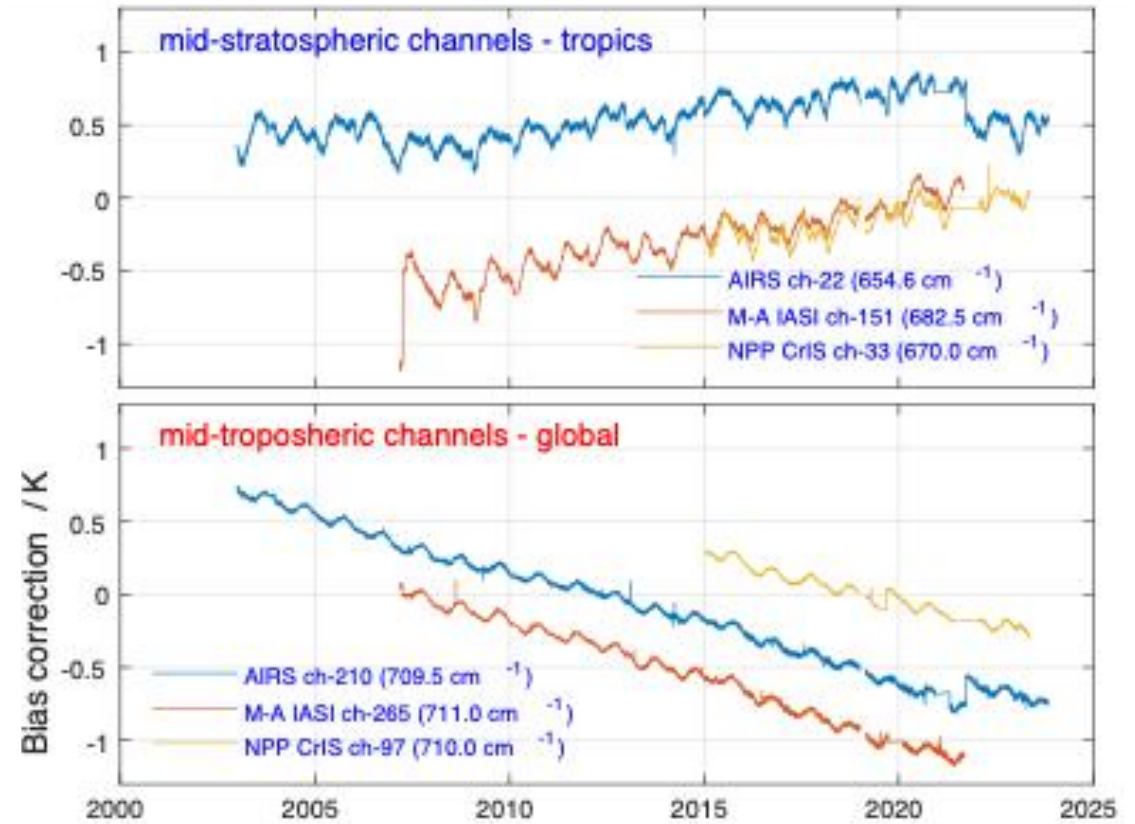
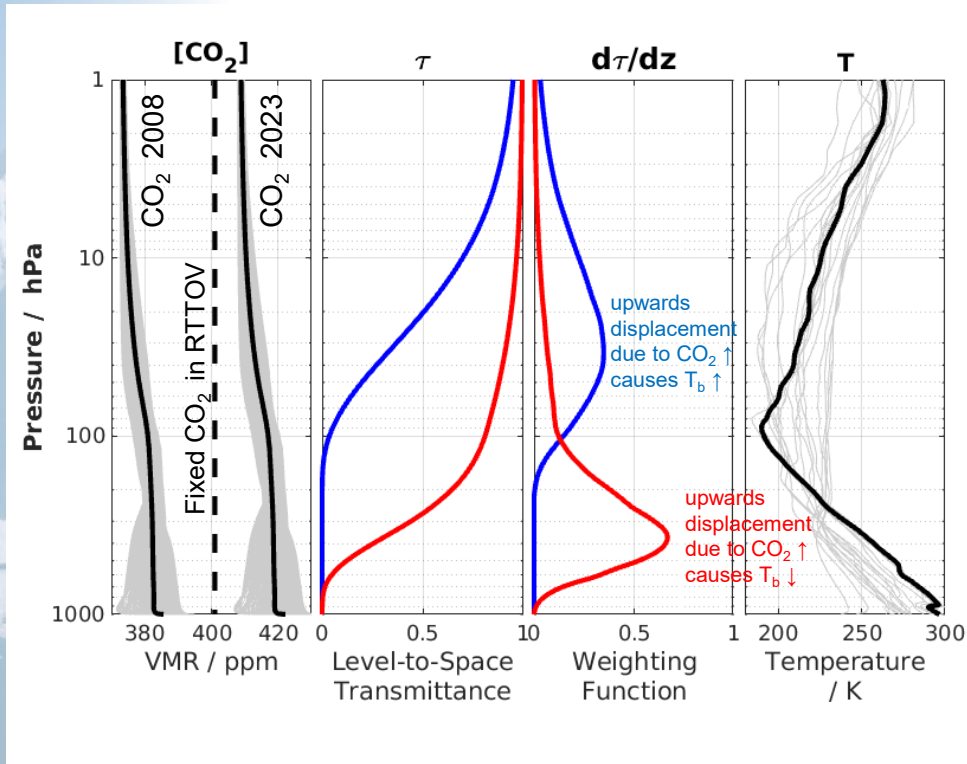
SST and sea ice





Climate Change

The treatment of CO₂ in the assimilation of advanced IR sounder observations in ERA5



Two effects of changing [CO₂] – when a fixed [CO₂] 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 [CO₂](time, space) and T(time, space))

Expect to **improve (1) & reduce the impact of (2) in ERA6** by using a more realistic CO₂ climatology (CO₂ (latitude, z, time))

(Marco Matricardi & Robin Hogan)



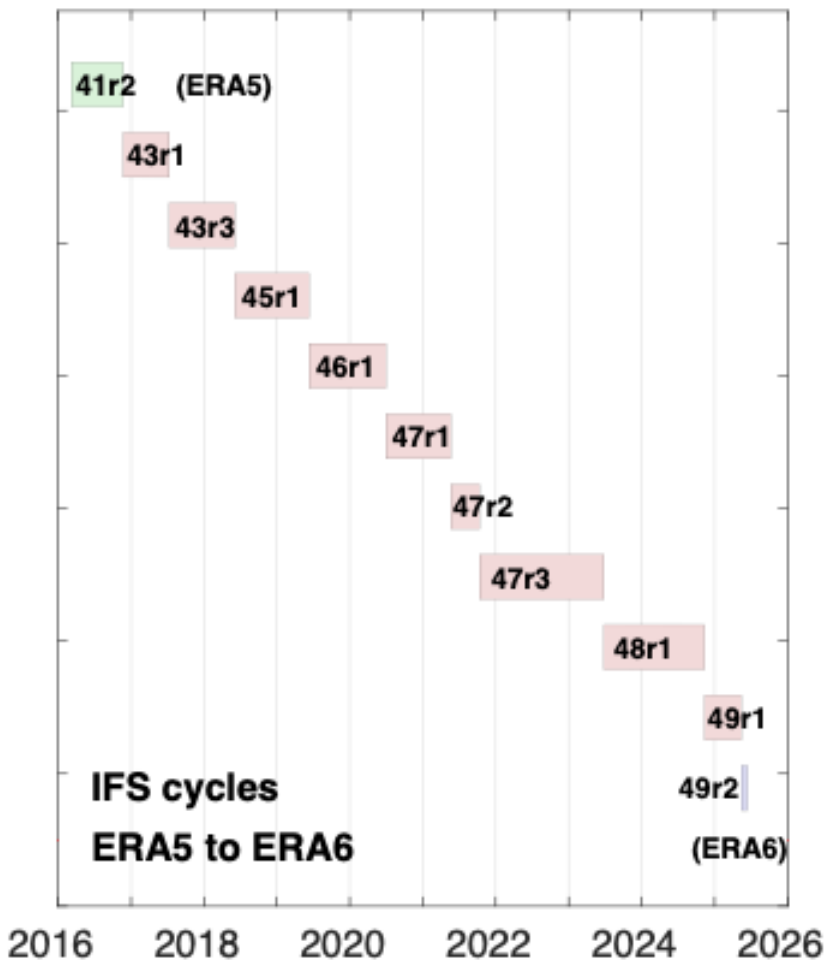


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'What do we get from ERA6 ?'

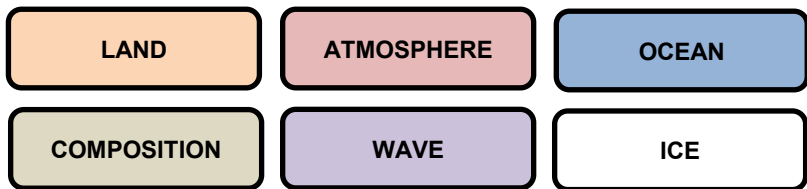
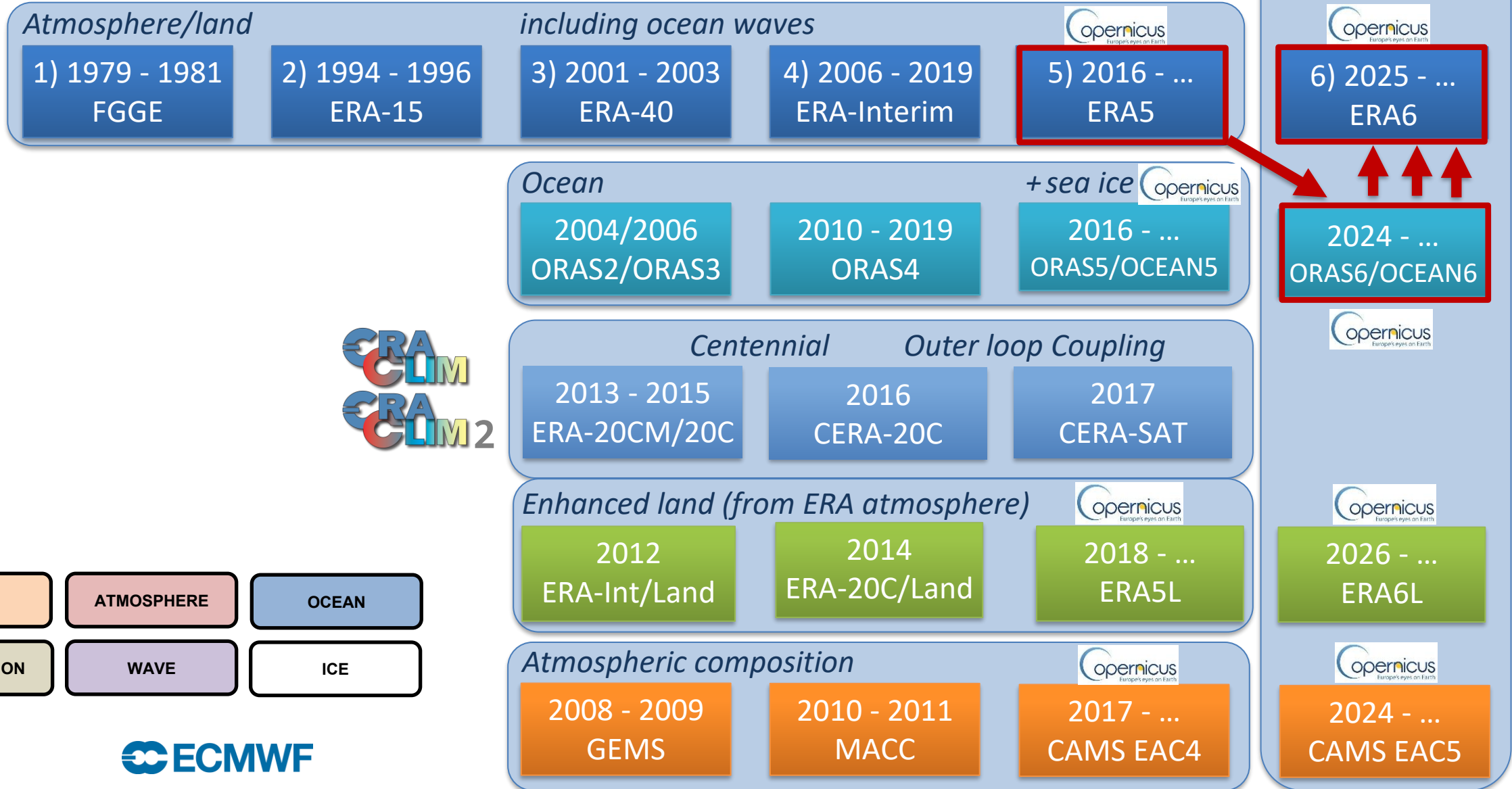
Integrated Forecasting System (IFS) upgrades since ERA5



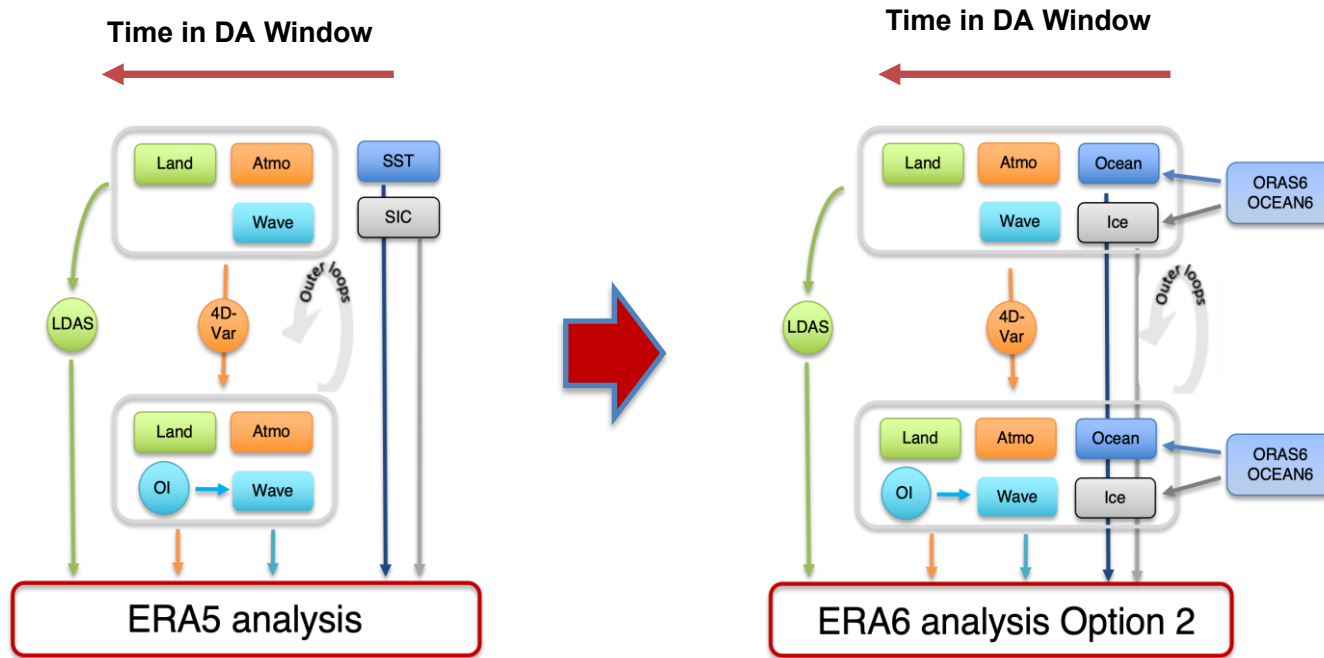
<p>Data assimilation</p> <ul style="list-style-type: none"> • SST • TL3 • WC-4 • Improved • OR 	<p>Data assimilation</p> <ul style="list-style-type: none"> • Improved • Revis 	<p>Observations</p> <ul style="list-style-type: none"> • Saph • 118 C • Harm • Scream • Impr 	<p>Model</p> <ul style="list-style-type: none"> • Improved • New • Improved • Improved 	<p>Data assimilation</p> <ul style="list-style-type: none"> • Weather • Improved • WC-4 	<p>Data assimilation</p> <ul style="list-style-type: none"> • Improved • WC-4 	<p>Observations</p> <ul style="list-style-type: none"> • Normal • MW • RTT • Cor • Improved • Acc • Improved • Jas 	<p>Observations</p> <ul style="list-style-type: none"> • S • F • k • Improved • Impr 	<p>Model</p> <ul style="list-style-type: none"> • Surface • CMIP • Quint • Improved • Improved • Improved • Improved • Improved • Improved 	<p>Data assimilation</p> <ul style="list-style-type: none"> • New • Improved • Represent • WC-4 	<p>Observations</p> <ul style="list-style-type: none"> • Re • Op • RT • All-sky • F-18 SS • Improved • MWS s • Improved • Optimis • GNSS-I • Improv 	<p>Model</p> <ul style="list-style-type: none"> • B-L tu • Improved • Improved • Improved • Improved • Improved • Improved • Improved • Improved 	<p>49r1</p> <p>Data assimilation</p> <ul style="list-style-type: none"> • RTTOV 13.2 • Improved T2m assimilation • VarQC & stratospheric balance • Land surface • Hourly • Soft rec <p>49r2</p> <p>Data assimilation & Observations</p> <ul style="list-style-type: none"> • Outer-loop coupling updates • 1D-OI → SEKF: soil and snow temp analysis • Orbital bias correction for AMSU-A and ATMS • VarBC for surface pressure • Time varying CO₂ for IR assimilation <p>Observations</p> <ul style="list-style-type: none"> • Scene c • Reduce • All-sky • All-sky • F-18 SS • Improved • MWS s • Improved • Optimis • GNSS-I • Improv <p>Model</p> <ul style="list-style-type: none"> • Time varying solar forcing • O₃(t) for HLO • Revised aerosol • Revised wave model bathymetry • Non-orographic GW drag changes • Reduced vertical diffusion in stable conditions <p>Model</p> <ul style="list-style-type: none"> • Wave model / land convection package • Land surface model updates • SPPT → SPP • Improved physics and numerics
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<https://confluence.ecmwf.int/display/FCST/Changes+to+the+forecasting+system>

ECMWF has many years experience with reanalyses

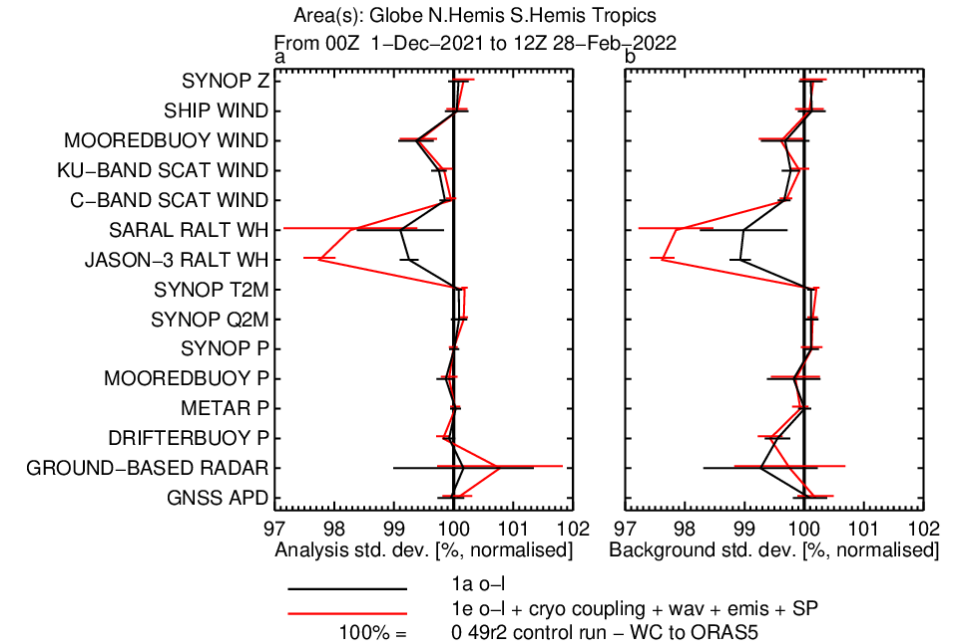


ERA6 is coupled with the ocean; but get the ocean initial state from ORAS6

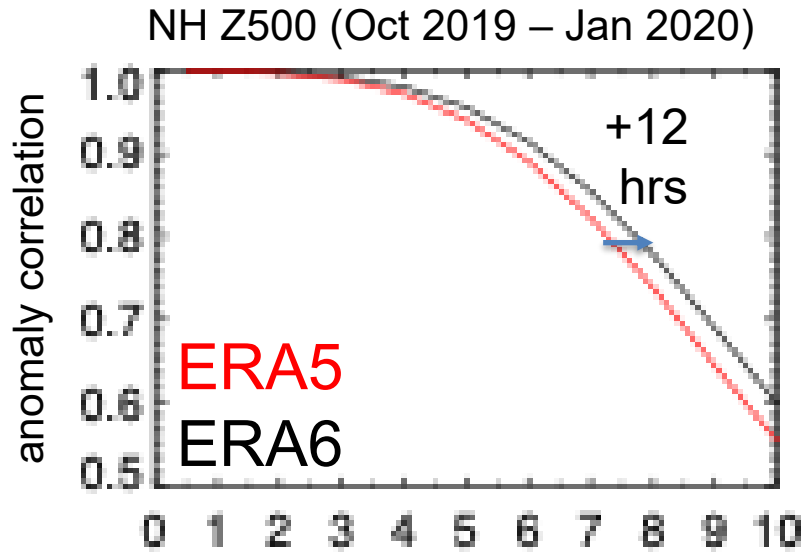


New! in Cy49r2

- 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

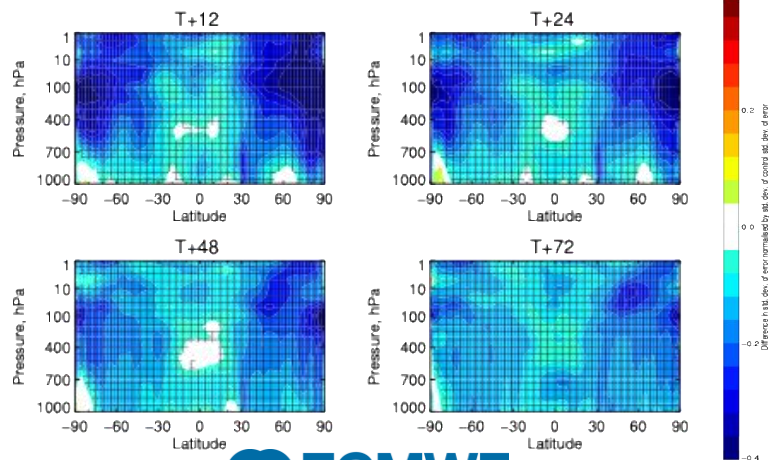


Performance of ERA6 test experiments



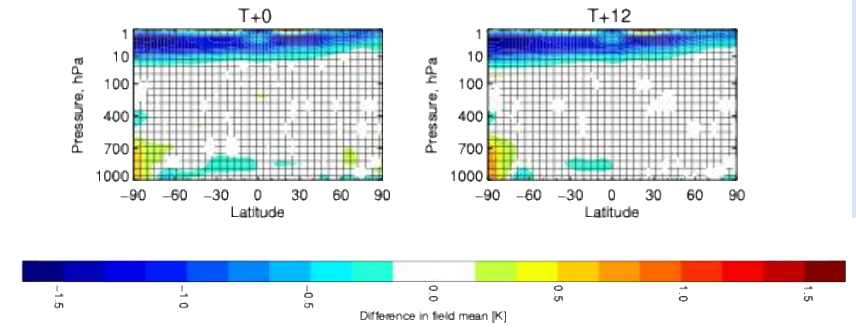
By this metric (remember slide 6) improvements from ERA5 to ERA6 are in-line with those achieved in previous generations of reanalyses

Change in std. dev. of error in Z (ERA6-test (ind5)-ERA5)
1-Oct-2019 to 31-Jan-2020 from 226 to 245 samples. Verified against own-analysis
Cross-hatching indicates 95% confidence with Sidak correction for 20 independent tests.



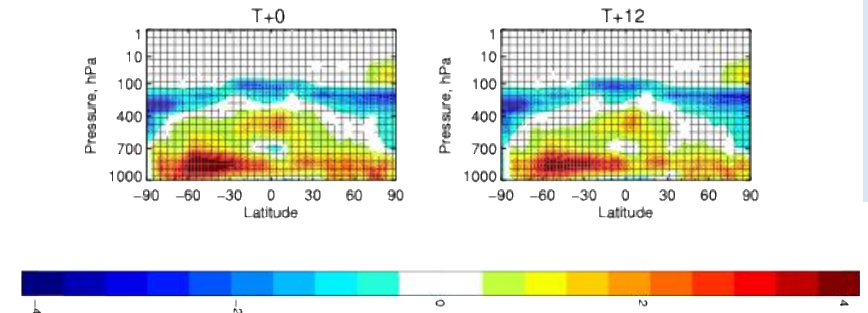
Mean state changes

Change in field mean in T (ERA6-test (ind5)-ERA5)
11-Oct-2019 to 31-Jan-2020 from 226 to 226 analyses.
Cross-hatching indicates 95% confidence with Sidak correction for 20 independent tests.



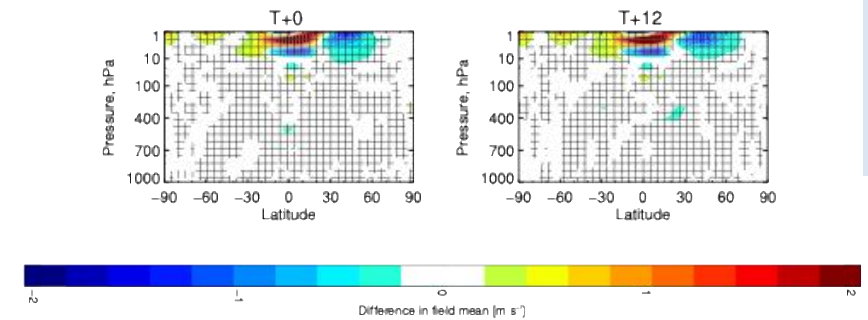
Temperature

Change in field mean in R (ERA6-test (ind5)-ERA5)
11-Oct-2019 to 31-Jan-2020 from 226 to 226 analyses.
Cross-hatching indicates 95% confidence with Sidak correction for 20 independent tests.



Humidity

Change in field mean in U (ERA6-test (ind5)-ERA5)
11-Oct-2019 to 31-Jan-2020 from 226 to 226 analyses.
Cross-hatching indicates 95% confidence with Sidak correction for 20 independent tests.



Winds

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Summary of important concepts

Reanalyses are extremely popular datasets:

- convenient: transform non-gridded historical observations into consistent and accurate 'maps without gaps'
- Many types of users (academic, commercial, policy makers) and applications (weather, climate)
- produced at several centres around the globe

Reanalysis is typically based on a recent NWP data-assimilation system

- for several decades or longer and at lower resolution to keep affordable
- focus is on the analysis, not the forecast (although of course better analyses produce better forecasts)

The long time dimension needs attention:

- Appropriate forcing fields for e.g., radiative forcing, SST, sea ice
- Reprocessing and data rescue of historical observations are important

The data assimilation system is more challenged in the data-sparses past:

- Need to evolve background (and observation) errors accordingly
- Systematic model error has more chance to grow
 - Can affect the mean state and changes as the observing system evolves
 - The method of weak constraint 4D-Var could alleviate this situation

An uncertainty estimate is important to reflect the increasing confidence when more observations become available

- Ensemble spread provides a proxy for the synoptic uncertainty, not the uncertainty of the mean state

In line with the developments in NWP, reanalysis is **progressing towards the Earth system approach**

Selected further reading and data access

Uppala et al. (2005), “The ERA-40 reanalysis”, *QJRMS*. **131** (612), 2961-3012, doi:10.1256/qj.04.176

Dee et al. (2011), “The ERA-Interim reanalysis: configuration and performance of the data assimilation system”, *QJRMS*. **137** (656), 553-597

Poli et al. (2016), “ERA-20C: An Atmospheric Reanalysis of the Twentieth Century”, <https://doi.org/10.1175/JCLI-D-15-0556.1>

Simmons et al. (2020), “*Global stratospheric temperature bias and other stratospheric aspects of ERA5 and ERA5. 1*”, European Centre for Medium Range Weather Forecasts.

Simmons et al. (2021), “on ERA5 surface temperature and humidity”, European Centre for Medium Range Weather Forecasts.

Hersbach, et al. (2020), "The ERA5 global reanalysis." *Quarterly Journal of the Royal Meteorological Society* 146.730: 1999-2049.

Bell, et al. (2021), “The ERA5 global reanalysis: Preliminary extension to 1950”. *Quarterly Journal of the Royal Meteorological Society*, <https://doi.org/10.1002/qj.4174>.

Soci, et al. (2024), “The ERA5 global reanalysis from 1940 to 2022”. *Quarterly Journal of the Royal Meteorological Society*, <https://doi.org/10.1002/qj.4803>

Laloyaux et al. (2018). CERA-20C: A coupled reanalysis of the twentieth century. *Journal of Advances in Modeling Earth Systems*, 10, 1172–1195. <https://doi.org/10.1029/2018MS001273>

Global and regional reanalyses: <http://www.reanalyses.org>

Copernicus Climate Change Service (C3S) Climate Data Store: <https://cds.climate.copernicus.eu/#!/home>

Google scholar to find the thousands of papers on reanalysis and ERA5

Thanks for your time !

Extra slides

ERA6 will benefit from an additional 8 years of R&D at ECMWF & improved compute capacity

Configuration: 75 years of reanalysis, to be maintained close to real time once completed, based on IFS Cy49r2

- Higher horizontal resolution of **14km** (TCo799) for all components (ERA5 31km for atmosphere, 40km for waves)
- **Improving** the estimate of historical **extreme weather**
- Uncertainty estimate at 28km (TCo399) from 11-member ensemble (63km for ERA5)

Science (selected):

- Coupled ocean, one-way coupled with ORAS6, providing a **consistent representation of ocean-atmosphere processes**
- **Improved realism**, such as introduction of an urban tile
- Improved treatment of systematic model errors with benefit on the quality of **climate trends**
- Evolve CO₂ in RTTOV and CH₄ for methane oxidation (better lower stratosphere humidity)
- Improved GHG and aerosol forcing, new HLO ozone model
- Snow on sea ice and reduce snow depth bias and inconsistencies in general
- Better forcing for large lakes, better initialization soil moisture
- **Resolve** several other ERA5 **known issues**

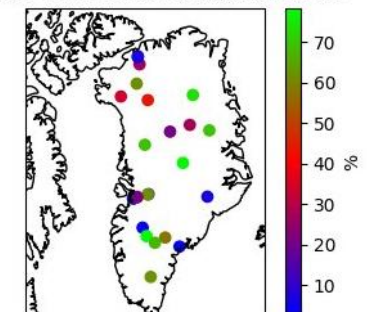
Ingest the best observations:

- Satellite+ in-situ reprocessing and data rescue
- Assimilation of T2m observations in 4D-Var

Products: based on user requirements

- 3D+2D **ocean parameters**
- Hourly, for extended list of (new) parameters, e.g., Rh2m, **clear-air turbulence (CAT)**
- **Height levels** for the lowest part of the atmosphere
- Daily in addition to monthly precalculated statistics

Geological Survey of Denmark
Max. number of days with reports: 12083
between 1990-06-01 and 2023-06-30



Source: Reuters, from www.bbc.co.uk