On reanalysis production and quality assurance

Dinand Schepers

Bill Bell, Paul Berrisford, Hans Hersbach, Andras Horanyi, Joaquin Munoz-Sabater, Julien Nicolas, Paul Poli, Raluca Radu, Adrian Simmons, Cornel Soci

And many others that contributed to ERA5

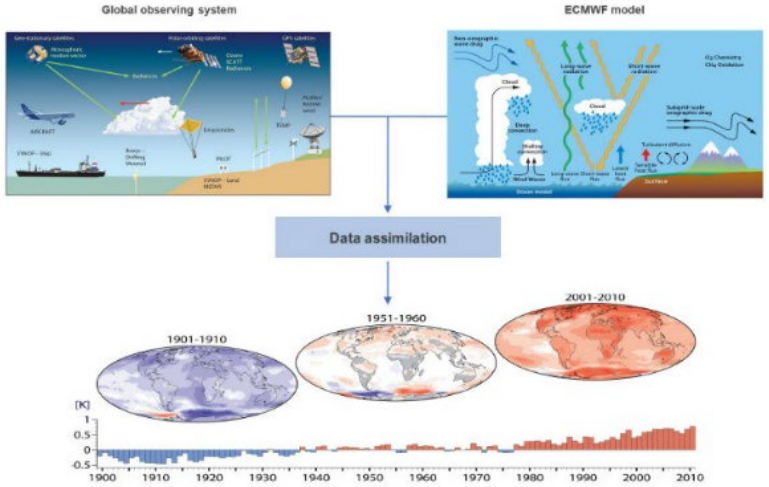
ECMWF

Reconstruction of the past weather&climate:

- ✓ **Input:** integrator of all observations we have
- ✓ **Output:** convenient and as accurate as possible ‘maps without gaps’ of 3D atmosphere (+ other domains)

State-of-the-art:

- ✓ Redo historical weather using a modern but fixed NWP system
- ✓ For extended period back in time, but at lower resolution
- ✓ Made available to users in a convenient way
- ✓ Maintained close to NRT



All observations we have

0.75 (1979) – 26 Million (2021) obs per day
Over 200 types of reports

Reprocessed data sets (In blue)

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

Improved data usage compared to ERA-I (in blue)

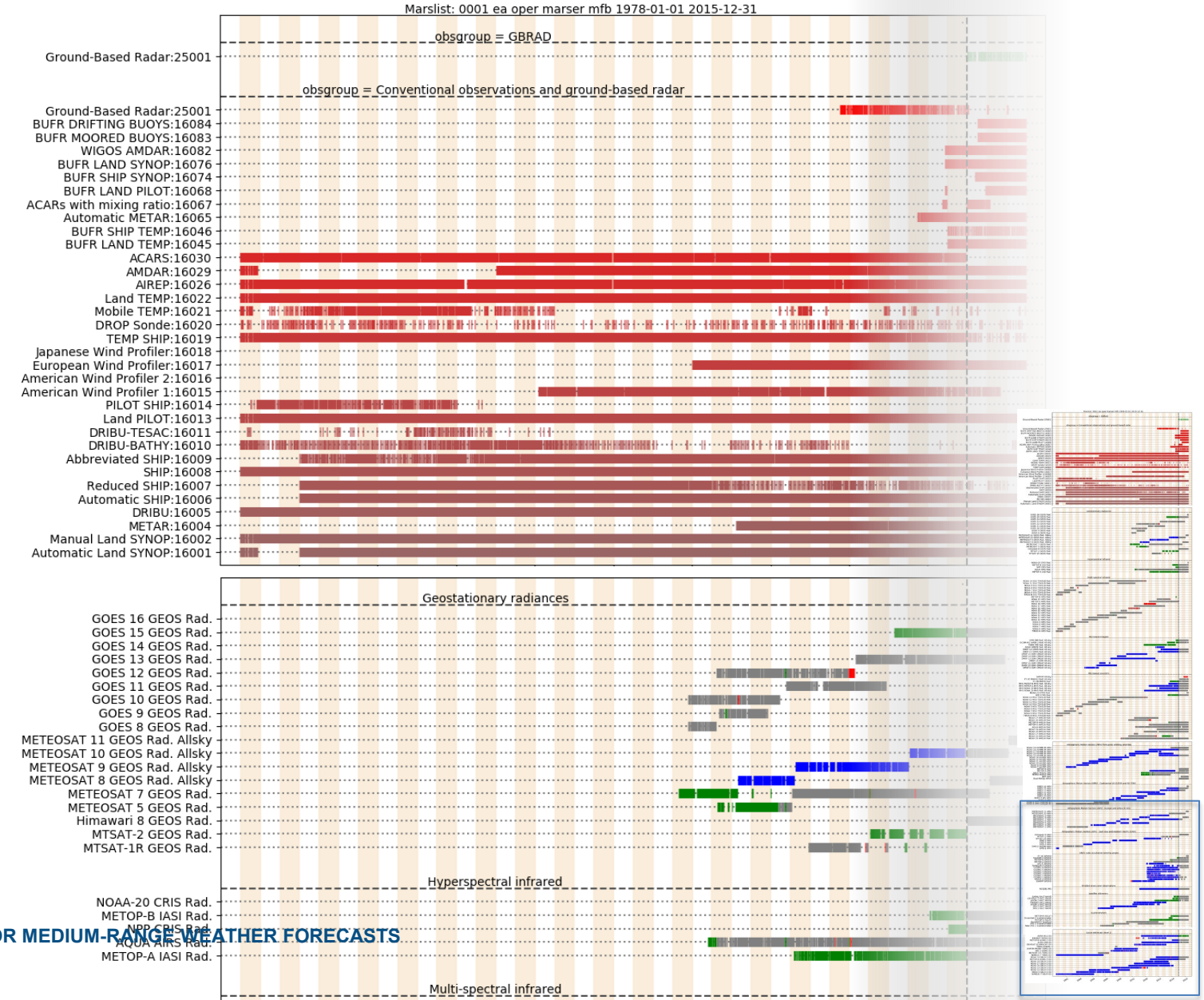
all-sky vs clear-sky assimilation,
latest radiative transfer function, corrections,
extended variational bias control

Latest instruments

IASI, ASCAT, ATMS, CrIS, MWHS, Himawari, …
TAMDAR, MODE-S

ERA5T vs ECMWF NWP operations:

ERA5 only: AURA MLS
ERA5 not possible: Saphir, Aeolus, TEMP descent, SPIRE



using a modern but fixed NWP system (I)

Every new generation of reanalysis benefits from years of research at ECMWF by about 110 staff in ECMWF Research Department

Projected benefits of ERA6 over ERA5

- **Improved realism of near-surface quantities and radiative forcing**
  - **vegetation** cover and type, **LAI, lake** cover and properties, the **urban tile**
  - New, and more species of, **aerosols** and **GHG's**
- **Improved ocean wave physics**
  - wave physics upgrade
- **4D-Var DA developments**
  - Dynamically evolving $\mathbf{B}_{cli}$
  - EDA developments
- **Land DA developments**
  - Revised conventional observation feedback for T2m, RH2m and snow analyses
- **Ocean DA developments**
  - ERA6 will be forced by ORAS6 and OCEAN6 fields

using a modern but fixed NWP system (II)

Add additional, specific functionalities

- **Support for non-current observations**

Revive and maintain IFS-support for *old, rescued* or *reprocessed* observation types

- **Optimization and setup**

System optimization for maximum throughput and high-volume analyses archiving

- **Postprocessing and archiving**

E.g. monthly means, vertical integrals, accumulations and high-frequency archiving of analyses of an extended parameter set.

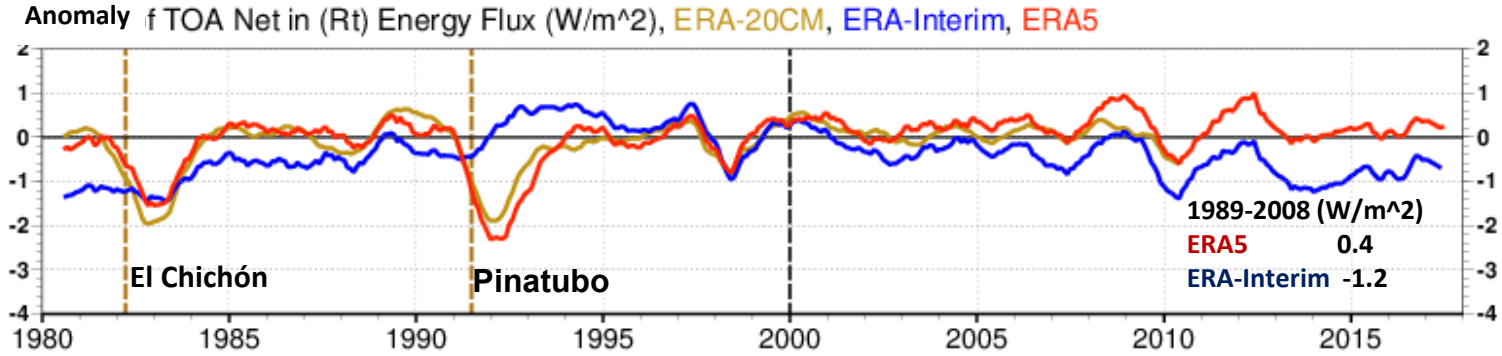
The challenge is to do this in a maintainable and sustainable way

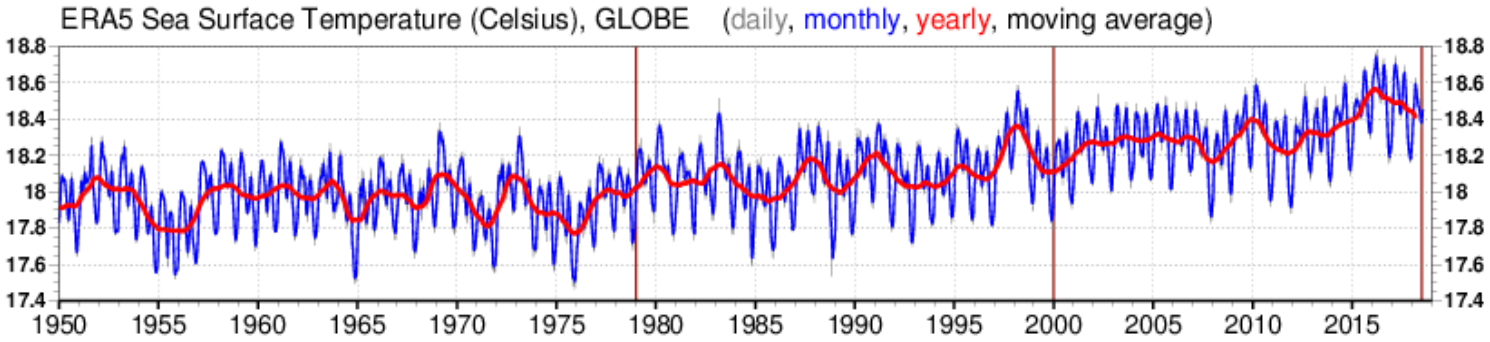
Accurate and for extended period back in time

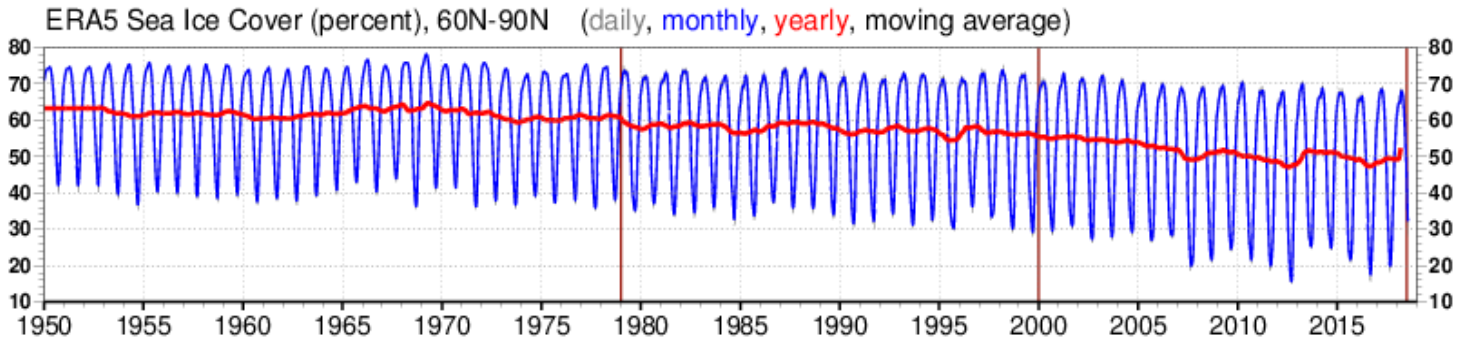
CMIP5 recommended data sets

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

(Prepared in the ERA-CLIM project, ERA-20CM)







SST and sea ice cover

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

Different ensemble members use different SST realizations

(Hirahara et. al., 2016)

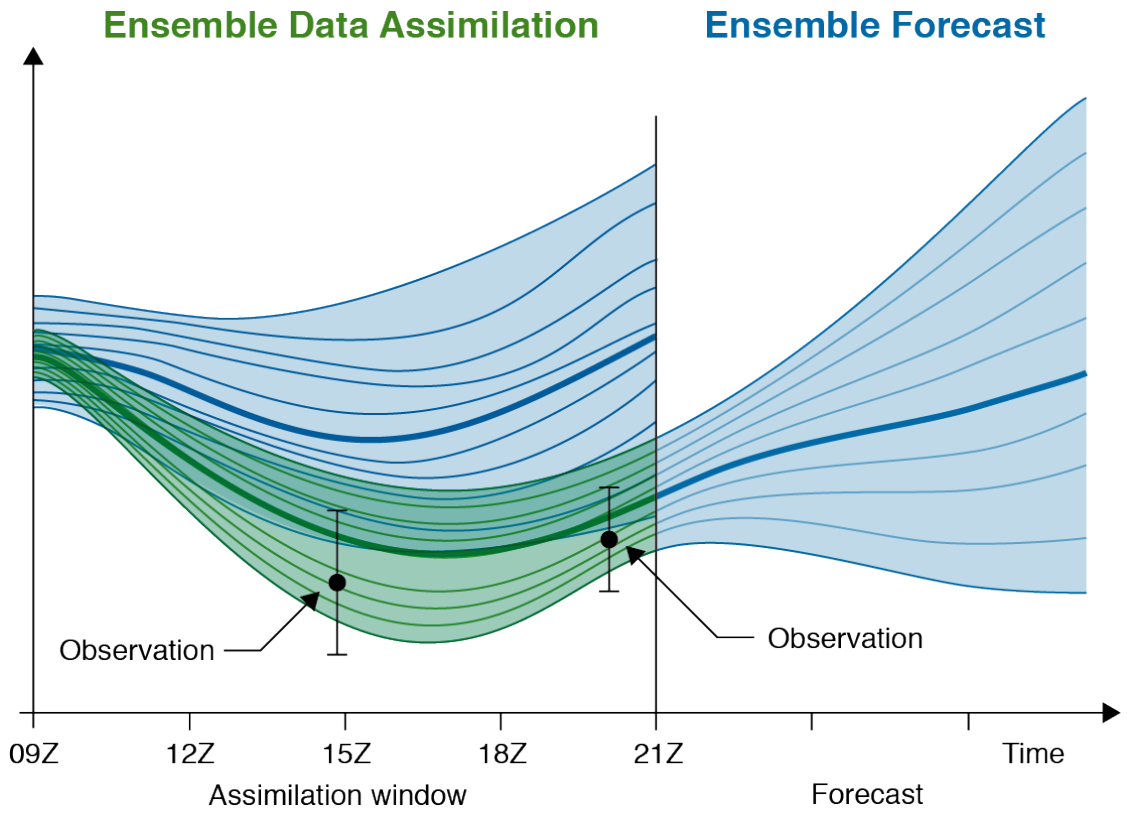
System design

- **Deterministic (HRES)**

Maximum *affordable* resolution

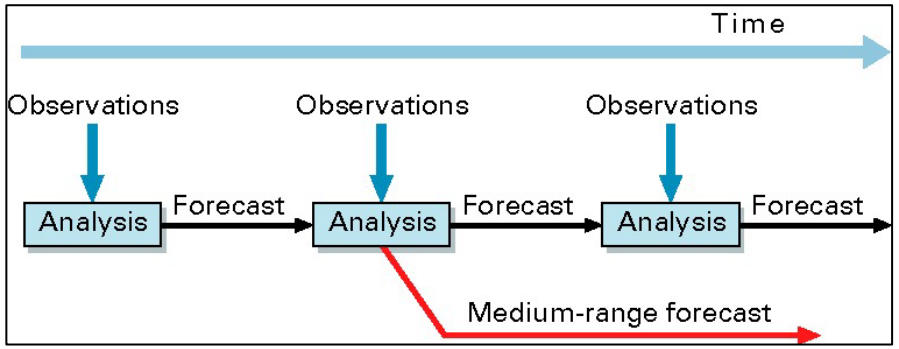
- **Ensemble Data assimilation (EDA)**

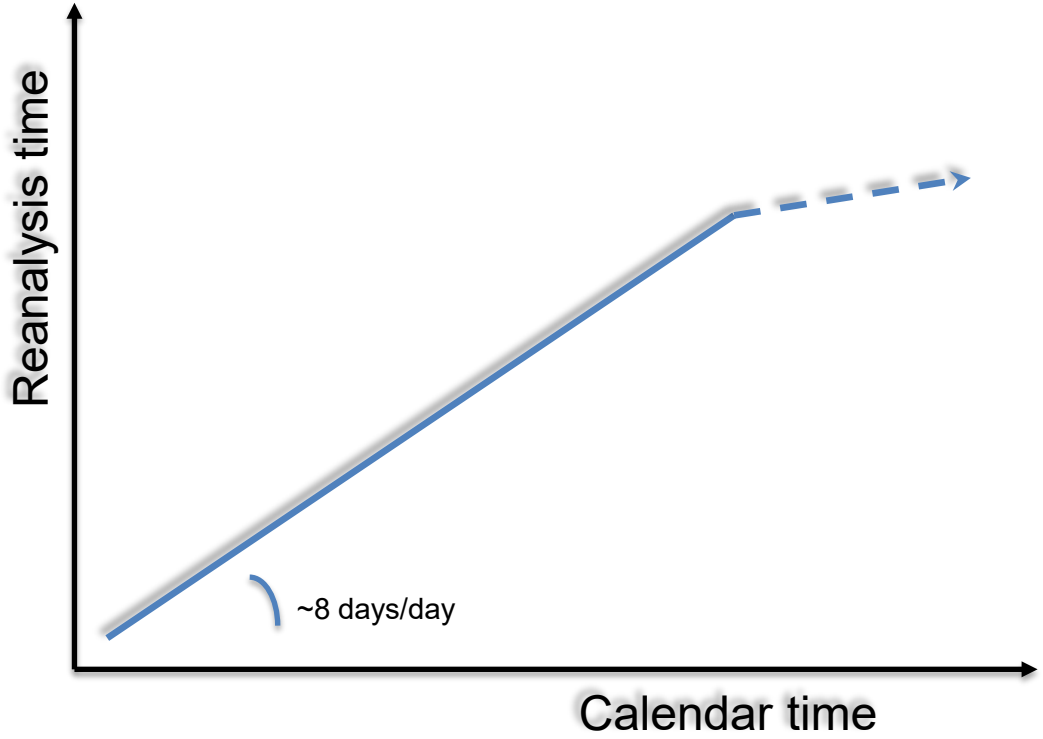
Reduced resolution, relatively few members
Provides flow-dependent B for the HRES
Provides uncertainty product in and of itself

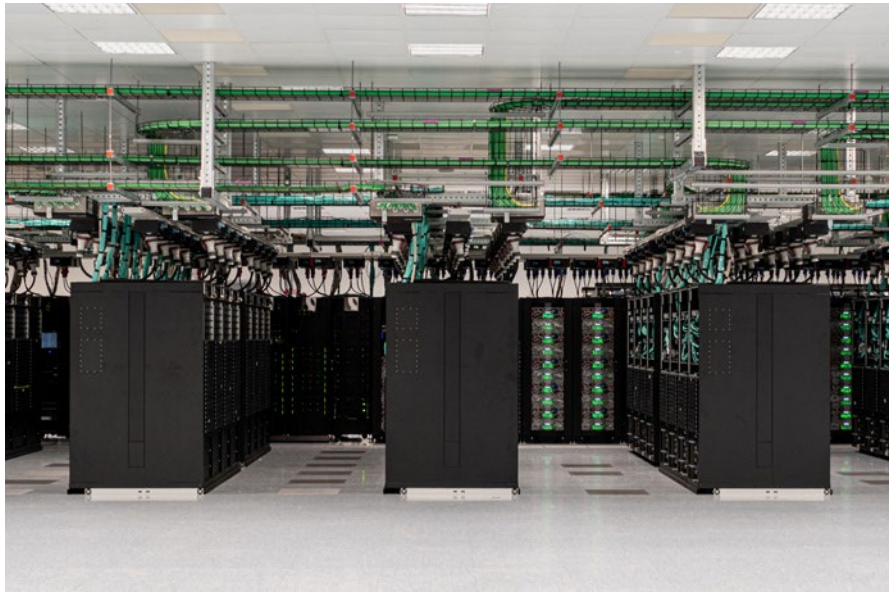


Projected production speed and resource requirements

Identify and resolve bottlenecks for continuous analysis cycling, with the goal of maximizing throughput and efficiency



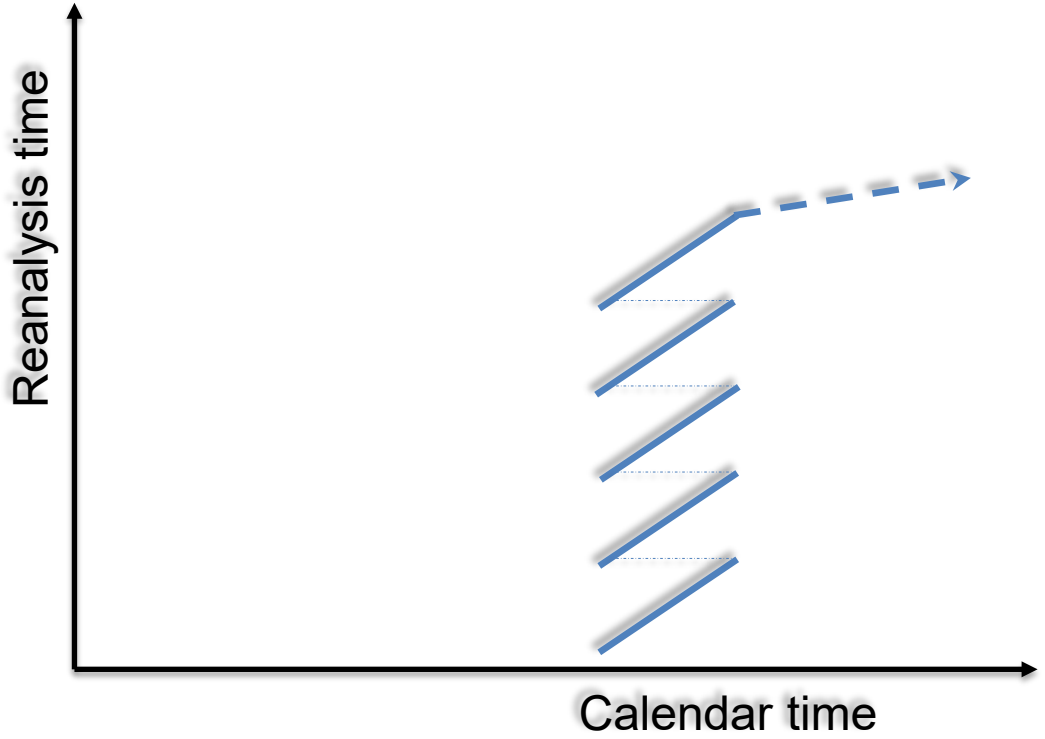


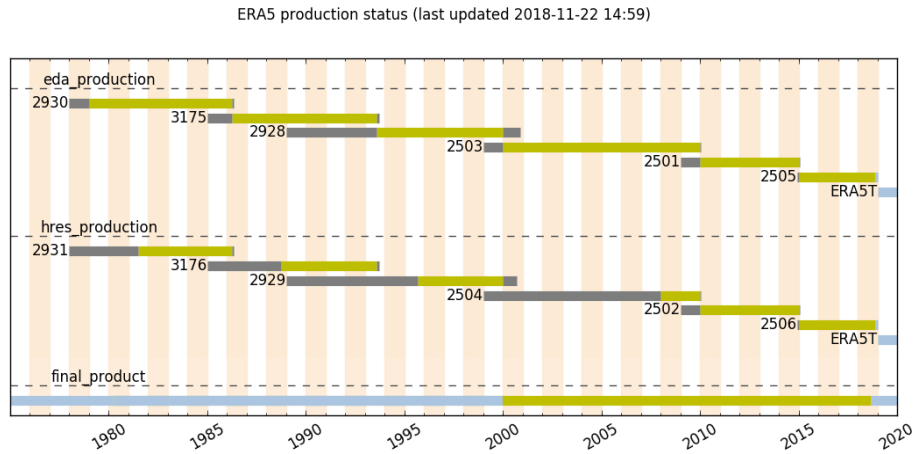


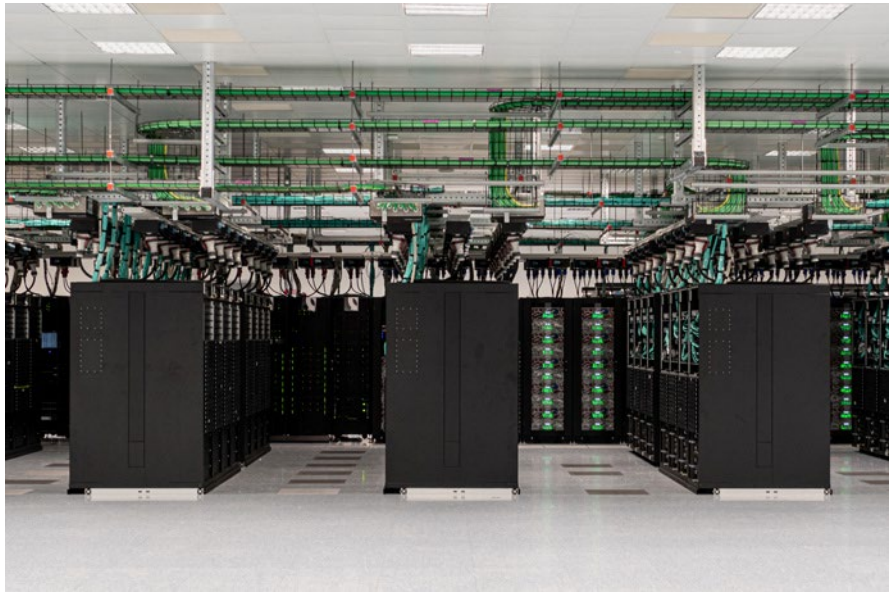
Projected production speed and resource requirements

Production of modern reanalyses is generally parallelized into production streams

Trading overall production time against instantaneous (compute) resource requirements



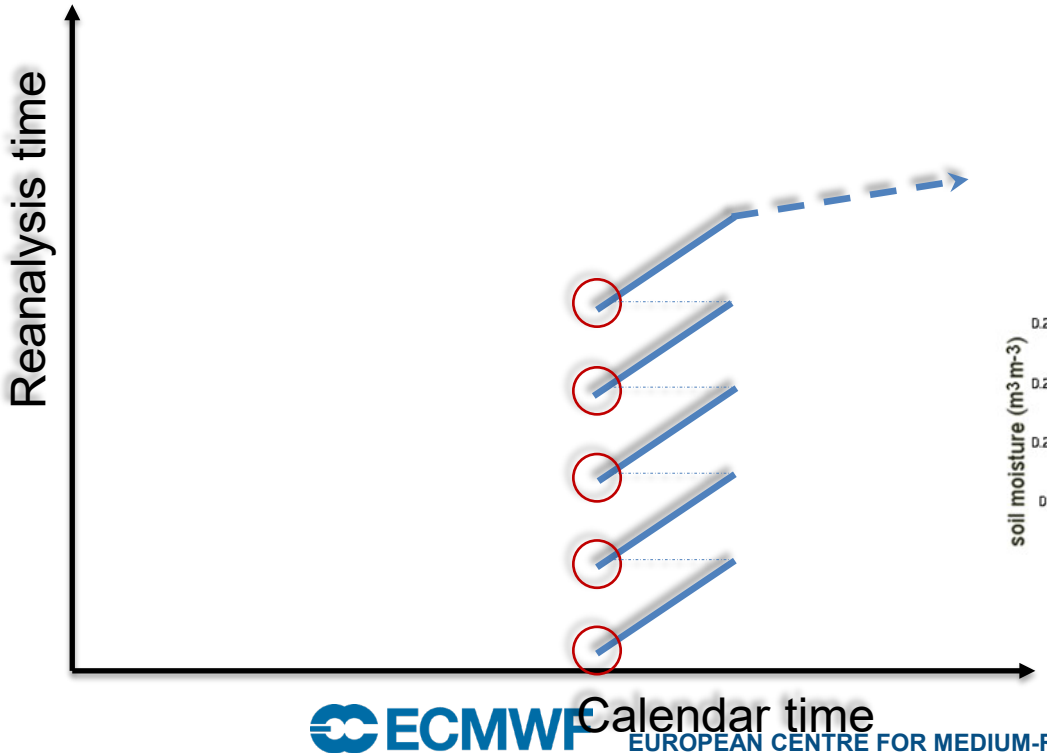


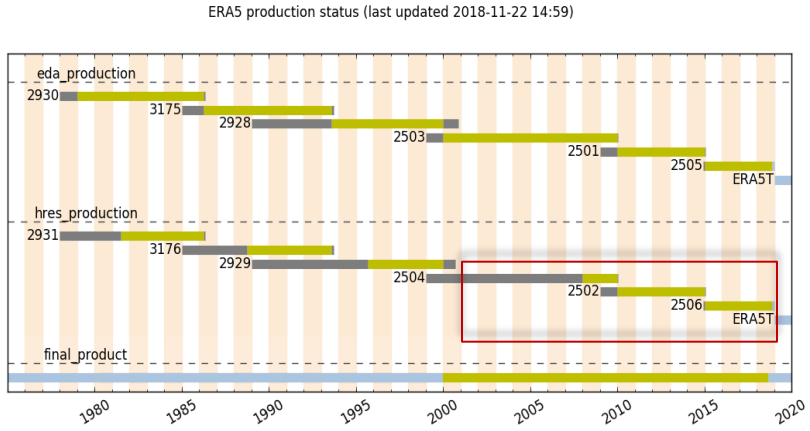


Consideration for parallel production

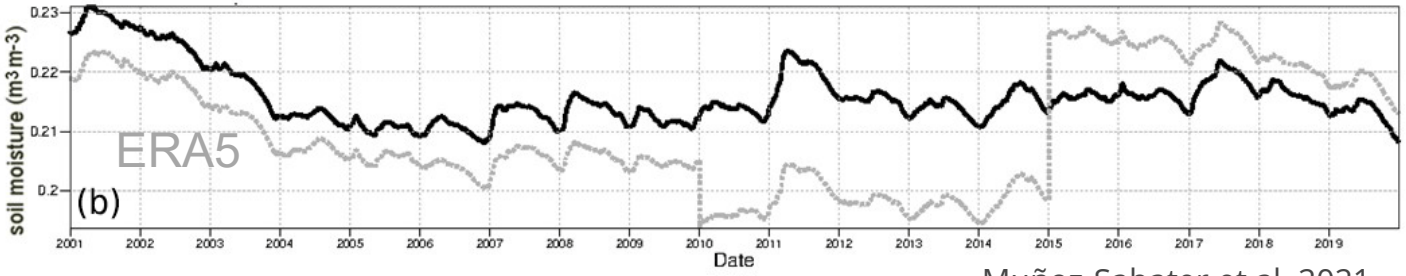
Added costs of spin-up for each stream

Initialization of poorly observed and/or slowly evolving parameters (e.g. deep soil moisture)





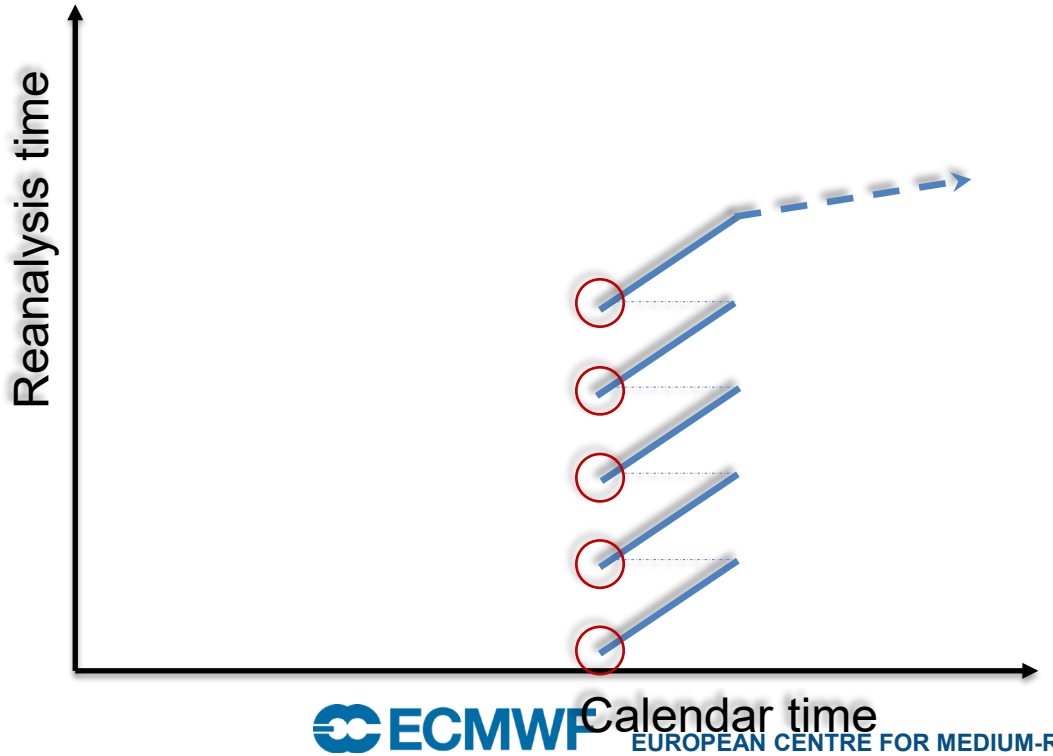
ERA5-Land and ERA5 soil moisture for the fourth (deepest) soil layer

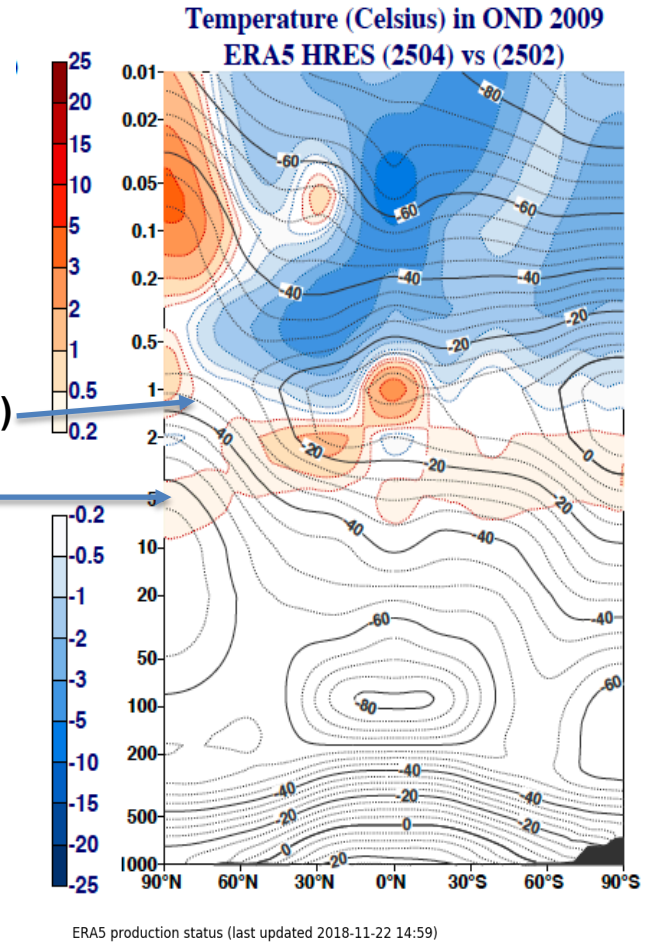


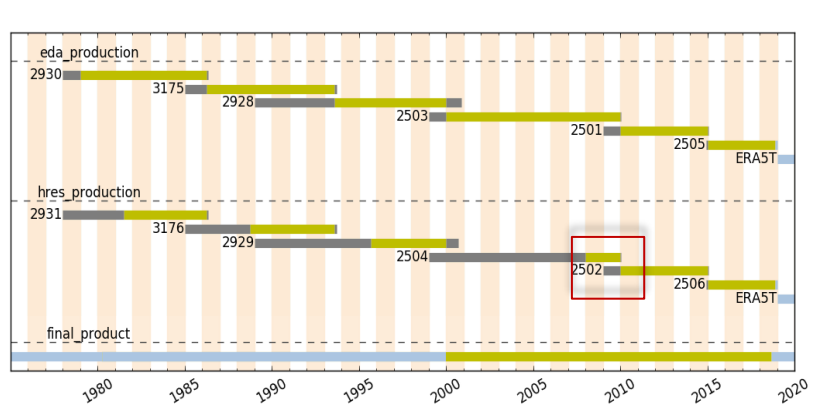
Muñoz-Sabater et al. 2021

Consideration for parallel production: Spin-up

Convergence of VarBC bias estimates is not guaranteed, even after allowing for spin-up

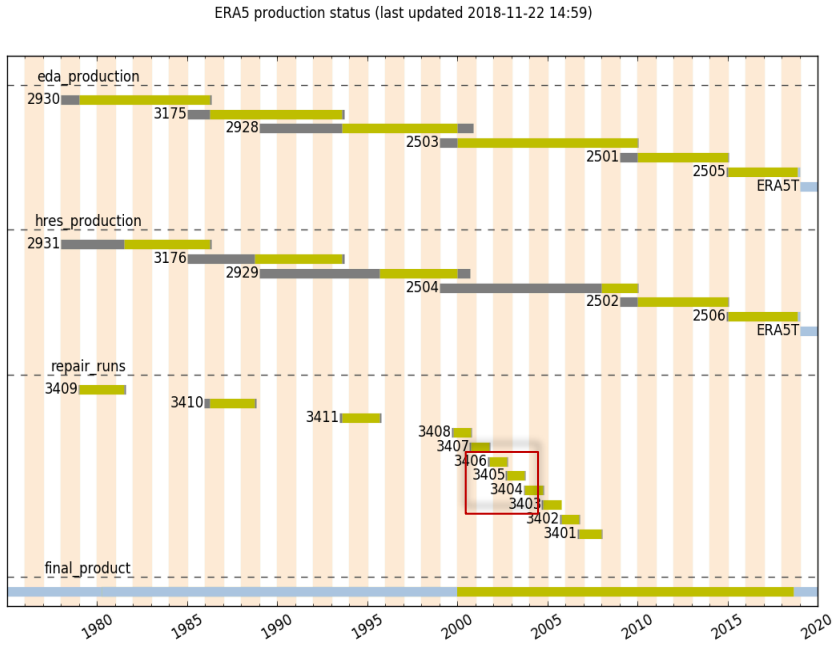


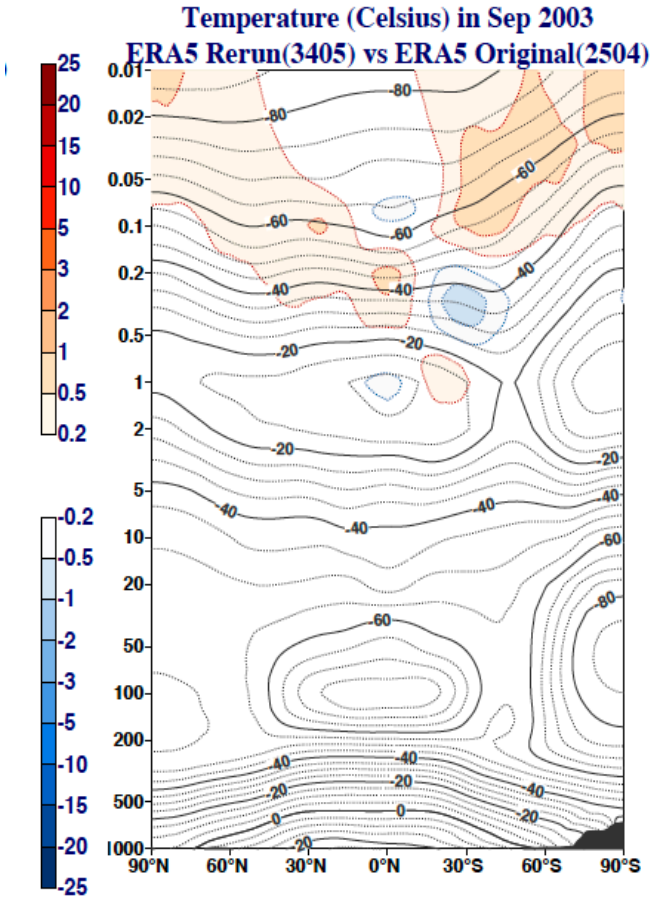




Consideration for parallel production: Spin-up

If we force convergence of VarBC bias estimates, by prescribing them to be equal, discontinuities at the seam virtually disappear



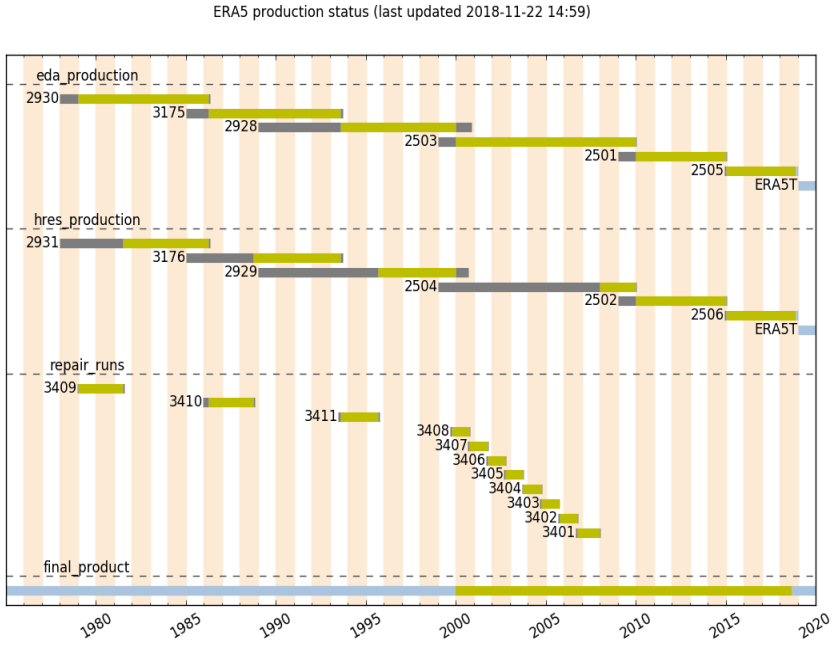


CASE STUDY: Baltic summer sea ice

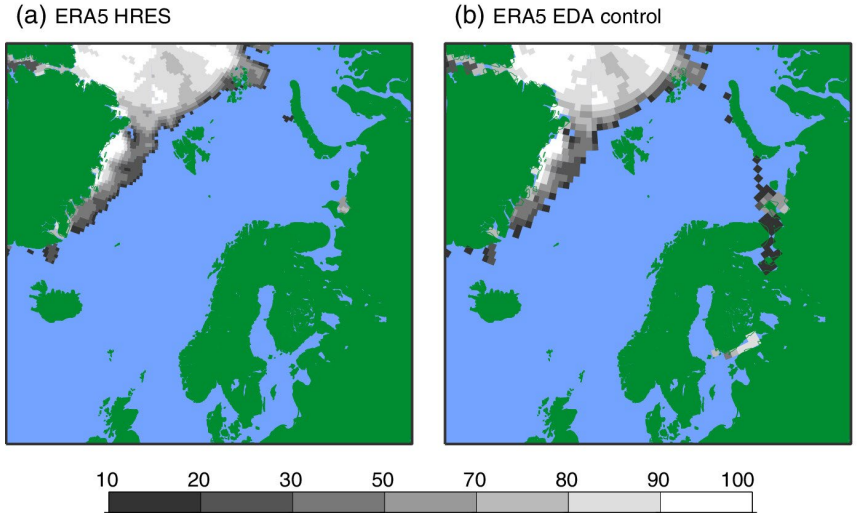
The prescribed sea ice field tends to exhibit sea ice in the Baltic Sea in summertime

Corrective action:
The spurious sea ice was removed from the prescribed field and HRES repaired in a series of repair reruns

The ERA5 ensemble was left as-is. The impact on the ensemble spread is found to be small.



Sea ice cover (percent) on 27 July 2006



Hersbach et al. 2020

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State-of-the-art:

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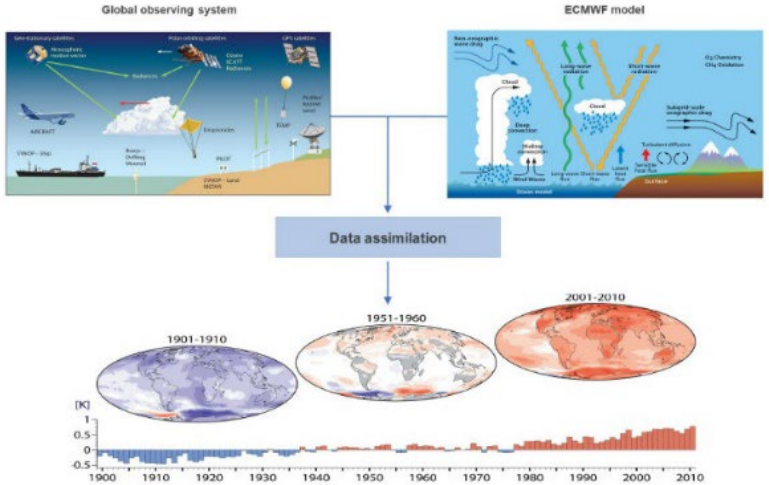


Multiple classes of applications:

- ✓ 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**
  - Statistics, e.g., of extremes

Operational monitoring during production

Observations

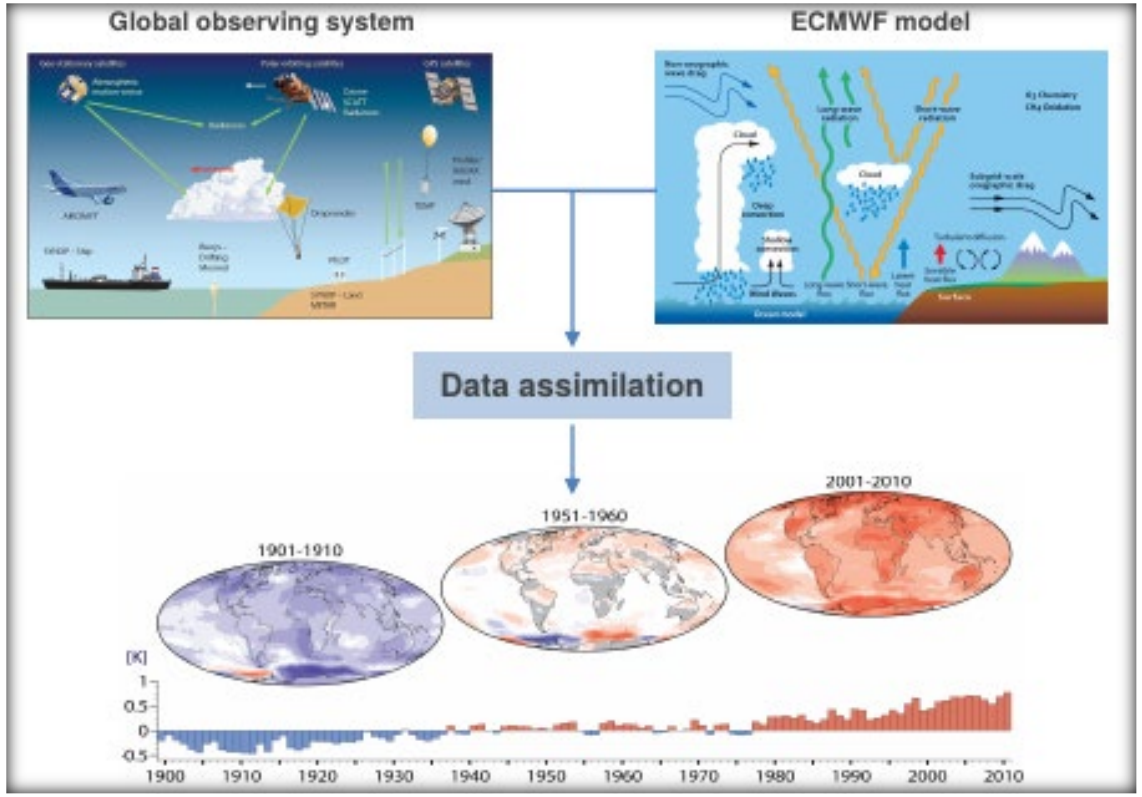
- **Observation system completeness**

Assimilation

- **Assimilation diagnostics and feedback**

Reanalysis product

- **Quality of the final product**



Routine monitoring – Observations space (I)

Completeness and consistency of observational input

We routinely monitor the observation types (reportypes) we assimilate, by comparing against a known reference

Observations used in ERA-Interim, NWP operations

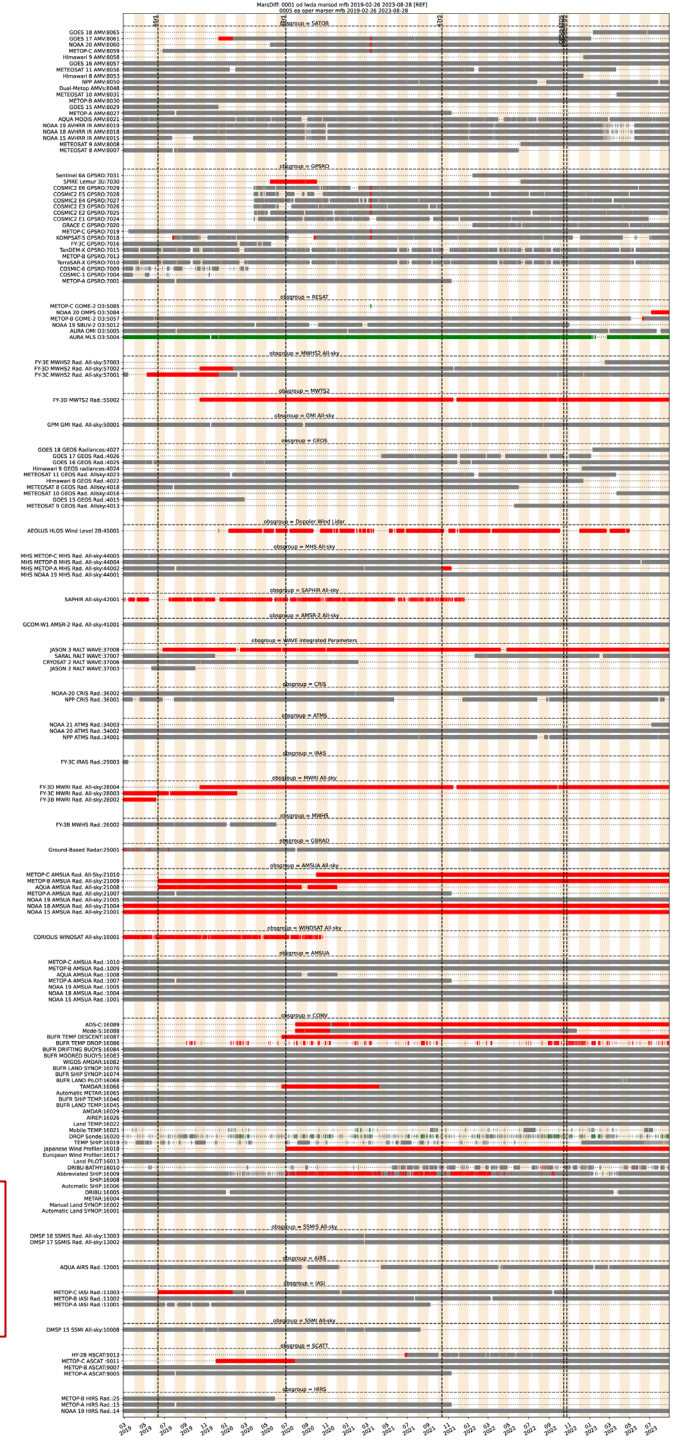
Provides a check on which observations make it into the assimilation

Observations used in ERA5 EDA

Provides a check on consistency with the underlying EDA

All unpacked observations

Provides a check on the fetching, block listing



Missing w.r.t. reference
Additional w.r.t. reference
Present in in both

Routine monitoring – Observations space (II)

Completeness and consistency of observational input

We routinely monitor the observation types (reportypes) we assimilate, by comparing against a known reference

Powerful

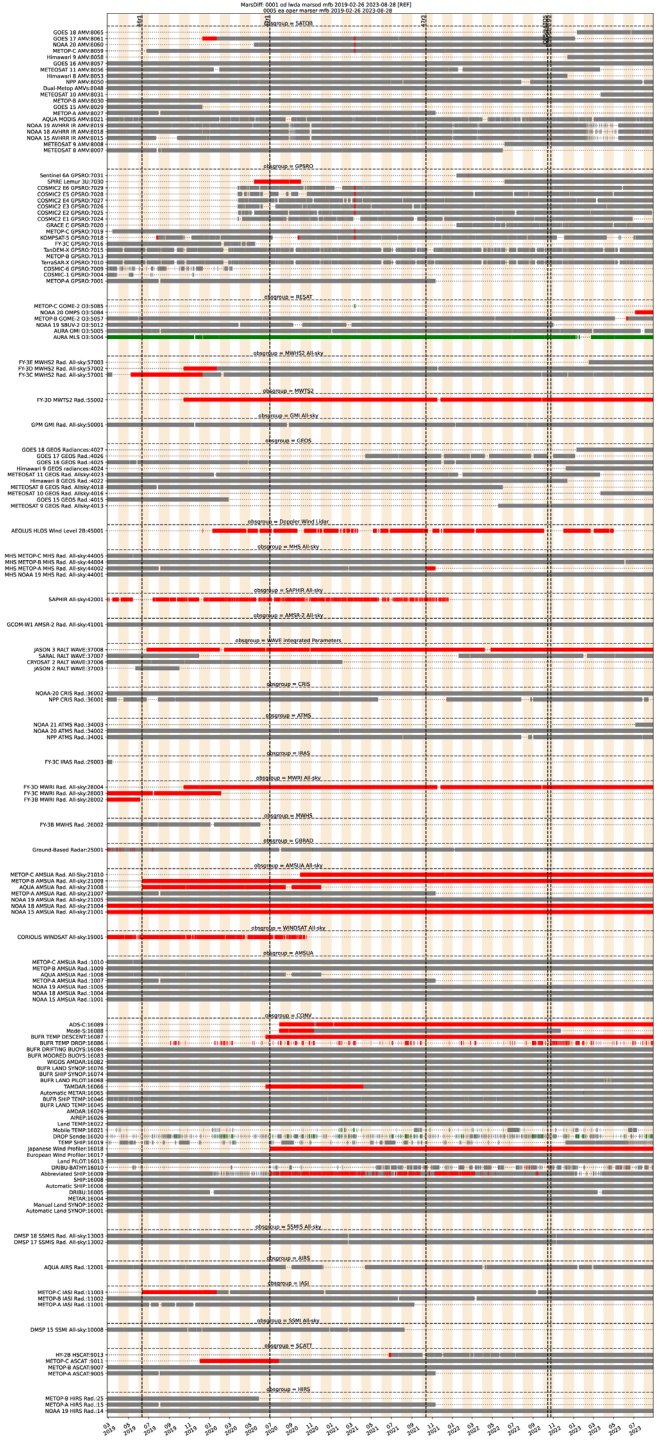
Provedes a high-level check through one single plot

Lightweight

Based on MARS *LIST*, functionality in its default form

Flexible

Can ingest full ODB feedback for more granulariry



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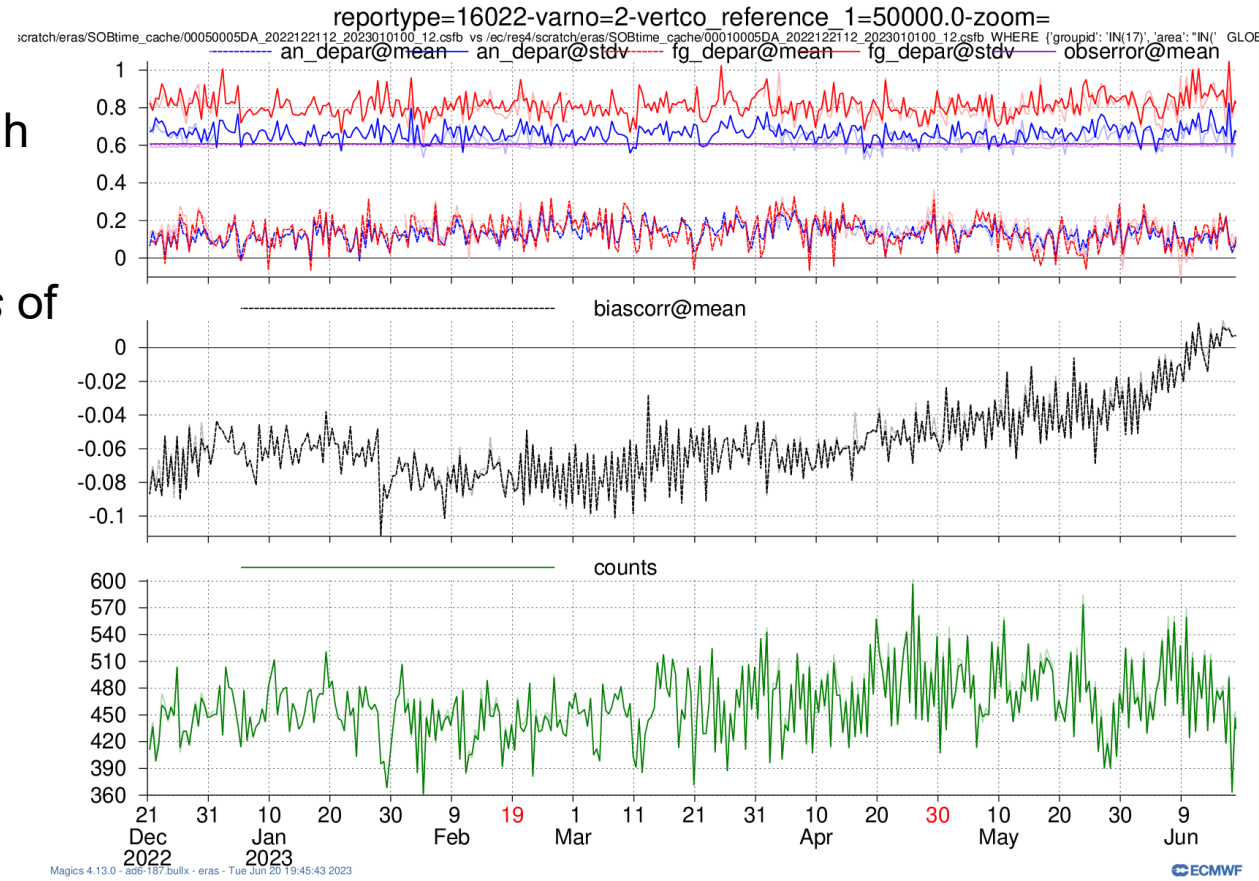
Routine monitoring – Assimilation space (I)

Ensure optimal assimilation of observations

We routinely monitor the assimilation system through *observation feedback*

Based on pre-computed, area-averaged *Timeseries* of

- Number of observations
- applied bias correction
- First guess and analysis departures



Routine monitoring – Assimilation space (II)

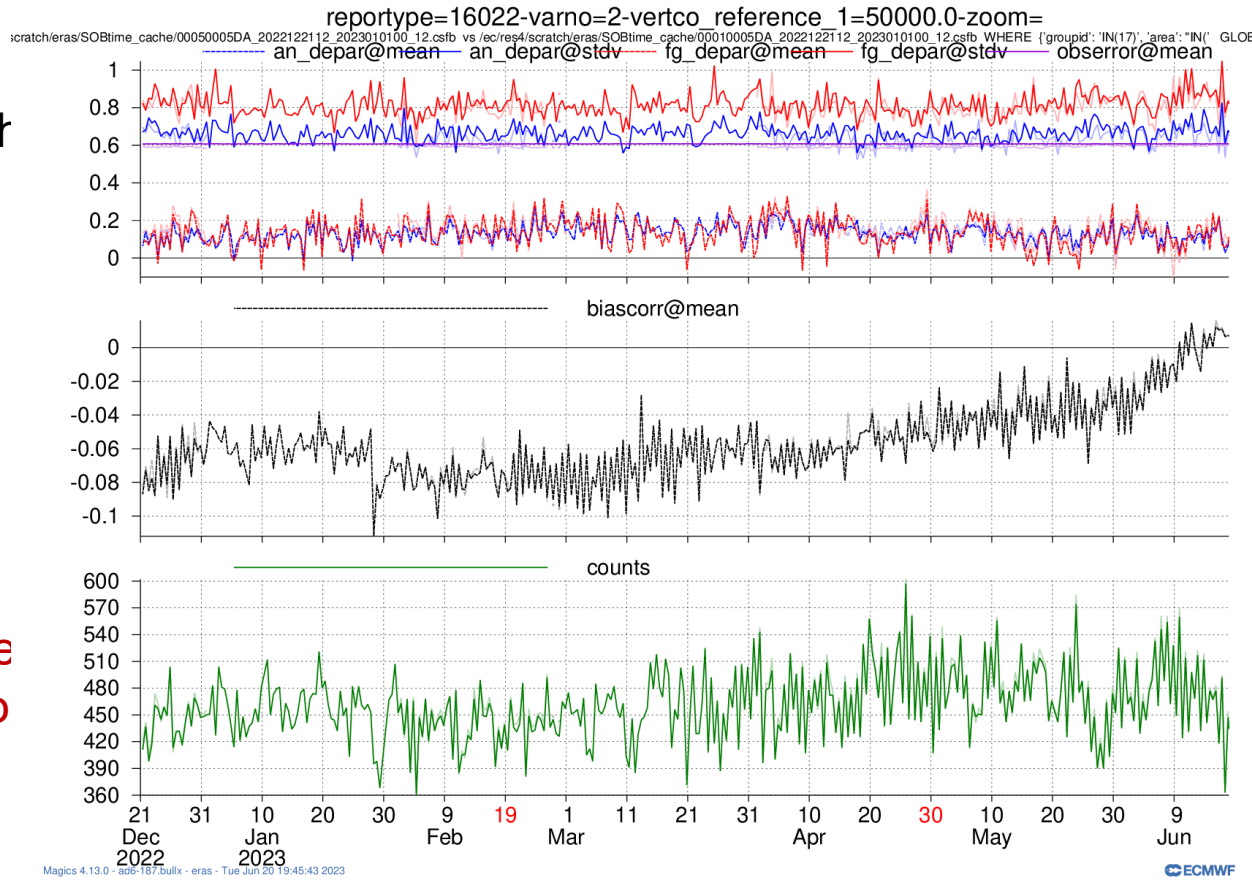
Ensure optimal assimilation of observations

We routinely monitor the assimilation system through *observation feedback*

Flexible, detailed and granular

- 6 predefined regions
- Per, instrument, channel, variable, datum_status
- Requires significant expertise to interpret

Typically, useful when a new observation or instrume introduced, or in case observation quality degradatio (rare)



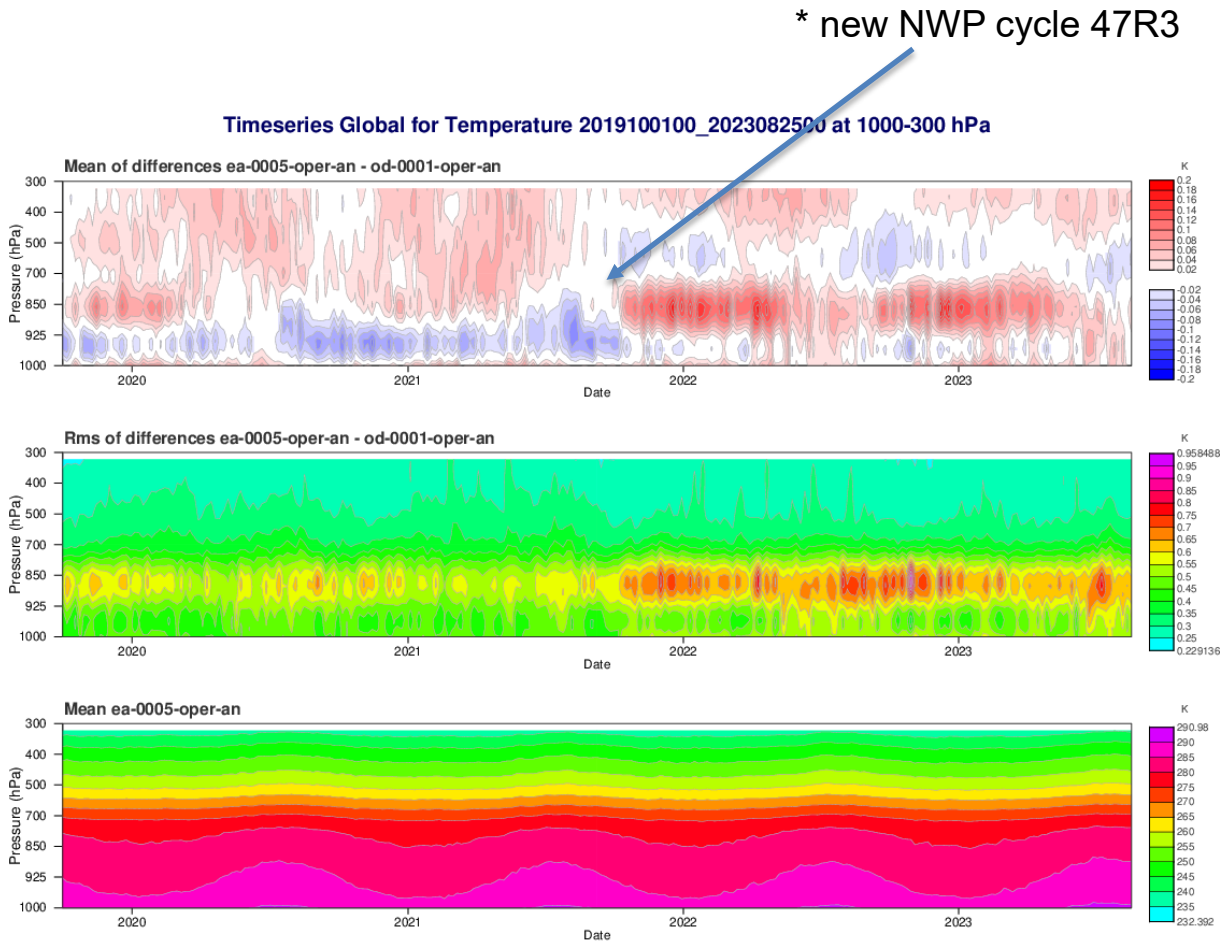
Routine monitoring – Model space (I)

Ensure an optimal reanalysis product

We routinely monitor the actual reanalysis product mainly through comparing the *area-averaged* analysis to a reference

ERA-Interim, NWP operations, …
Provides a handle on gross errors in the mean state and consistency in time*

The ERA5 background forecast
Provides quasi-increments, a particularly sensitive metric for monitoring mean state



Routine monitoring – Model space (II)

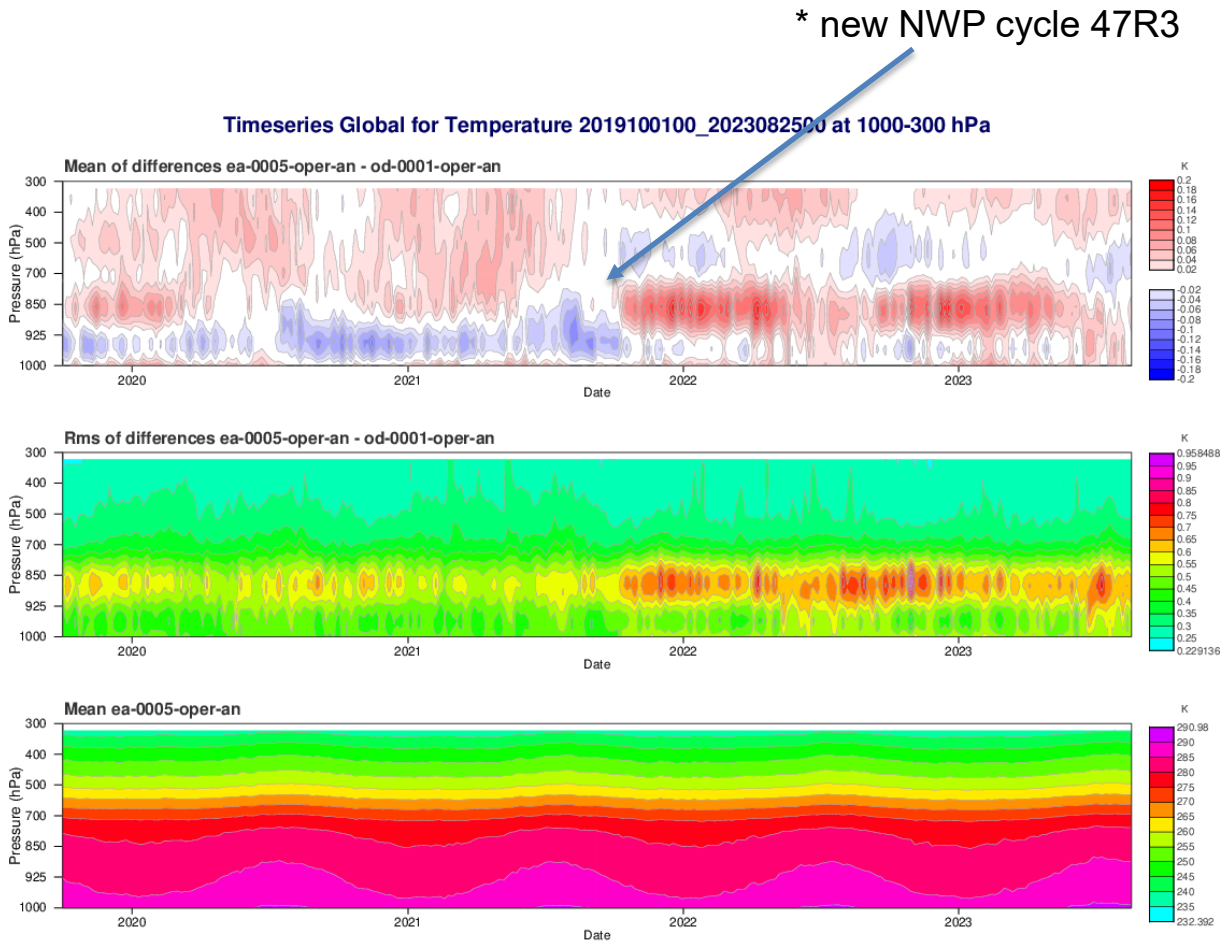
Ensure an optimal reanalysis product

We routinely monitor the actual reanalysis product mainly through comparing the *area-averaged* analysis to a reference

High level, aggregated in model space

- Area-averaged
- pair-wise pre-computed
- Fairly straight-forward to interpret

Typically, useful for catching gross errors or time-inconsistencies in the analyzed state

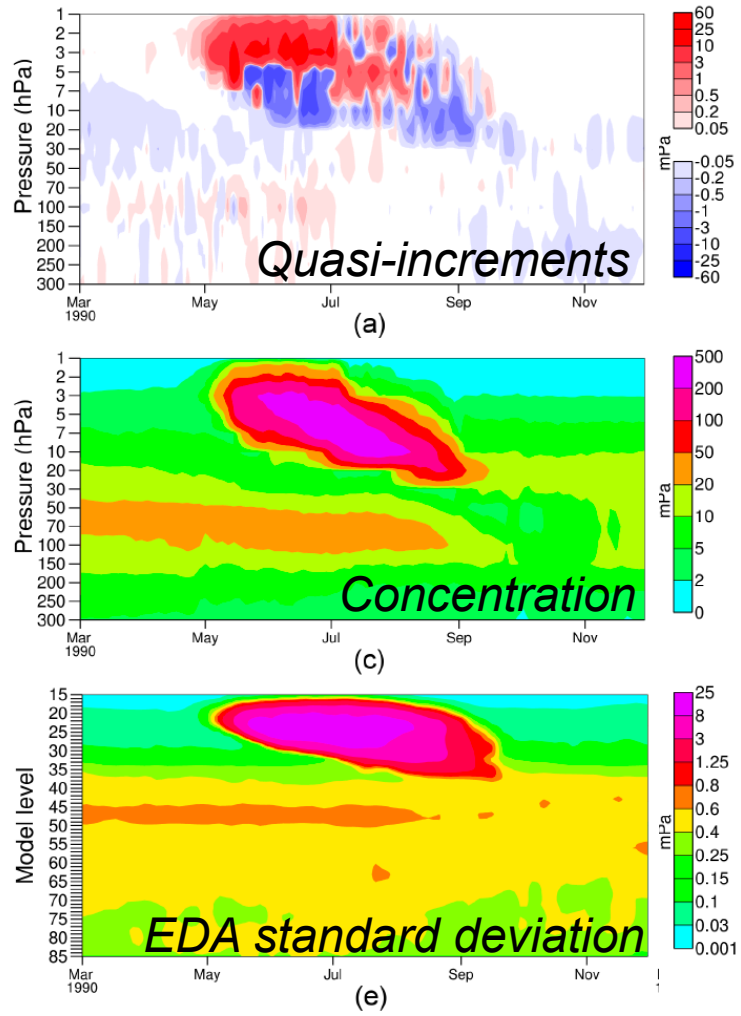


CASE STUDY: Anomalous ozone in Antarctic polar night

In polar night conditions during the 80's and 90's ERA5 produced physically unrealistic amounts of ozone in the high stratosphere

Diagnosis:
Assimilating SBUV observations above 5 hPa induces increments over the *unobserved* winter pole, adding ozone and simultaneously inflating the EDA spread. Establishing a positive feedback loop.

Area-averaged (Antarctic) ozone-



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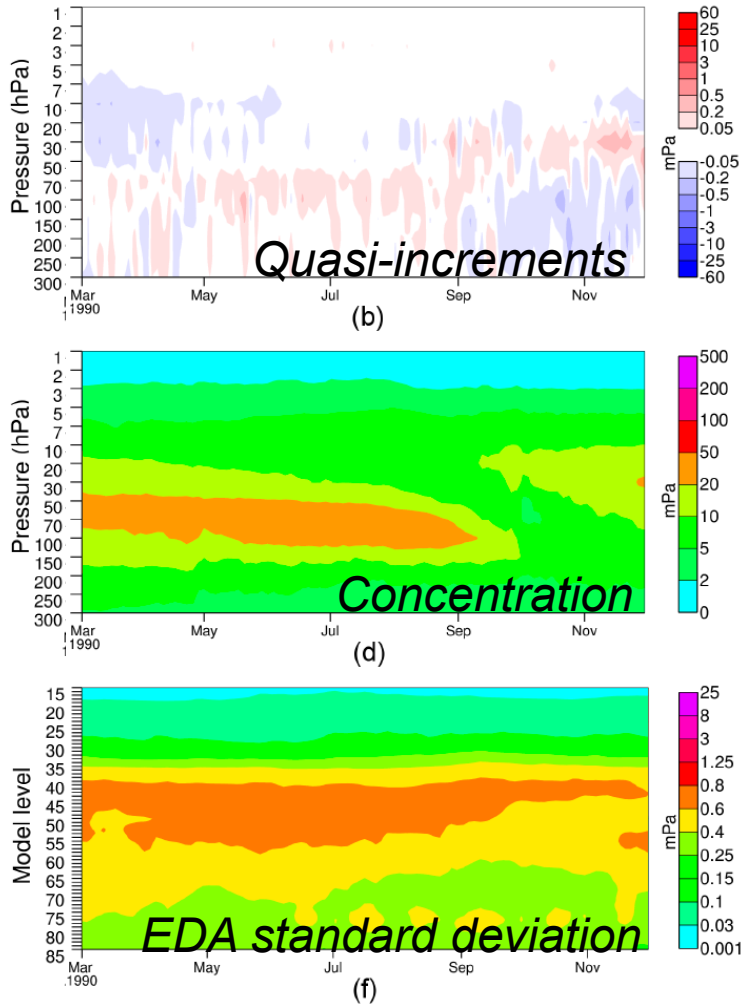
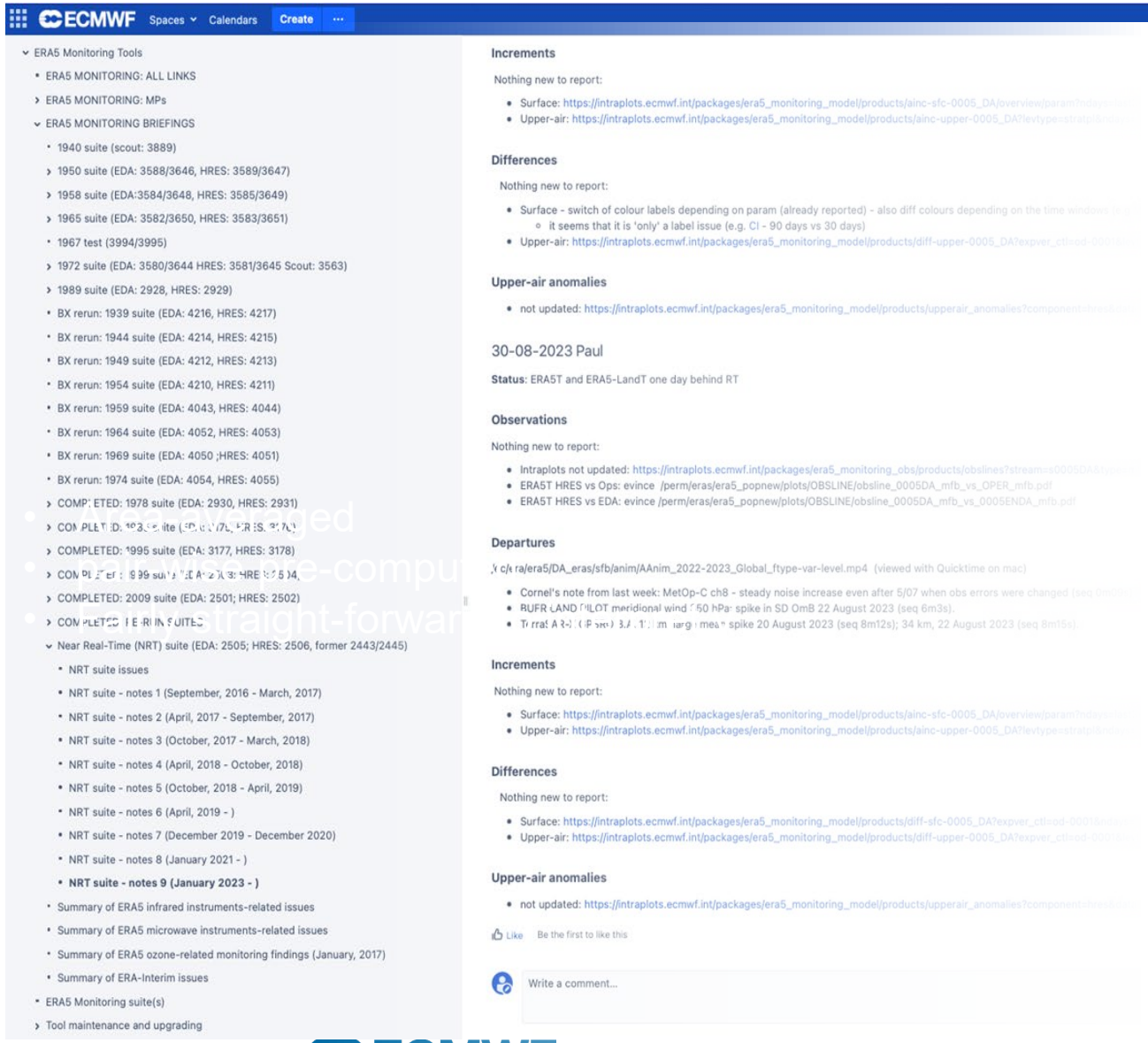
Corrective action:
Partial blacklisting of SBUV in ERA5 (above 5 hPa) and full blacklisting in the EDA was shown to prevent occurrence. And the corrected fields were released to the public.

Work has been done on the IFS to prevent reoccurrence in future reanalysis

Are



Routine monitoring – Implementation for ERA5

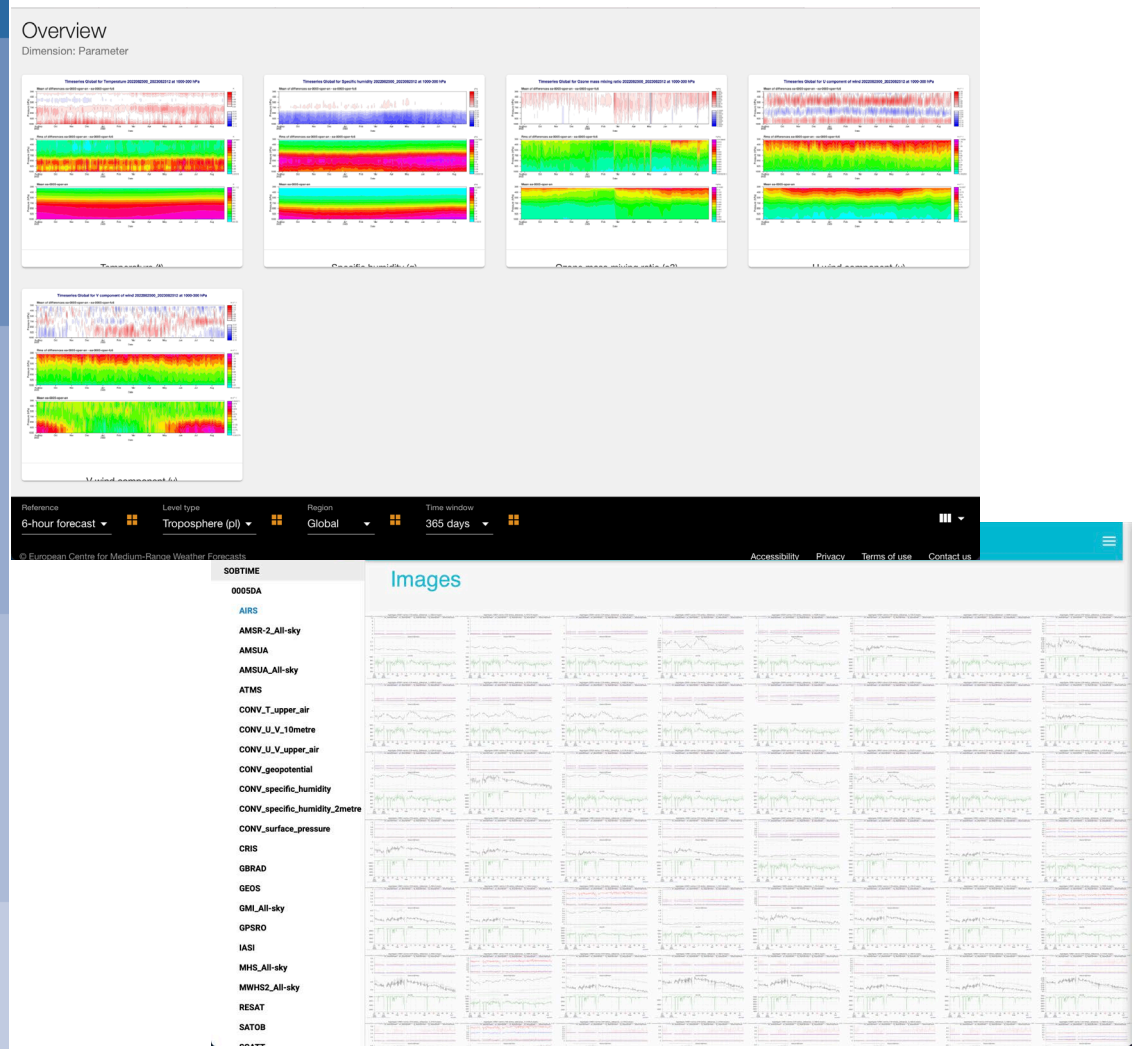


Weekly monitoring team meetings with one or more designated 'monitoring person(s)' or MP

- Up to 6 production experiments per MP
- In the observation-rich era, 1,000s of plots/metrics to monitor, per stream
- Findings are documented, discussed, and actioned if needed

Full 'production log' for all ERA5 streams

Routine monitoring – Reflection and lessons



- The vast majority of issues logged were identified and actioned in manner that has not negatively affected the final ERA5 product
- Time for investigations and options for corrective actions are often limited
- Monitoring is effectively done per-stream, complicating early assessment of long-term trends and slowly varying (climate) signals
- This manner of monitoring is labor intensive, and it does not scale well
- Practically, it becomes a challenge to quickly and efficiently access all monitored metrics

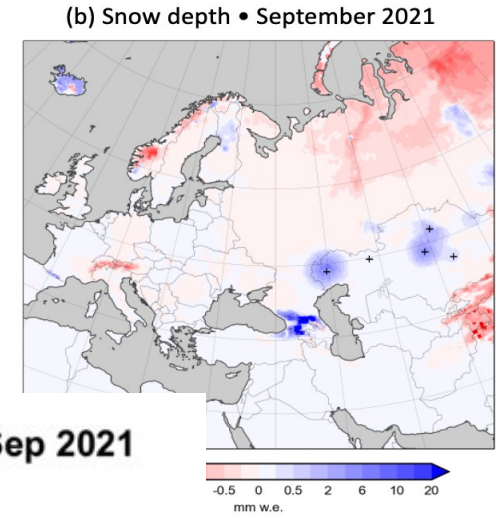
To get better, we need to learn from our mistakes…

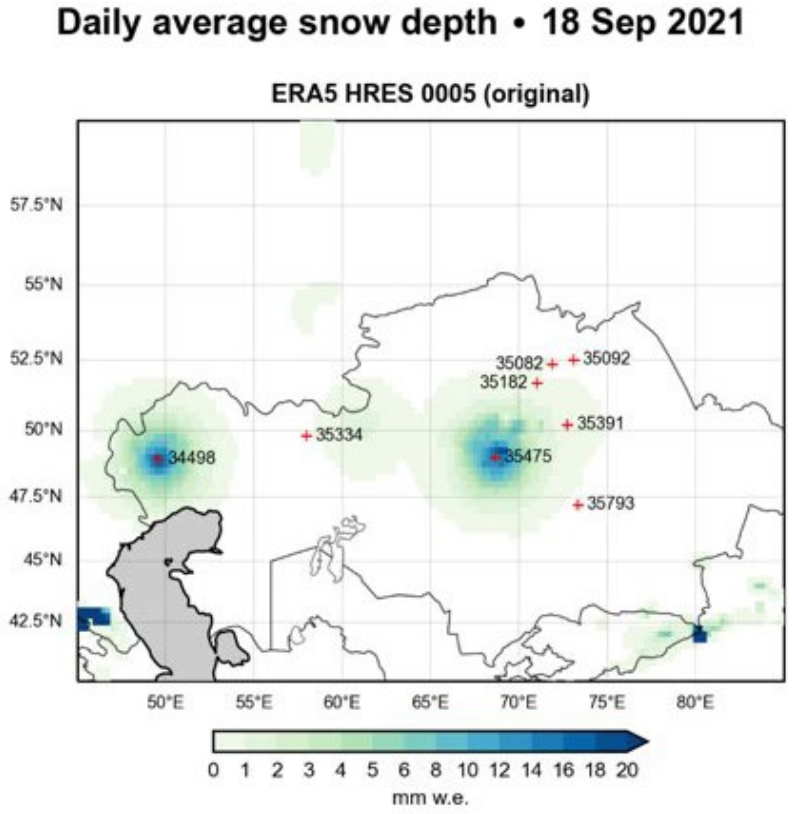
CASE STUDY: Anomalous snow depth in ERA5T

Anomalous snow depth in the *preliminary* ERA5 NRT product

<u>Hourly analysis</u> of snow depth in ERA5 inadvertently Interfered with the observation quality control

Anomalous snow depth observations were assimilated





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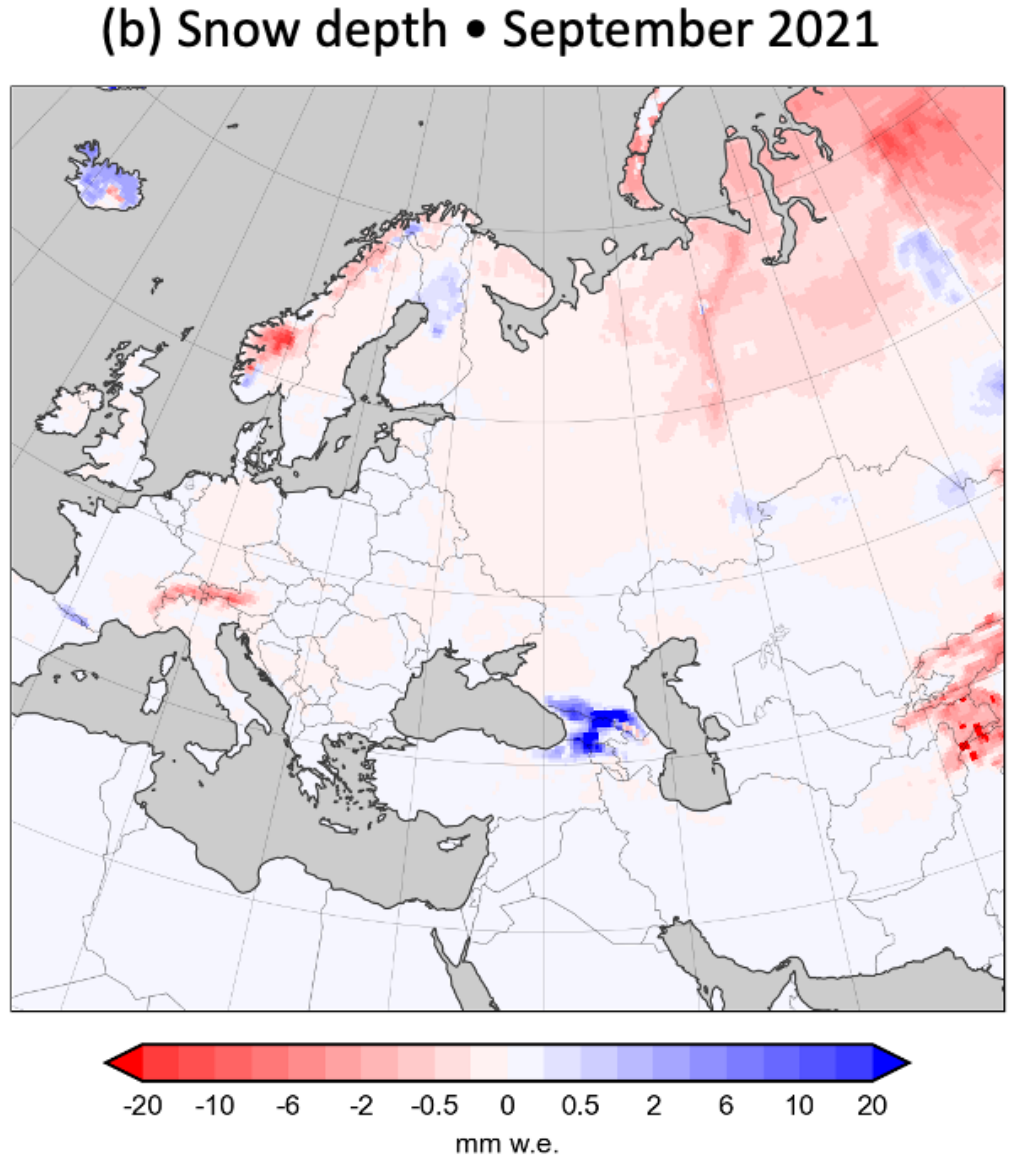
Anomalous snow depth observations were assimilated

Corrective action:
Adopt NWP Quality Control assessments, applying them to ERA5T – preventing the anomalous obs from being assimilated

Rerun and repair the affected *preliminary* released data and inform users



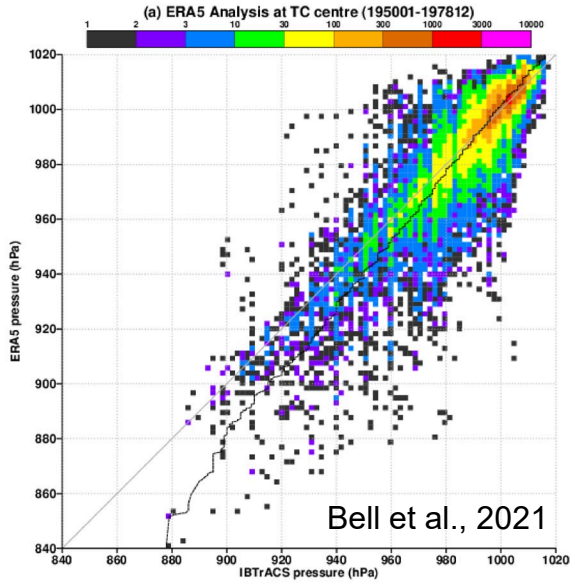
CASE STUDY: Unrealistically strong cyclones in early ERA5

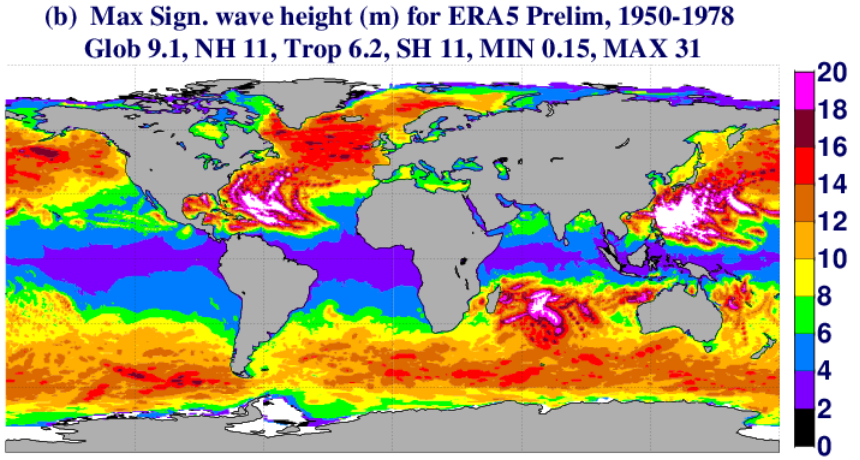
Unrealistically strong cyclones up to 840 hPa and ocean waves up to 31 metres

In the original back extension, IBTrACS observations had been given high weight

The data was well assimilated, departure statistics at obs location looked ok.

However, 4D-Var regularly moved the minimum of extreme cases away from the obs location



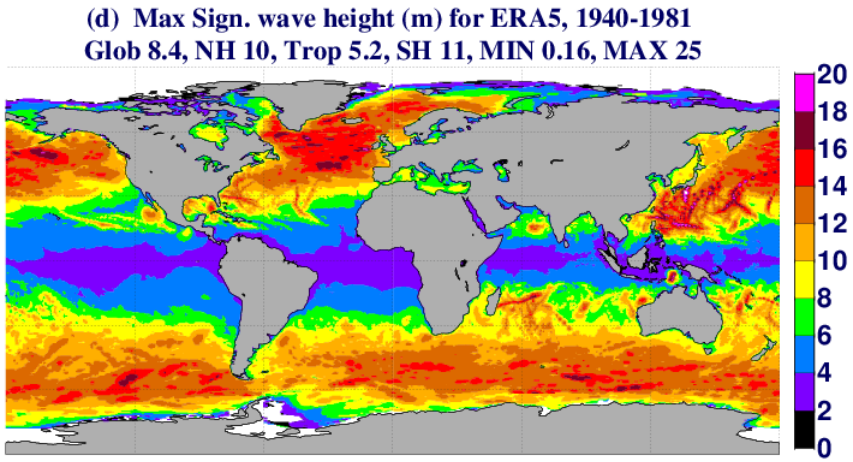


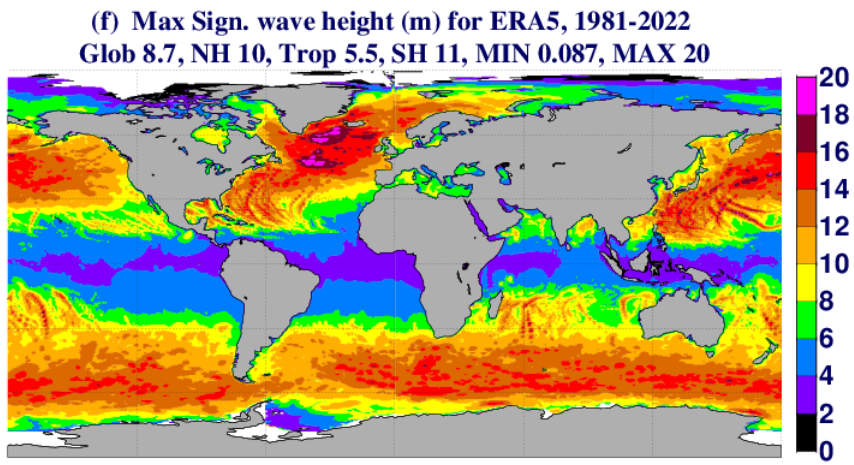
CASE STUDY: Unrealistically strong cyclones in early ERA5

RESOLVED: An improved production, now going back to 1940, resolves this

Additional, 'stricter' variational quality control (Huber norm) significantly reduces the weight assigned to IBTrACS observations, and rejects the vert lowest central pressures (< 910hPa

Extreme statistics are now more in line with 1980 onwards





Soci et al., in prep.

Ongoing maintenance in NRT

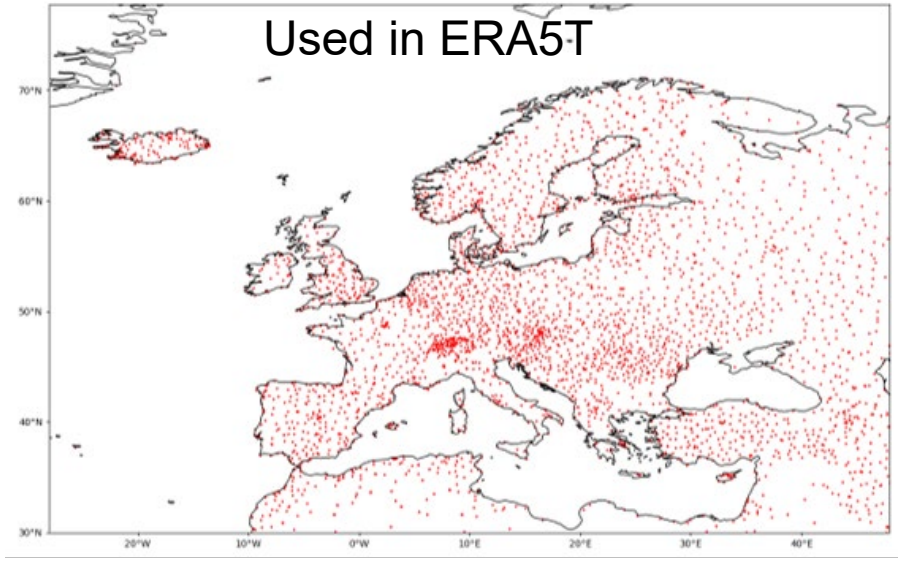
Continuous maintenance needed in Near-Real-Time

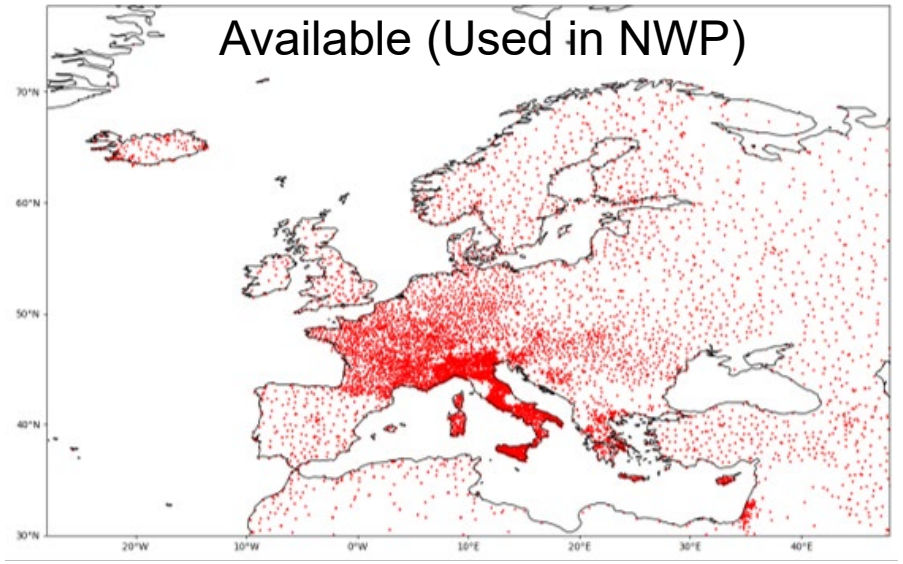
- ***Newly available (or reformatted!) observations***
- ***System- and software maintenance***

Requires close cooperation with research and operational teams

Requires dedicated testing and assessment for *each update*

T2m observations @ Feb 13, 2023





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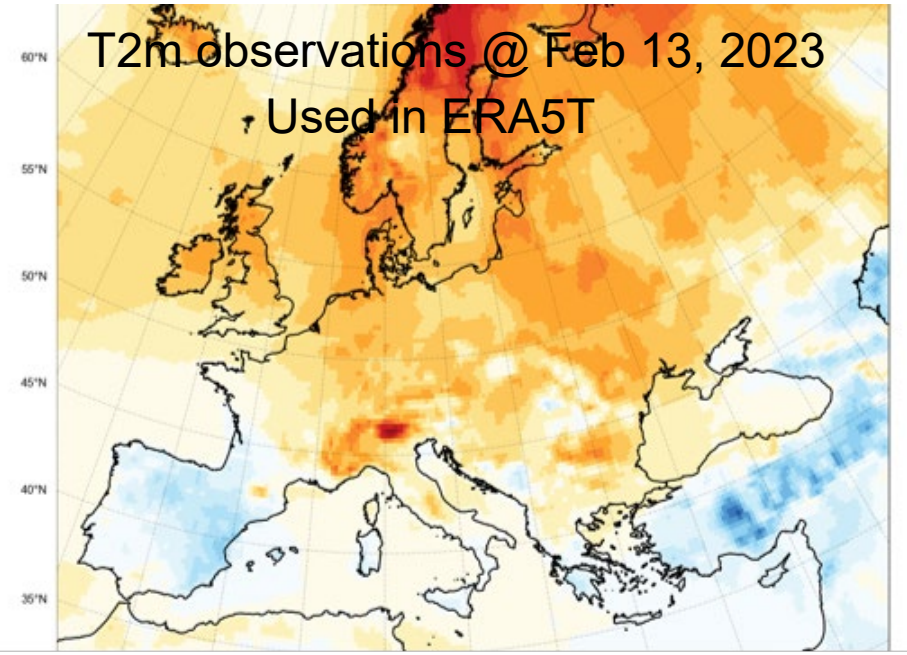

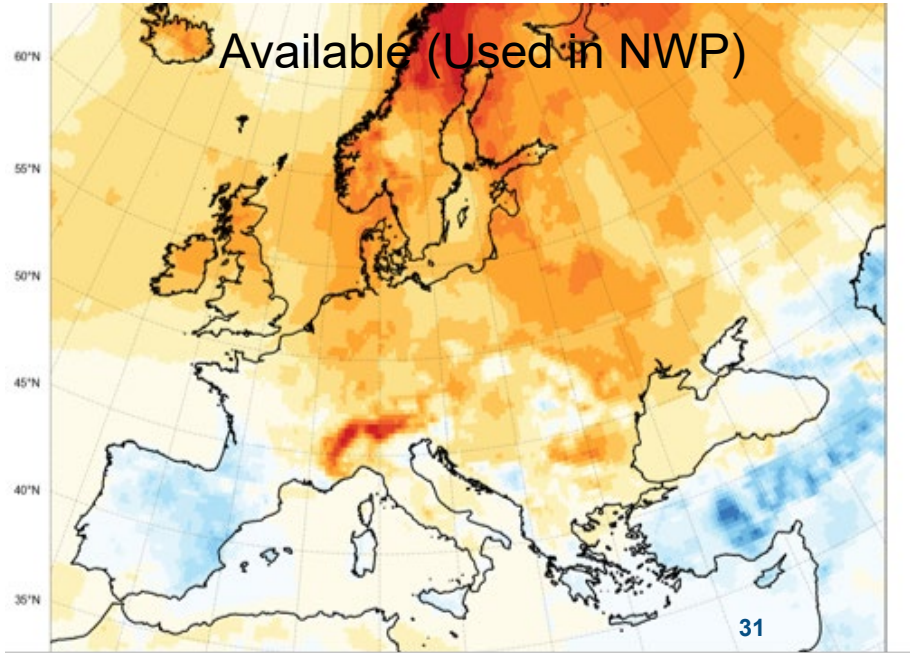

In summary (I)

Reanalysis benefits from the work of large and diverse community which take time to collect, assess and integrate

Production of a reanalysis is resource intensive and not a (yet) a routine, fire-and-forget exercise. It requires close and continuous monitoring throughout its production lifetime

Routine monitoring as implemented for ERA5 is providing good handles on the assimilation system and the mean state of the reanalysis product, it has shown weaknesses in detecting localized anomalies, even if severe.

Monitoring and QA methods applied during production of a ERA5 ultimately rely on having eyes on plots and expert judgement, and are therefore weigh heavy on available human resources

With an increased number and diversity of applications for reanalyses, product requirements are diversifying. This spawns the need for monitoring and QA at production-time to adapt.

To reflect upon

Based on what we've seen, can we confidently, positively answer the following questions

Are we monitoring the right things?

- **long term trends vs.(?) localized, rare problems**
- **move towards more complex, coupled reanalysis systems**

Are we monitoring enough? Can we monitor enough? Do we want to?

- **(human) resources, experience, expert knowledge**
- **Growing breadth of applications**

Are we monitoring in the right way? Leveraging the right tools?

- **Can a machine (learning application) assist?**