ECMWF reanalysis activities: from research to operations

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and many others inside and outside ECMWF!

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Overview

- **Towards operational reanalysis**
- The ERA5 reanalysis
  - Data assimilation system
  - Observations
  - Gridded observations
- How accurate is ERA5?
- Towards Earth system reanalysis; ERA6 and beyond
- Summary

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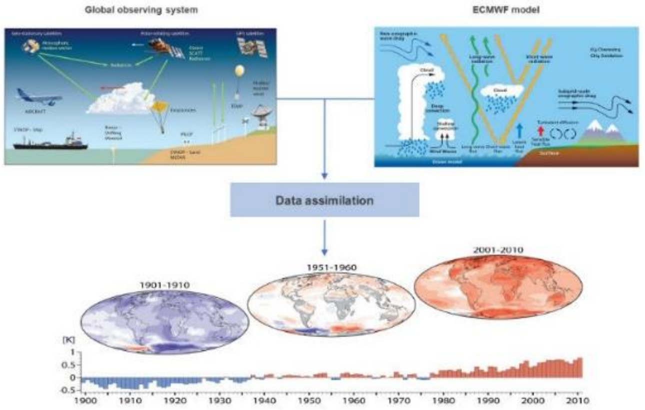
Reanalysis

Reconstruction of the past weather & climate:

- ✓ **Input:** integrator of all available ‘sub-daily’ observations and gridded observations prepared as boundary or forcing
- ✓ Deal with inhomogeneities, relative biases, data formats, range of observables
- ✓ **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



Started as a research activity, but progressively entered into the area of operations

- ✓ ORAS2 and onwards ocean reanalysis for seasonal forecasting;
  ORAS5 ocean initial conditions to NWP after catching up in NRT
- ✓ ERA-Interim in the last few years of its production
- ✓ Production of ERA5 from the start

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Towards operational reanalysis

Make use of mature science and methodologies:

- ✓ based on latest IFS cycle that went through the full process from research to operations
  - NWP and Reanalysis R&D go progressively hand in hand with a common goal
- ✓ reanalysis-specific developments to optimize the quality for the entire reanalysis period
  - In main IFS cycle but under reanalysis switch, to flow forward into future cycles

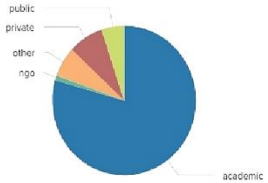
Quality assurance during production: see presentation by Dinand Schepers

- ✓ Close monitoring of latest products in both observation and model space
- ✓ Address flagged issues where possible before release:
  - Depends on: level of understanding, available solution, timing, consistency of products
  - Leave time for correction: ERA5T vs final product
  - Document unsolved known issues

Enhanced products:

- ✓ Based on user requirements
- ✓ Hourly output, extended list of variables and levels, uncertainty estimate
- ✓ provide easy and convenient access (e.g., via the Climate Data Store), especially for non-experts

ERA5 users



Maintain close to real time:

- ✓ Conducted by the Forecast Department to provide a level of guarantee for availability of daily updates

Online documentation and (expert) user support

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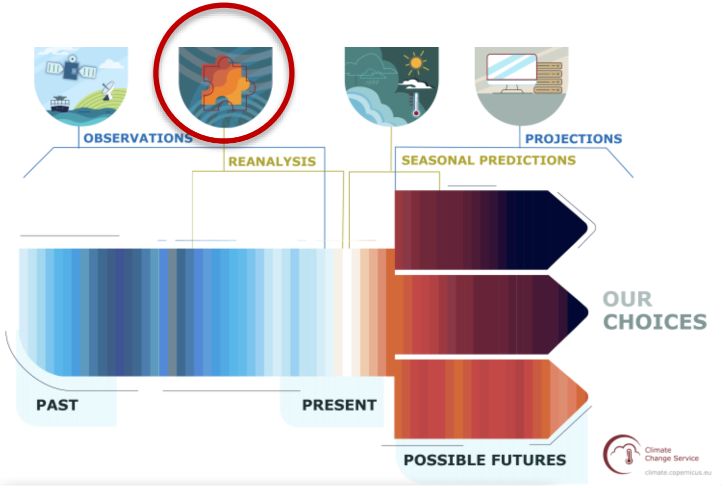


The ERA5 global reanalysis

ERA5: *A full-observing-system global reanalysis for the atmosphere, land surface and ocean waves*

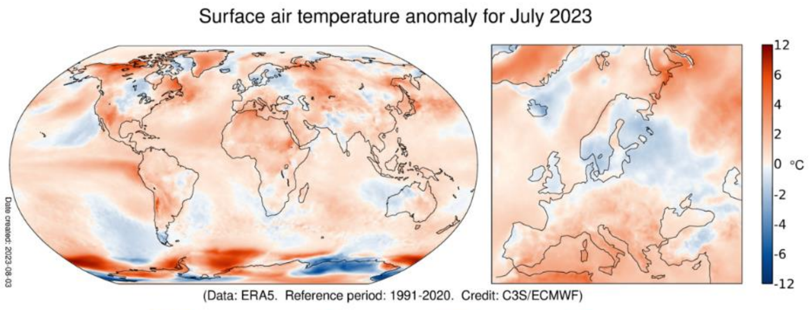
- Produced at ECMWF, by the **Copernicus Climate Change Service**
- **Served via the C3S Climate Data Store**
- 127,000 users to date, ~100 Tbyte of downloads per day

- Daily updates **5 days behind real time from 1940 onwards**

- **Hourly snapshots** at **31km resolution** up to about 80km height
- **Uncertainty estimate** from a 10-member ensemble at half resolution

- **ERA5-Land**: Dynamically downscaled land product at **9km** from 1950.

- Total dataset about 12 petabyte



Observation usage:

- Over 100 billion so far
- Many sources (in-situ, satellite) and observables

And usage of external (gridded) products 'as is':

- SST and sea-ice cover
- GHGs, aerosols, TSI, (diagnostic) ozone

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ERA5 CDS catalogue entries; pressure + single levels; hourly and monthly aggregates

ERA5 hourly data on pressure levels from 1940 to present

Overview | Download data | Quality assessment | Documentation

Clear all

Product type

- [x] Reanalysis
- [ ] Ensemble members
- [ ] Ensemble mean
- [ ] Ensemble spread

Select all Clear all

Variable

At least one selection must be made

- [ ] Divergence
- [ ] Geopotential
- [ ] Potential vorticity
- [ ] Specific cloud ice water content
- [ ] Specific humidity
- [ ] Specific snow water content
- [ ] U-component of wind
- [ ] Vertical velocity
- [ ] Fraction of cloud cover
- [ ] Ozone mass mixing ratio
- [ ] Relative humidity
- [ ] Specific cloud liquid water content
- [ ] Specific rain water content
- [ ] Temperature
- [ ] V-component of wind
- [ ] Vorticity (relative)

Select all

Pressure level

At least one selection must be made

1 hPa	2 hPa	3 hPa	5 hPa
7 hPa	10 hPa	20 hPa	30 hPa
50 hPa	70 hPa	100 hPa	125 hPa
150 hPa	175 hPa	200 hPa	225 hPa
250 hPa	300 hPa	350 hPa	400 hPa
450 hPa	500 hPa	550 hPa	600 hPa
650 hPa	700 hPa	750 hPa	775 hPa
800 hPa	825 hPa	850 hPa	875 hPa
900 hPa	925 hPa	950 hPa	975 hPa
1000 hPa			

Select all

Year

At least one selection must be made

1940	1941	1942	1943	1944	1945
1946	1947	1948	1949	1950	1951
1952	1953	1954	1955	1956	1957

Help

Get help

Licence

Licence to use Copernicus Products

Publication date

2018-06-14

Resource updated

2023-08-22

References

Citation

Acknowledgement

DOI: 10.24381/cds.bd0915c6

Related data

Complete ERA5 global atmospheric reanalysis

ERA5 hourly data on pressure levels from 1950 to 1978 (preliminary version)(deprecated 2023-08-15)

ERA5 hourly data on single levels from 1940 to present

ERA5 hourly data on single levels from 1950 to 1978 (preliminary version)(deprecated 2023-08-15)

ERA5 monthly averaged data on pressure levels from 1940 to present

ERA5 monthly averaged data on pressure levels from 1950 to 1978 (preliminary version)(deprecated 2023-08-15)

ERA5 monthly averaged data on single levels from 1940 to present

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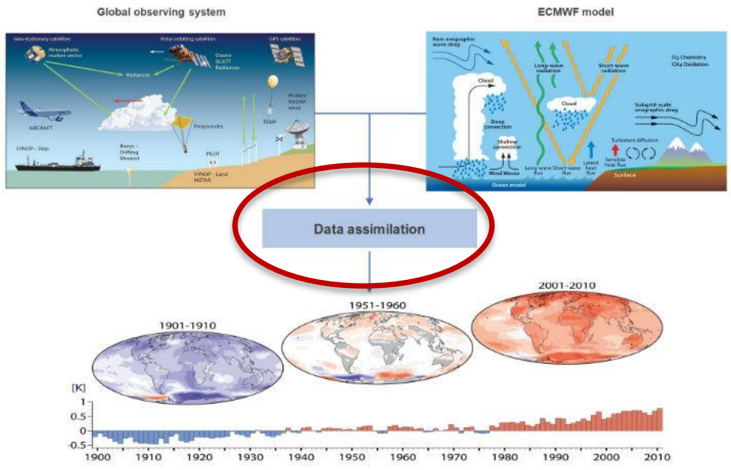

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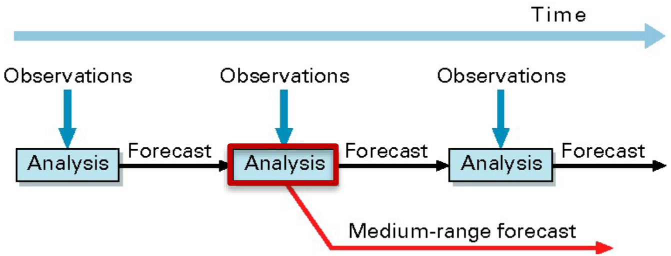
The ERA5 DA system and how does it differ from NWP?

It is good practice to base an operational reanalysis on a recent NWP system

✓ E.g., at ECMWF, ERA5 (2016) is based on Cy41r2



Differences:

✓ In principle the focus is on the quality of the analysis, not the forecast

❖ The NWP system is well-tuned for the recent data-rich era
Ensure that it also works well for the data-sparser past, e.g.:

- Data rescue and reprocessing of observations
- Appropriate:
    - Forcing fields
    - Background errors
    - Observation errors
    - Quality control
- Be aware of systematic model and observation errors

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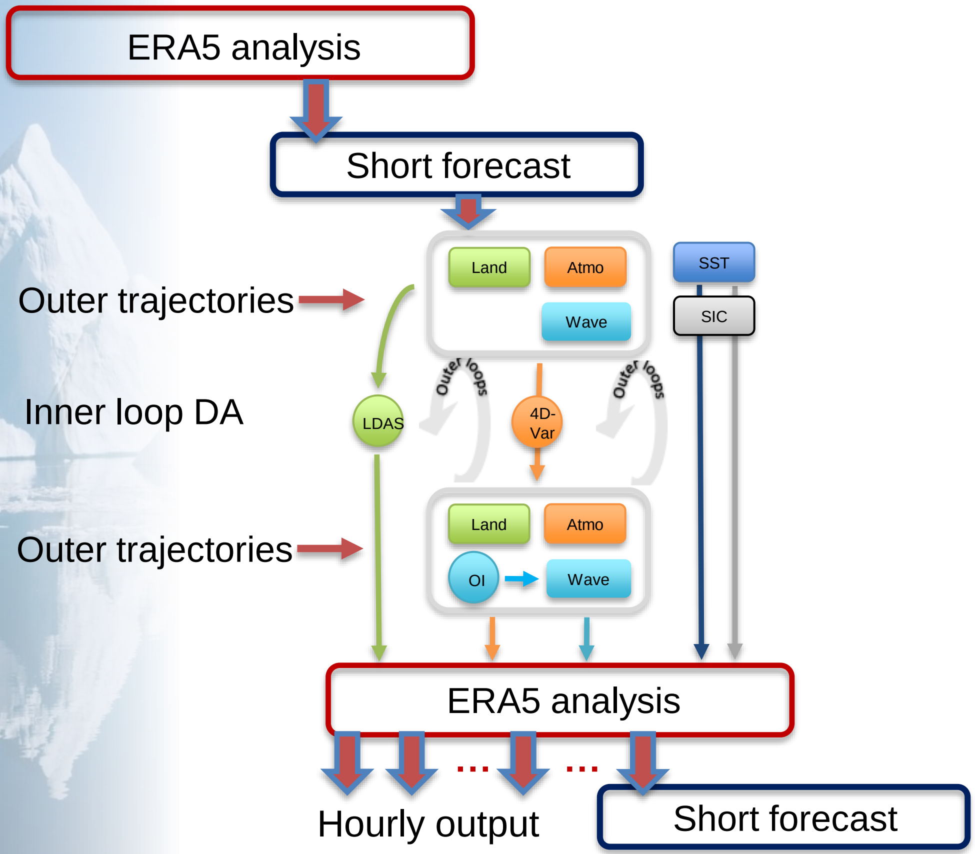
The ERA5 assimilation system for atmosphere, land and ocean waves



Incremental 4D-Var for atmosphere:

- Upper-air variables plus a number of surface parameters
- Assimilation window is 12 hours, but time evolution of 4D-Var allows for hourly output within the window (ERA-Interim was 6-hourly)
- three outer loops for ERA5 (2 for the EDA component)

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)
- has a simple ‘analysis’ step to match the ERA5 land sea mask and some internal consistency checks

Note that:

- A number of parameters are taken from the short forecasts
- e.g., precipitation, accumulations, energy budgets, surface + 3D

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

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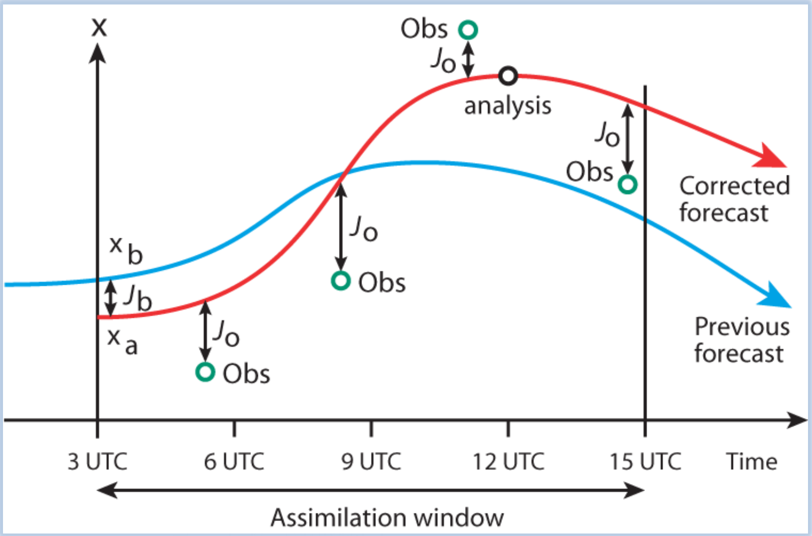
background constraint (J_b) observational constraint (J_o)

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

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



Recipe:

- Start with a first guess $\mathbf{x_b}$, $\boldsymbol{\beta}_\mathbf{b}$ from the previous analysis
- Compare with observations **y** via observation operator **h**
- Calculate the misfit: the cost **J**
- Change the first guess such that the fit is optimal
- Solve in an incremental way

Result depends on:

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

Result:

- The reanalysis $\mathbf{x_a}$, $\boldsymbol{\beta}_\mathbf{a}$
- Also, to provide first guess for next analysis

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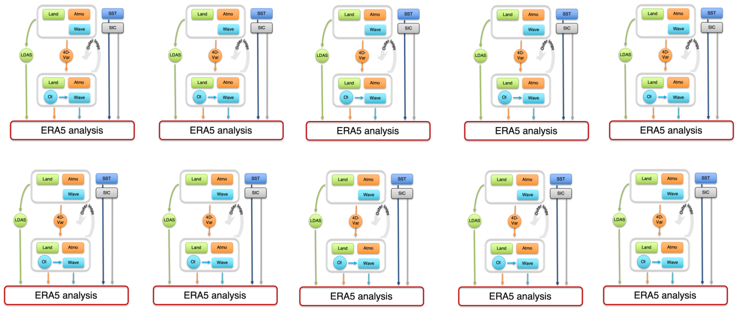
The ERA5 Ensemble of Data Assimilations (EDA)

10 DA systems at half resolution. Per member:

- Perturb observations (including SST and sea ice)
- Perturb model in short forecasts linking analyses

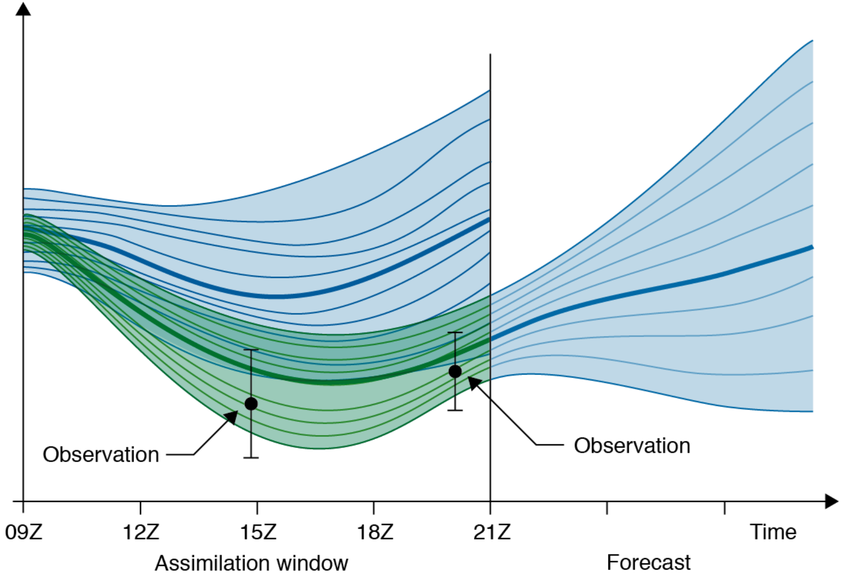


From this we estimate:

- a flow-dependent **B** matrix
- the quality of the synoptic situation

Less observations and/or high model sensitivity leads to less confident estimate of **B**

Bonavita *et al.*, 2016



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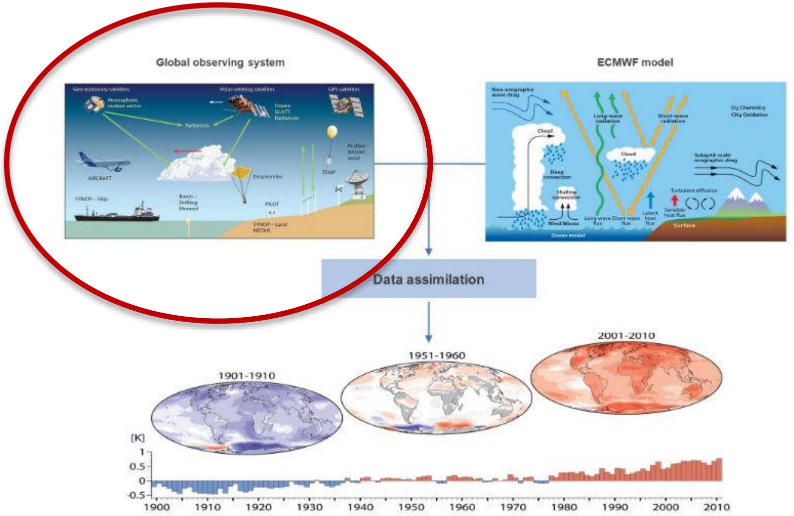

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The ERA5 observing system

Over 200 types of satellite instruments and types of in-situ reports

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

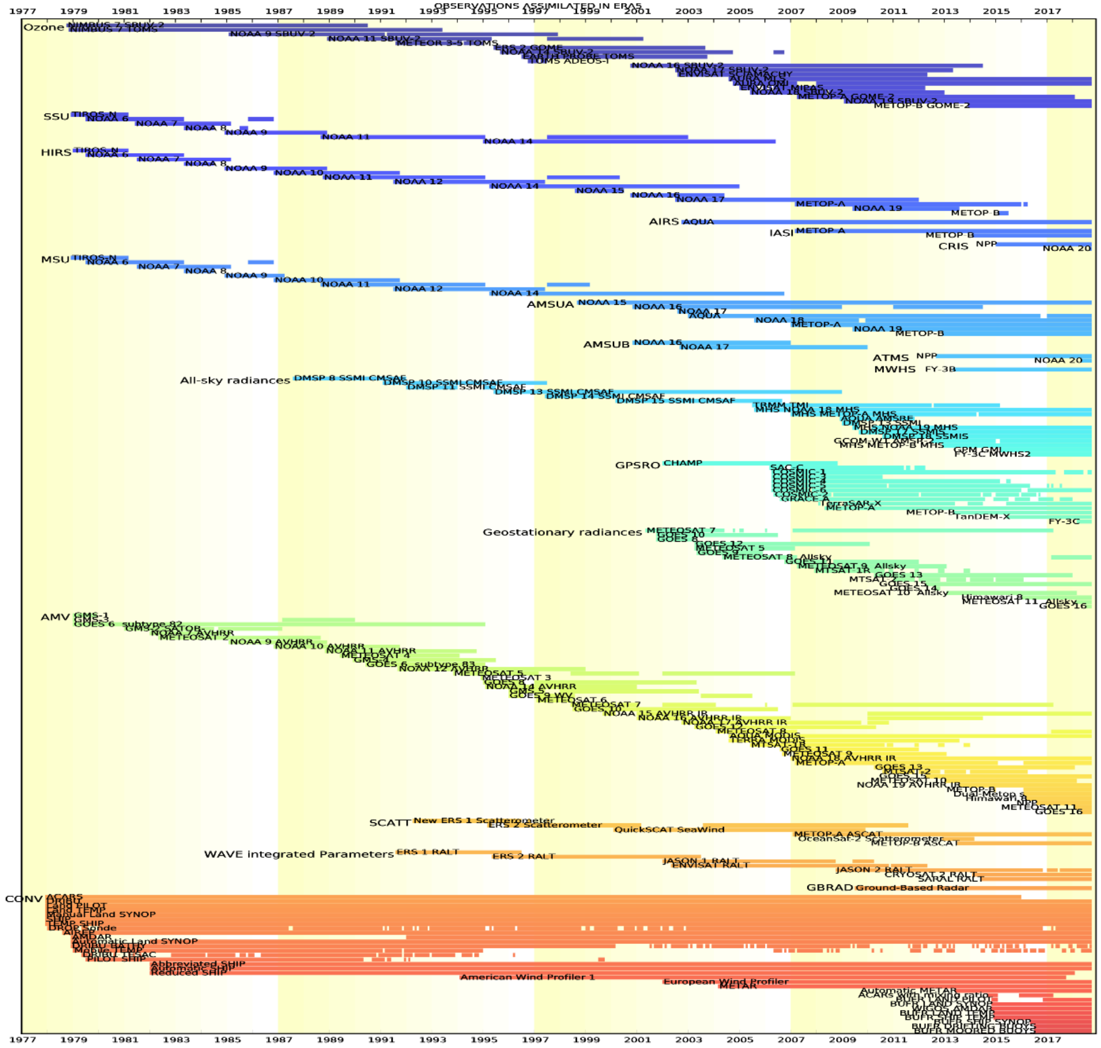
Scatterometer: ocean wind + land soil moisture
Altimeter wave height

Ozone level 2 retrievals + level 1B

Snow cover (IMS)

Conventional observations

Surface: Land stations, buoys, ships
Upper-air: Balloons, dropsondes, aircraft, profilers



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The evolving observing system

Impact: see presentation by Tony McNally

Data sources:

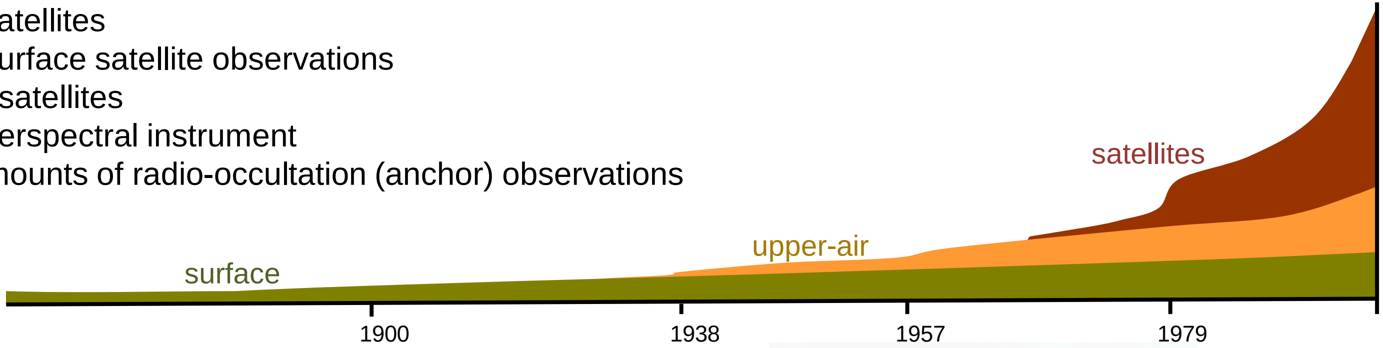
- satellites
- surface observations
- upper air (‘anchor’ observations)

In the ERA5 reanalysis we daily use about:

- **17,000** obs in 1940, **25 Million** in 2022

There have been boosts in the observing system:

- Mid 1940s: start of upper-air observations
- 1957-1958: International Geophysical Year
- Mid 1970s: early satellites, e.g., VTPR
- 1979: TOVS satellites
- 1991: ocean surface satellite observations
- 1998: ATOVS satellites
- 2002: first hyperspectral instrument
- 2006: large amounts of radio-occultation (anchor) observations



Evolution of the ERA5 background error covariance matrix

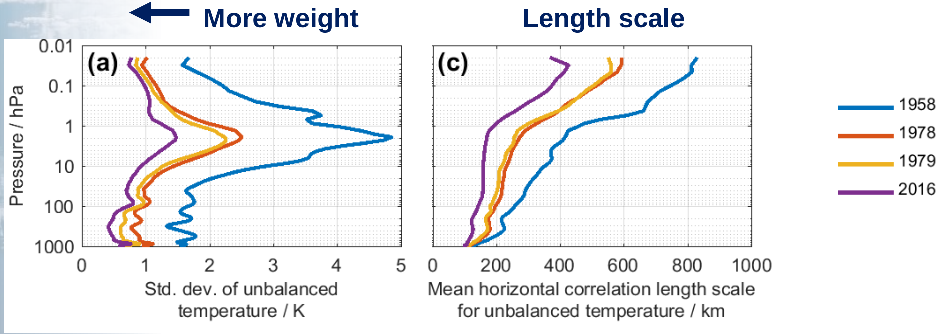
B has a climatological and error-of-the-day part:

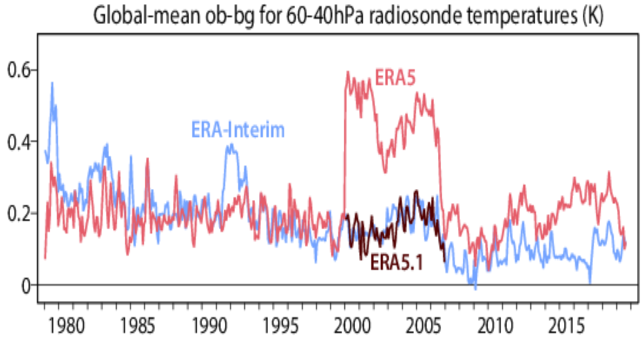
$$B(t) = (1-\alpha)B_{cli} + \alpha B_{EDA}(t)$$

Obs. system as a whole

'Error of the day'

For ERA5 $\mathbf{B_{cli}}$ needed retuning at large changes in the observing system





Choice needed extra care between 2000-2006

2000: ATOVS satellites →

- 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 → ERA5.1: use of pre-ATOVS Bcli until 2006

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Observation-based (gridded) forcing and boundary conditions

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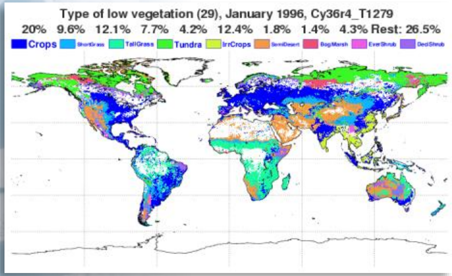
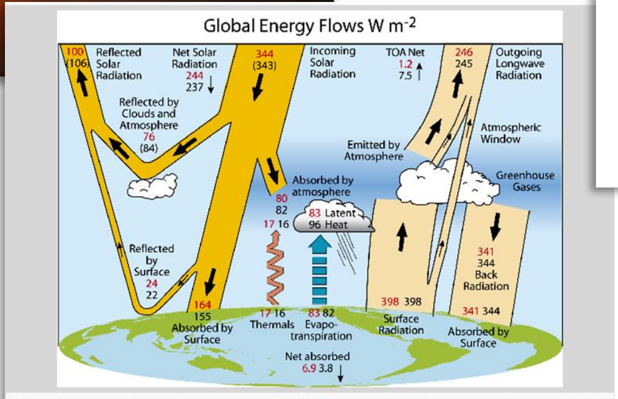
mostly based on CMIP5-recommended datasets that reflect the 20th and 21th century evolution

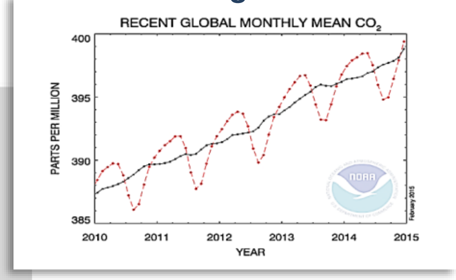
Solar forcing



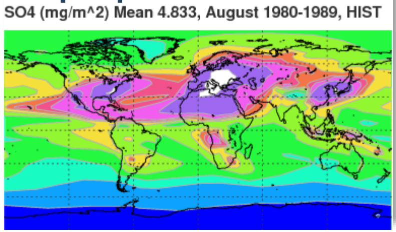


Energy flow in ERA-Interim (red) and ERA-40 (black), Berrisford et. al. 2011; figure adapted from Trenberth et.al., 2009

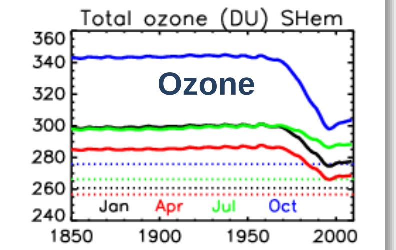
Greenhouse gases



Tropospheric Aerosols

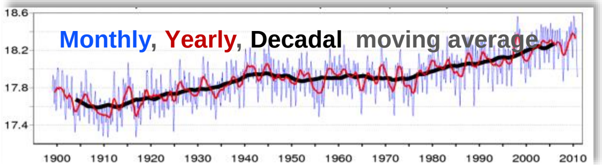


Volcanic eruptions



AC&C SPARC ozone

SST and sea ice



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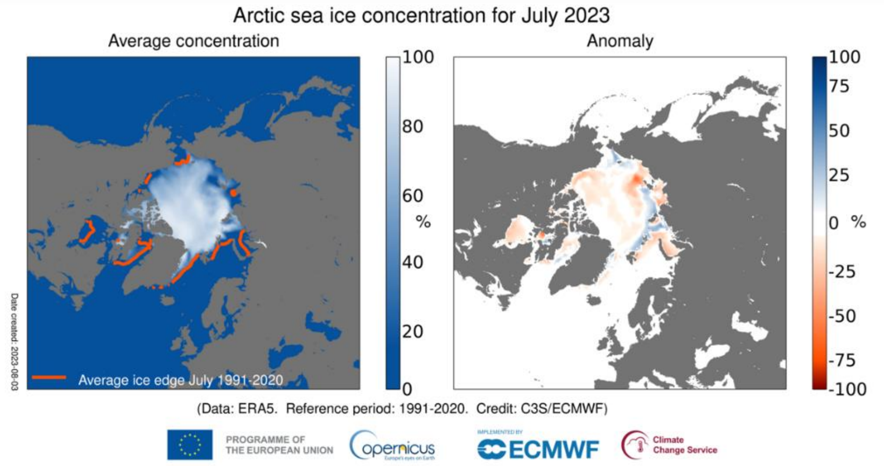
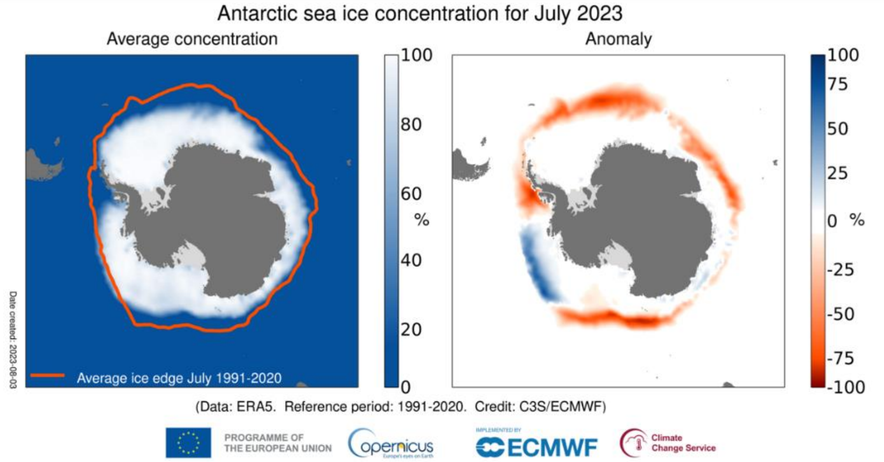
Need for temporally consistent datasets





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Accounting for volcanic aerosols: model and observations work together

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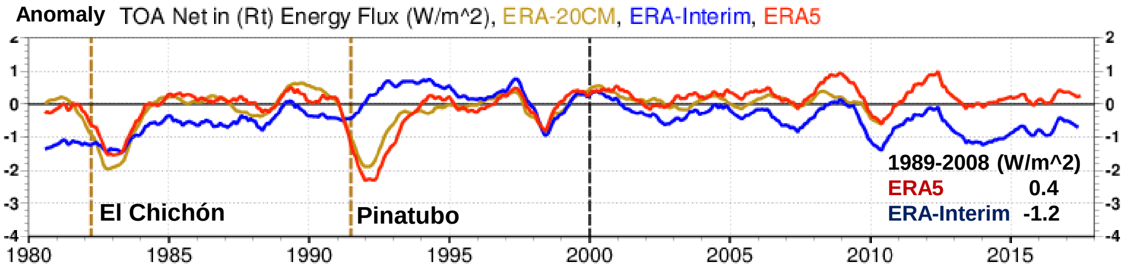
CMIP5 recommended data set

Based on Sato et al, 2010

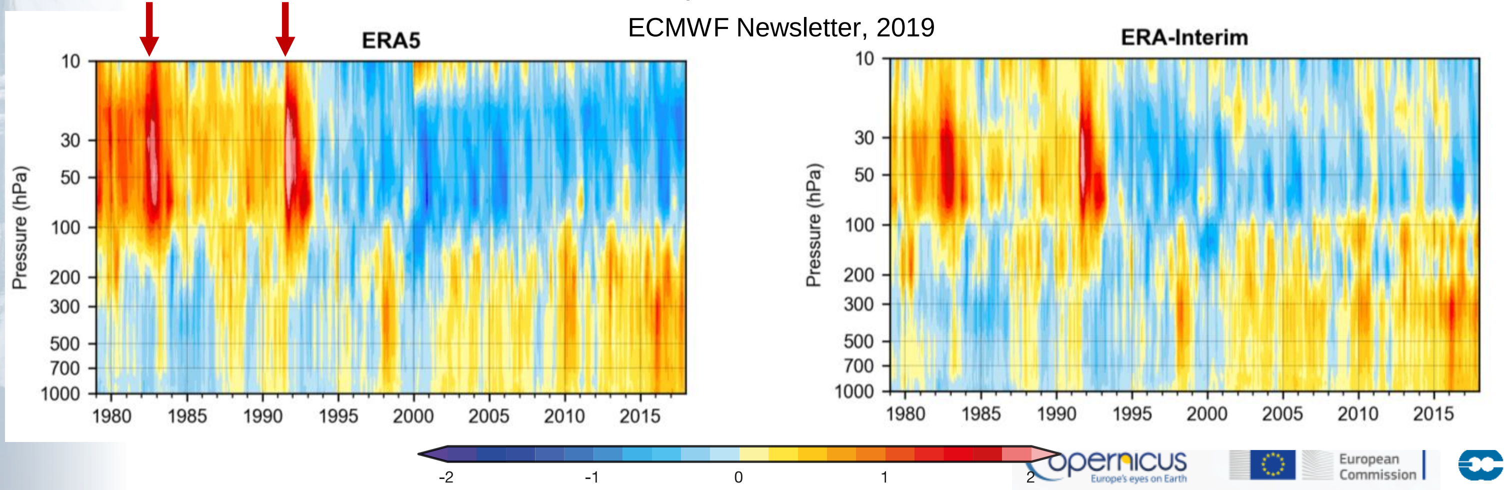
Monthly zonal-mean optical depth

Zero from 2010 onwards



Global mean temperature relative to 1981-2010

ECMWF Newsletter, 2019



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ERA5: hourly resolution from 1940 operational close to real time

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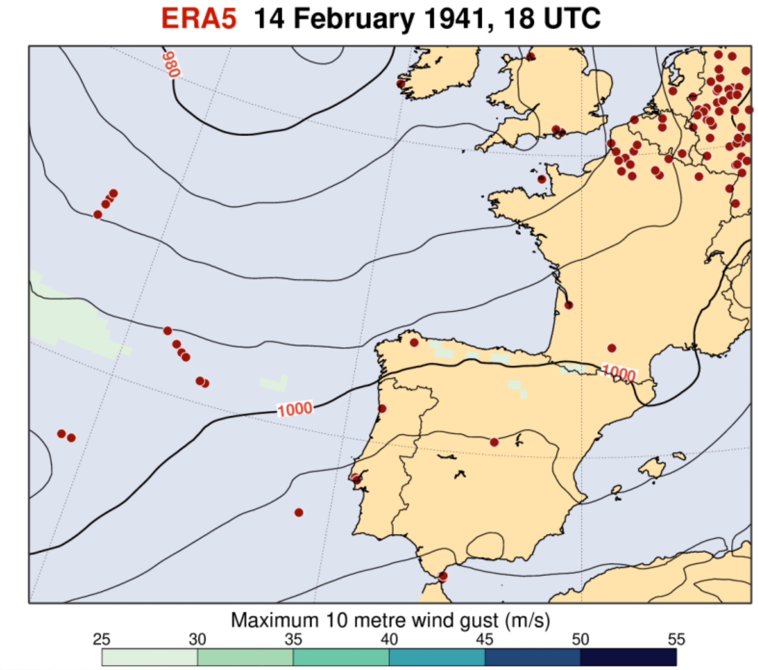
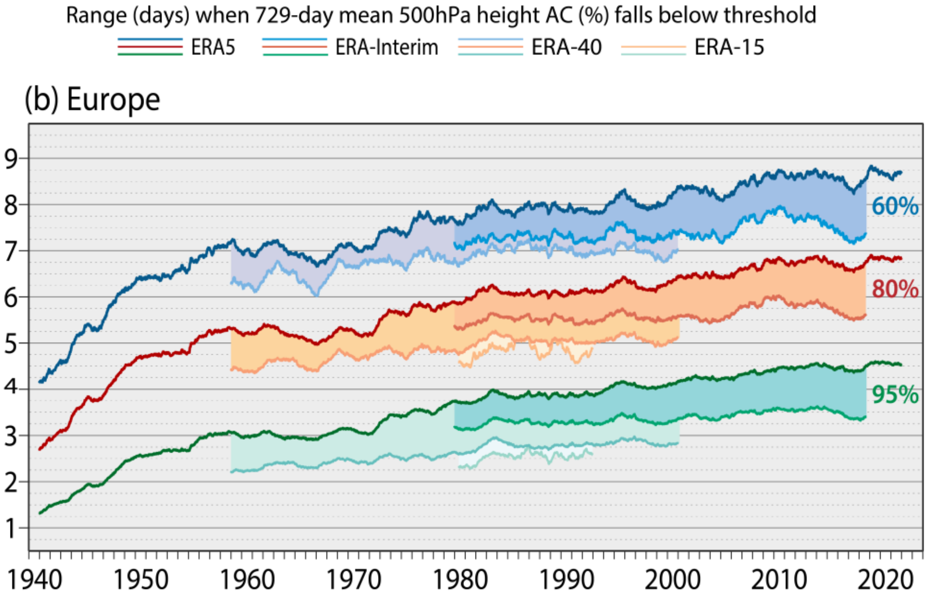


Iberian storm case of 1941



Skill of 10-day forecasts initialized from ERA against ERA at verification time

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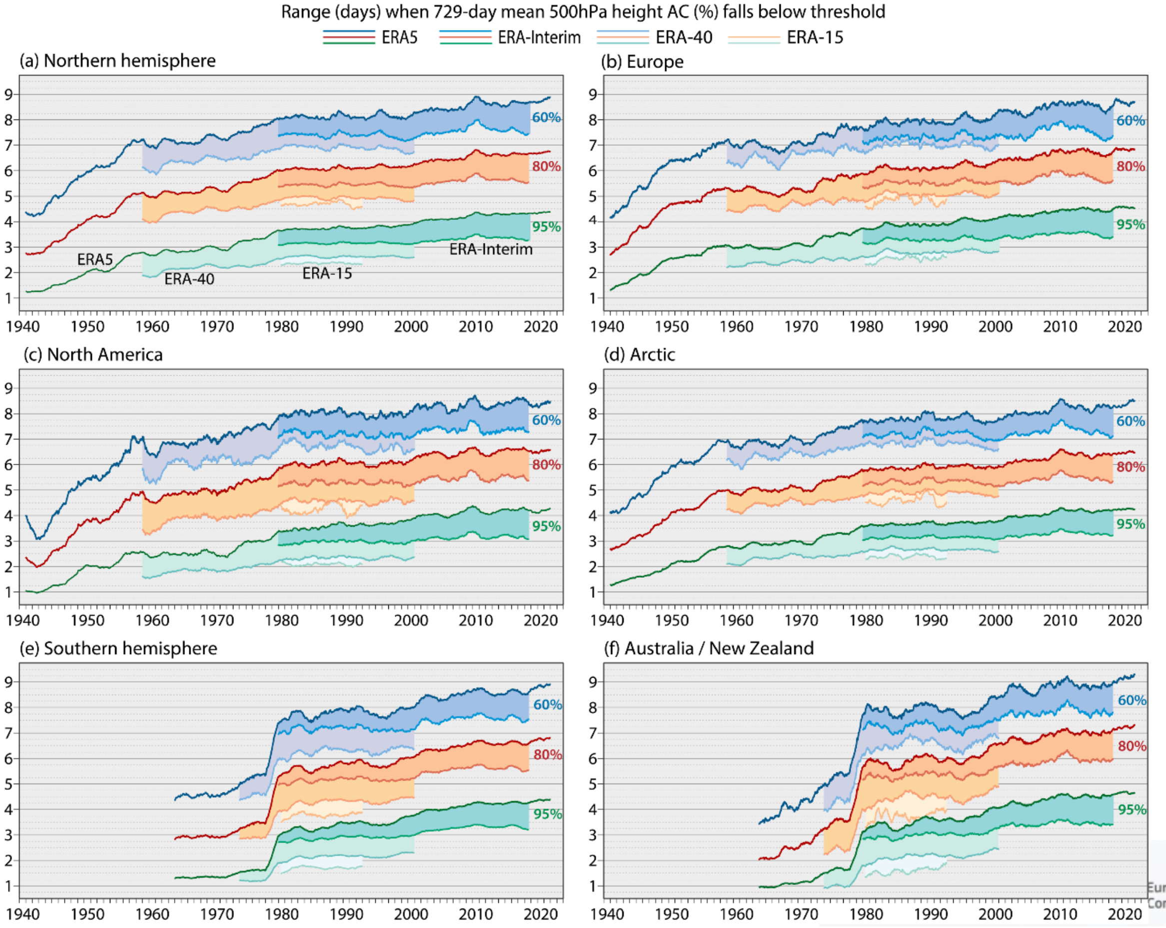
Skill of forecasts from ERA5 over several areas



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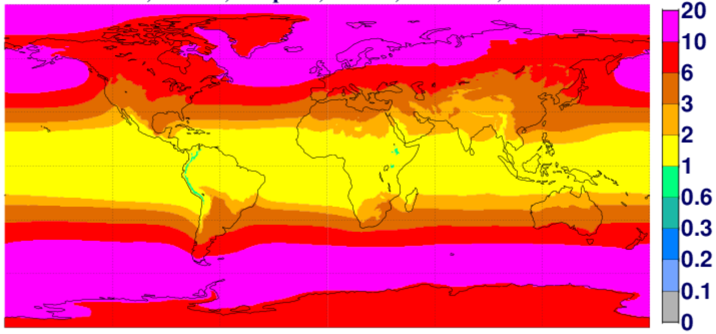
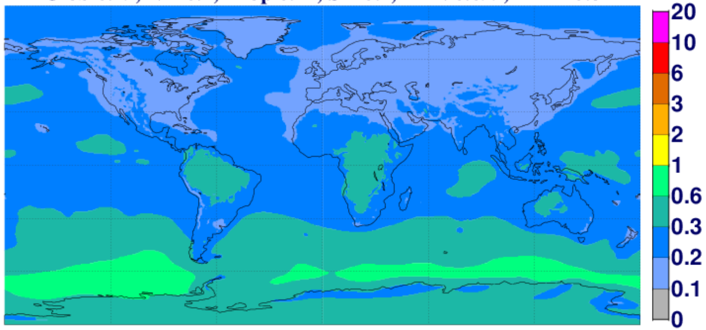
ERA5 synoptic accuracy versus climatology; the value of ensemble spread

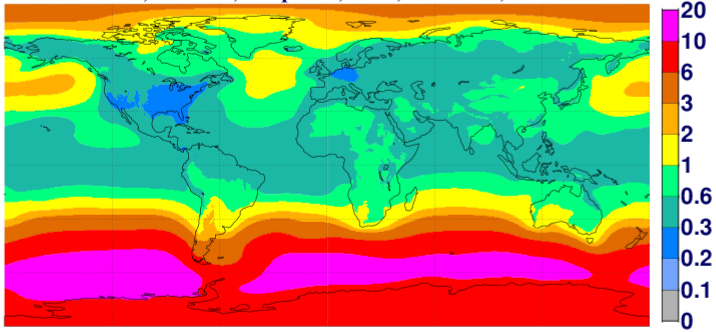
(a) ERA5 Variability for Surface Pressure (hPa), 1940-2022
Glob 5.5, NH 6.8, Trop 1.5, SH 8.2, MIN 0.75, MAX 15



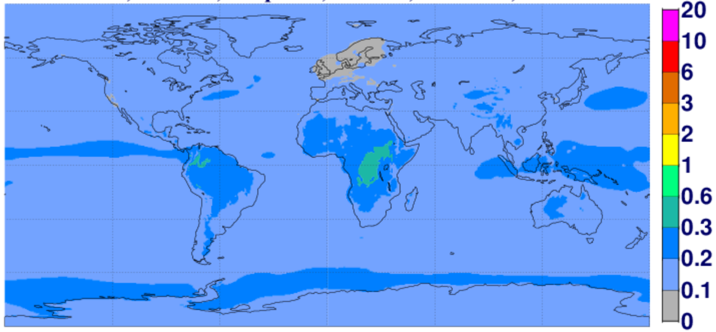
(g) ERA5 Ensemble Spread for Surface Pressure (hPa), 1980-1989
Glob 0.29, NH 0.2, Trop 0.27, SH 0.4, MIN 0.099, MAX 0.8



(c) ERA5 Ensemble Spread for Surface Pressure (hPa), 1940-1949
Glob 2.5, NH 0.81, Trop 0.59, SH 6, MIN 0.21, MAX 13



(i) ERA5 Ensemble Spread for Surface Pressure (hPa), 2013-2022
Glob 0.17, NH 0.15, Trop 0.19, SH 0.17, MIN 0.08, MAX 0.35



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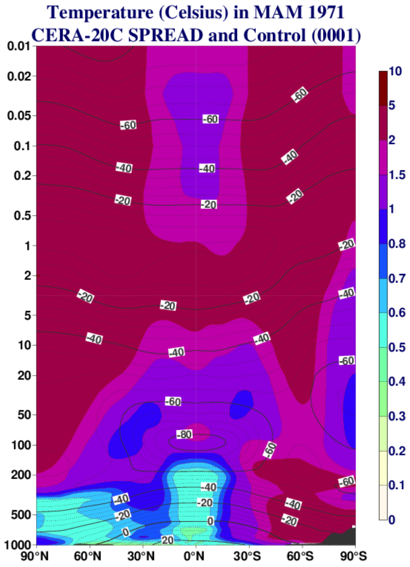
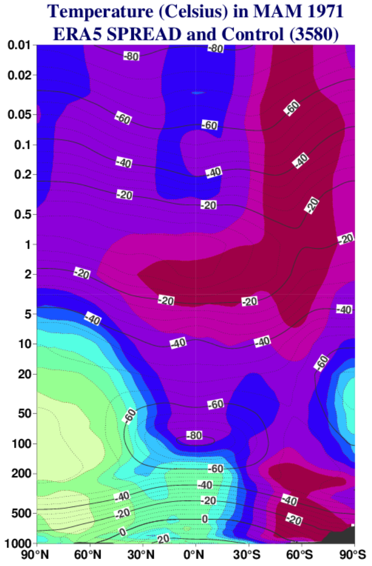
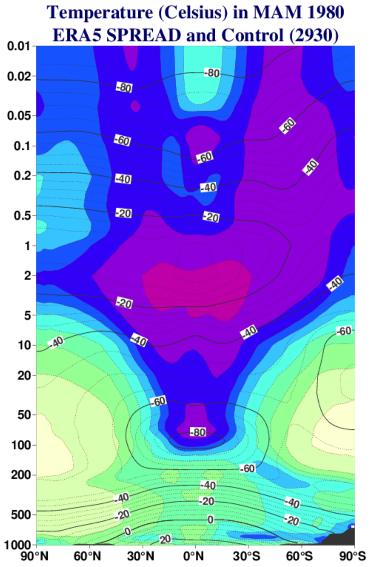
The evolution of ensemble spread; also proxy for synoptic uncertainty



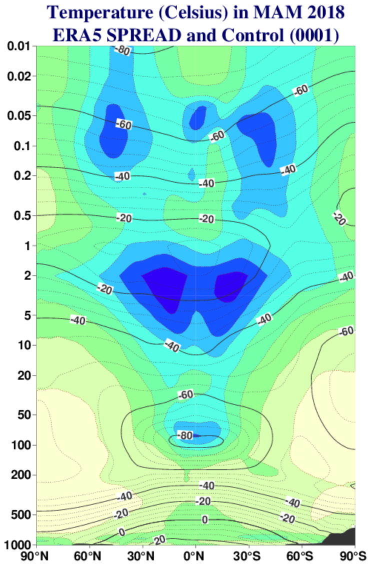
1971 CERA-20C:
Surface pressure, marine wind, only



1971 ERA5:
Upper-air data



1980 ERA5:
Early-satellite era



2018 ERA5:
Recent observing system

ECMWF Newsletter, 2019

Stratospheric Sudden Warming, February 1952

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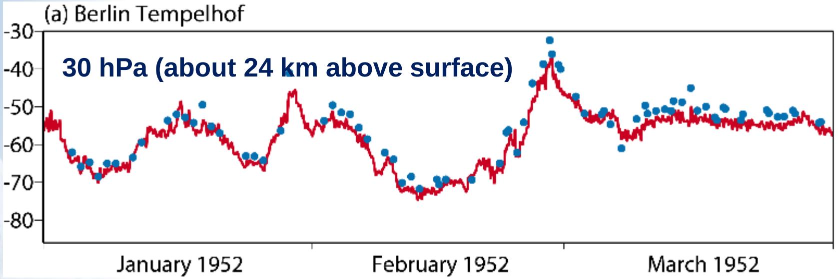
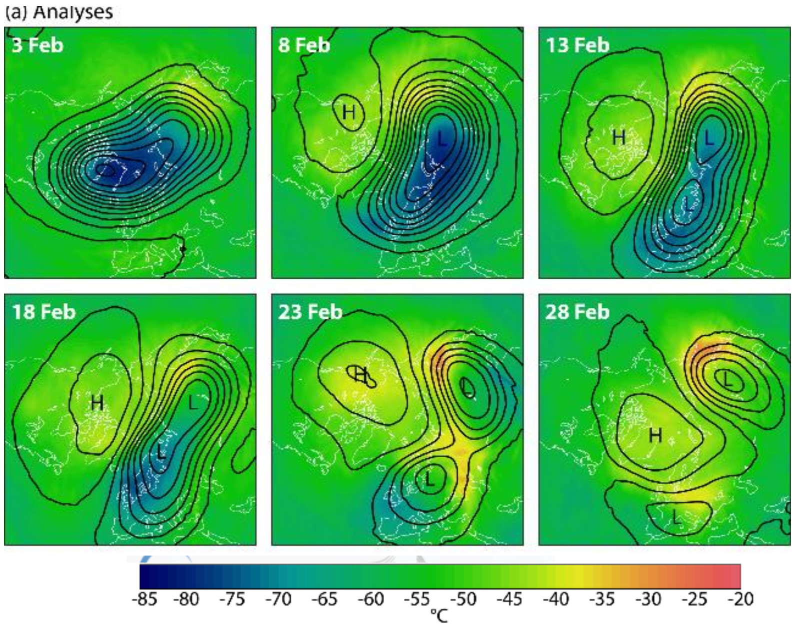
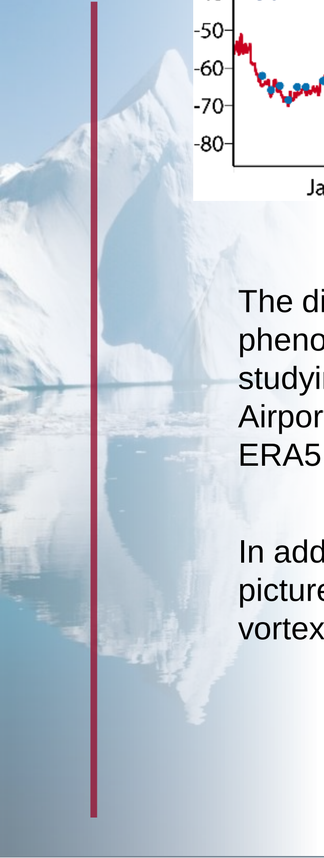


Bell et. al., 2021



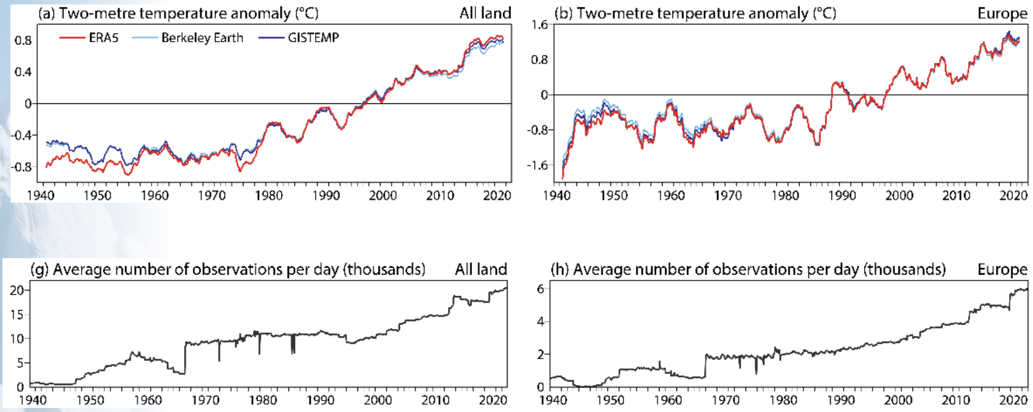
The discovery of the stratospheric sudden warming phenomenon, was made by Scherhag (1952) by studying radiosonde ascents from Tempelhof Airport, Berlin, many of which were assimilated by ERA5.

In addition, ERA5 shows the full three-dimensional picture of the related split of the stratospheric polar vortex.



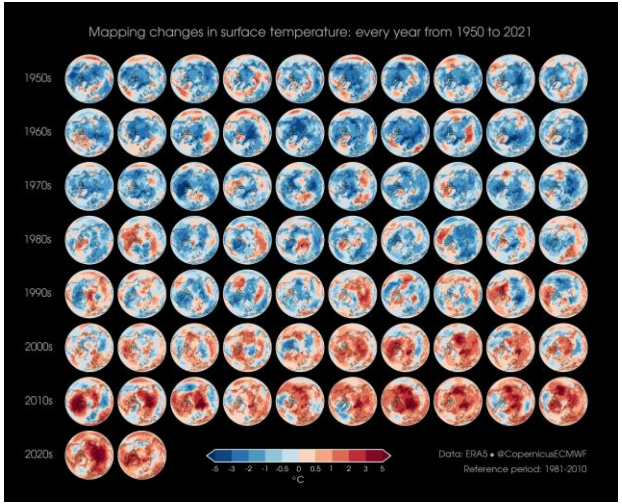
Climate Change

Climate change: evolution of 2m temperature and comparison with other datasets



Temperature trends:

- The global mean temperature shows little trend from 1940 to the mid 1970s.
- After that global warming becomes clearly visible and concerning



Courtesy: Ed Hawkins

Consistency between datasets:

reanalyses and more direct observation-based datasets:

- In general, quite good and reassuring
- However, there are some small discrepancies in certain periods and certain areas

See the presentation by Adrian Simmons for more details on inter-comparison

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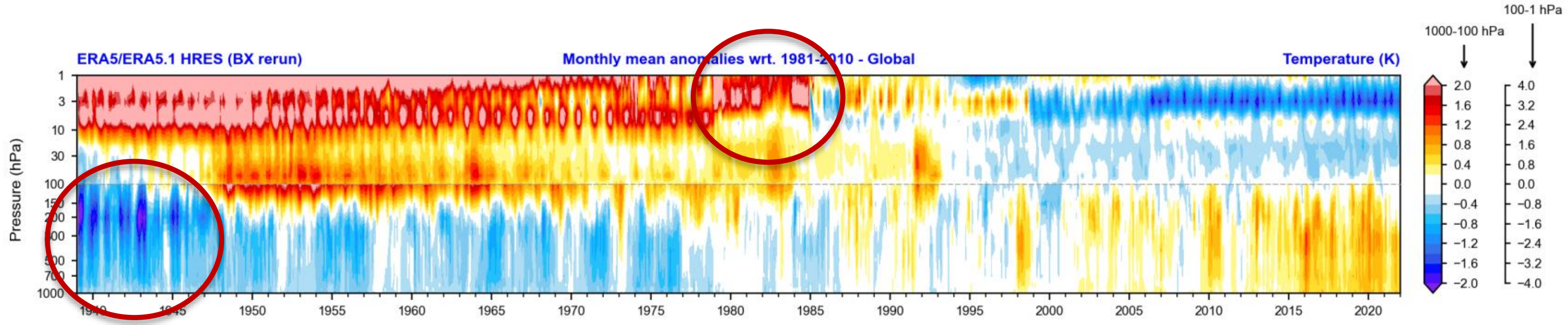
European Commission
ECMWF

Climate Change

Upper-air climate trends in ERA5



25ºN – 25ºS, Temperature trends 1980-2018

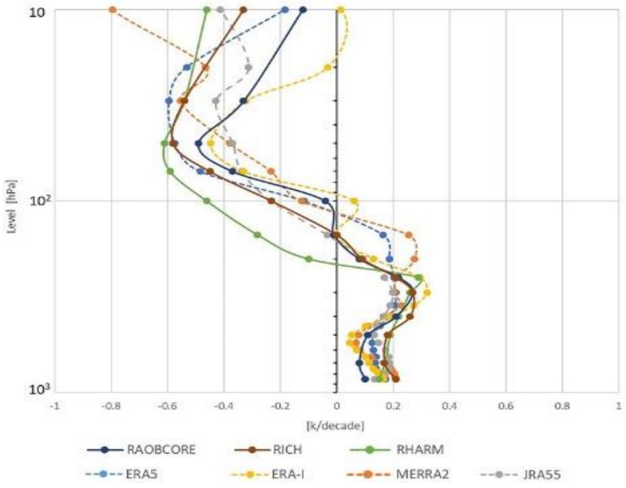


Fig. 9 from Essa et al., 2022, Front. Earth Sci.
doi:10.3389/feart.2022.935139

- Reanalyses increasingly credible for climate trend analysis

  (*e.g.*, for surface parameters, see Simmons, Weather Clim. Dynam, 2022)

- More challenging in stratosphere, particularly upper stratosphere
- ERA5: downwards from 10 hPa temperature looks OK in general, except for the early 1940s due to the lack of radiosondes

- Trend analyses usually don't take into account (time-varying) systematic biases in the mean state
  (as the relevant uncertainty components are generally not estimated)

Details in the presentation by Bill Bell

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Overview

- Towards operational reanalysis
- The ERA5 reanalysis
  - Data assimilation system
  - Observations
  - Gridded observations
- How accurate is ERA5?
- **Towards Earth system reanalysis; ERA6 and beyond**
- Summary

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ECMWF has a long experience with reanalysis

Atmosphere/land *including ocean waves*

- 1) 1979 - 1981 FGGE
- 2) 1994 - 1996 ERA-15
- 3) 2001 - 2003 ERA-40
- 4) 2006 - 2019 ERA-Interim
- 5) 2016 - … ERA5

Ocean *+ sea ice*

- 1997-2006 ORAS1,2,3
- 2010 - 2019 ORAS4
- 2016 - … ORAS5/OCEAN5

ERA CLIM

ERA CLIM2

Centennial *Outer loop Coupling*

- 2013 - 2015 ERA-20CM/20C
- 2016 CERA-20C
- 2017 CERA-SAT

Enhanced land (from ERA atmosphere)

- 2012 ERA-Int/Land
- 2014 ERA-20C/Land
- 2018 - … ERA5L

Atmospheric composition

- 2008 - 2009 GEMS
- 2010 - 2011 MACC
- 2017 - … CAMS EAC4

Next generation

- 6) 2024 - … ERA6
- 2024 - … ORAS6/OCEAN6
- 2026 - … ERA6L
- 2024 - … CAMS EAC5

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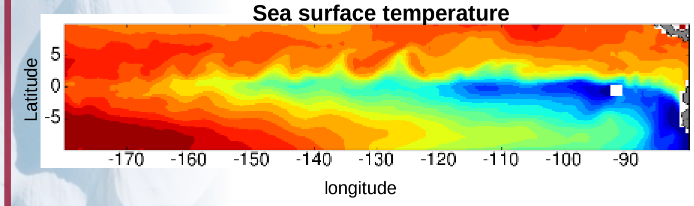
Benefits from coupled processes: tropical instability waves

Tropical instability waves (TIW)

westward-propagating waves near the equator



ERA20C (Forced reanalysis)

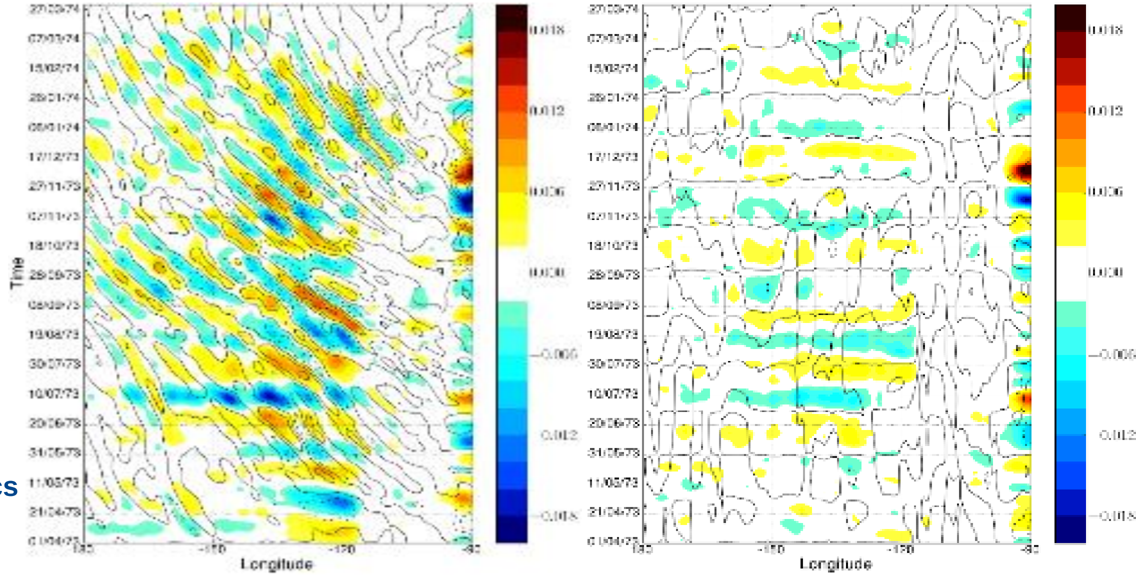
- no TIWs or wind stress signals (forced by 'monthly' SST)

CERA-20C (Coupled reanalysis)

- represents TIWs thanks to the ocean dynamics
- atmosphere responds accordingly (surface wind stress is sensitive to the ocean TIW)

high-pass filtered SST (colour) and wind stress (contour)

CERA-20C **ERA-20C**



Laloyaux et. al., 2018

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Planning towards ERA6: production to start in July 2024

From IFS Cy41r2 -> Cy49r1: ERA6 will benefit from an additional 8 years of R&D at ECMWF & improved compute capacity

Higher resolution: TCo799 (639) @ 14km (18km) vs 31km for ERA5

Selection of recent developments:

4D-Var DA
- Better EDA that evolves the background error covariance matrix
- Weak constraint 4D-Var to handle syst. model error (talk by Bill Bell)
- Evolution of VarBC for observations

Land DA
- Reduce biases in snow and improve assimilation of snow observations
- Include soil temperature DA in SEKF

Improved ocean wave physics
- At same resolution as the atmosphere (@14km or 18km)
- Improved drag for extreme situations

Improved atmosphere:
- New ozone model (HLO) and prognostic with radiation
- Revision of moist physics (clouds, precipitation, radiation)

Enhanced products:
- Height levels, additional parameters
- Extended monthly and daily pre-calculated quantities

More and better observations & better usage:
- Assimilate T2m observations in 4D-Var
- Reprocessed satellite observations (from EUMETSAT)
- Rescued data (satellite and in-situ, talk by Paul Poli)

Improved near-surface quantities and radiative forcing
- Vegetation cover and type, LAI, lake cover and properties, urban tile, potentially time-evolving (talk by Magdalena Alonso Balmaseda)
- New, and more species of aerosols and GHG's

ORAS6/OCEAN6:
- NEMOv4 + SI3 ocean and ice model
- Historical part driven by hourly ERA5 atmospheric forcing
- Details in presentation by Hao Zuo

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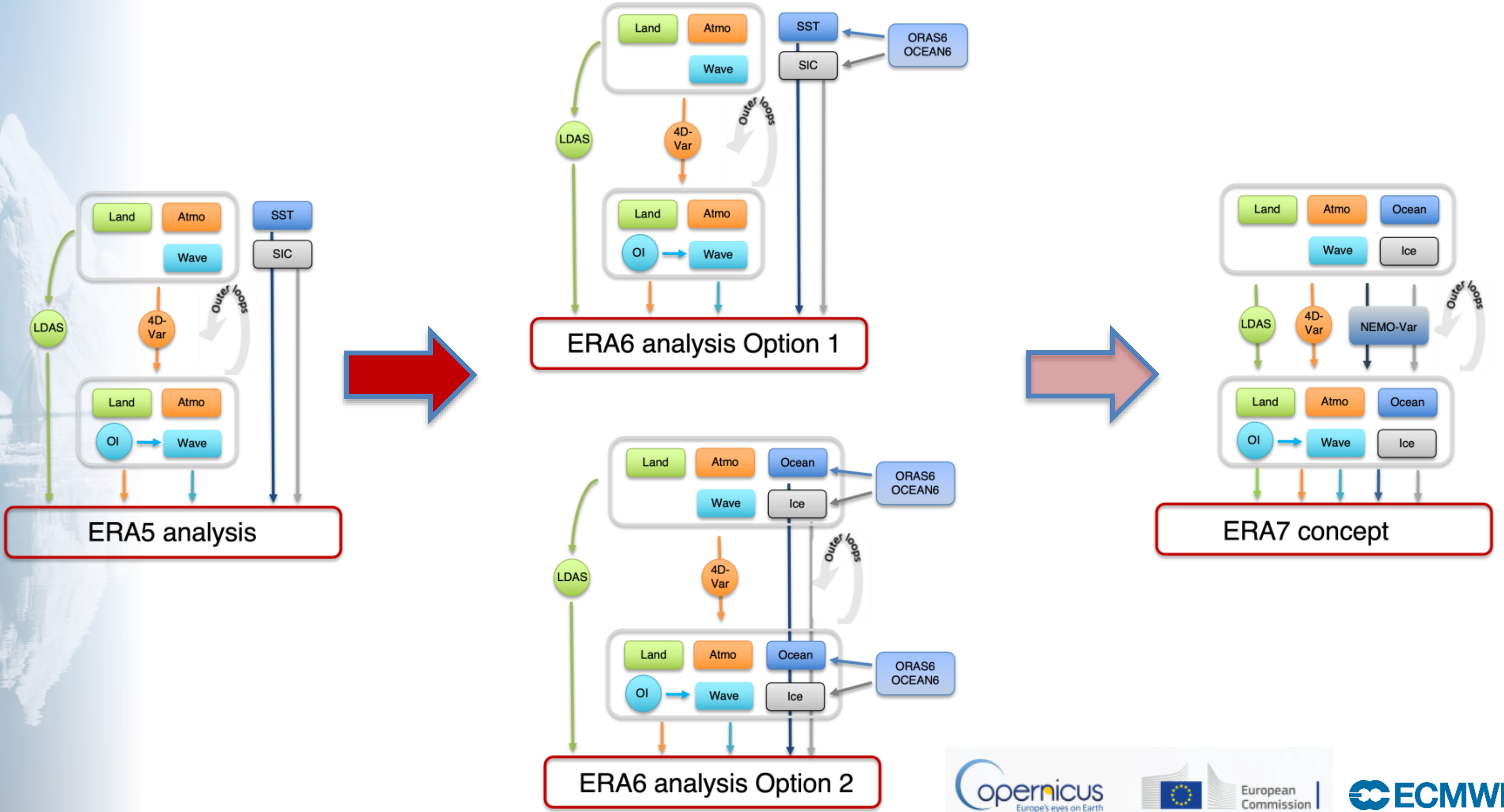
The ERA6 data assimilation system



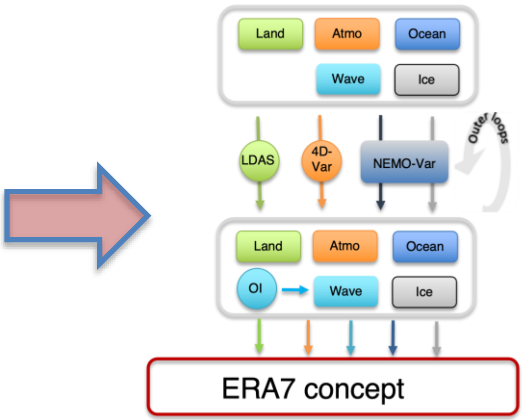
Beyond ERA6: building on and synergy with R&D at ECMWF

Details described in: De Rosnay et al., 2022 (doi.org/10.1002/qj.4330)

A key focus of ECMWF R&D on DA is to identify an optimal degree of coupling across the Earth system components for the benefit of seamless NWP and reanalysis:

- **Enhance the consistency of individual components**
  Examples: an improved description of ocean covariances, evolution of the LDAS into one, multivariate system.
- **Establish the optimal degree of coupling across components**
  Example: outer loop coupling where observations in each component have an influence on any other
- **Enhance the exploitation of interface observations** that have sensitivity to more than one component. See presentation by Phill Brown

Outcomes are expected to flow into ERA7.



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Summary and Final Remarks

--------> We are currently hiring: https://jobs.ecmwf.int/Home/Job (VN 23-30)   <--------

The **ERA5** reanalysis provides **hourly snapshots** of the atmosphere, land surface and ocean waves for **over 83 years**

- Very popular dataset on the C3S Climate Data Store: https://cds.climate.copernicus.eu/#!/home
- Synoptic quality evolves over time when more observations become available; boosts with boosts in observing system
- For upper-air temperature low-frequency variability looks reliable downwards from 10 hPa from mid 1940s onwards
- Humidity and ozone (not shown) is more challenging.

We are preparing for ERA6

- Higher resolution and based on an additional 8 years of R&D state-of-the-art and increased compute power at ECMWF
- Better and more observations; together with C3S contractors
- Improved realism of boundary conditions and forcing
- Address several ERA5 challenges

Future operational Earth System Reanalysis continues to be aligned and to have synergies with R&D at ECMWF

- Towards enhanced and stronger coupling of components
- Also, with help from external funding, such as ESA CERA, EU-FP7 ERACLIM-2, EU-H2020 CONFESS, and EU-HE CERISE

We receive a lot of feedback from our users and listen to them: **we are user-driven**

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