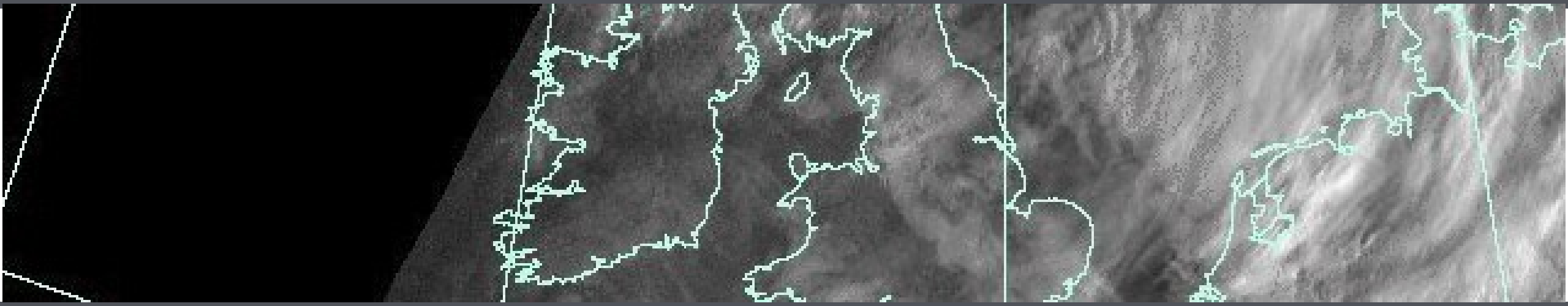
Department of Meteorology
Department of Mathematics & Statistics

National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL

University of Reading

Introduction to Reanalysis



Prof Sarah L Dance

s.l.dance@reading.ac.uk

@DrSarahDance.bsky.social (me)
@unirdg-darc.bsky.social (DARC group)

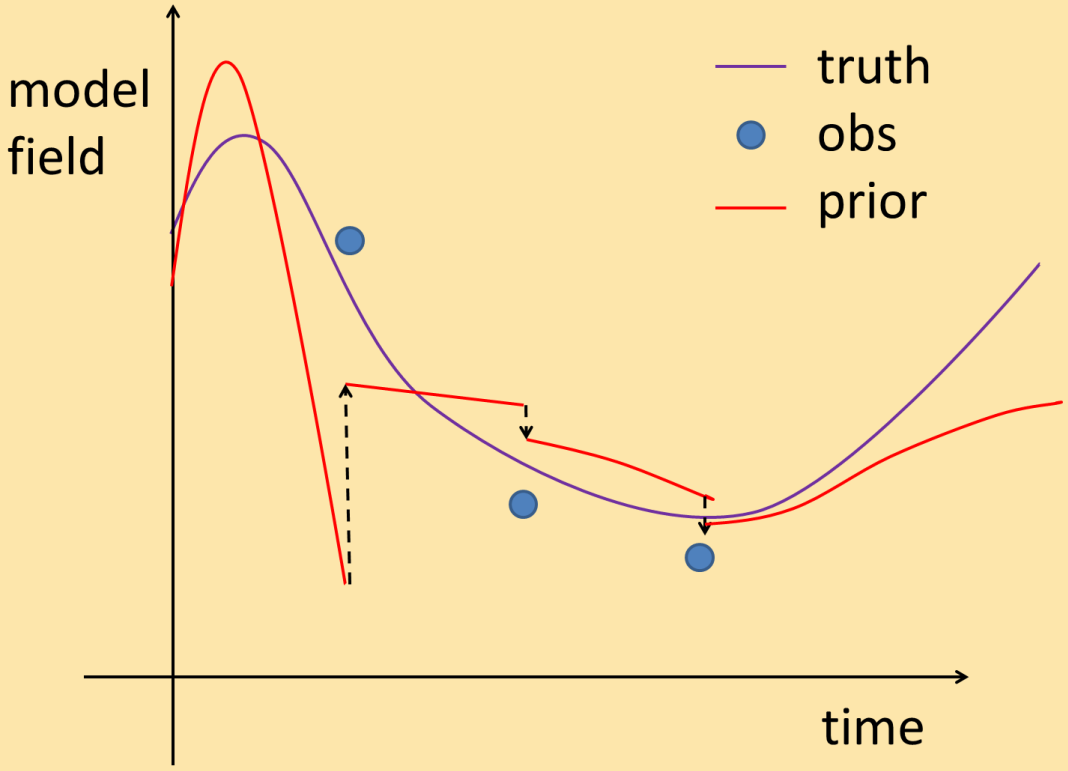
Outline

- What is reanalysis?

- Reanalysis strengths and weaknesses

- Please note that I will talk with examples from ocean and atmosphere weather data for simplicity, but of course you can do this will all components of the earth system!

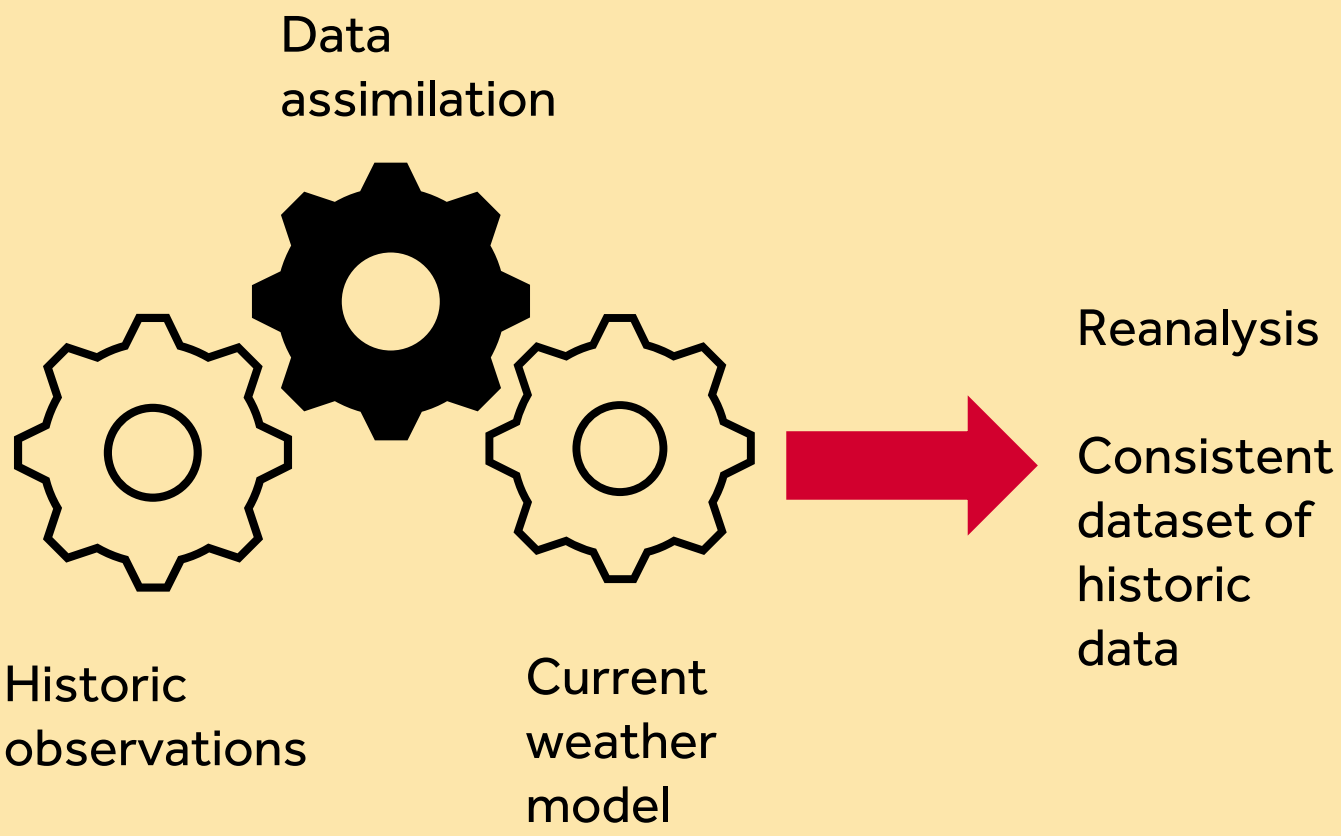
Recap



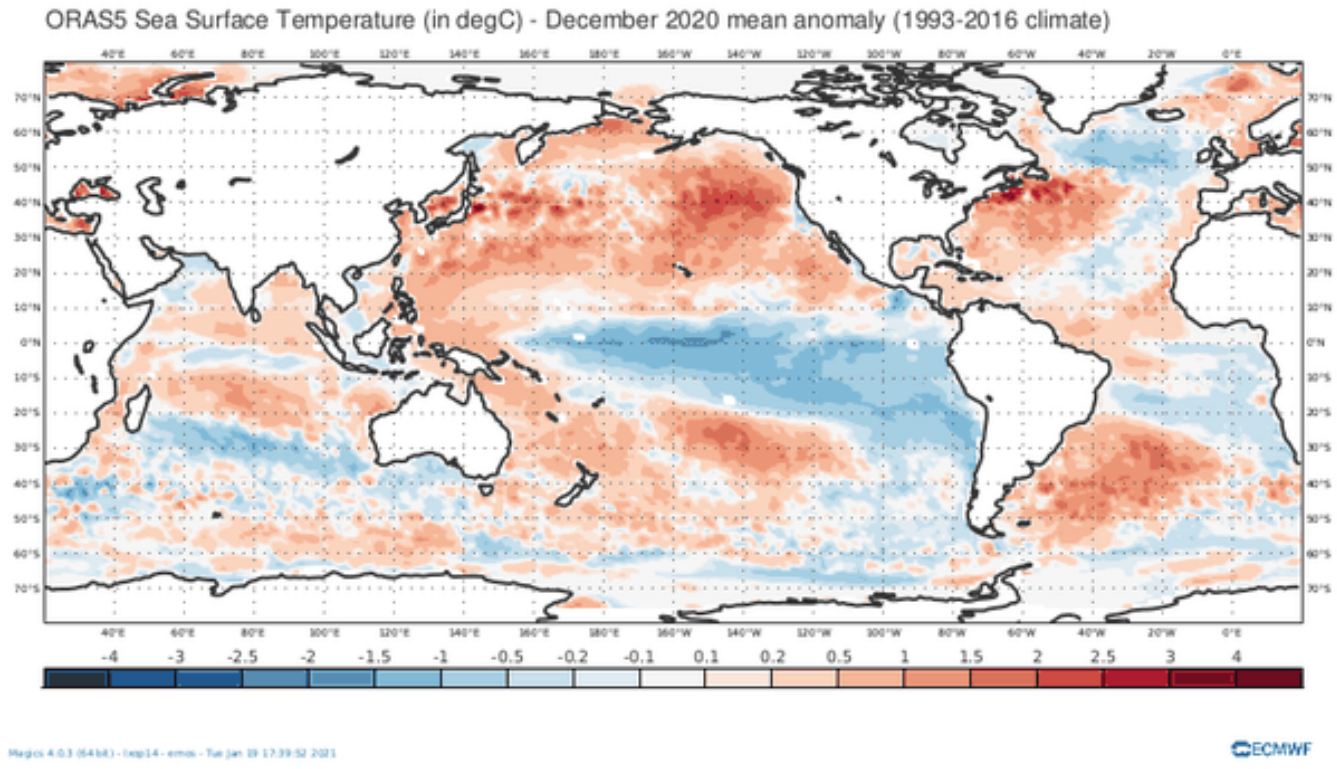
- Data assimilation combines dynamical model information with observation information
- Takes account of uncertainties in the model and the observations
- Uses incomplete observation information and physical process information to give a gap-free estimate of the “real world”

What is reanalysis?

- A consistent set of historic weather data, at regular time and space intervals
- An optimal combination of the current state-of-the-art weather prediction model with observations taken at the time.
- By historic observations, we mean any type of observational data from as far back as records begin to the present day.



Uses of reanalysis

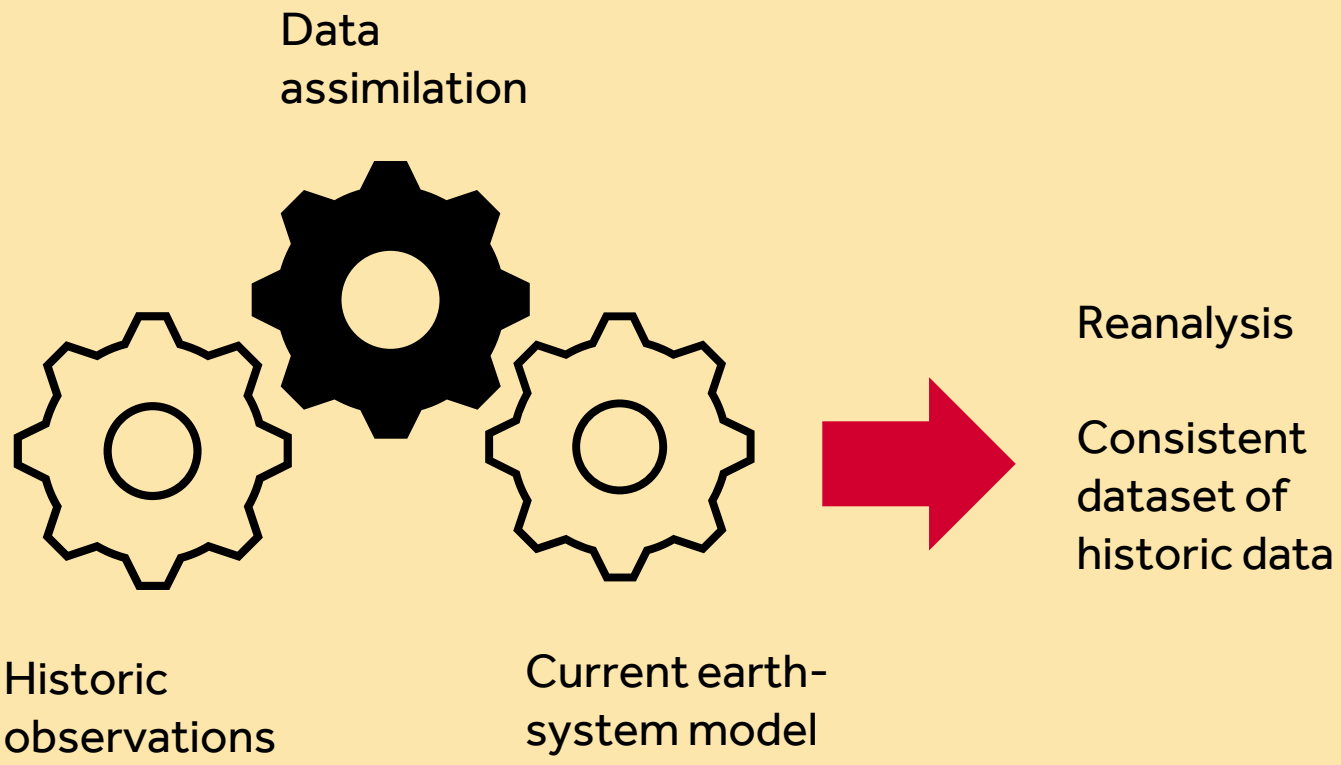


https://www.copernicus.eu/en/access-data/copernicus-services-catalogue/oras5-global-ocean-reanalysis-monthly-data-1958-present

- Study and evaluate long-term behaviour e.g., ocean currents, sea-surface temperature, wave climate, sea level
- Climate change impact assessments (changes with time)
- Identification of past extremes
- Monitoring (recent past) e.g., international treaties such as OSPAR (convention for protection of marine environment etc)
- Offshore energy system design
- Training data for machine learning models
- ERA5 has over 100,000 users!

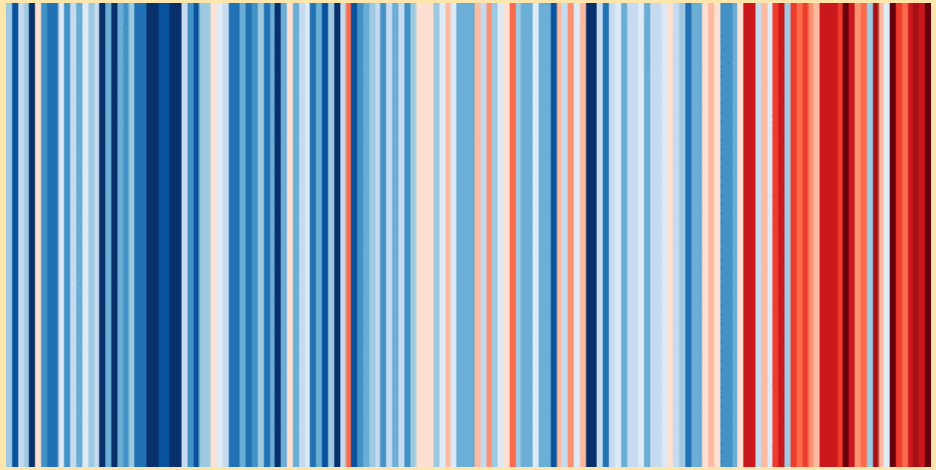
Strengths and weaknesses of reanalyses

- Come from the ingredients used to make them
  - Observations
  - Dynamical model
  - Assimilation system



Observation datasets

- A long-term dataset of observations provides important information about a range of features, including short-term and underlying trends as well as specific events
- But data may be spatially or temporally limited, or very uncertain

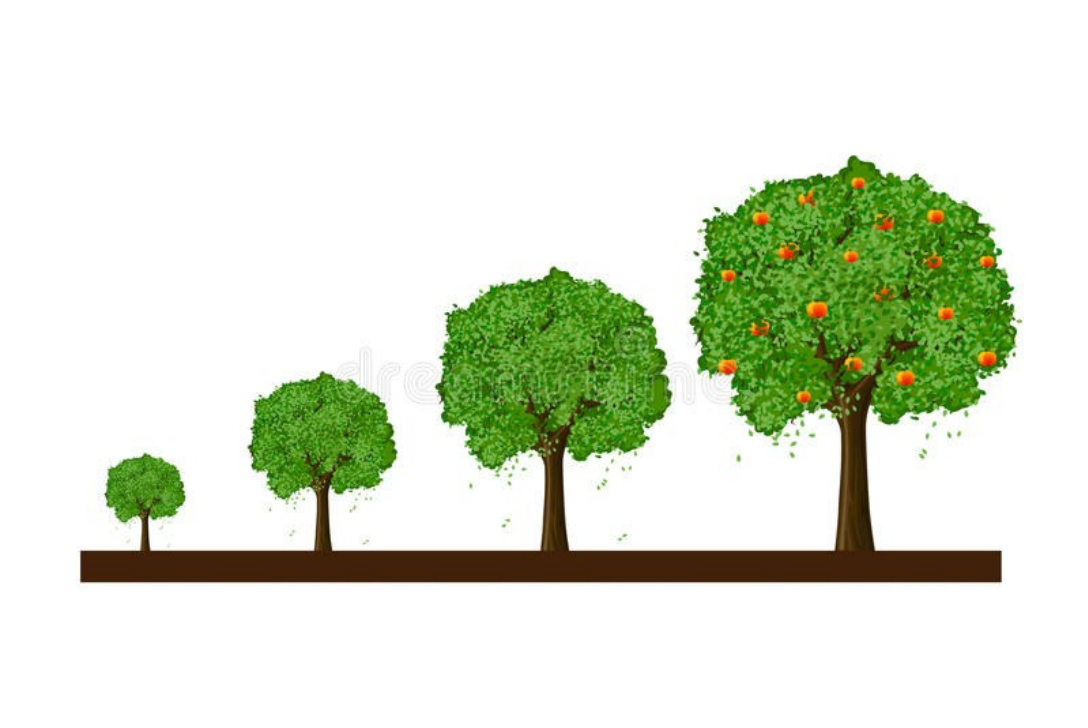


Warming stripes for Berkshire, showing average annual temperature in Berkshire from 1863-2020

Temporal consistency

For long time-series over decades, data consistency is likely to be an issue

- The observing instruments may change over time
- There may be gaps in the records, and fewer observations as you go back in time
- The position of the “same” observation may may move by a few or possibly hundreds of metres
- A single location may change over time as trees grow, buildings come and go and the land-use of the surrounding area may change (e.g., urbanization)



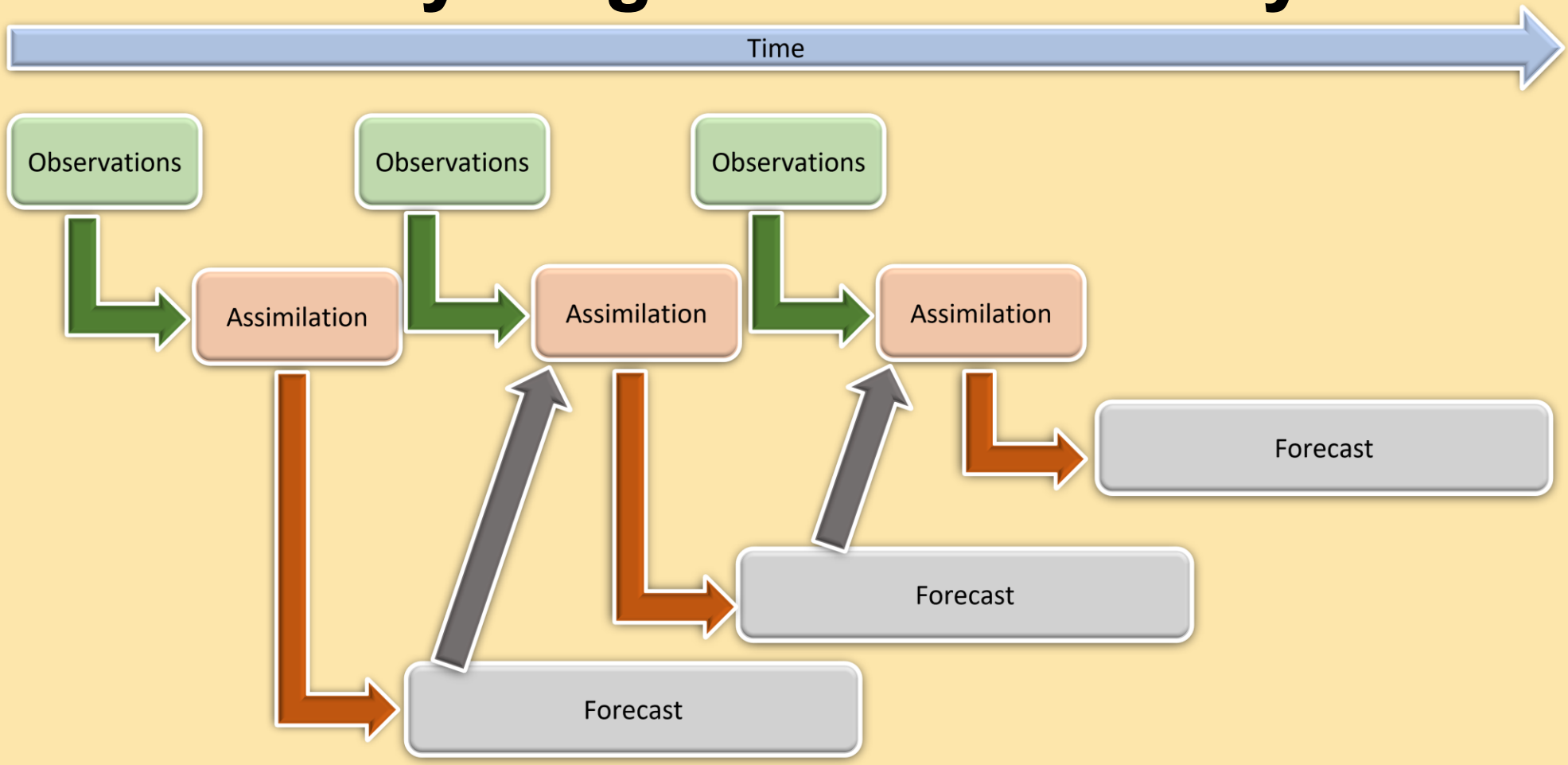
Data latency

- How long does it take for observations to arrive? (aka data latency)

Example 1

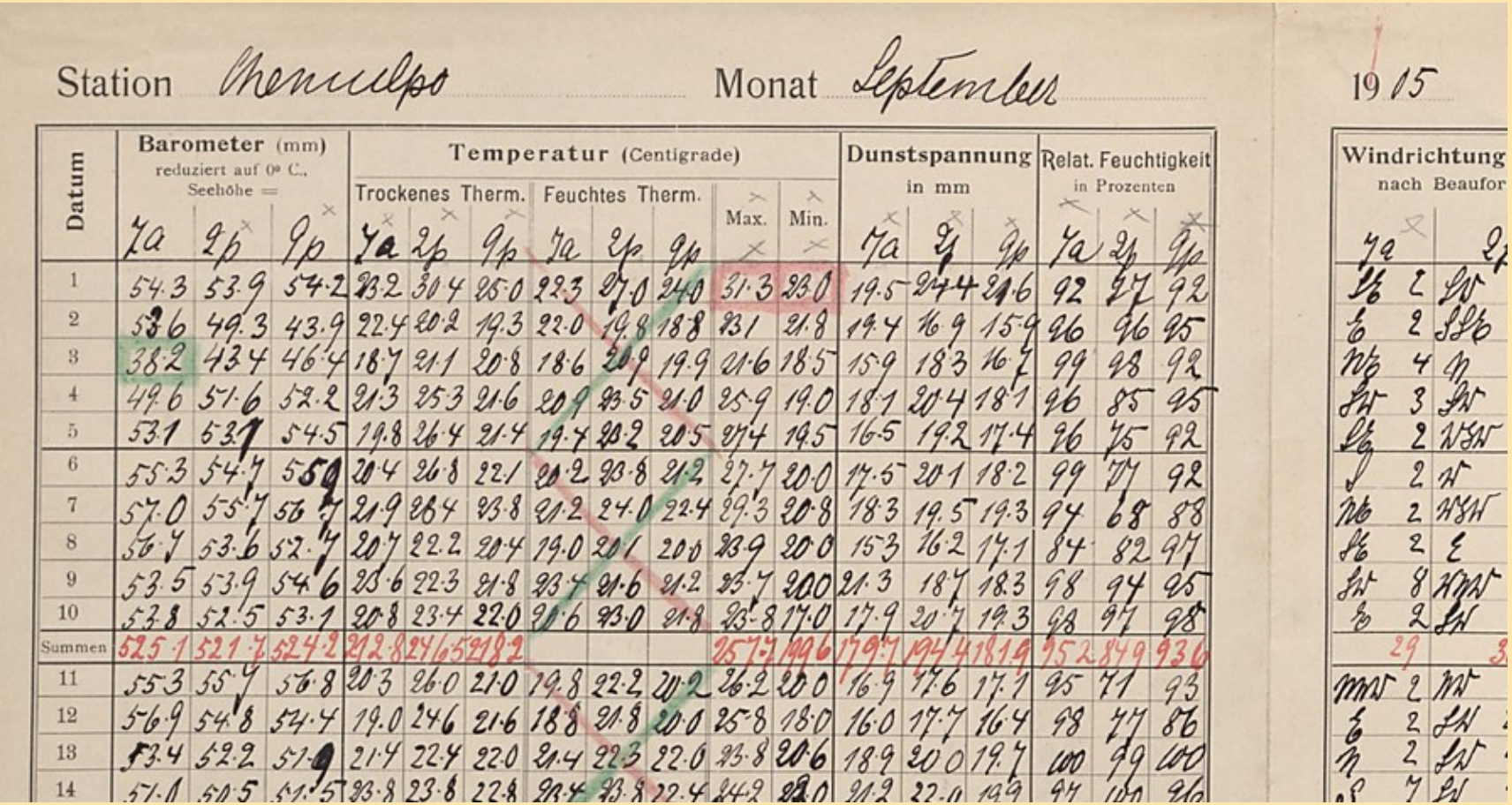
- The UK Met Office takes hourly observations from around 270 weather stations in near real time
- BUT daily summary observations from around 170 human observers come in at the end of each month

Assimilation cycling and data latency



Reanalysis allows us to assimilate modern observations that arrive too late to be used for forecasting

Example 2 – Data Rescue



Station Chemulpo Monat September 1905

Datum	Barometer (mm) reduziert auf 0° C., Seehöhe =			Temperatur (Centigrade) Trockenes Therm.			Feuchtes Therm.			Max.	Min.	Dunstspannung in mm			Relat. Feuchtigkeit in Prozenten		
	7a	2p	9p	7a	2p	9p	7a	2p	9p			7a	2p	9p	7a	2p	9p
1	54·3	53·9	54·2	23·2	30·4	25·0	22·3	27·0	24·0	31·3	23·0	19·5	24·4	21·6	92	57	92
2	53·6	49·3	43·9	22·4	20·2	19·3	22·0	19·8	18·8	23·1	21·8	19·4	16·9	15·9	96	96	95
3	38·2	43·4	46·4	18·7	21·1	20·8	18·6	20·9	19·9	21·6	18·5	15·9	18·3	16·4	99	98	92
4	49·6	51·6	52·2	21·3	25·3	21·6	20·9	23·5	21·0	25·9	19·0	18·1	20·4	18·1	96	85	95
5	53·1	53·7	54·5	19·8	26·4	21·4	19·7	20·2	20·5	27·4	19·5	16·5	19·2	17·4	96	75	92
6	55·3	54·7	55·9	20·4	26·8	22·1	20·2	23·8	21·2	27·7	20·0	17·5	20·1	18·2	99	77	92
7	57·0	55·7	56·7	21·9	26·4	23·8	21·2	24·0	22·4	29·3	20·8	18·3	19·5	19·3	94	68	88
8	56·7	53·6	52·7	20·7	22·2	20·4	19·0	20·1	20·0	23·9	20·0	15·3	16·2	17·1	84	82	97
9	53·5	53·9	54·6	23·6	22·3	21·8	23·7	21·6	21·2	25·7	20·0	21·3	18·7	18·3	98	94	95
10	53·8	52·5	53·1	20·8	23·4	22·0	20·6	23·0	21·8	25·8	17·0	17·9	20·7	19·3	98	97	98
Summen	525·1	521·7	524·2	212·8	246·5	218·2				257·7	199·6	179·7	194·4	181·9	952	849	936
11	55·3	55·4	56·8	20·3	26·0	21·0	19·8	22·2	20·2	26·2	20·0	16·9	17·6	17·1	95	71	93
12	56·9	54·8	54·7	19·0	24·6	21·6	18·8	21·8	20·0	25·8	18·0	16·0	17·7	16·4	98	77	86
13	53·4	52·2	51·9	21·4	22·4	22·0	21·4	22·3	22·0	23·8	20·6	18·9	20·0	19·7	100	99	100
14	51·1	50·5	51·5	23·8	23·8	22·8	23·4	23·8	22·4	24·2	22·0	21·2	22·0	19·9	94	100	96

Kaspar et al (2015)
https://doi.org/10.5194/asr-12-57-2015

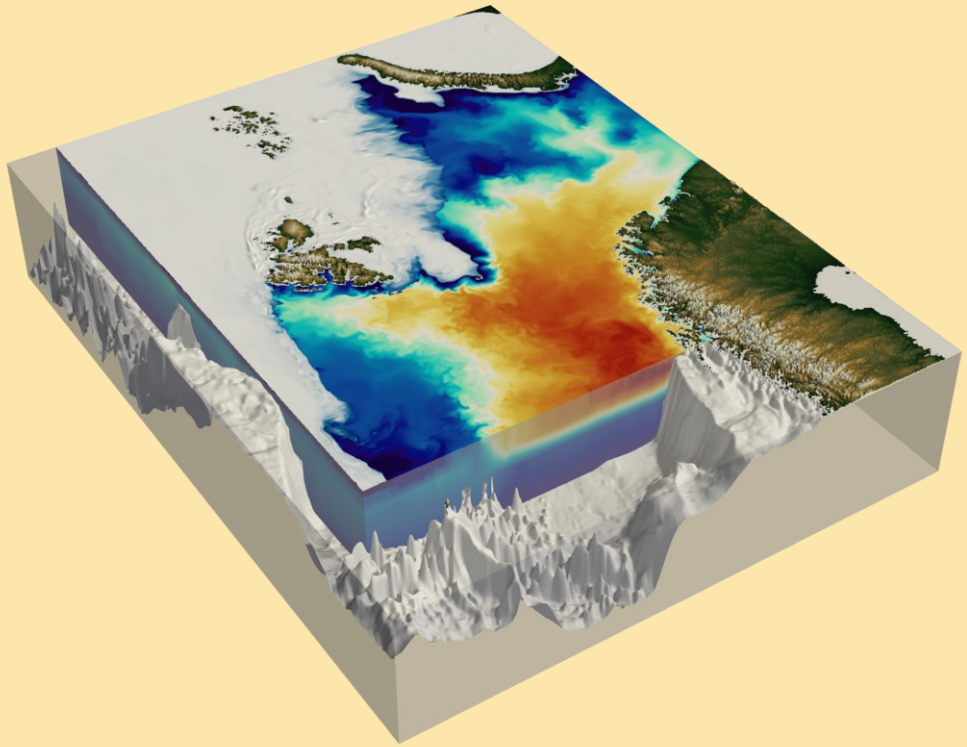
- Paper records can also be digitized and used for reanalysis
- Image from Chemulpo, South Korea from September 1905, from the DWD archives at Deutscher Wetterdienst
- Such records can't be digitized automatically (e.g., via optical character recognition) as this would result in too many errors.
- Citizen science projects instead

The dynamical model

- Model provides **physical consistency** in space and time

- “Maps with no gaps”
- Spatially and temporally comprehensive (at the resolution of the model output)
- Internally consistent
- Variables changing in a physically credible way

- DA allows for uncertainties to be accounted for objectively

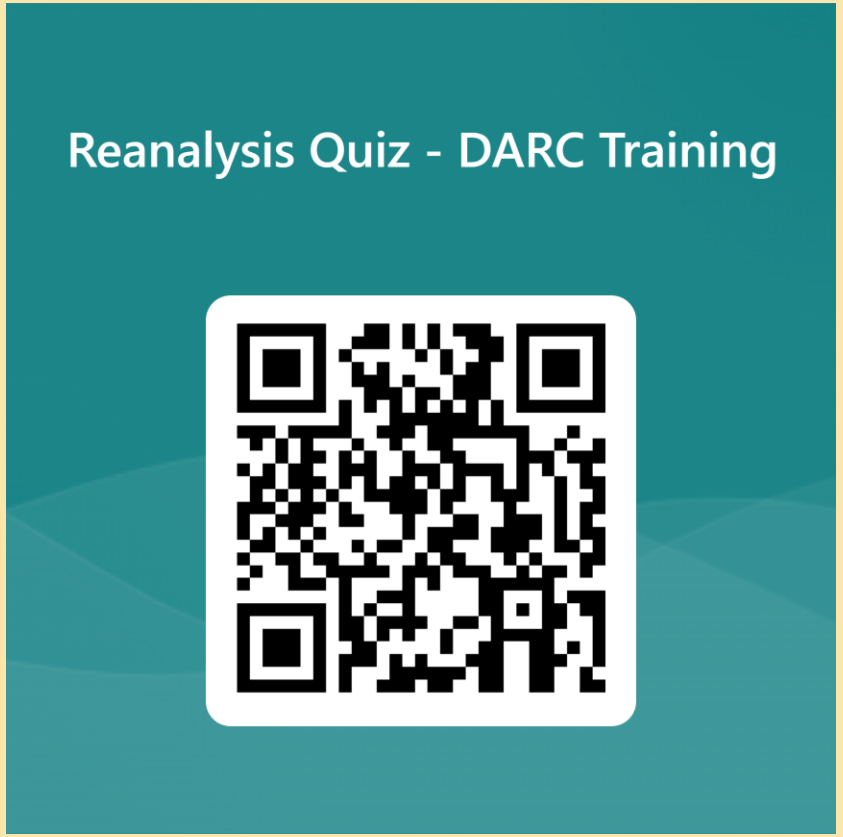


Barents Sea Model from Met Norway

https://ocean.met.no/models

Quiz

- https://forms.office.com/e/MHMc8JxLXx



Key concepts and cautions

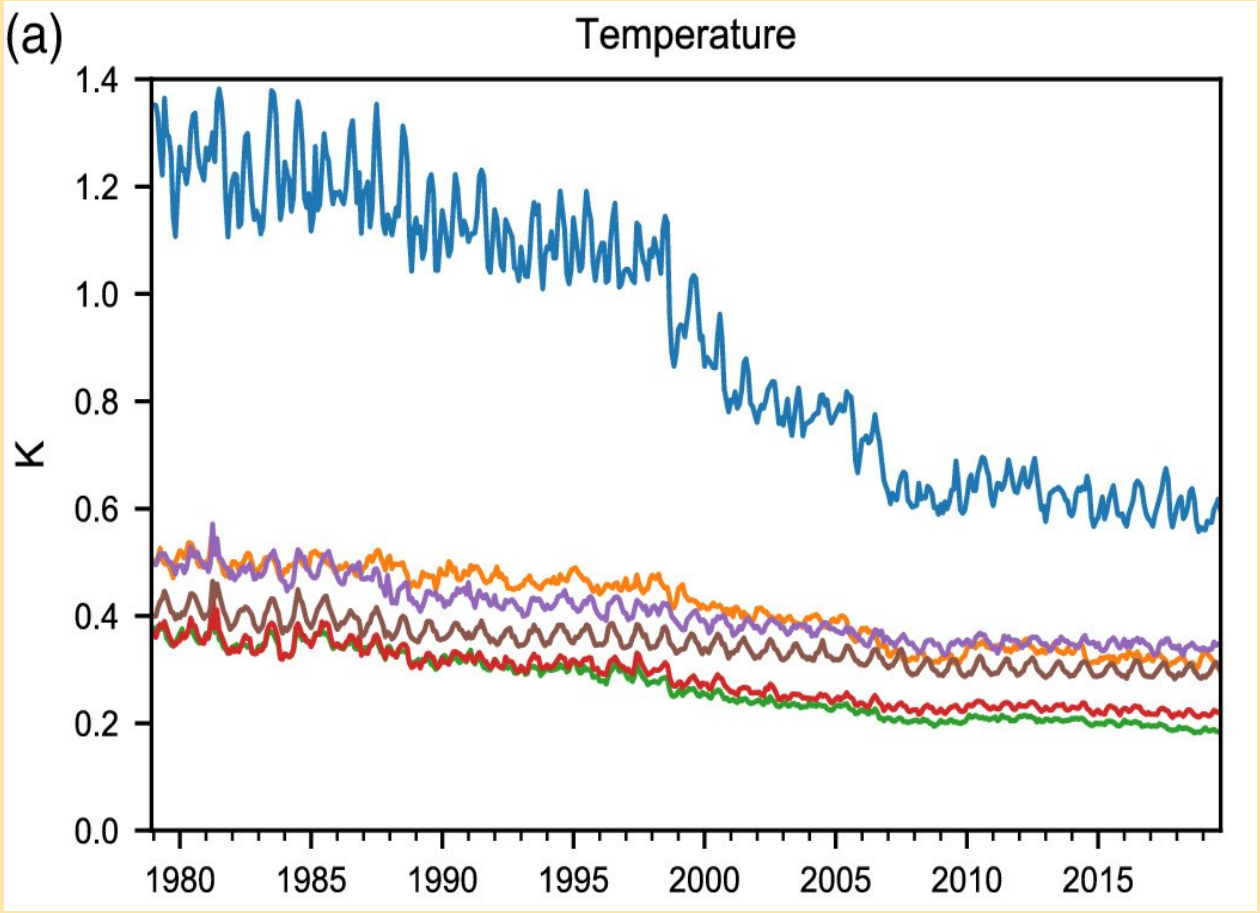
- Reanalyses are created using an unchanging DA system and model that ingests all of the (QC-ed) observation data available over the reanalysis period

- While the model and DA system are kept constant the **nature of the observation data changes with time**, due to changes in the observing network.

Reanalysis Uncertainty

- DA takes account of the uncertainties in the observation and model data (see other lectures) to produce an improved estimate of the atmospheric system.
- However, the reanalysis data nevertheless contains residual uncertainties.
- Some reanalysis products come with uncertainty metadata
- These are NOT usually a complete, classical metrological estimate of the uncertainty
- Instead they are a by-product from the assimilation, and thus don’t take into account any systematic errors that are not accounted for in the DA system

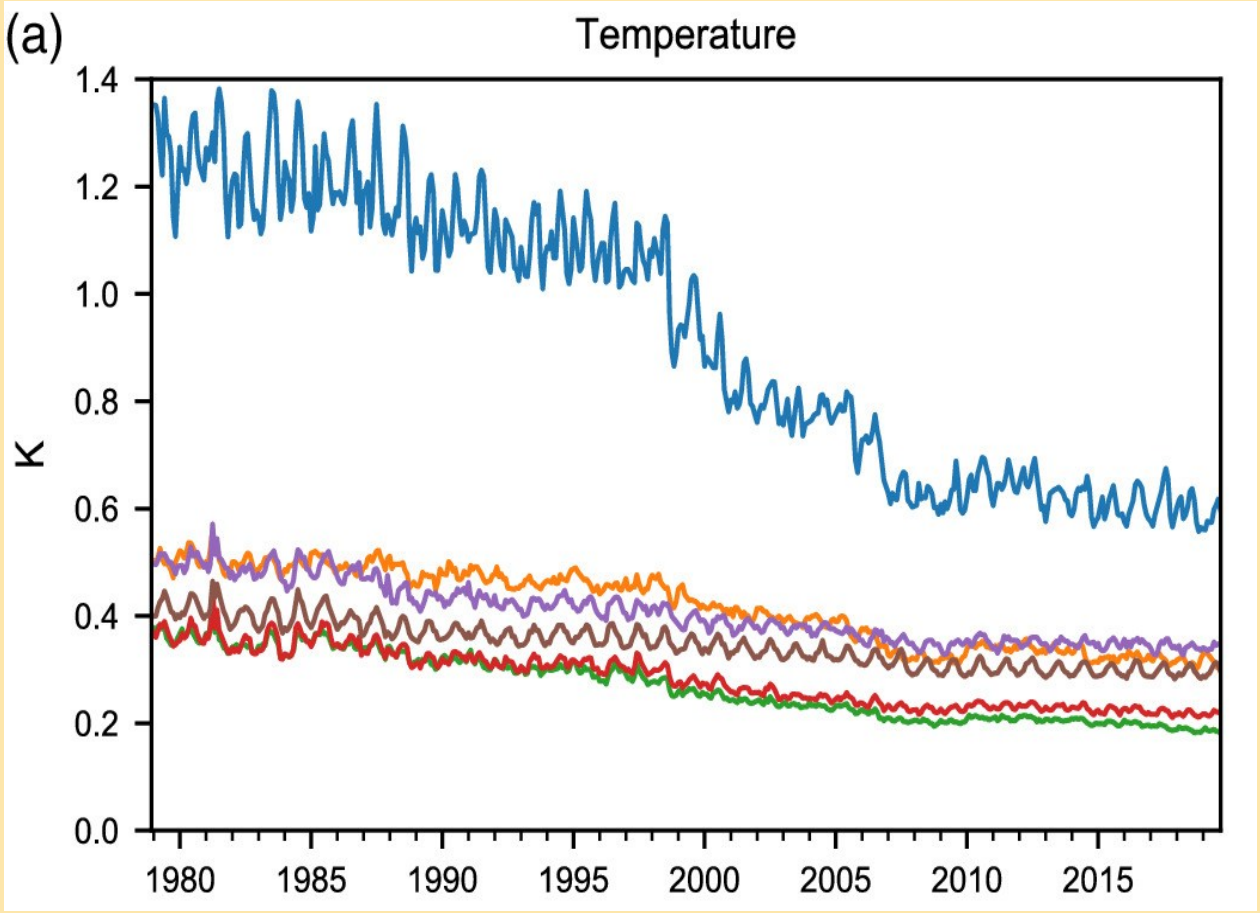
Uncertainty Example



- Time series of monthly and globally averaged ERA5 ensemble spread from 1979 to 2018 at indicated pressure levels for temperature (K).
- Different colours are different heights in the atmosphere
- Large ensemble spread should indicate high uncertainty

from Hersbach, et al. Q J R Meteorol Soc. 2020; 146: 1999– 2049. https://doi.org/10.1002/qj.3803

Uncertainty Example



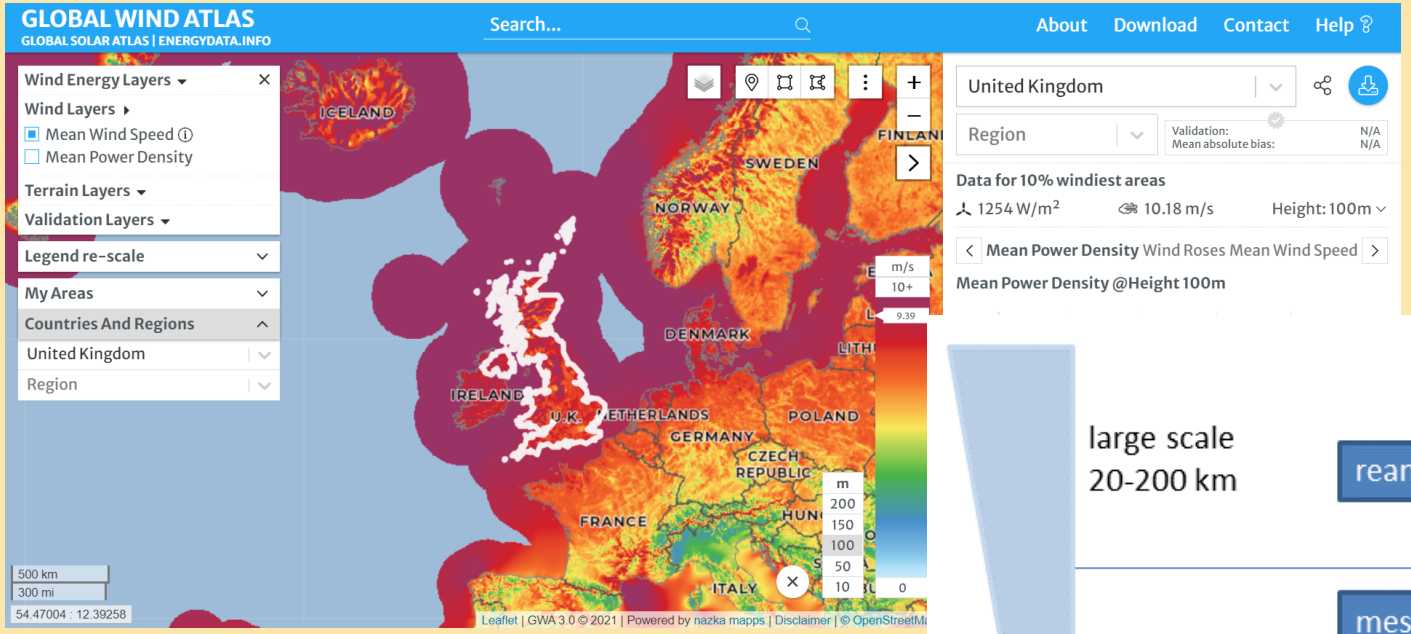
from Hersbach, et al. Q J R Meteorol Soc. 2020; 146: 1999– 2049. https://doi.org/10.1002/qj.3803

- Improvements often coincide with introduction of a new observing instrument
- Blue line is ensemble spread in the stratosphere
- Large improvements coincide with the coming of a new satellite instrument (ATOVS) 1998 and growth in numbers of another type of satellite data (GNSS RO) in 2006.

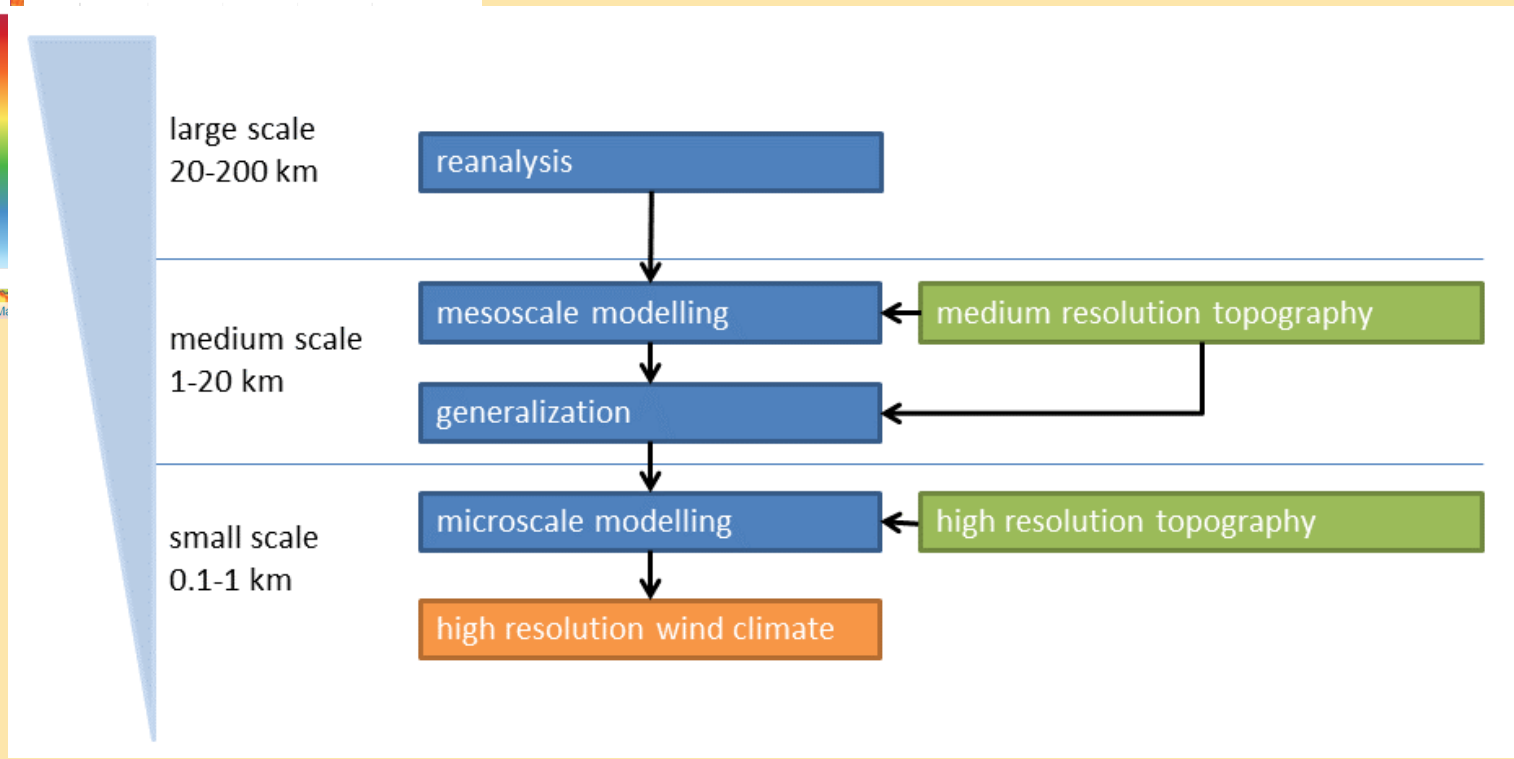
Representative scales

- A typical spatial temporary temporal gridding for global reanalysis **is 3 hourly intervals** and **30 kilometres** in the horizontal
- These scales may not resolve the details of the variables of interest required for studies of systems impacted by extreme events
- For studies involving complex terrain such as mountains or coasts it may be better to use the reanalysis to drive a physically consistent downscaling model

Example – using reanalysis to site wind-turbines



"Global Wind Atlas 3.0, a free, web-based application developed, owned and operated by the Technical University of Denmark (DTU). The Global Wind Atlas 3.0 is released in partnership with the World Bank Group, utilizing data provided by Vortex, using funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: https://globalwindatlas.info"

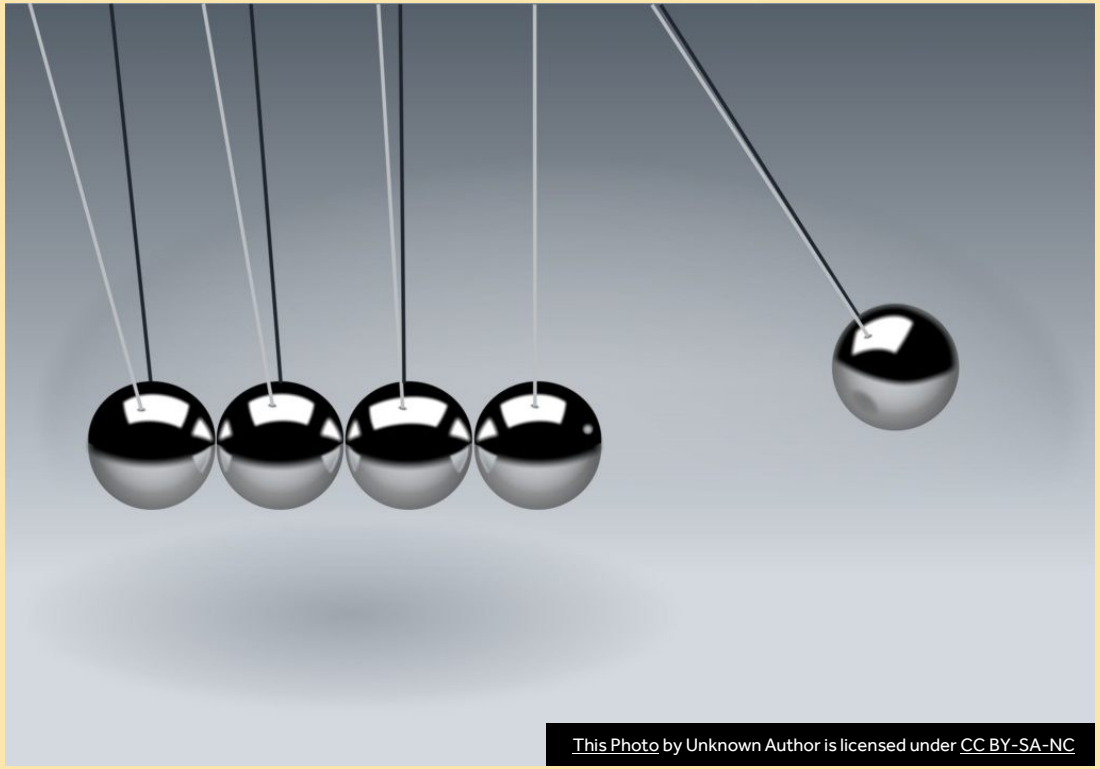


Non-conservative system

- Reanalyses do not preserve physically conserved quantities (e.g., energy)

- The assimilation acts to keep the model “on-track”, closed to the observed quantities.

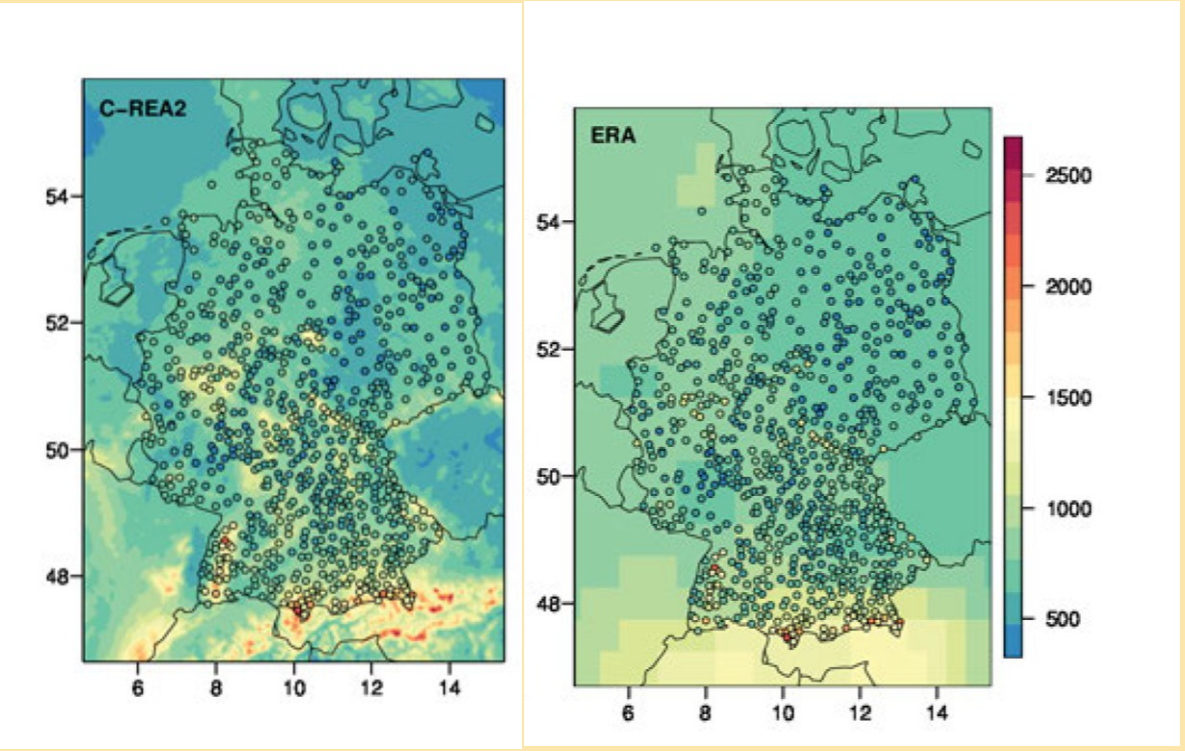
- For example, if a model has a warm bias compared with the real world, then the assimilation will remove energy so that the analysis fits the observations more closely.



Some variables are more trustworthy than others

- Reanalyses **inherit limitations** from the dynamical model used
- Often models cannot represent the complex process is associated with cloud and precipitation very well
- This makes variables like **pressure** more reliable than variables related to **precipitation**

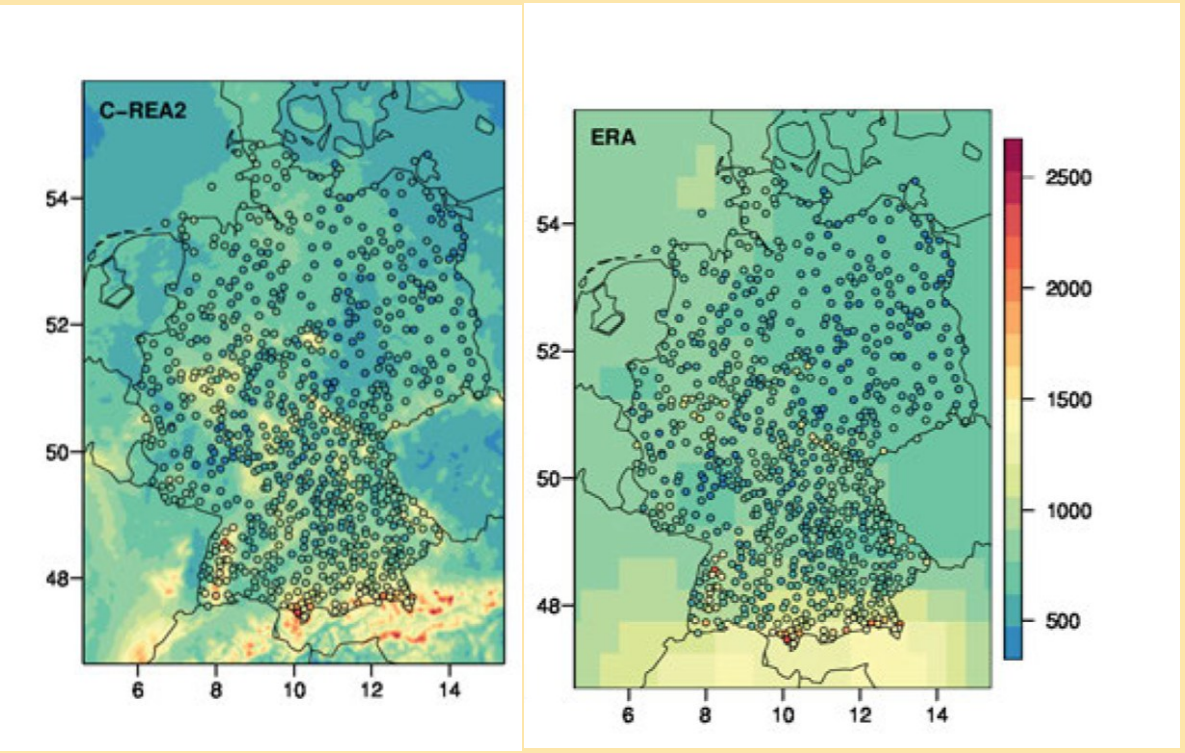
Example - precipitation over Germany



Wahl, et al 2017.
https://doi.org/10.1127/metz/2017/0824

- Mean annual precipitation in mm/year over Germany for the period 2007-2013, from a regional reanalyses (C-REA2, 2km grid) and the global reanalysis ERA-Interim (80km grid).
- Independent data from 755 raingauges is overplotted (small circles).
- The mean annual precipitation received at a raingauge station between the years 2007 and 2013 varies between 500 and 2300mm/yr.
- The regional reanalysis is on average able to capture this variability, but the ERA-Interim misses the extreme events and only has a range of between 600 and 1400mm/yr.

Example - precipitation over Germany



- This difference in variability between the regional and global reanalyses is in part due to the differences in grid-length between the systems and ability to capture extremes.
-
- Nevertheless they both underestimate the frequency of large events and overestimate the frequency of small events.

Wahl, et al 2017.
https://doi.org/10.1127/metz/2017/0824

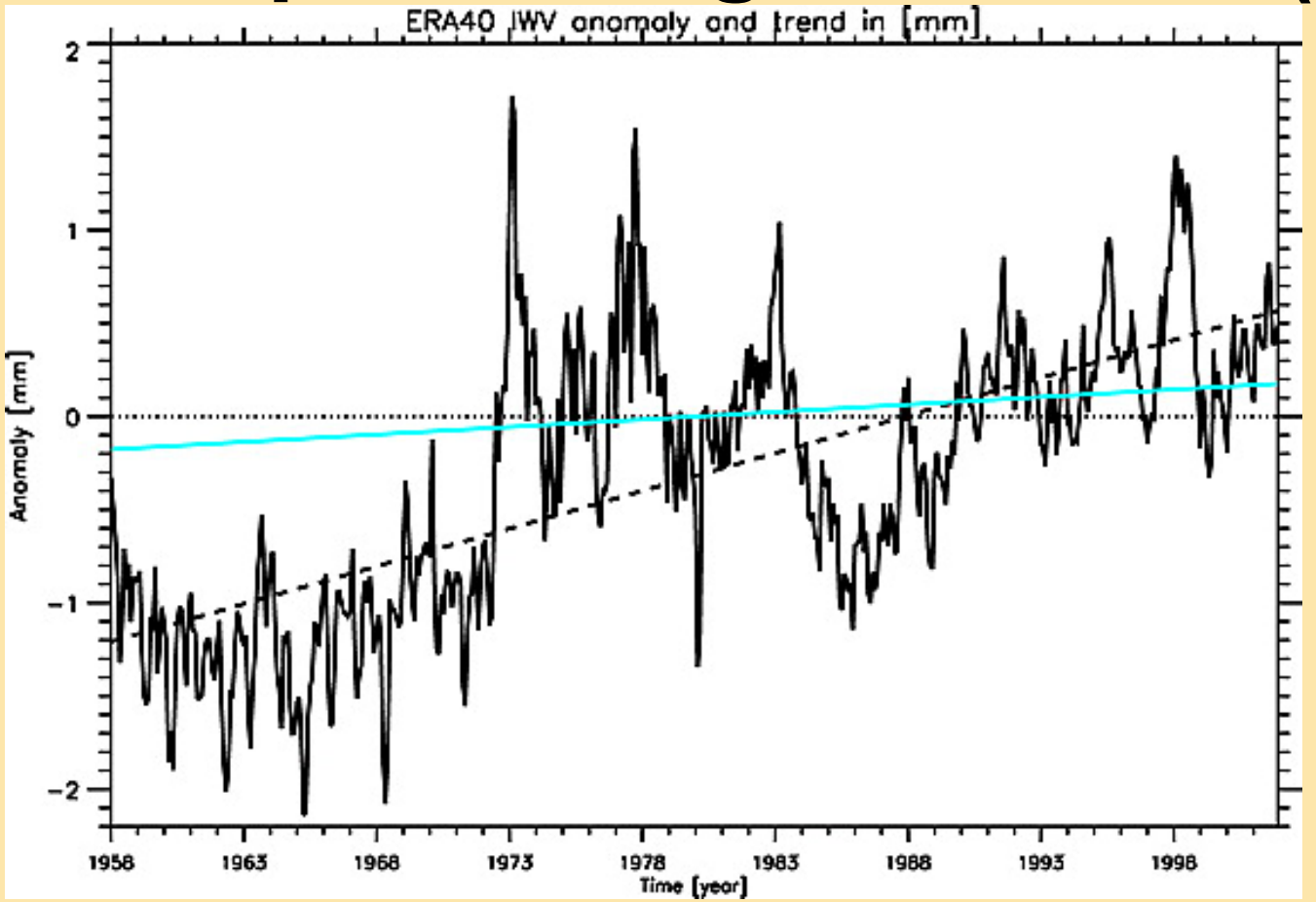
Changes in the system with time – beware trends

- While the model used in the reanalysis system is kept constant with time the observing network changes

- Reanalysis developers put significant effort into reducing or removing spurious jumps and trends introduced by
  - changes in the observing system
  - time varying biases in models and observations

- Long term climate signals are inevitably affected in these data and should be viewed with caution

Example – Bengtsson et al (2004



- Vertically integrated water vapour (IWV) anomalies (differences from a reference value) from the ERA40 reanalysis for the period 1958–2001.
- Black line shows the data from ERA-40.
- Dashed line shows an increasing trend calculated from these data.
- Cyan line – trend from reanalysis experiment with no satellite data

Bengtsson et al (2004). Can climate trends be calculated from reanalysis data?. Journal of Geophysical Research: Atmospheres, 109(D11).

Choice of reanalysis products

National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL

University of Reading

What time period?

Which variable are you interested in?

Which temporal and spatial resolution for you need?

What do you want to use it for?

Satellite data or not?

Which model and assimilation system would you prefer?

Useful websites

• Comparison of atmospheric reanalyses

https://reanalyses.org/atmosphere/comparison-table

• Comparison of ocean reanalyses

https://reanalyses.org/observations/ocean-reanalyses-table

Summary

- Reanalyses are very useful consistent gridded datasets of historic weather data

- But they have inherent uncertainties and should never be treated as “the truth”
  - They inherit the deficiencies of the modelling system
  - They should not be used for trend analysis due to changes in the observing system
  - They are not conservative
  - Uncertainty metadata is a useful qualitative guide, but is not calculated by metrological techniques

  - Practical session will explore some of these ideas!

Extras

Exercise - if time

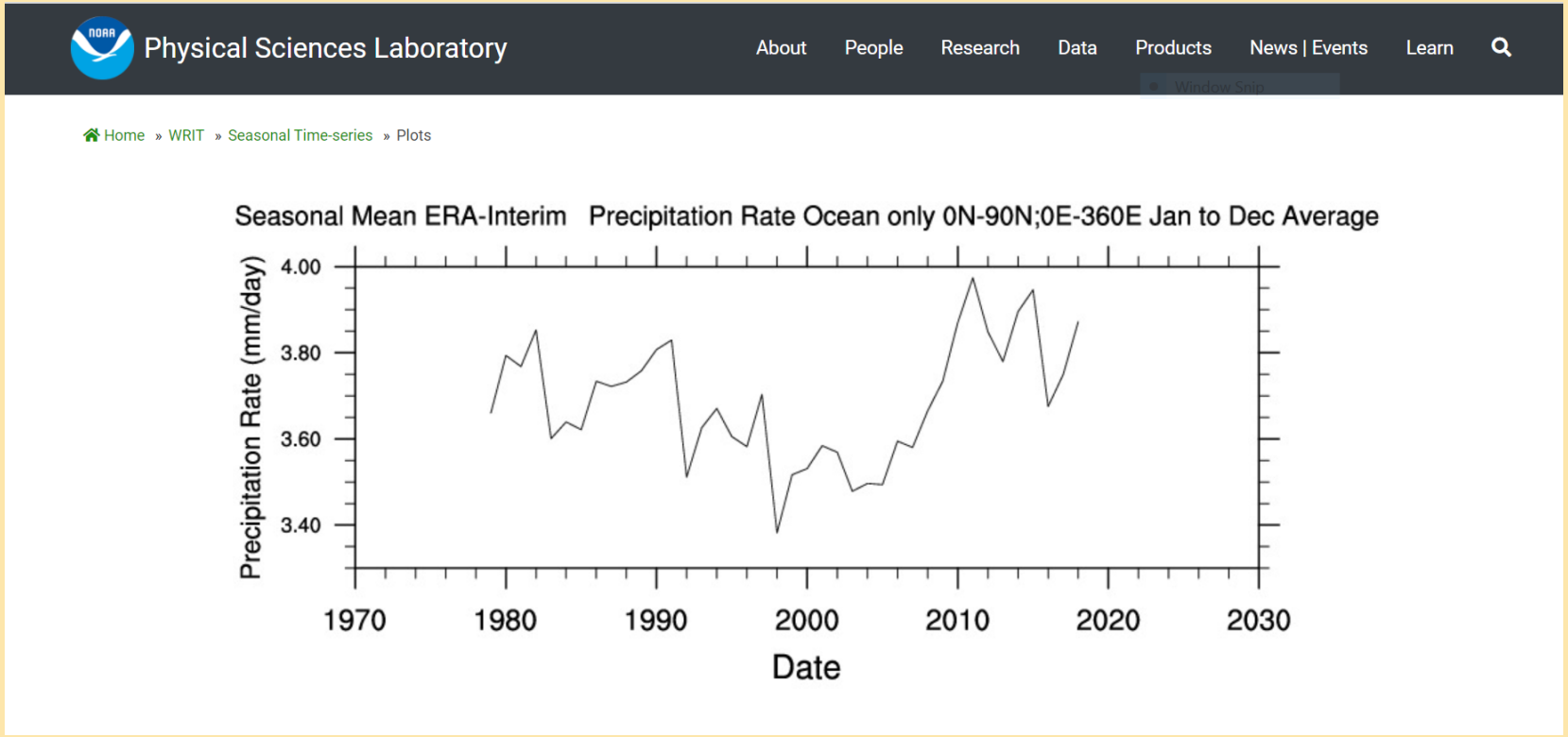
1. Visit https://psl.noaa.gov/data/atmoswrit/timeseries/ - we will use this website to produce a timeseries plot of some reanalysis data.

2. Select the following on the webpage (leave the other settings as default)
   - Dataset 1 – ERA Interim
   - Which variable for D1? – Precipitation Rate
   - Time averaging – Seasonal
   - Land/Ocean Mask options – Ocean

   - Then click create plot

Exercise cont

3. The plot should look like this



4. Q What do you think might have happened in 1992?

- Answer: A new observation type was added, namely rain-affected SSM/I satellite radiances. The impact of these satellite observations on the assimilation is most directly felt over the oceans where there are few other in situ observations to constrain the precipitation estimates.

- For more information see Dee, et al. (2011), The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Q.J.R. Meteorol. Soc., 137: 553-597. https://doi.org/10.1002/qj.828)

Quiz (in person/poll online)

Match the limitations to the components of the system

Components
Observations
Models

Limitations
A Limited resolution: small details are missed or have to be approximated
B Limited coverage in space or time
C Updated versions will give different results with the same input data
D Can be inconsistent over time

https://forms.office.com/e/MHMc8JxLXx