Traceable Observations in Support of the Copernicus Climate Change Service (C3S)

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C3S Reanalysis Team, Copernicus Department , ECMWF

Climate Change

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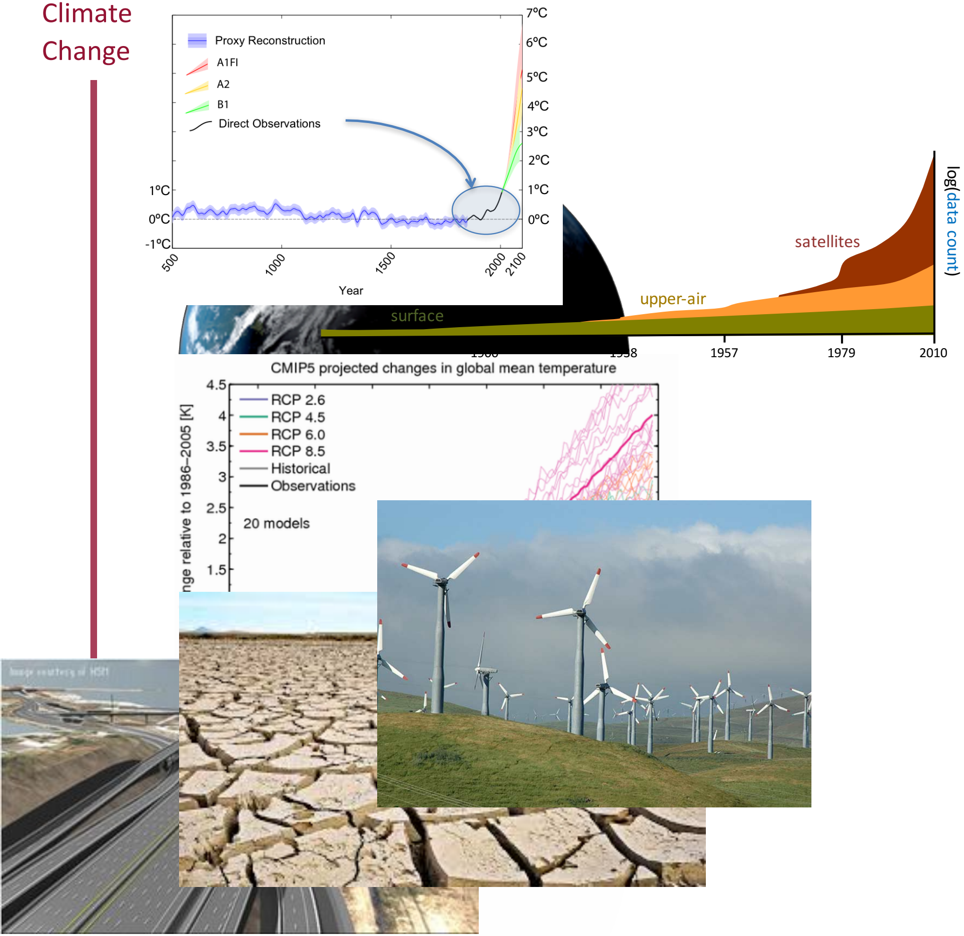
Climate
Change

Climate Change Service



Provision of a suite of data products to support a broad community of users in addressing key climate-related questions

- **How is climate changing?**
  - Earth observations
  - Reanalyses
- **Will climate change continue/accelerate?**
  - Predictions
  - Projections
- **What are the societal impacts?**
  - Climate indicators
  - Sectoral information

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Overview

- C3S & The ERA5 global reanalysis
    - Characteristics, performance and user-base
    - Observations
    - Bias & uncertainty
- C3S & Essential Climate Variables
- Conclusions & future perspectives

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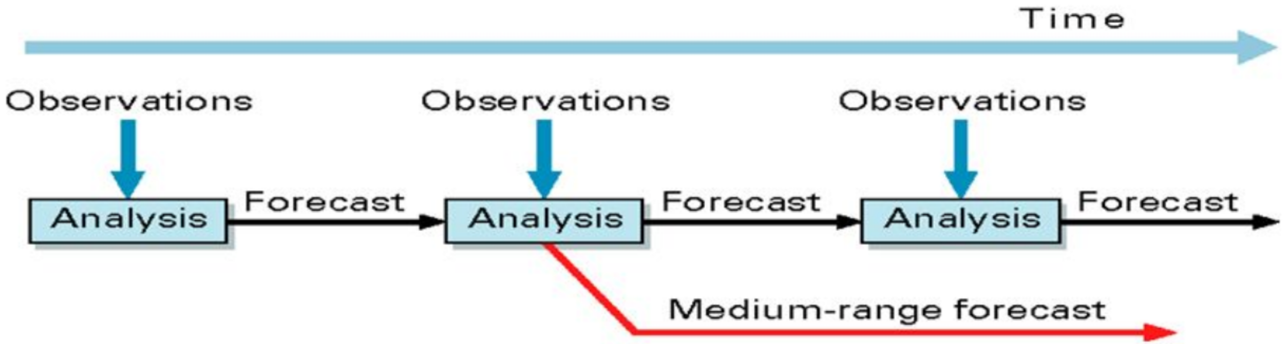
NWP and Reanalysis



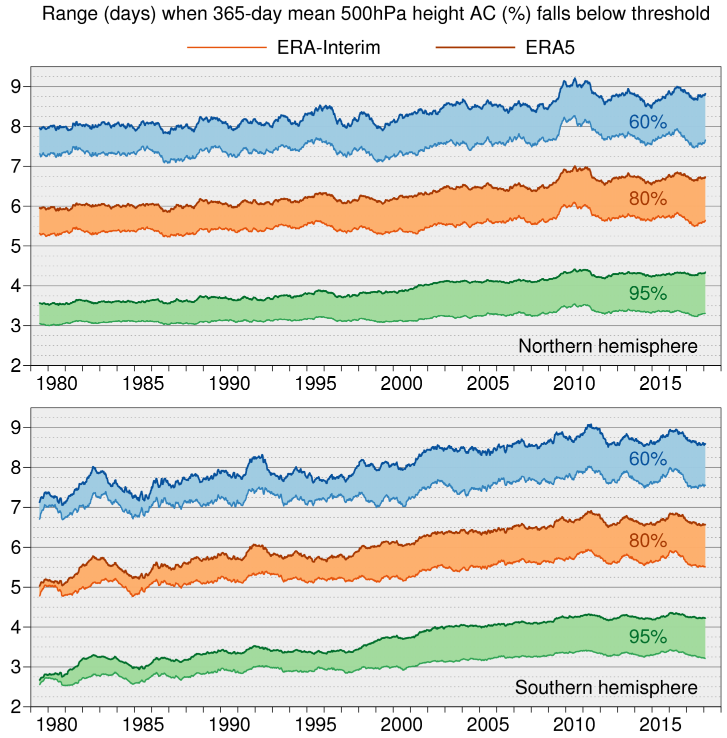
- NWP is primarily concerned with **prediction** (the Medium Range Forecast)
  - NWP models are upgraded every 6-12 months
  - Observations lose (most of their) value after ~0.5 day

- Reanalysis is concerned with the **retrospective analysis** of the atmosphere, in a **consistent** way, over **many decades**
  - Uses state-of-the-art NWP systems (but using a fixed configuration over decades)
  - Observations (*esp*. reprocessed/ recalibrated) continue to have value
  - Reanalyses updated every 5-10 years (ERA**5** is the **5**th generation ECMWF reanalysis)

The ERA5 global reanalysis

ERA5 is in production at ECMWF for C3S

ERA5 will replace its predecessor, ERA-Interim



Improvements compared to ERA-Interim:

- Benefit from 10 years model development (2006 to 2016)
- Much higher resolution; **31km** versus 80km
- More and better input data
- Hourly output
- 10-member EDA-based uncertainty estimate (at 63km)
  - Perturbations to: SST, model tendencies & obs
- Will reach further back in time (1950 versus 1979)

Climate Data Store (CDS) public release plan:

- **Published to date:** 1979 – June 2019
- **Q3 2019:** updates 2-5 days behind real time: ERA5T
- **Q1 2020:** 1950-1978.
  Production of ERA-Interim is no longer supported

ERA5 user uptake

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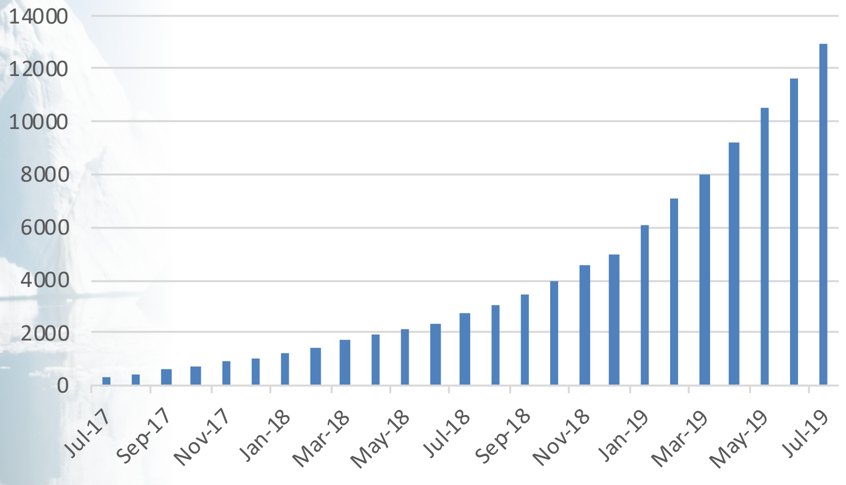
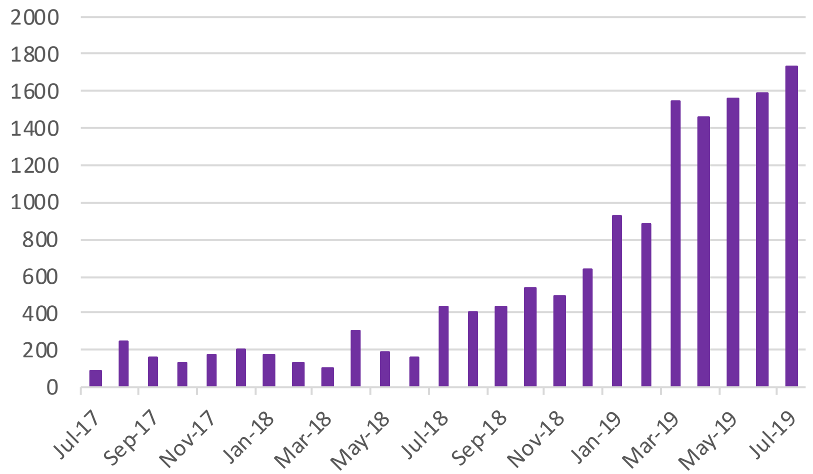
C3S ERA5: total number of data users



C3S ERA5 downloads (TB)



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The ERA5 Global Reanalysis

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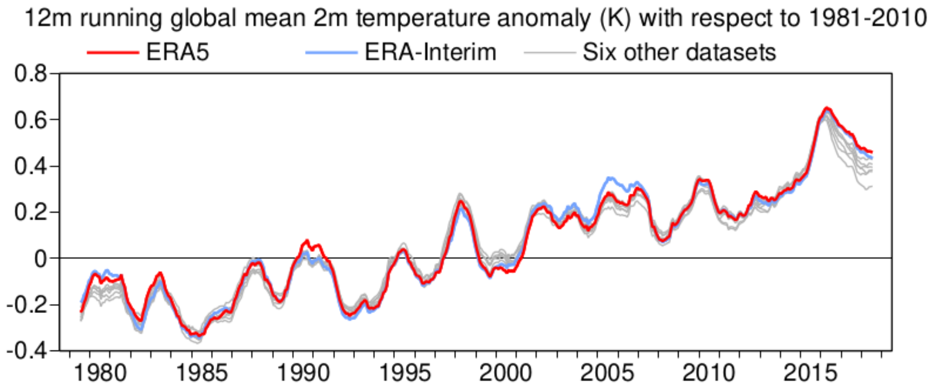
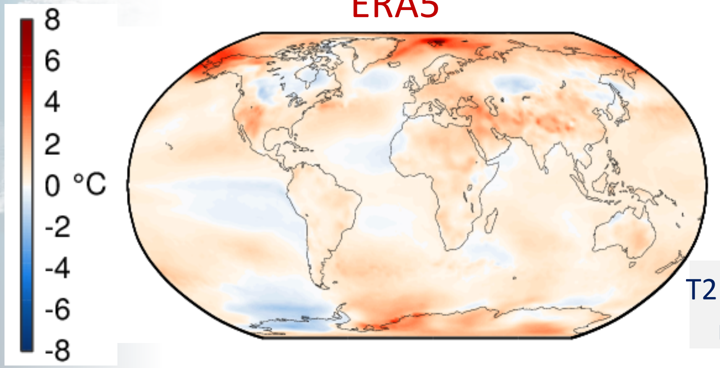
Better model, better and more consistent input data, higher resolution



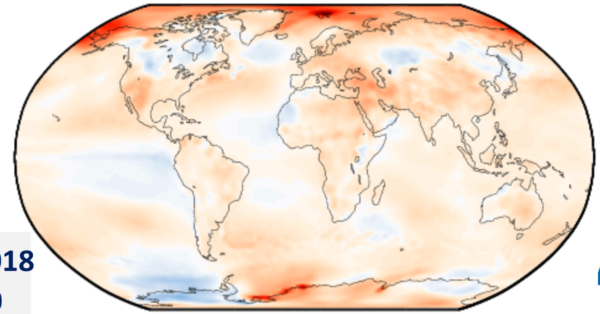
- JRA-55 (*Kobayashi et al. 2015*)
- GISTEMP version 4 (*Hansen et al. 2010*)
- HadCRUT4 (*Morice et al.2012*)
- NOAA GlobalTemp v5 (*Karl et al. 2015*)
- HadCRUT4 (*Cowtan and Way 2014*)
- Berkeley Earth Surface Temperature Project

ERA5

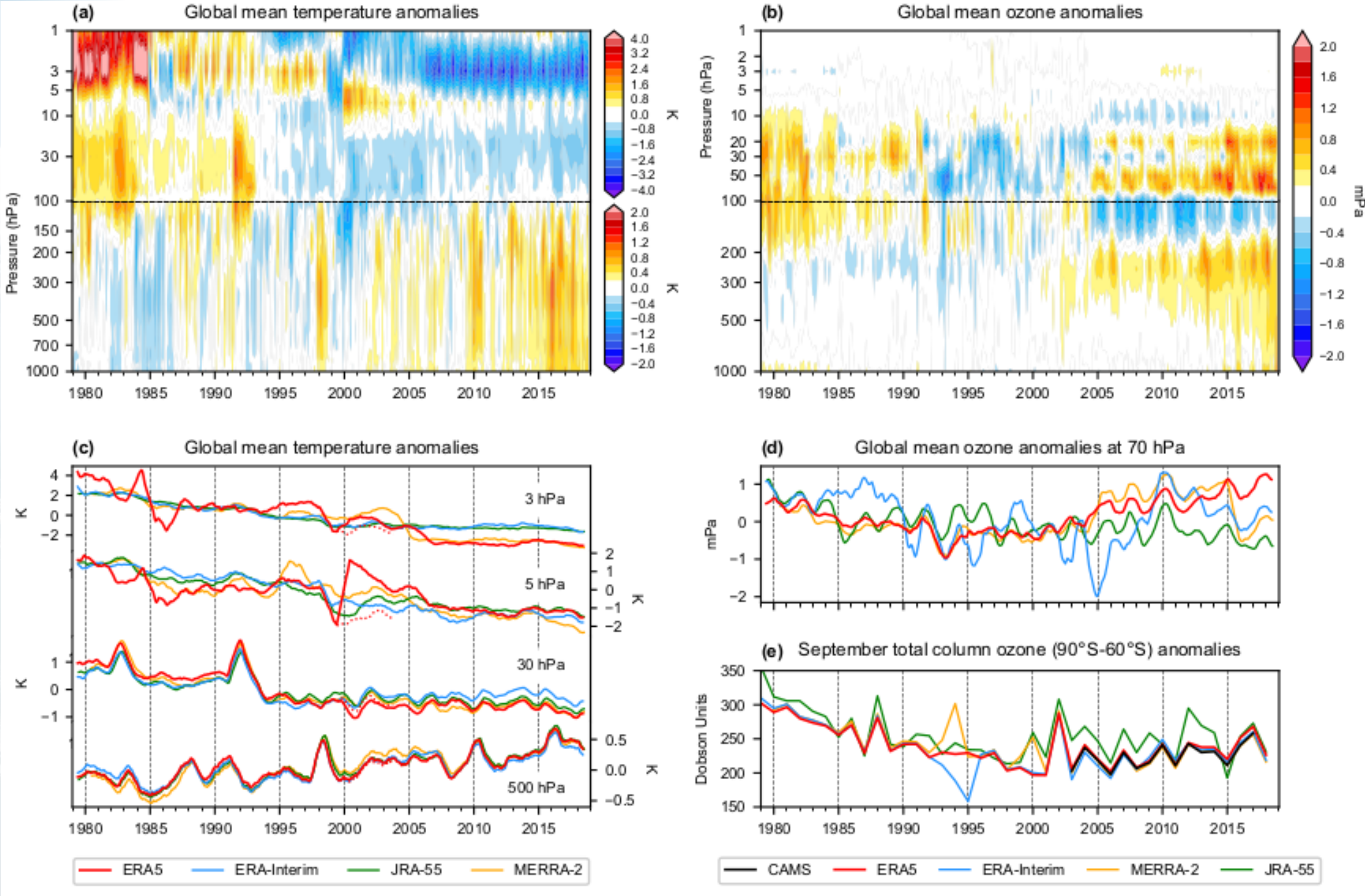


T2m, **Sep 2017 - Aug 2018**
relative to 1981-2010

ERA-Interim



Upper air anomalies in ERA5



Anomalies relative to monthly mean climate 1981-2010

Much more accurate and detailed

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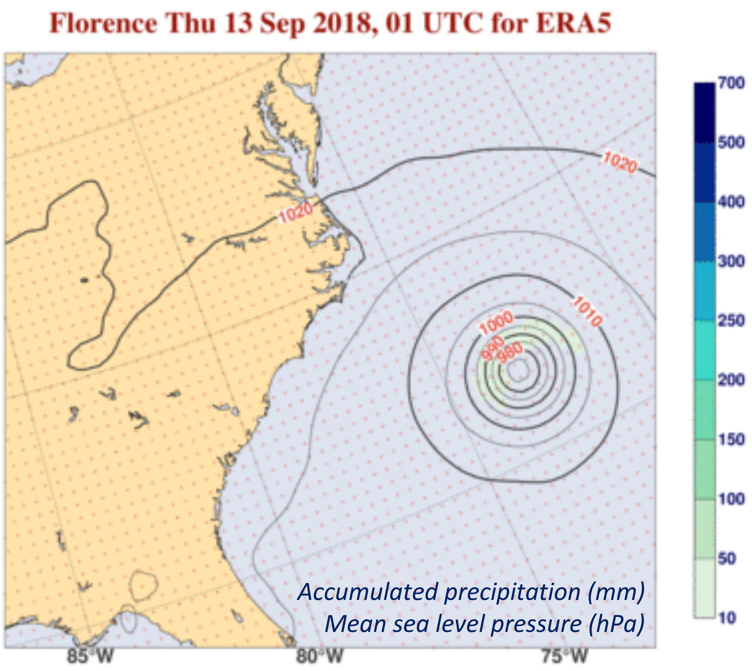
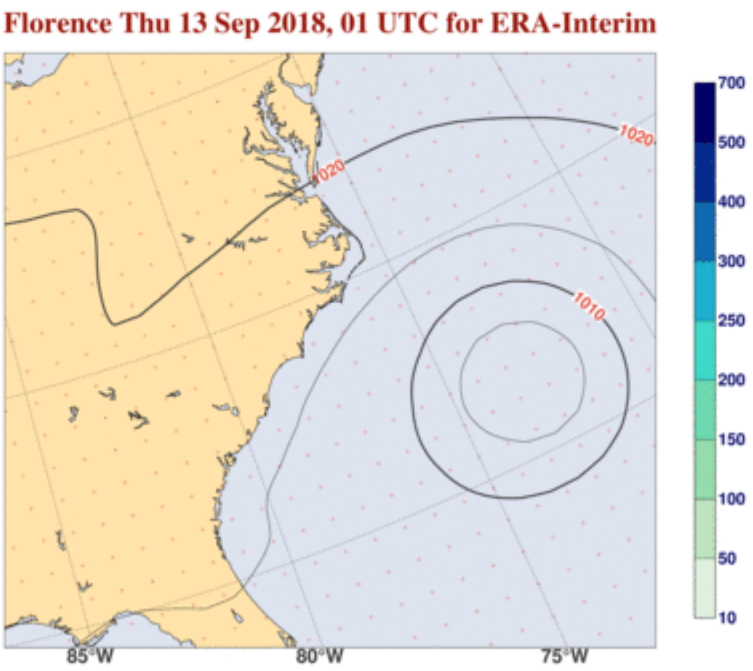
Better model, better and more observations, higher resolution, hourly output



ERA5



ERA-Interim

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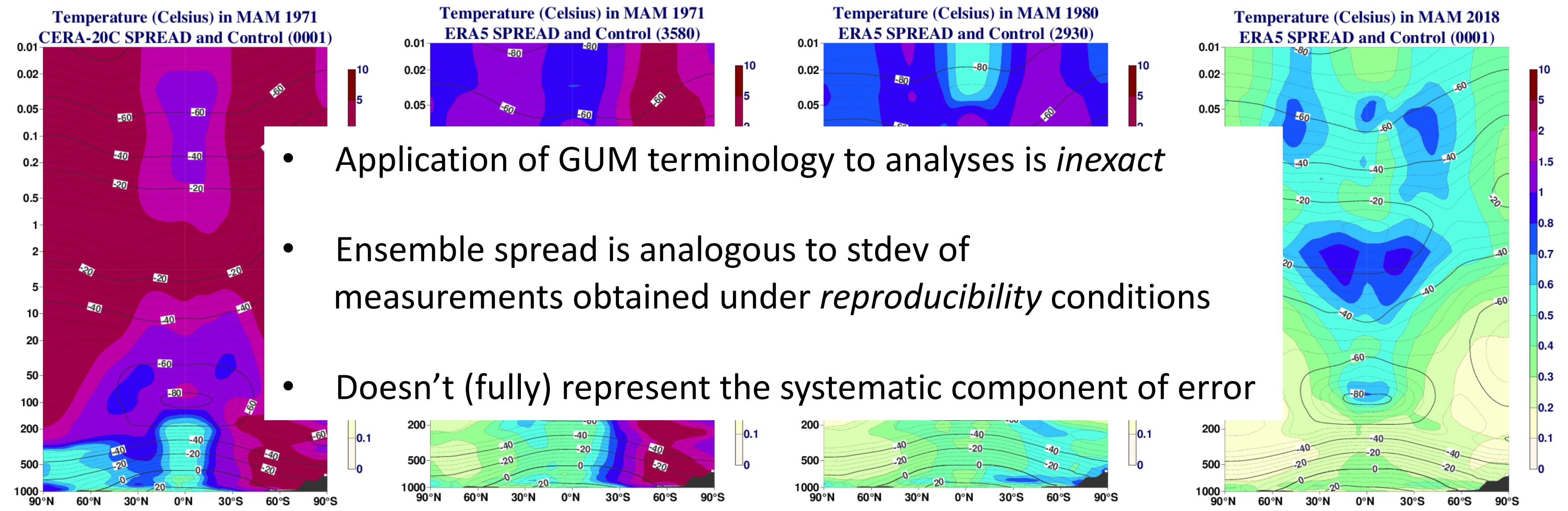
Ensemble spread (temperature)



- Application of GUM terminology to analyses is *inexact*
- Ensemble spread is analogous to stdev of measurements obtained under *reproducibility* conditions
- Doesn't (fully) represent the systematic component of error

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

1971 ERA5:
Upper-air data

1980 ERA5:
Early-satellite era

2018 ERA5:
Current observing system

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ERA5 data usage compared to ERA-Interim

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ERA5 data usage has increased from 0.75 (1979) to 24 million/day (2019).

87 Billion observations assimilated (1979 - 2019)

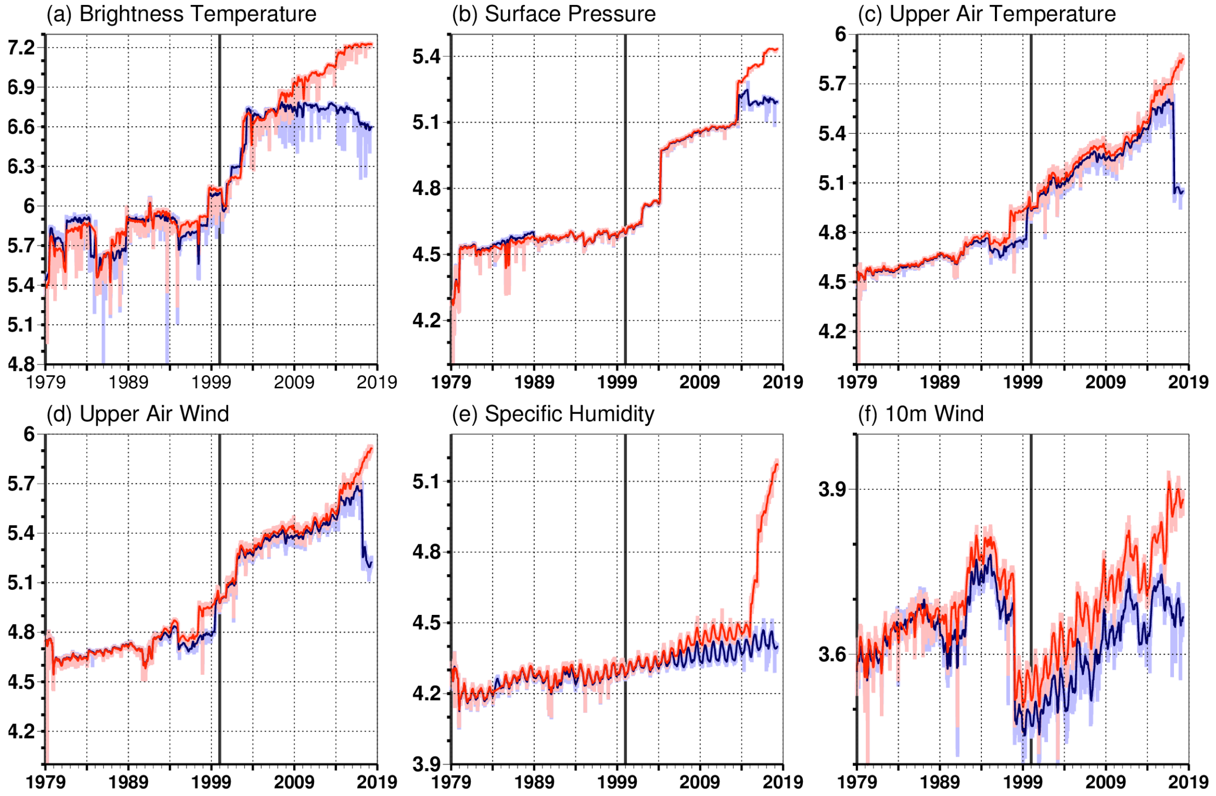
Over 200 types of reports:

- Reprocessed data sets
- Latest instruments
- Improved data usage

ERA-Interim is progressively getting outdated. It is *not* able to:

- use the latest instruments
- respond to changes in data format

*Number of used observations per day (log_{10} scale) for **ERA5** and **ERA-Interim***



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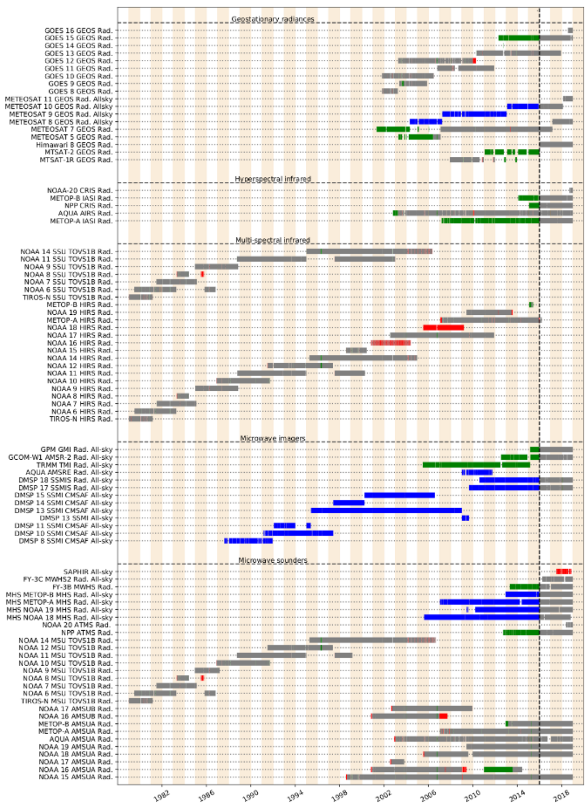
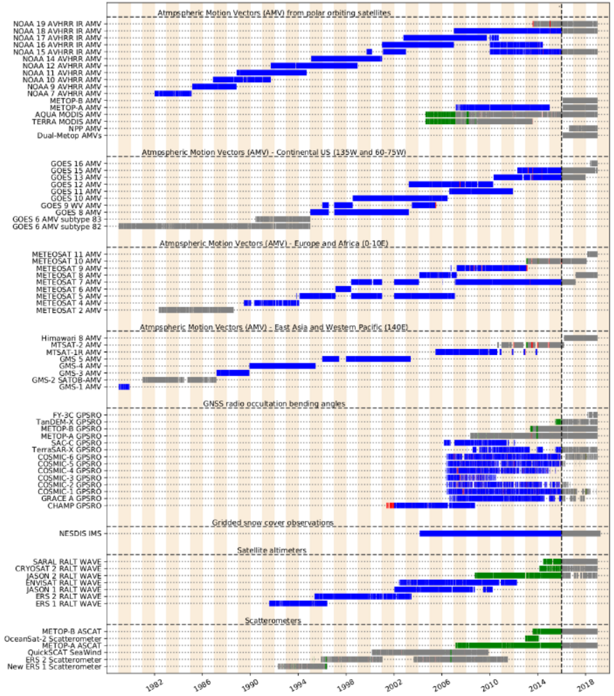
Observations assimilated in ERA5

Satellite radiances 1979-2019



Satellite non-radiances 1979-2019



Reprocessed data, or change in processing since ERA-Int

Same as ERA-Int

Not used in ERA5, but used in ERA-Int

Not used in ERA-Int, but used in ERA5

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Bias correction in reanalysis

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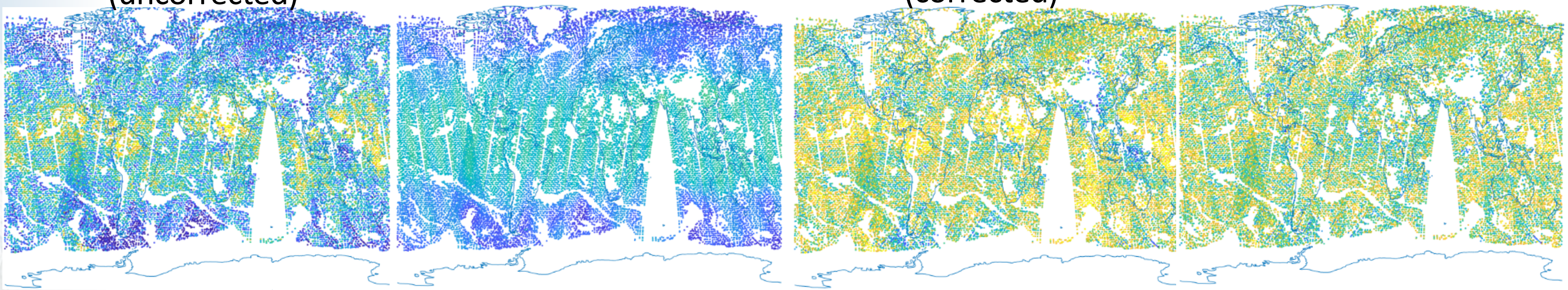
first guess departures (uncorrected) | bias correction | first guess departures (corrected) | analysis departures



NOAA-20 ATMS-7
ERA5 departures & bias correction

- Forecast model errors are ~0.1K for mid-trop. T- sounding channels
- Bias corrections (parametrised, accounting for radiometric & spectral biases, RT & forecast model biases) are larger
- Aims for future reanalyses:
  - Improved characterisation, minimisation & parameterisation of biases, through …
    - Reprocessing (the focus for C3S activities)
    - Improved calibration & traceability (this workshop, looking forward)
    - Improved forecast modelling
    - Improved RT modelling

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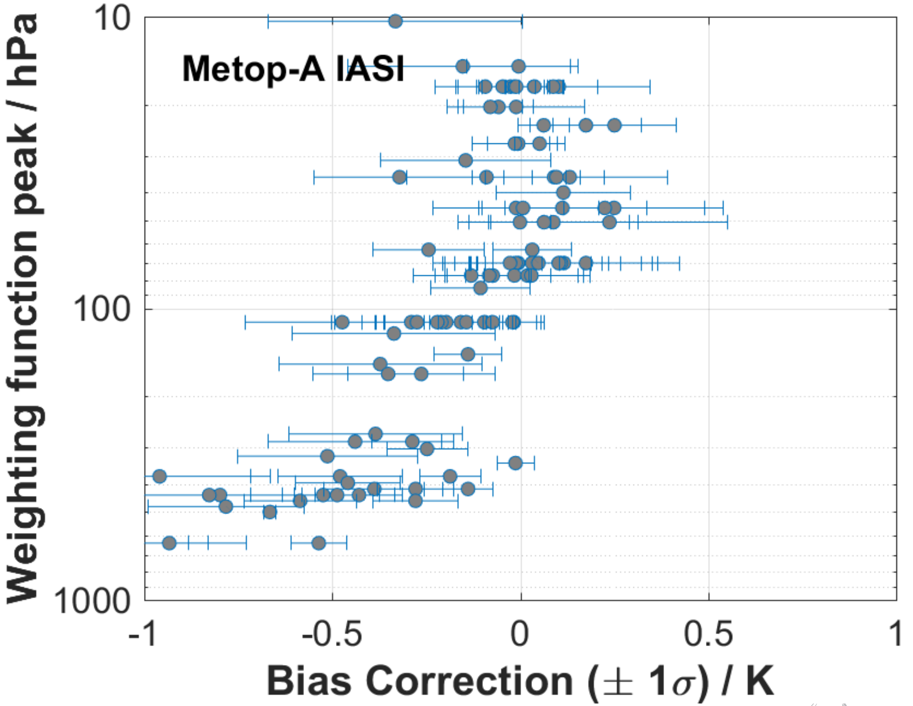
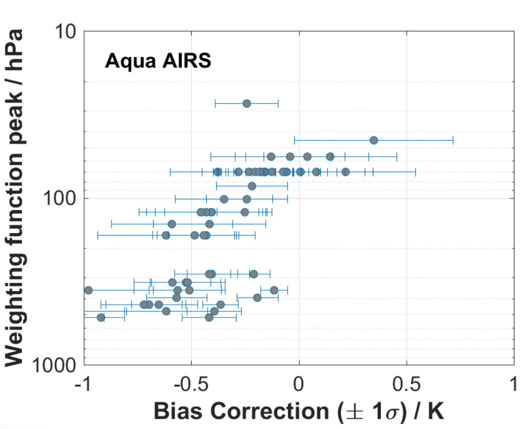
ERA5 Bias corrections

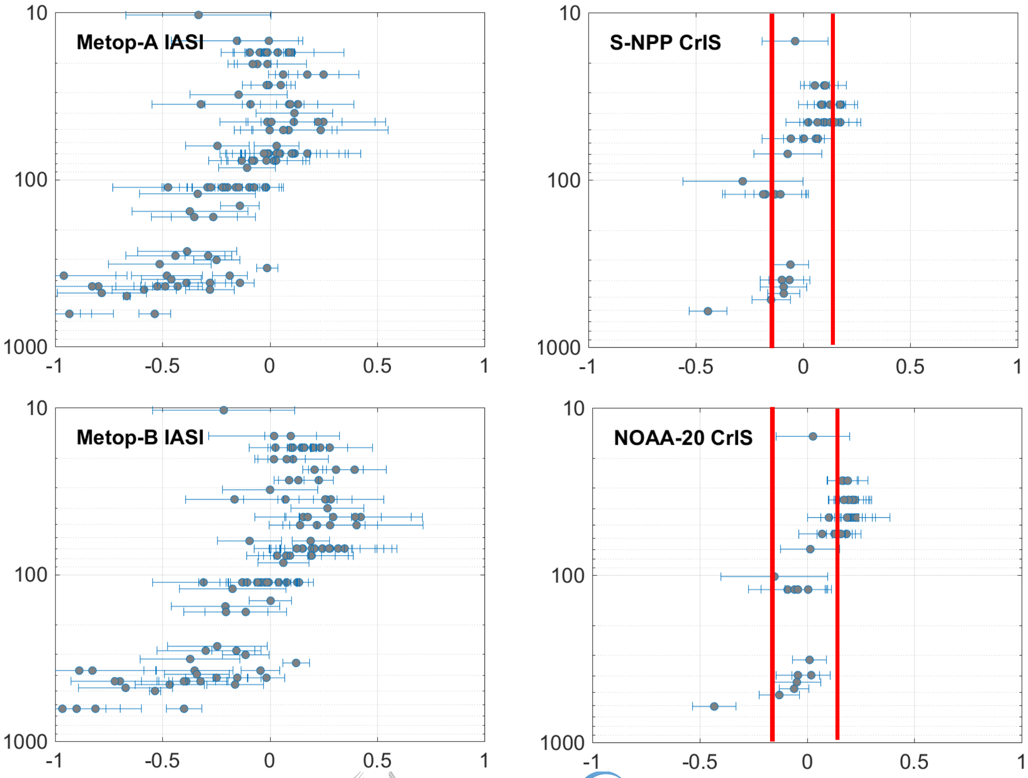


- One assimilation cycle 00Z 12/06/2019
- Temperature sounding channels shown (λ > 10µm)
- Error bars represent variation (±1σ) of applied bias corrections for all observations assimilated

ERA5 Bias corrections



- Metop-A IASI ~ Metop-B IASI & S-NPP CrIS ~ NOAA-20 CrIS
- Radiometric uncertainties for CrIS shown (0.14K at 3σ)
- Use uncertainties to <u>passively</u> assess consistency of analysis with observations



00Z 12/06/2019

VTPR Bias corrections (25th January 1973)

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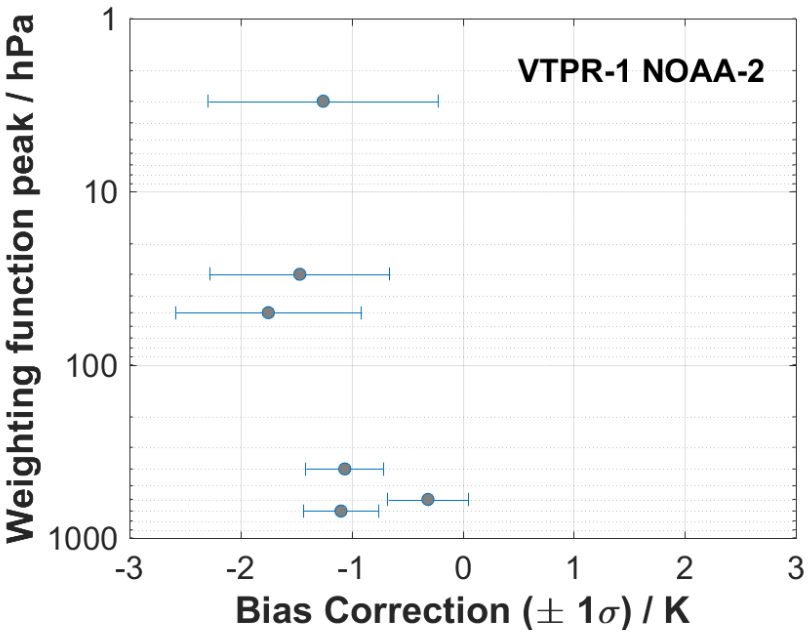

- T- sounding channels shown (CO_2 band)
- Bias corrections larger, at 1-2K typically
- Radiometric uncertainties unknown

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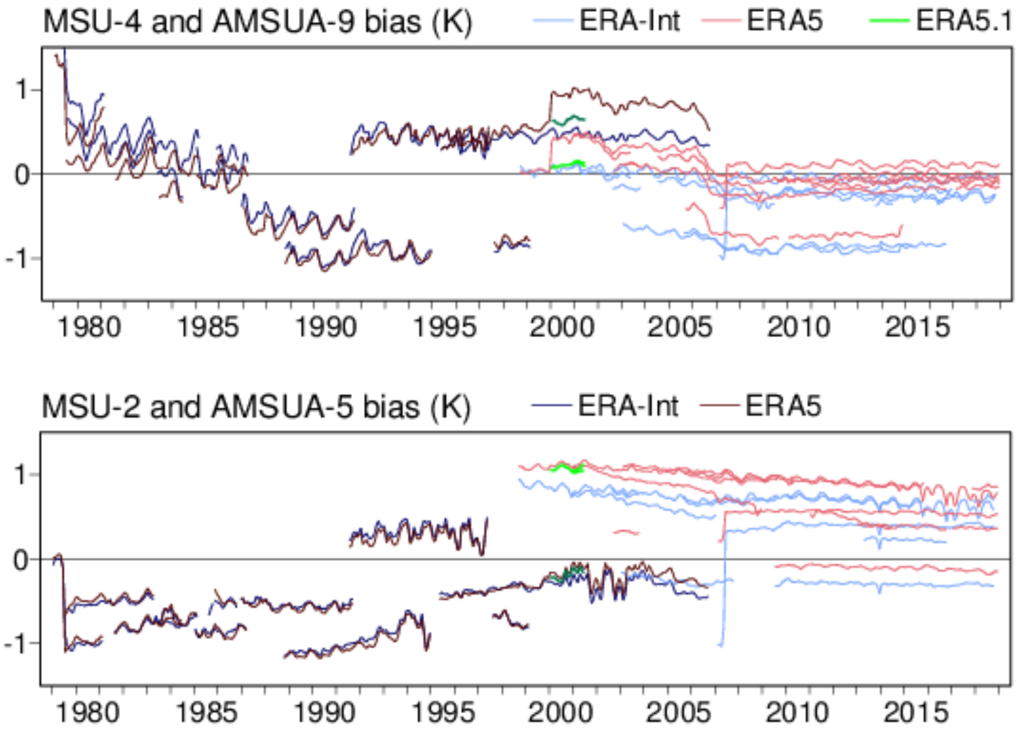
Bias corrections for microwave sensors



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Constrained variational bias correction

$$J(x,\beta) =$$
$$\frac{1}{2}(x_b - x)^{\mathbf{T}}\mathbf{B}_x^{-1}(x_b - x)$$
$$+\frac{1}{2}(\beta - \beta_b)^{\mathbf{T}}\mathbf{B}_\beta^{-1}(\beta - \beta_b)$$
$$+\frac{1}{2}[y - H(x) - b(x,\beta)]^{\mathbf{T}}\mathbf{R}^{-1}[y - H(x) - b(x,\beta)]$$
$$+\frac{1}{2}\gamma^2[b(x,\beta) - b_0]^{\mathbf{T}}\mathbf{R}_b^{-1}[b(x,\beta) - b_0]$$

Cost function J to be minimised measures misfit between ….

<u>state estimate </u>(x) and <u>background</u> (x_b) given background error covariance ($\mathbf{B}_x$)

Constrained variational bias correction

Climate Change

$$J(x,\beta) =$$
$$\frac{1}{2}(x_b - x)^{\mathrm{T}}\mathbf{B}_x^{-1}(x_b - x)$$
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Cost function J to be minimised measures misfit between ….

<u>state estimate</u> (x) and <u>background</u> (x_b) given background error covariance ($\mathbf{B}_x$)

<u>bias coefficients</u> (β) and <u>prior estimates</u> (β_b) given error covariance in bias coefficients ($\mathbf{B}_\beta$)

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Constrained variational bias correction

Climate Change

$$J(x,\beta)=$$
$$\frac{1}{2}(x_b - x)^{\mathrm{T}}\mathbf{B}_x^{-1}(x_b - x)$$
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Cost function J to be minimised measures misfit between ….

<u>state estimate</u> (x) and <u>background</u> (x_b) given background error covariance ($\mathbf{B}_x$)

<u>bias coefficients</u> (β) and <u>prior estimates</u> (β_b) given error covariance in bias coefficients ($\mathbf{B}_\beta$)

<u>observations</u> (y) and <u>model background equivalent</u> (H(x), where H is the observation operator) given the bias correction b(x,β) and observation error covariance (**R**).

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Constrained variational bias correction

$$J(x,\beta) =$$
$$\frac{1}{2}(x_b - x)^{\mathbf{T}}\mathbf{B}_x^{-1}(x_b - x)$$
$$+\frac{1}{2}(\beta - \beta_b)^{\mathbf{T}}\mathbf{B}_\beta^{-1}(\beta - \beta_b)$$
$$+\frac{1}{2}[y - H(x) - b(x,\beta)]^{\mathbf{T}}\mathbf{R}^{-1}[y - H(x) - b(x,\beta)]$$
$$+\frac{1}{2}\gamma^2[b(x,\beta) - b_0]^{\mathbf{T}}\mathbf{R}_b^{-1}[b(x,\beta) - b_0]$$

Cost function J to be minimised measures misfit between ….

state estimate (x) and background (x_b) given background error covariance ($\mathbf{B}_x$)

bias coefficients (β) and prior estimates (β_b) given error covariance in bias coefficients ($\mathbf{B}_\beta$)

observations (y) and model background equivalent (H(x), where H is the observation operator) given the bias correction b(x,β) and observation error covariance (**R**).

bias correction (b(x,β)) and prior estimate of bias (b_0) given the error covariance in bias ($\mathbf{R}_b$), and a regularisation parameter (γ)

Atmospheric physics

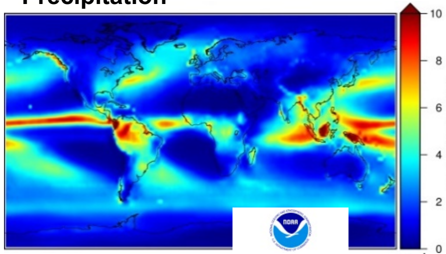
Climate Change

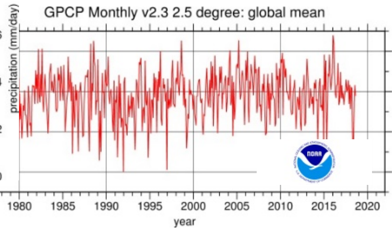
Addresses the following five Essential Climate Variables:

- Precipitation
- Surface radiation budget
- Earth radiation budget
- Water vapour
- Cloud properties

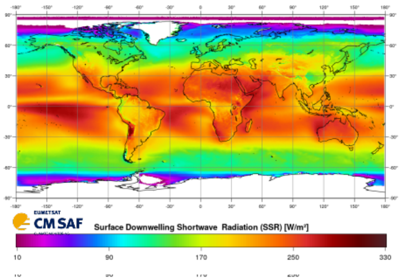
Examples of CDRs to be produced or brokered:

Precipitation

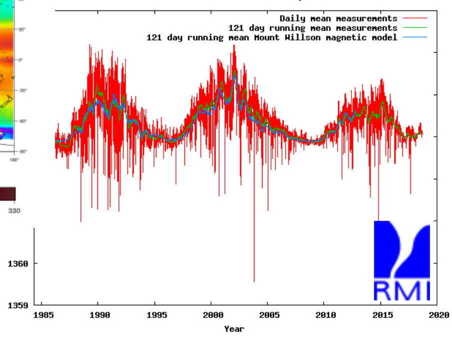




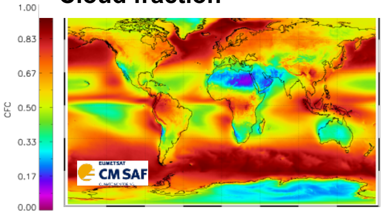
Surface radiation budget



Earth radiation budget



Cloud fraction



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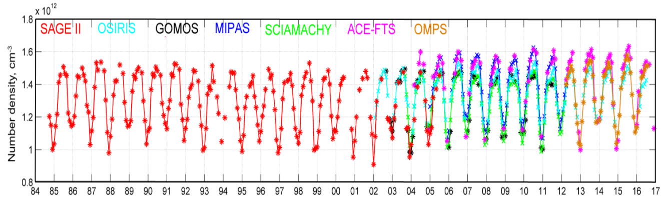
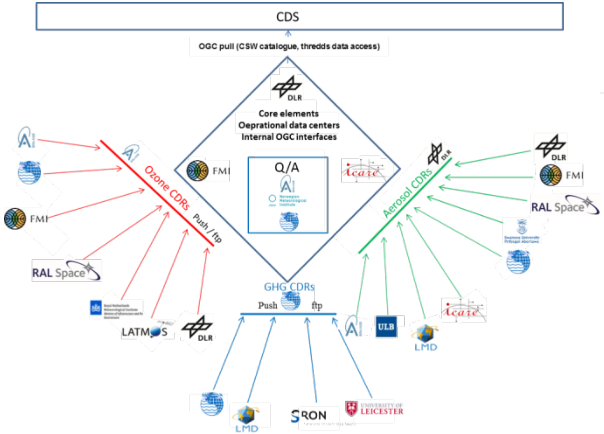
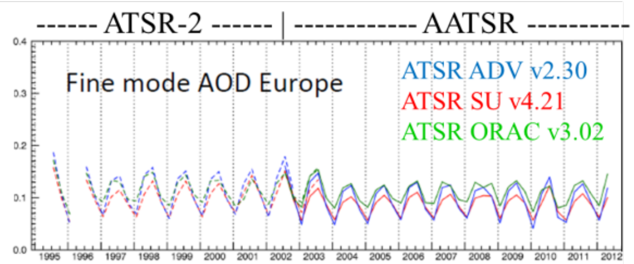
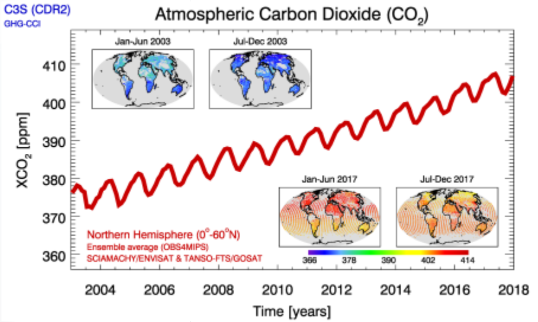
Atmospheric composition

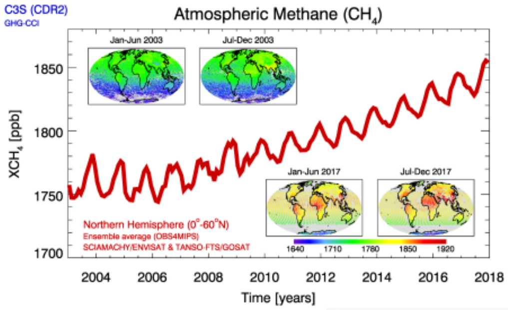
deliver to the Climate Data Store a suite of Satellite-based datasets on atmospheric composition covering several Essential Climate Variables:
ozone, aerosol properties, carbon dioxide (CO_2) & methane(CH_4)











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Ocean

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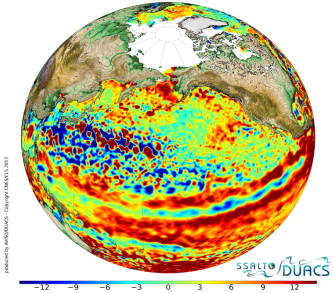
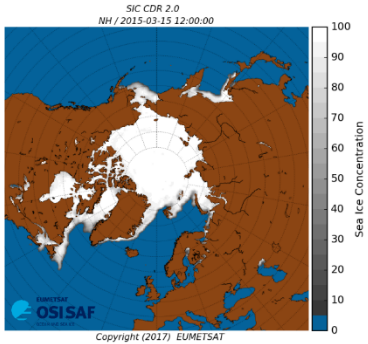
Sea Level

- Based on **satellite altimetry**
- **1993 to 2018**.
- Products are **daily gridded maps** (1/4°) of **Sea Surface Heights** and associated derived variables (**surface velocities**).



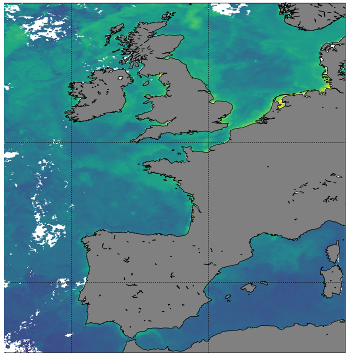
Sea Ice

- Four variables: Sea Ice **concentration**, Sea Ice **Thickness**, Sea Ice **Edge** and Sea Ice **Type**.
- **1973-2018**
- **Sea Ice concentration** is brokered from **EumetSat OSI SAF.**



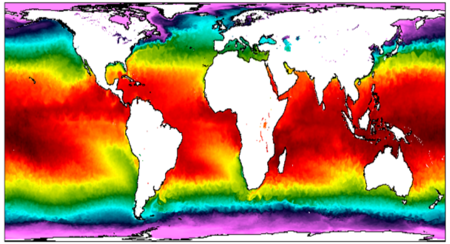
Ocean Colour

- **Two variables** for the **surface waters** of the **global** oceans: - Surface **reflectance**,
  - **Chlorophyll-a** concentration.
- **Based on 4 different sensors**
- **1997-2018**.
- **Products are gridded daily maps** (1/24°)



Sea Surface Temperature

- Based on **infra-red satellite radiometers**
- Data are processed using **consistent algorithms** from the **ESA CCI** project.
- **1981-2018**



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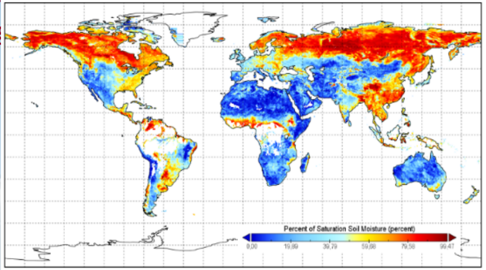
Land hydrology & cryosphere

Surface Soil Moisture



Percent of saturation soil moisture

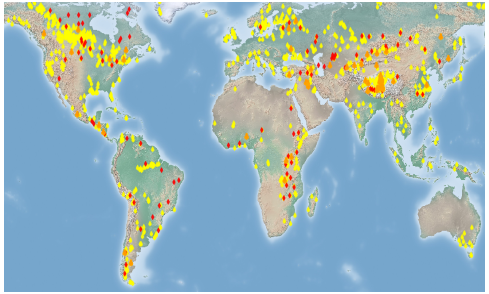
Passive sensors from 1978
Active sensors from 1991
Combined from 1978

3 Global products as CDR ; All provided as ICDR on a 10-day basis

Lakes

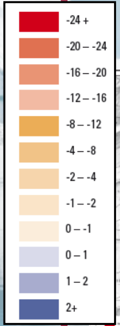
Lake Surface Water Temperature (CDR/ ICDR)
Targets 1000 lakes worldwide; from 1995; daily monitoring

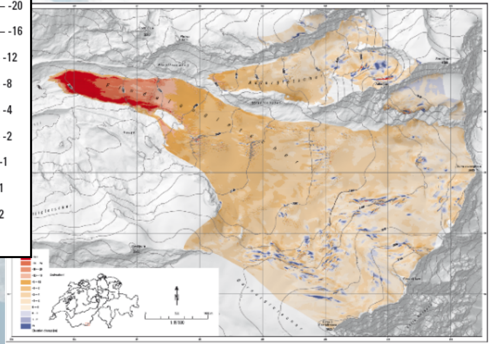
Lake Water Level (CDR/ ICDR)
Targets 155 lakes world wide;, From 1993; Daily to decadal monitoring



Lakes and Reservoirs monitored (Yellow: Lake Surface Water Temperature, Red: Lake Water Level : Orange (LSWT, LWL) both variables available

Glaciers





Findel Glacier, Zermatt (CH): Elevation Change 2005 to 2010: - 3.2m, Joerg et al. (2012), in WGMS (2012)

Glacier Area CDR/ICDR
globally complete glacier outlines;
> 30 years monitoring

Elevation Change CDR/ICDR
CDR from 1900 to present; ICDR focus on 2000-2015

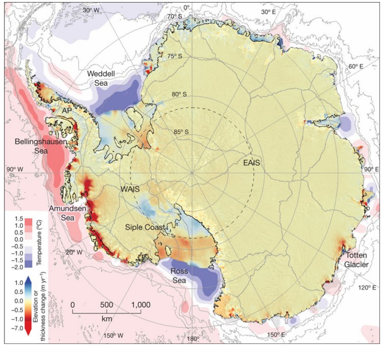
Mass Change CDR Annual update brokered from WGMS FoG database

Ice Sheets and Ice Shelves

Surface Elevation Change (CDR/ ICDR), Antarctic and Greenland from 1992, Monthly Updates

Ice Velocity (CDR/ ICDR), high resolution coverage, from 2014 for Greenland Ice Sheet

Gravimetric Mass Balance (CDR), Antarctic and Greenland from 2002 to 2017, Monthly basin values



*Surface Elevation Change: Shepherd, Fricker and Farrell, Nature **558**, 223-232, 13 June 2018*

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Climate Change

Land biosphere

Climate Change

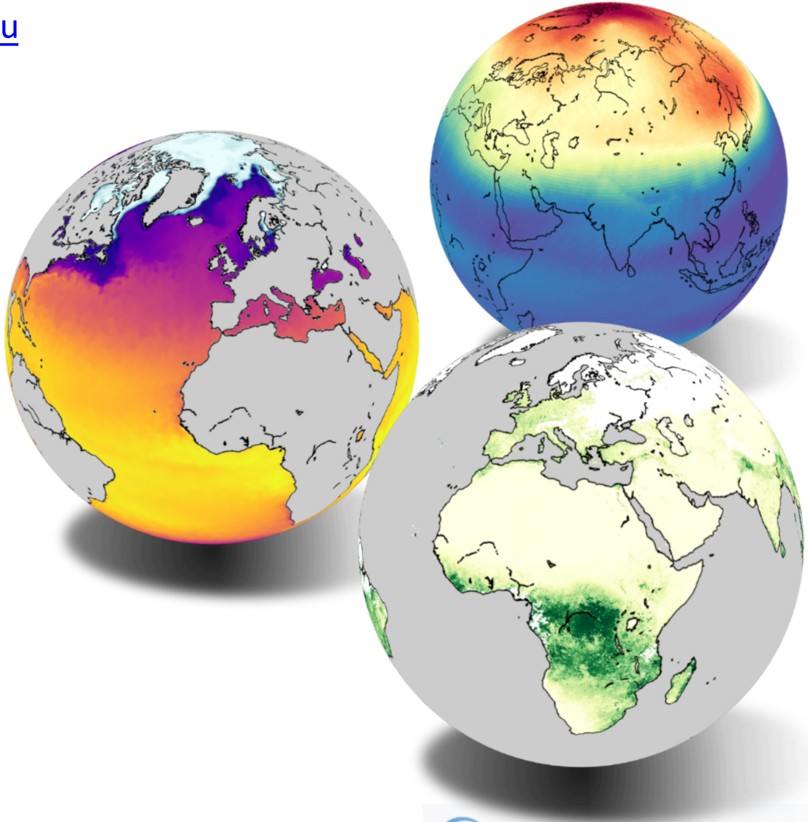
ECVs available on the CDS

https://cds.climate.copernicus.eu

Soil moisture
Glaciers
Leaf Area Index
fAPAR
Albedo

Ozone
Methane
Carbon dioxide (CO_2)

Sea ice
Sea surface temperature
Sea level



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Summary, conclusions and future perspectives

- The Copernicus Climate Change Service (C3S) provides a suite of data-products to support a large, diverse and growing user-base in addressing climate change issues. Reanalyses and ECVs from satellite observations form part of that suite, the quality of those depend on the associated observational uncertainties – driving a *general* need for traceable observations.

- Atmospheric reanalyses are already a key tool in assessing global trends & regional variability in the atmospheric state. Successive reanalyses, over the coming decades, will deliver ever higher accuracies at finer spatial scales (*due to improved forecast models, data assimilation methods, reprocessed observations, new & traceable observations*). ERA6, for example, is planned to start 2023.

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Summary, conclusions and future perspectives

- Future reanalyses will see ever greater degrees of integration & coupling between the components of the Earth System (ocean, land, atmospheric composition, …) - providing a more natural and optimal framework for extracting information from Earth observations.

- Estimation of **mean state uncertainties** remains a challenge for reanalysis, and requires new ideas and approaches.

- There are specific approaches that could usefully exploit uncertainty information:

    - (v. short-term) by **passively** assessing the consistency of bias corrections and observational uncertainties – for those observations where uncertainties are available

    - (medium-term) by **actively** using uncertainty information to constrain bias corrections (*eg* using CVarBC).

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More information

The ERA5 Global Reanalysis

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- In the meantime, see: Hersbach *et al* 2018, *Operational global reanalysis: progress, future directions and synergies with NWP* (from https://www.ecmwf.int/en/publications/)
- For ERA5 data from the C3S Climate Data store: https://cds.climate.copernicus.eu

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Improved 2m temperatures (wrt to ERA-Int)

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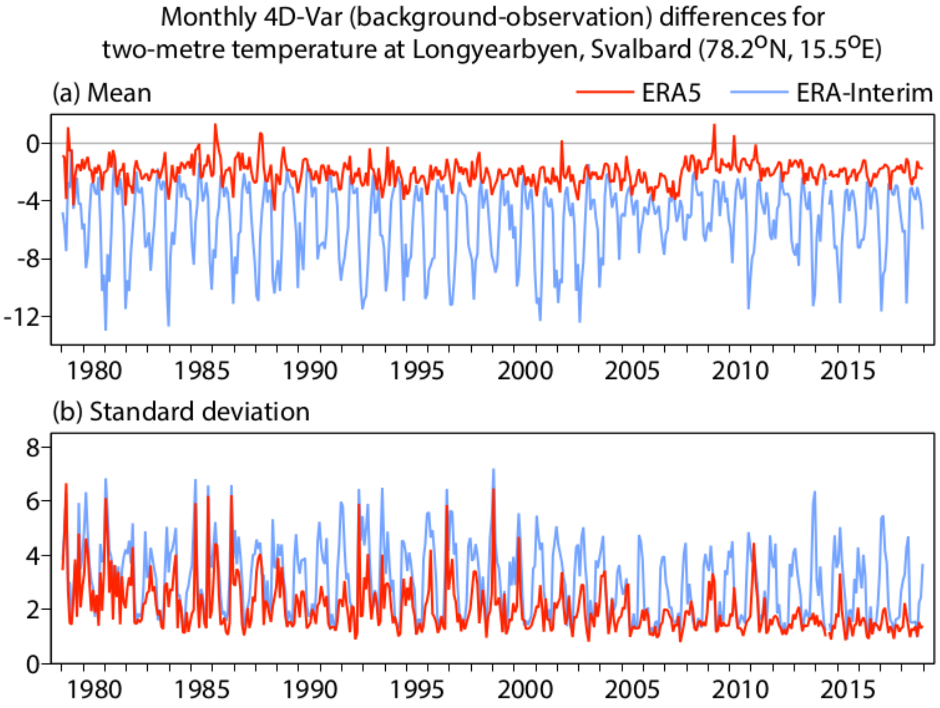

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