Global and regional reanalysis needs for current satellite observations

from the perspective of C3S activities

Climate Change

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European Commission

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Overview

- **Overview of C3S reanalysis activities**
- The principle of reanalysis
- Some details on data usage in ERA5
- Needs for current satellite observations
- Final remarks

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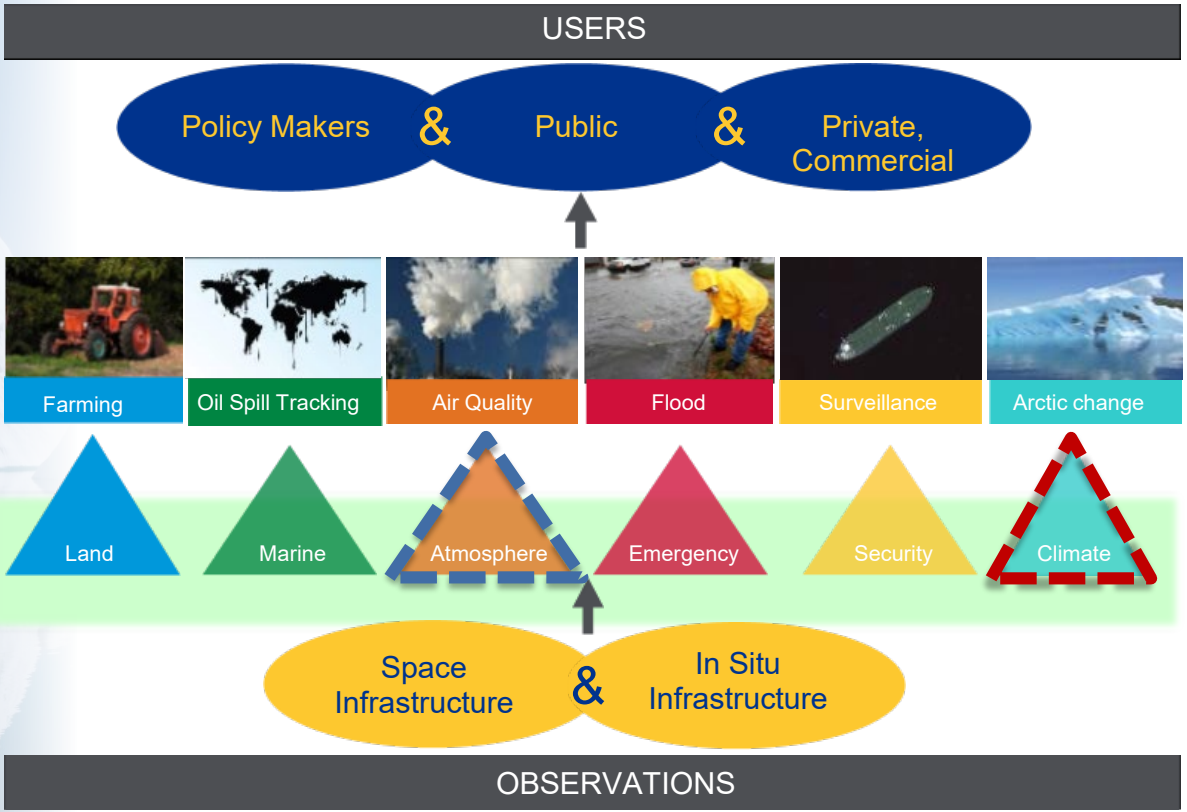
The Copernicus Climate Change Service



Different Needs

Examples of areas covered

6 Information Services

Sustainable observation capabilities

ECMWF operates the Copernicus Climate Change Service (C3S) and Copernicus Atmosphere Monitoring Service (CAMS) on behalf of the European Commission.

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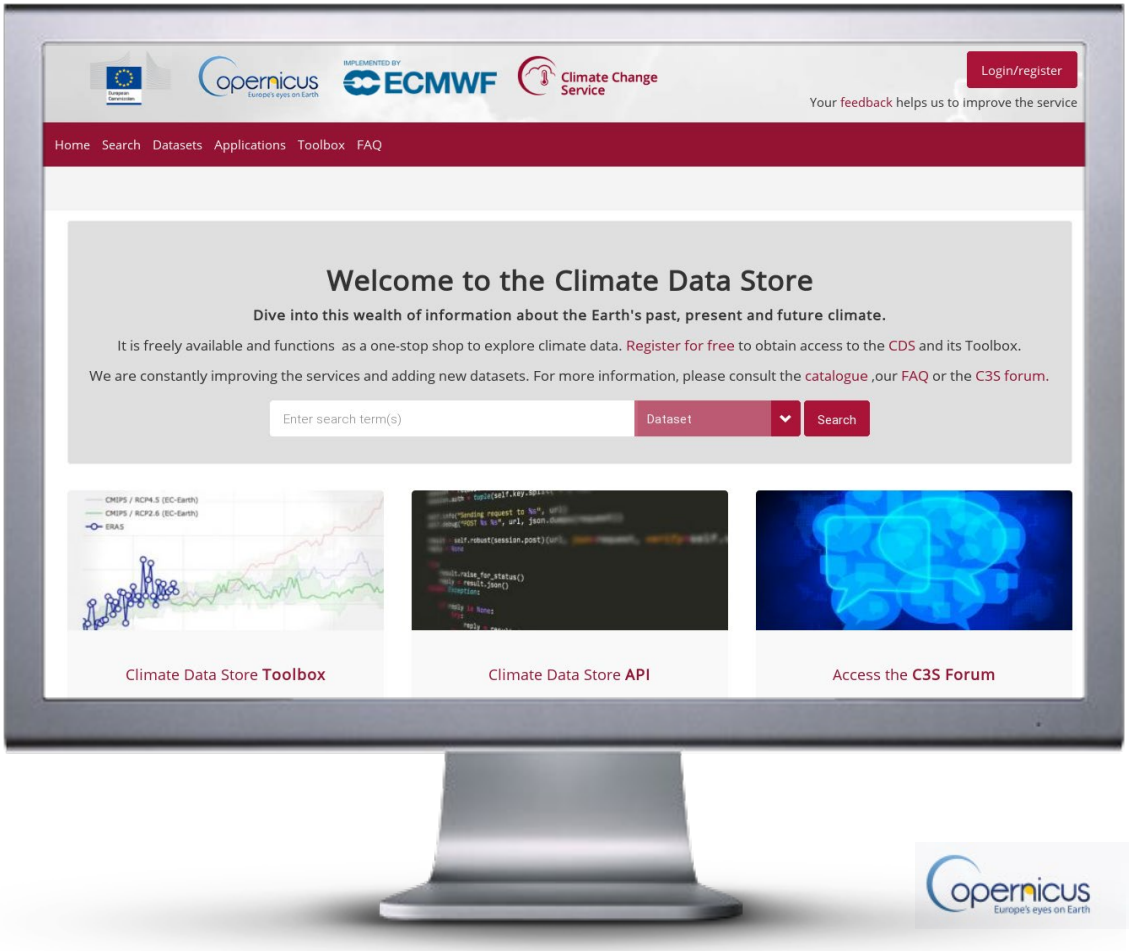
The C3S Climate Data Store



Climate Data Store content

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C3S ECMWF: Global Climate Reanalysis
C3S_322: Regional Reanalysis for Europe and the European Arctic
C3S_312a/b: Satellite-based ECV products
C3S_311a: In situ observations
C3S_311b: Satellite data reprocessing
C3S_311c: Support for climate reanalysis including satellite data rescue

Observations	Global estimates of ECVs from satellite and in-situ observations	Reprocessed CDRs, reference observations	Support for data rescue, climate data collections
Climate reanalysis	Global atmosphere, ocean, land	Regional reanalysis for Europe	Coupled climate reanalysis for 100 years
Model output	Multi-model seasonal forecast products	Access to CMIP data and products (global and regional)	Reference set of climate projections for Europe

Climate Indicators

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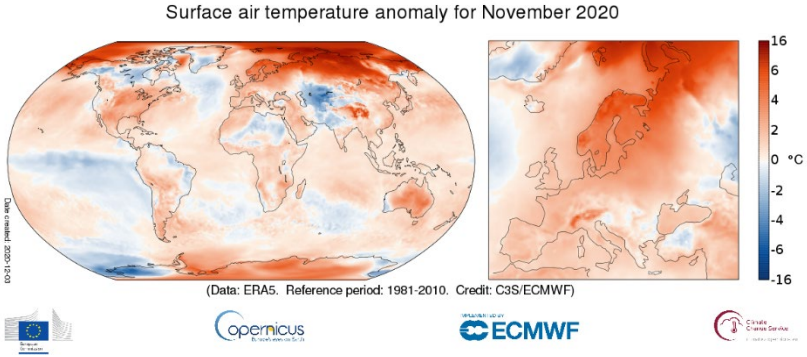
The ERA5 global reanalysis

ERA5 is in production at ECMWF for C3

Atmosphere, land, ocean waves

ERA5 has replaced ERA-Interim

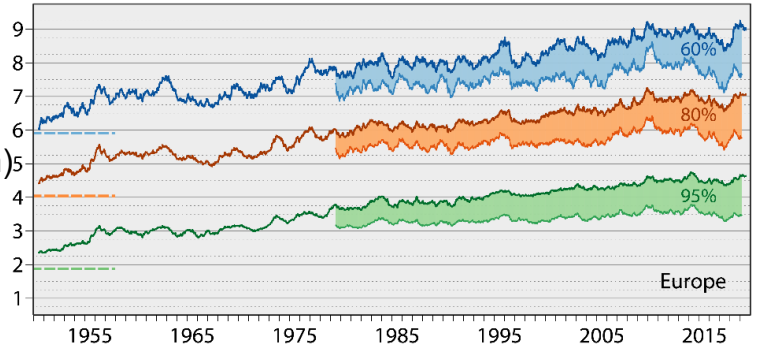
(ERA-I was stopped end August 2019)



Improvements compared to ERA-Interin

- Benefit from additional 10 years R&D development
- Much higher resolution; **31km** versus 80km
- More and better input data
- **Hourly output**
- 10-member EDA-based **uncertainty estimate** (at 63km)
- Continued close to real time; latency of 5 days

- Reaches further back in time (1950 versus 1979)
  (highest quality over data rich areas)



Forecasts from ERA5 have higher skill than those from ERA-Interim

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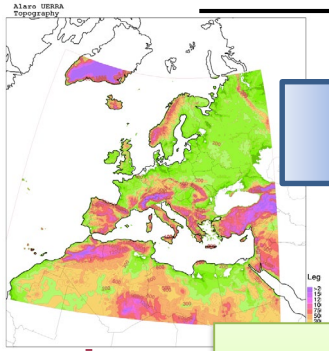
Copernicus regional reanalysis for Europe (CERRA)

2017 | 2018 | 2019 | 2020 | 2021



UERRA system in near real time (11km resolution)

HARMONIE ALADIN model and 3D-VAR with ensemble information

New system in operational mode (5.5km resolution)

Development of the new system

EDA system (10 members at 11km resolution)

User support and guidance

Uses satellite observations

- **11 km** (565x565 grid points), 65 levels
- Surface downscaling analysis 5.5 km (MESCAN)
- 1961 to July 2019 (no timely updates)

- **5.5 km** (1069x1069 grid points), 106 levels
- Surface analysis at 5.5 km – no downscaling
- Plus 10 ensemble members at 11km
- Started from September 1984

Contractor : SMHI – subcontractors: Météo-France - MET Norway

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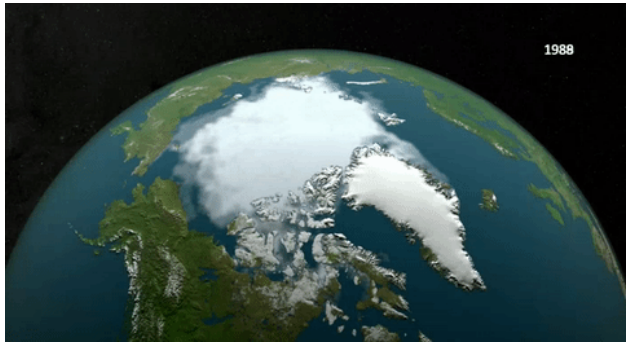
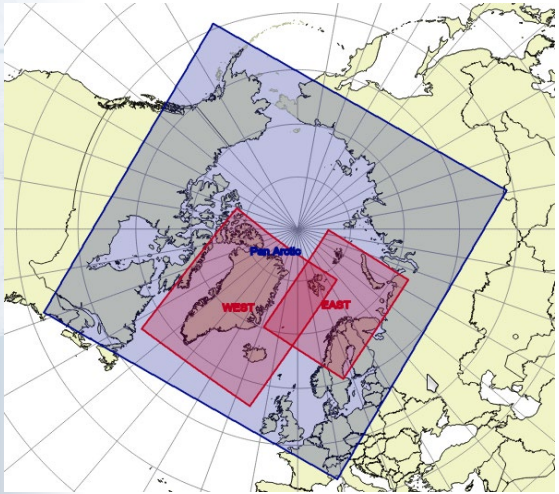
Copernicus Arctic Regional Reanalysis (CARRA)

Met Norway (lead), the Nordic countries and Météo-France.

- Warming in the Arctic (observational records and future scenarios) roughly twice as high as global average
- Need for understanding and management of change processes
- Increased economic activity in the region



Animated gif: NASA



- Two domains, main areas of interest in the European sector of the Arctic
- High resolution, **2.5 km,** adds value to global products
- Reanalysis period July 1997 – June 2021 (24 years)
- Extensive use of satellite data
- Use local surface observation datasets available in the partner countries
- Special emphasis on NWP schemes and observations for the handling of "*cold surfaces*": Snow, sea ice, glaciers
- One year proof of concept (grey area) pan-Arctic reanalysis at **3.75km**.

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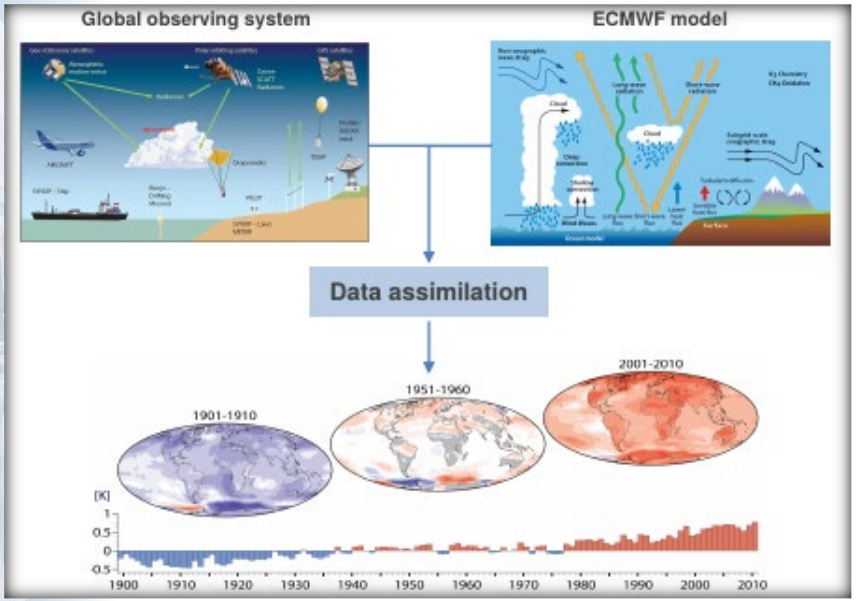
Reanalysis uses past observations with today's weather model

The data from reanalysis are widely used (39,000 users of the ERA5 reanalysis, so far)



- ✓ Complete: combining vast amounts of observations into (global) fields using data assimilation
- ✓ Consistent: use the same physical model and data assimilation system throughout
- ✓ Convenient: "maps without gaps", always available in the same way
- ❖ *Observations are absolutely key!! availability has evolved drastically over time*
  - ➢ Reanalysis uncertainty product is important

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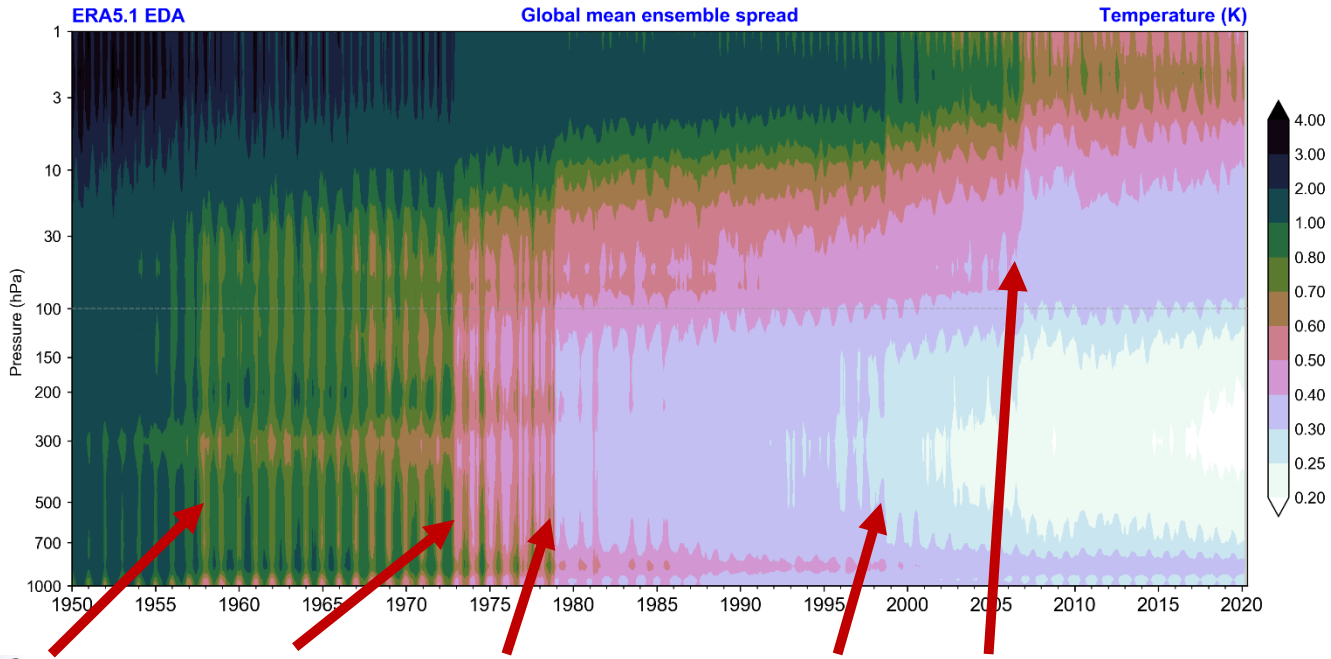
Ensemble spread as a measure for the *synoptic* ERA5 uncertainty

Spread decreases over time when more and more observations become available

Major changes in the observing system are clearly visible



ANNÉE GÉOPHYSIQUE INTERNATIONALE 1957 1958 INTERNATIONAL GEOPHYSICAL YEAR

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The ERA5 observing system

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0.75 (1979) – 24 Million (2019) obs per day
Over 200 types of reports

Reprocessed data sets

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

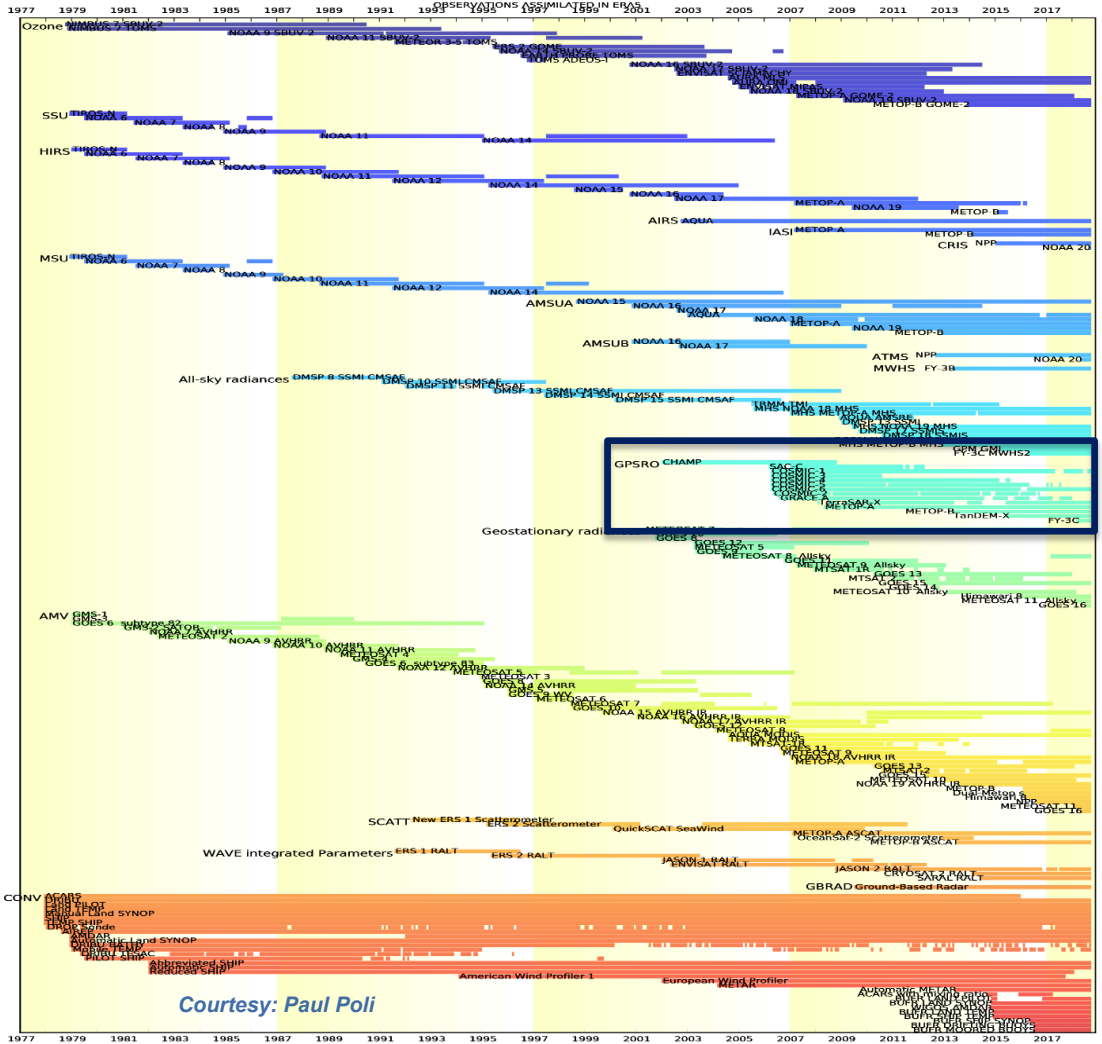
Wave Height: ERS-1,ERS-2, Envisat, Jason

Latest instruments

IASI, ASCAT, ATMS, CrIS, MWHS, Himawari, …

Improved data usage

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



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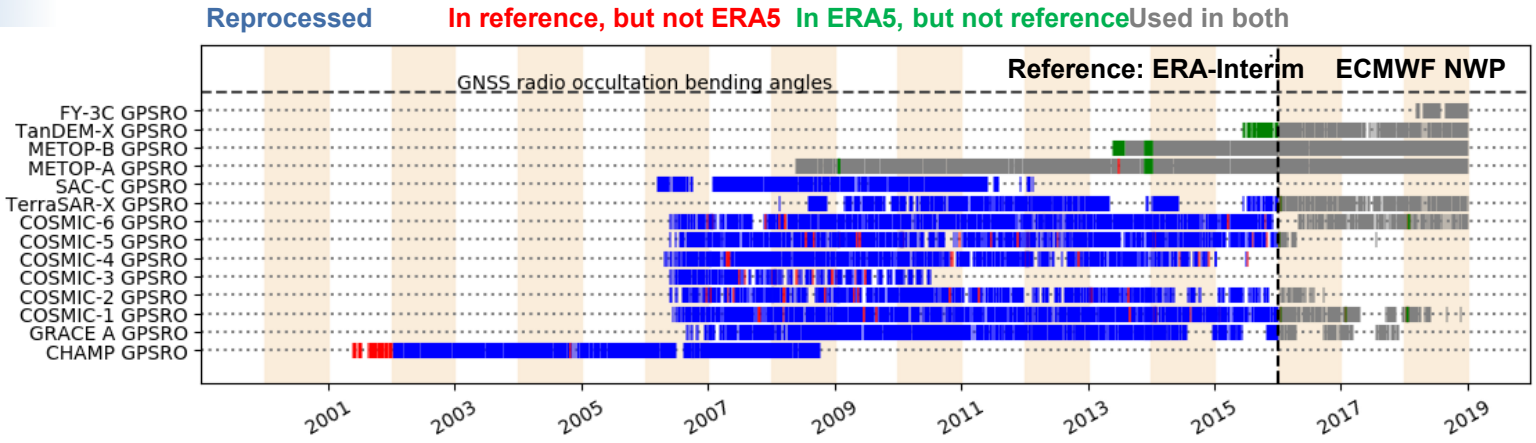
GNSS-RO observations assimilated in ERA5



Reprocessed (from UCAR):

CHAMP, GRACE-A, SAC-C

TerraSAR-X, COSMIC 1-6

Operational product:

METOP-A, B and C (from March 2019)

TanDEM-X

FY-3C

KompSAT-5 (from end July 2019)

COSMIC 2 (from March 2020)

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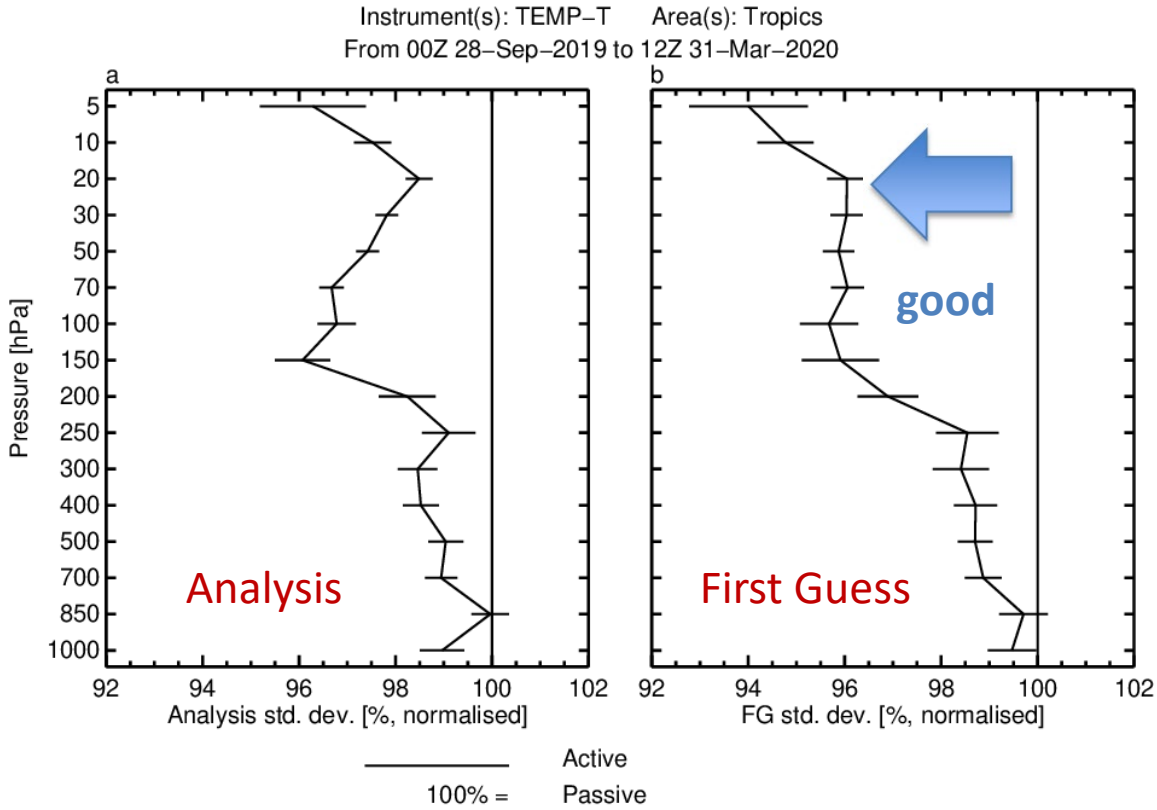
Positive impact of COSMIC 2 ; improved fit of radiosondes to the **NWP** model



Courtesy: Sean Healy

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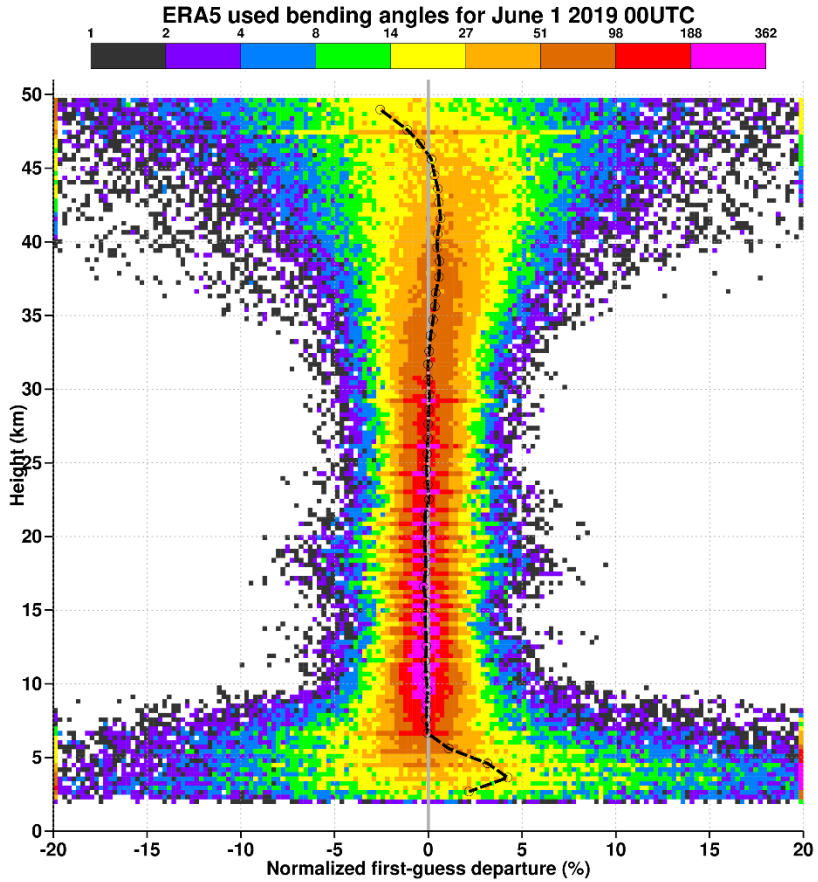
Assimilation of GNSS-RO data in ERA5; use bending angles rather than level 2 retrievals



Observation operator for bending angle:

- ✓ 2-Dimensional
- ✓ account for both temperature and humidity
- ✓ account for tangent drift point

Assimilation:

- ✓ Increased weight compared to ERA-Interim
- ✓ Use from 2-50 km

Anchor measurements

- ✓ Do not bias correct
- ❖ Note: radiosonde temperatures *are* subject to *prescribed* corrections (RICH)

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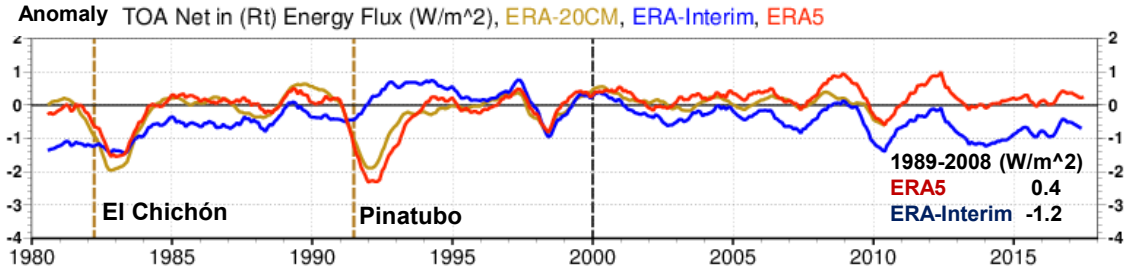
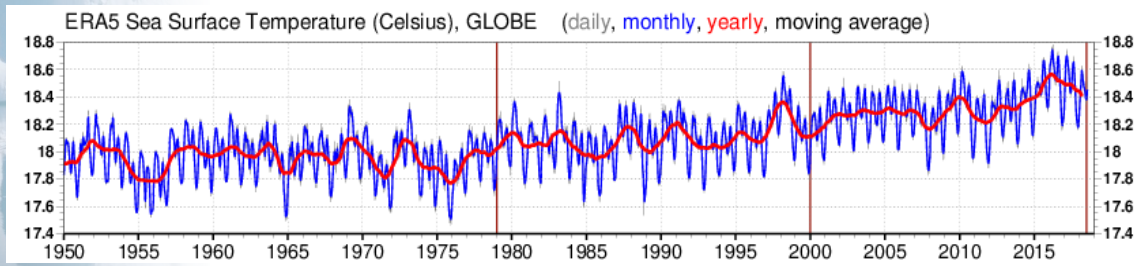
ERA5 forcing appropriate for climate; these are ingested ‘as is’ and need to be level 4

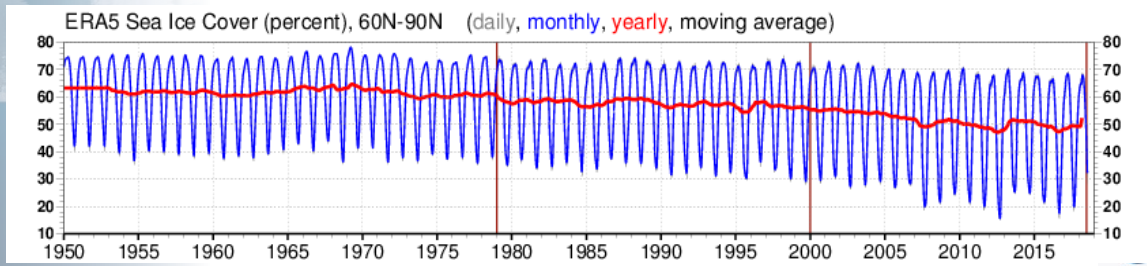
CMIP5 recommended data sets

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

*(Prepared in the ERA-CLIM project, ERA-20CM, **Hersbach et. al., 2015**)*







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)

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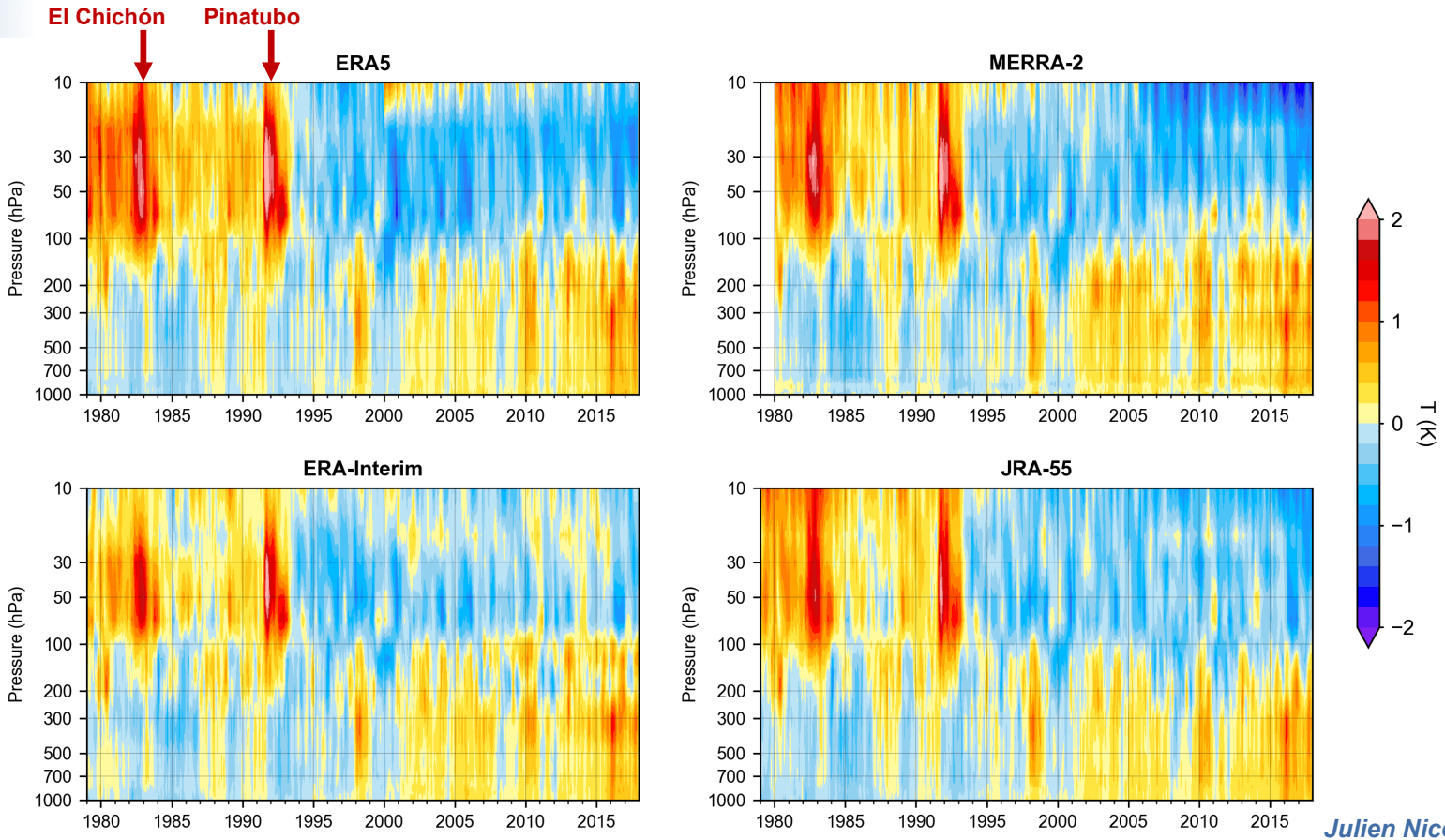
Intercomparison with reanalysis products from other major centres



Julien Nicolas

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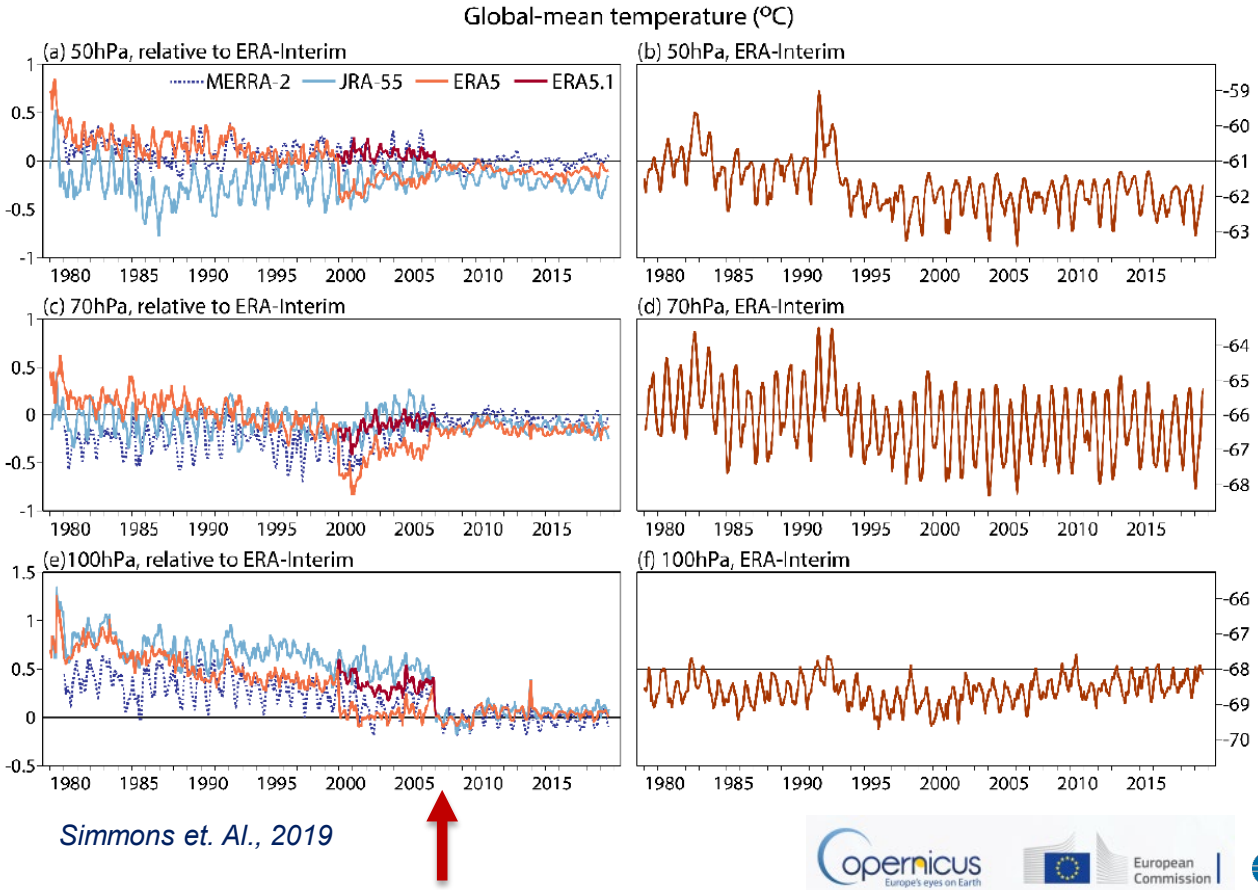
Inter-comparison of global reanalyses: convergence from 2006 COSMIC anchor observations



Simmons et. Al., 2019

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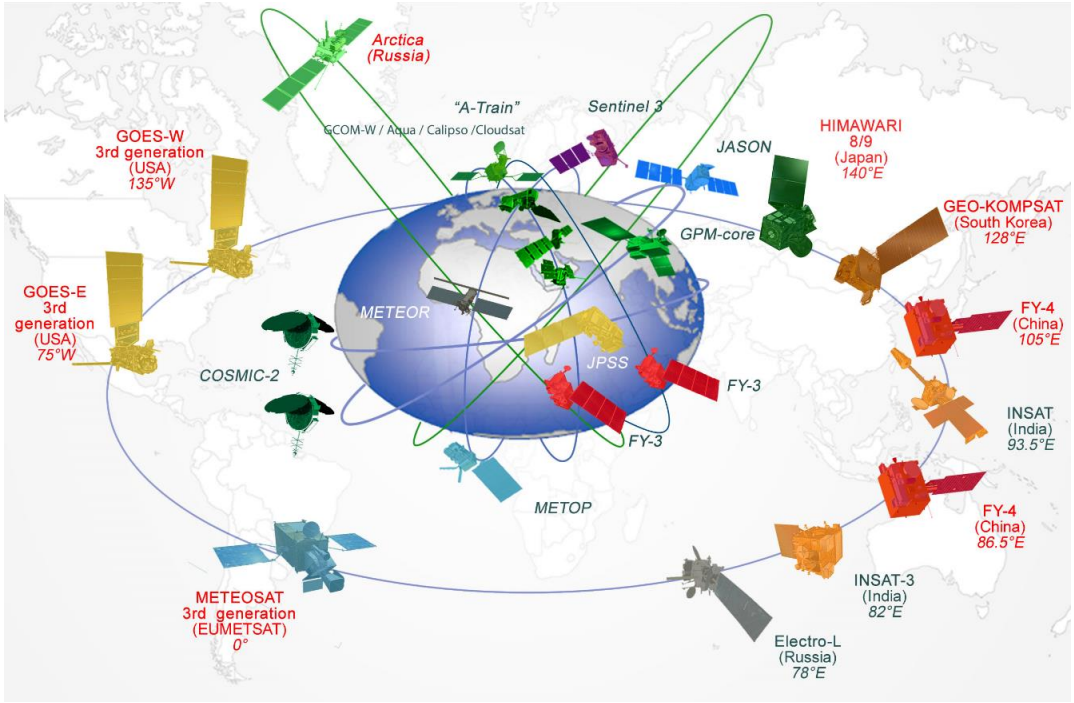
WMO Integrated Global Observing System



In 2020 there are **190** active satellites supporting weather, climate, earth system and space weather

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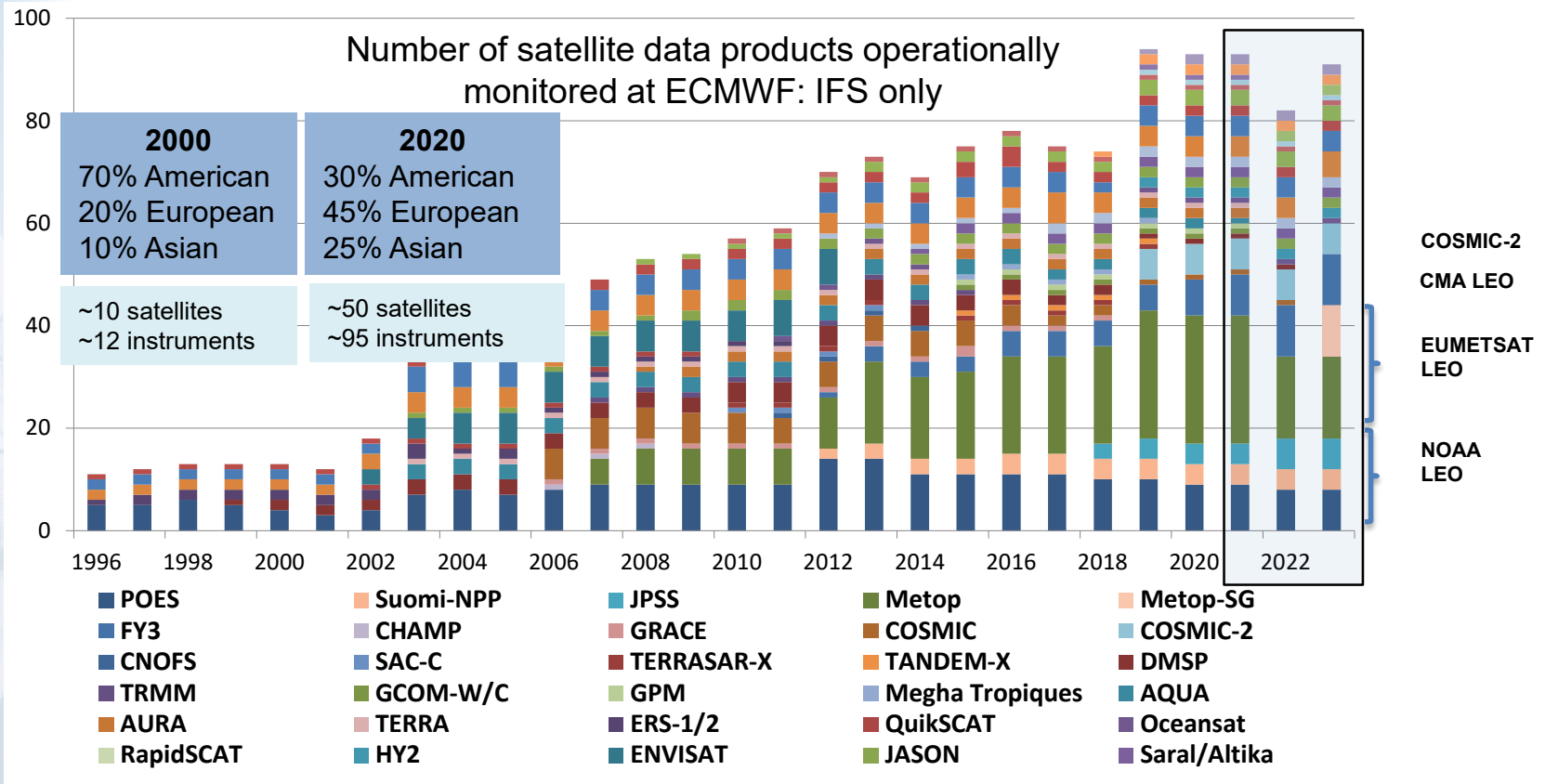

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Impact of observing systems in the ECMWF NWP system, January 2020 (FSOI based)

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Reanalysis enjoys a ***synergetic*** relationship with NWP:

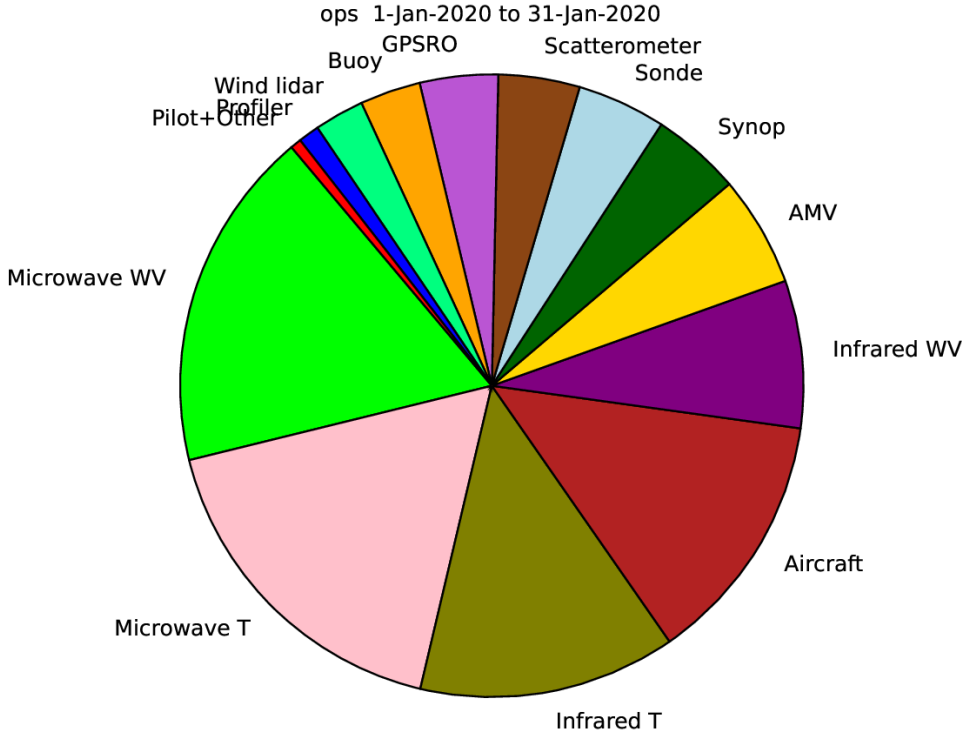
- essentially uses the same observing system, and;
- uses the data assimilation system developed for NWP
- Both global and regional

Therefore, the requirements for reanalysis are *largely* the same as for NWP:

- Continuation of the main components of the satellite observing system: radiances (IR & MW), RO, Scat & AMVs are important, as well as the likely evolution (*e.g.* Aeolus DWL for tropical winds)

However, there are some differences:

- **Requirement for NRT data** is more relaxed, enabling the use of research missions (*e.g.* MLS O_3);
- **Accurately representing the whole atmosphere** is more important for reanalysis, regardless of forecast skill, *eg*:
  - stratospheric humidity (MLS H_2O);
  - upper stratospheric & mesospheric temperatures (SSMIS Upper Atmospheric Sounding channels)
- **Anchor missions** and high quality calibration will, most likely, become increasingly critical for RA (*e.g.* RO + CLARREO-like missions + TRUTHS)



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In addition

Reanalyses typically directly assimilate satellite observations

- Level 1B radiances rather than level 2 retrievals

Reanalyses typically use online bias-estimation methods

- However, the stability of satellite products remains important

ERA5 is maintained close to NRT

- Use the same input streams in the ECMWF operational observation stream for those observations we share
- For the 'historical part' access to the best data (like reprocessed) is very important, though
- Tries to keep in pace with ingesting the latest instruments; not always possible (need for new generations of reanalysis)

Reanalyses need in addition appropriate forcing fields and continuity of these is absolutely essential

- SST, sea-ice cover, ~~greenhouse gases, aerosols~~, surface physiographic dataset (Arctic reanalysis)
- These are typically taken 'as is' as level 4, so they need to be complete, accurate and guaranteed.

Special requirements for regional reanalysis

- E.g. high horizontal resolution (AMVs, Geo hyperspectral-IR, MVIRI, SEVIRI)
- Snow cover, satellite glacier albedo (both from IR imagers), high-res sea ice (including the Baltic), soil moisture

The availability of high-quality conventional observations remains essential

- Ground truth, used for calibration of satellite observations, etc.

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Final remarks and outlook for future C3S reanalysis-related activities

Reanalysis provides 'maps without gaps' and are able to deliver consistent estimates based on the entire observing system, rather than focused on a specific subset.

The ongoing production of ERA5 and regional reanalysis is undertaken within the Copernicus C3S framework at ECMWF as part of the C3S operational service.

Many reanalysis-related tasks are being carried out by C3S providers:

- satellite reprocessing (EUMETSAT), data rescue, consolidation of historical datasets, to be fed into ERA6
- the production of two high-resolution regional reanalyses, for Europe and the Arctic

ECMWF's vision for C3S post-2020 continues to allocate a high priority to reanalysis:

Potentially expanding ERA5 further back to 1940 or earlier.

Next full-observing-system coupled reanalysis (ERA6)

- State-of-the-art NWP system, coupled with the ocean
- CMIP6 forcing
- Improve the handling of model bias
- Improve the uncertainty estimate, especially for the mean state
- Production to start early 2024

Next high-resolution regional reanalyses going further back in time

- Truly pan-Arctic reanalysis

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Back-up slides

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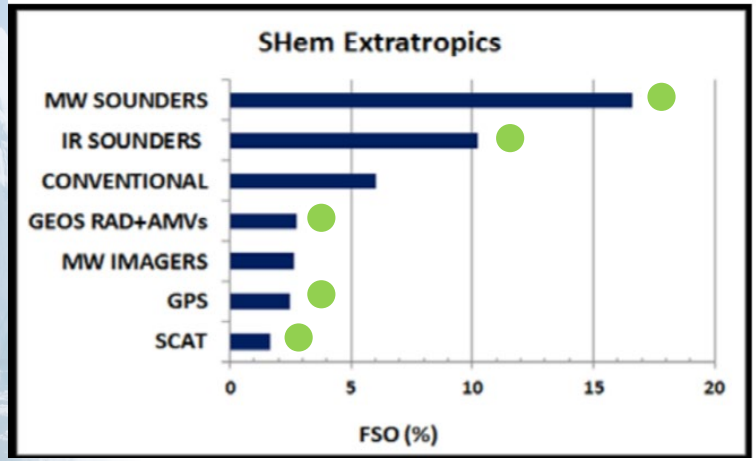
What is new in ERA5?

	ERA-Interim	ERA5
Period	1979 – present	***1950 – present***, produced in 2 phases
Availability behind real time	2-3 months	2-3 months (final product) ***2-5 days*** (ERA5T)
Assimilation system	2006 (31r2), 4D-Var	***2016*** (41r2), ***4D-Var, hybrid EDA providing B***
Model input (radiation and surface)	As in operations, *(inconsistent SST and sea ice)*	***Appropriate for climate***, e.g., evolution greenhouse gases, volcanic eruptions, sea surface temperature and sea ice
Spatial resolution	79 km globally 60 levels to 10 Pa	***31 km globally*** 137 levels to 1 Pa
Uncertainty estimate		***from*** 10-member ***EDA at 62 km***
Output frequency	6-hourly Analysis fields	***Hourly*** (three-hourly for the ensemble), Extended list of parameters ~ 9 Peta Byte (1950 - timely updates)
Extra Observations	Mostly ERA-40, GTS	Various ***reprocessed CDRs***, ***latest instruments***
Variational Bias control radiosondes	Satellite radiances, RAOBCORE	Also ozone, aircraft, surface pressure, RISE
Land downscaling product	ERA-Interim land, 79km	ERA5L, ***9km*** (forced by ERA5)

IWF

Satellite Data Records for ERA6

EUMETSAT provides high impact CDRs for ERA6 back to the 1970s



Ranked contributions to forecast error reduction estimated by Adjoint Sensitivity Diagnostics averaged over the test period in the Southern Hemisphere. From McNally (2014).

- Atmospheric Sounding Radiance (Microwave and Infrared)
- Meteosat Radiance and Atmospheric Motion Vectors
- Radio Occultation bending angle profile
- Metop ASCAT backscatter
- Meteorological CDRs:
  - Metop global and polar Atmospheric Motion Vectors (LEO)
  - Metop multi-sensor aerosol AOD product

Aims at going back in time as far as possible, best possible individual instrument correction, error flagging, advanced uncertainty estimates and harmonisation over the time series.

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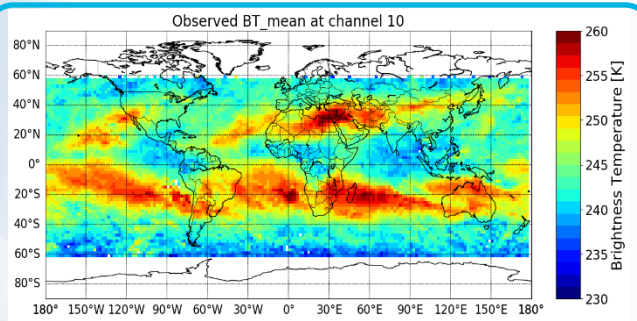
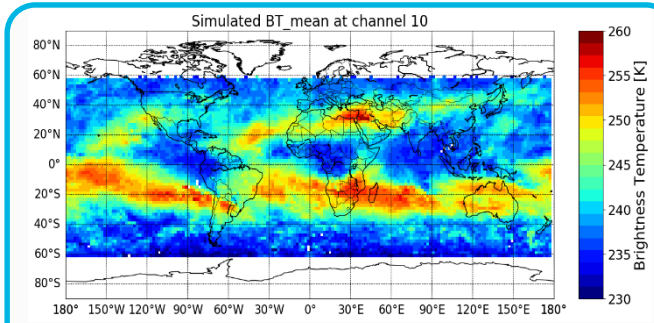
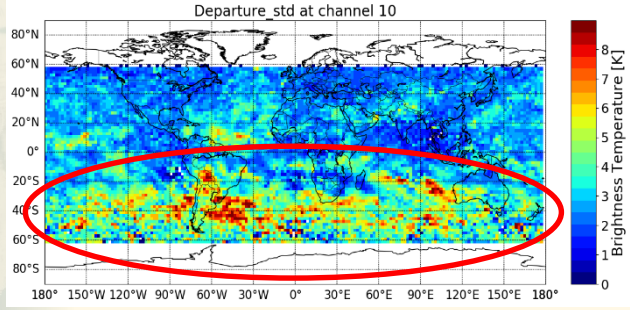
Analysis of NIMBUS-6 HIRS-1 Data



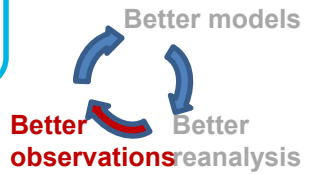
Nimbus-6 (Aug 1975)



ERA5 (Aug 1975)



Standard Deviation
Nimbus-6 – ERA5 departures



- Reanalysis provides a tool to analyse historical data in absence of satellite and ground-based references;
- High standard deviations in SH may point to additional information from HIRS-1 if assimilated.

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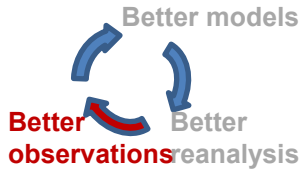
C3S_311c:Support for climate reanalysis including satellite data rescue

Sensor	Task					
	2 Data provision	3 Quality assessment	4 RT modelling	5 Quality control	6 Uncertainty assessment	7 Bias modelling
Early infrared sensors						
PMR	✓	✓	?	✓	✓	✓
HIRS-1	EUMETSAT	EUMETSAT	?	?	EUMETSAT	✓
MVIRI	EUMETSAT	✓	?	?	✓	✓
IRIS	?	✓	✓	✓	✓	✓
VTPR	✓	ECMWF	✓	✓	✓	✓
HRIR	✓	LP	LP	LP	LP	LP
MRIR	✓	LP	LP	LP	LP	LP
SIRS	✓	LP	LP	LP	LP	LP
THIR	✓	✓	✓	✓	✓	✓
Early microwave sensors						
SMMR	CM SAF	✓	CM SAF	?	?	✓
SSM/T-2	EUMETSAT	✓	✓	✓	FIDUCEO	✓
Reprocessed radiance data						
HIRS-2→-4	FIDUCEO	✓	?	ECMWF	FIDUCEO	ECMWF
SSU	?	✓	✓	✓	✓	✓
MSU	✓	ECMWF	✓	ECMWF	✓	ECMWF
SSM/I	CM SAF	✓	CM SAF	ECMWF	CM SAF	ECMWF
SSMIS (imaging channels)	CM SAF	✓	CM SAF	ECMWF	CM SAF	ECMWF
MVIRI	EUMETSAT	✓	?	?	?	✓
Reprocessed wind retrievals						
AVHRR	EUMETSAT	✓	NA	?	?	NA
MVIRI	EUMETSAT	✓	NA	?	?	NA



Lot 1 Satellite Data Rescue

- Focus on early datasets
- Range of activities: data provision → bias modelling and uncertainty assessment

Lot 2 Historical Upper Air Data

- Focus on observations prior to 1979
- Includes development of bias adjustments and uncertainty estimates

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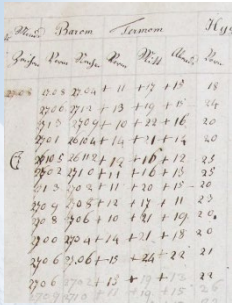
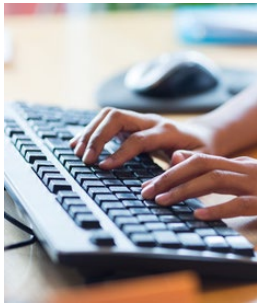
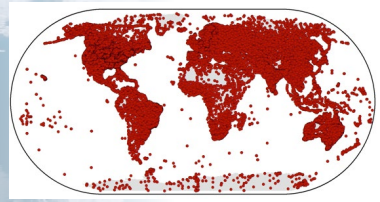
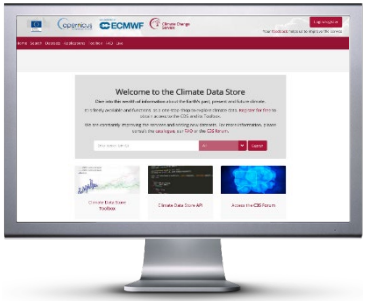
Collection and processing of in situ observations









Historical in situ observations play an important role in C3S, e.g.:

- for accurate climate monitoring,
- as input to global and regional reanalyses,
- as 'ground truth' for verification of ECV products.

C3S focuses on:

- the facilitation of data rescue activities,
- the improvement of historical records,
- collection into well-maintained archives,
- to provide access via the C3S Climate Data Store.

Some challenges:

- data rescue and improvement is an enormous task,
- urgency due to degradation of original records,
- non-gridded, irregular in space and time
- a wide range of data licenses.

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ERA5 data counts; satellite observations are increasingly dominant

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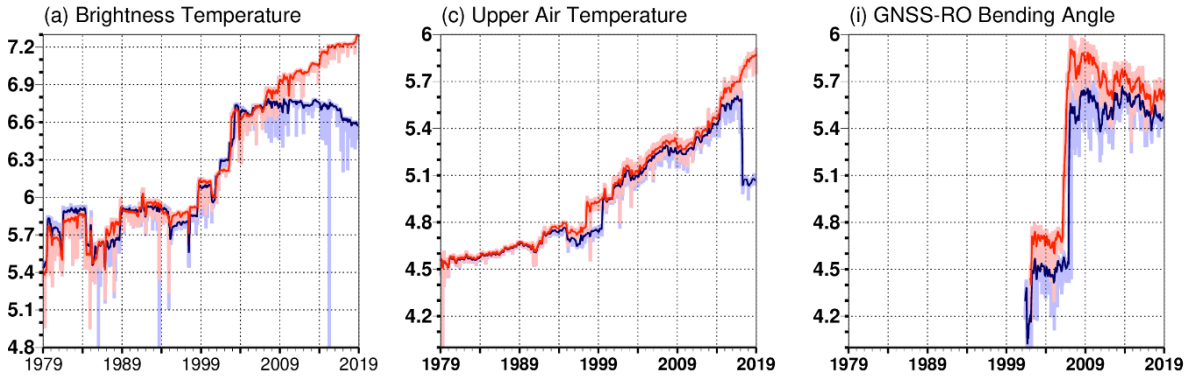
ERA5 data usage has increased from 0.75 (1979) to 24 million/day (2019).

Around 100 Billion observations Assimilated (1979 - 2020)

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



Radiances:
Largest volume

Conventional:
Radiosondes, aircraft

GNSS-RO:
Initially low numbers
Counts ~ conventional
Some recent decline

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Inter-comparison of global 2m temperature anomalies

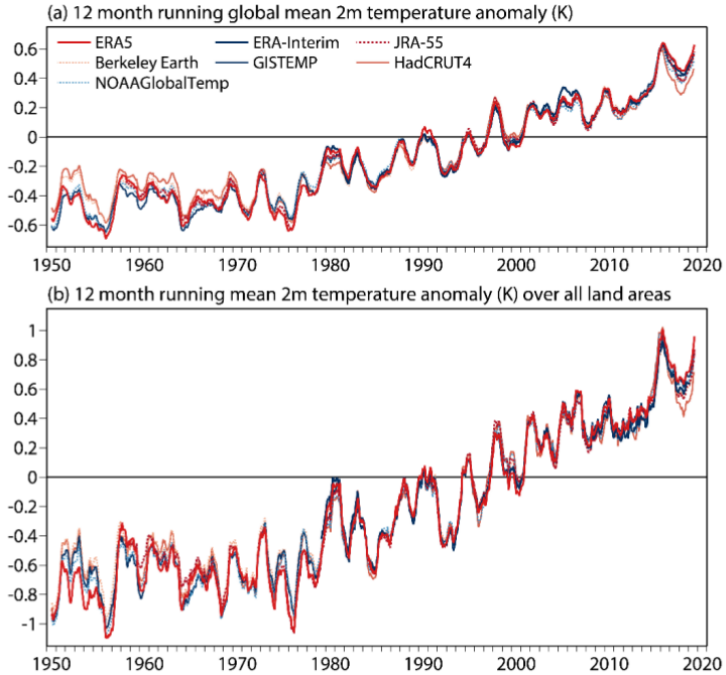
Simmons, A. et al., 2020 (in preparation):

In general there is a good agreement between datasets.

Each dataset shows considerable warming over the period shown, with a peak early in 2016 associated with a strong El Niño event and generally high values over the past six years. ERA5 and ERA-Interim are the datasets with the largest anomalies since 2016, but not the datasets with the largest
trends over the period since 1979.

Trends from ordinary least squares fits to monthly values for
the forty years 1979 to 2018 are 0.182K/decade for ERA5, 0.183K/decade for ERA-Interim, 0.180K/decade for JRA-55 and otherwise range from 0.171K/decade for NOAAGlobalTemp to 0.188K/decade for Berkeley Earth.

The reanalyses are colder prior to 1970.



Time series of monthly values from 1950 to 2020. (a) Twelve-month running averages of the global average two-metre temperature (K) anomaly with respect to 1981-2010 from ERA5, ERA-Interim, JRA-55, Berkeley Earth, GISTEMP, HadCRUT4 and NOAAGlobalTemp. (b) As (a), but for averages over land only.

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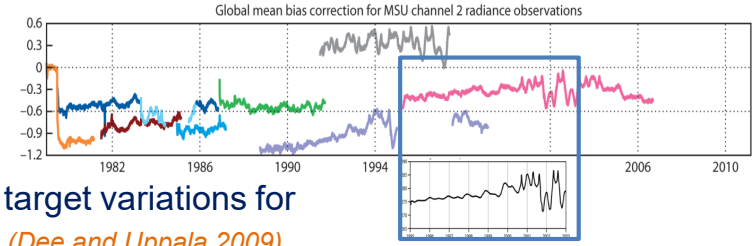
The merits of variational bias correction

Like ERA-Interim, ERA5 has a dynamic way of estimating biases in the observing system:

- ✓ time-evolving biases (both gradual and abrupt)
- ✓ relative biases between different components
- ❖ Note: need **anchors**.

The bias parameters are included in the variational control:

$$\mathbf{J}(\mathbf{x},\beta) = (\mathbf{x_b} - \mathbf{x})^{\mathrm{T}}\,\mathbf{B}^{-1}(\mathbf{x_b} - \mathbf{x}) + \left[\mathbf{y} - \mathbf{h}(\mathbf{x},\beta)\right]^{\mathrm{T}}\mathbf{R}^{-1}\left[\mathbf{y} - \mathbf{h}(\mathbf{x},\beta)\right]$$



On-board warm target variations for MSU NOAA-14: *(Dee and Uppala 2009)*

Resulting bias estimates also provide a path to more homogeneous observational records