Climate reanalysis at ECMWF

From research to operational services

Dick Dee
JCSDA

Many thanks to Hans Hersbach and his reanalysis team at ECMWF
Also: Sakari Uppala, Adrian Simmons, Jean-Noël Thépaut

EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS

From research to services development

Implementation of operational services on behalf of the European Commission

Copernicus
Europe's eyes on Earth

Research to support development of new environmental services in Europe

ERA CLIM

Climate Change Service

Research to support development of ECMWF's Integrated Forecast System

macc Monitoring atmospheric composition & climate

Atmosphere Monitoring Service

ECMWF

ECMWF reanalysis productions over the years

Atmosphere/land — *including ocean waves*

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

Ocean — *including sea ice*

2006	2010 - …	2016 - …
ORAS3	ORAS4	ORAS5

Centennial — *Coupled*

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

Enhanced land

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

Atmospheric composition

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

Why does ECMWF invest in reanalysis?

Reanalysis provides an excellent testbed for data assimilation

- It reveals a great deal about the quality of the forecast model
- It leads to new ways to make better use of observations
- It exposes bugs and other technical problems in the IFS

Reanalysis data are essential for ECMWF research and development

- It provides a comprehensive verification dataset for testing new model developments
- It allows development of new forecast products that rely on accurate climatologies
- It is needed for calibration of monthly and seasonal forecasts

Reanalysis data are extremely popular with external users

- Global datasets for research and education
- Input for downstream models and systems
- Essential data for services development

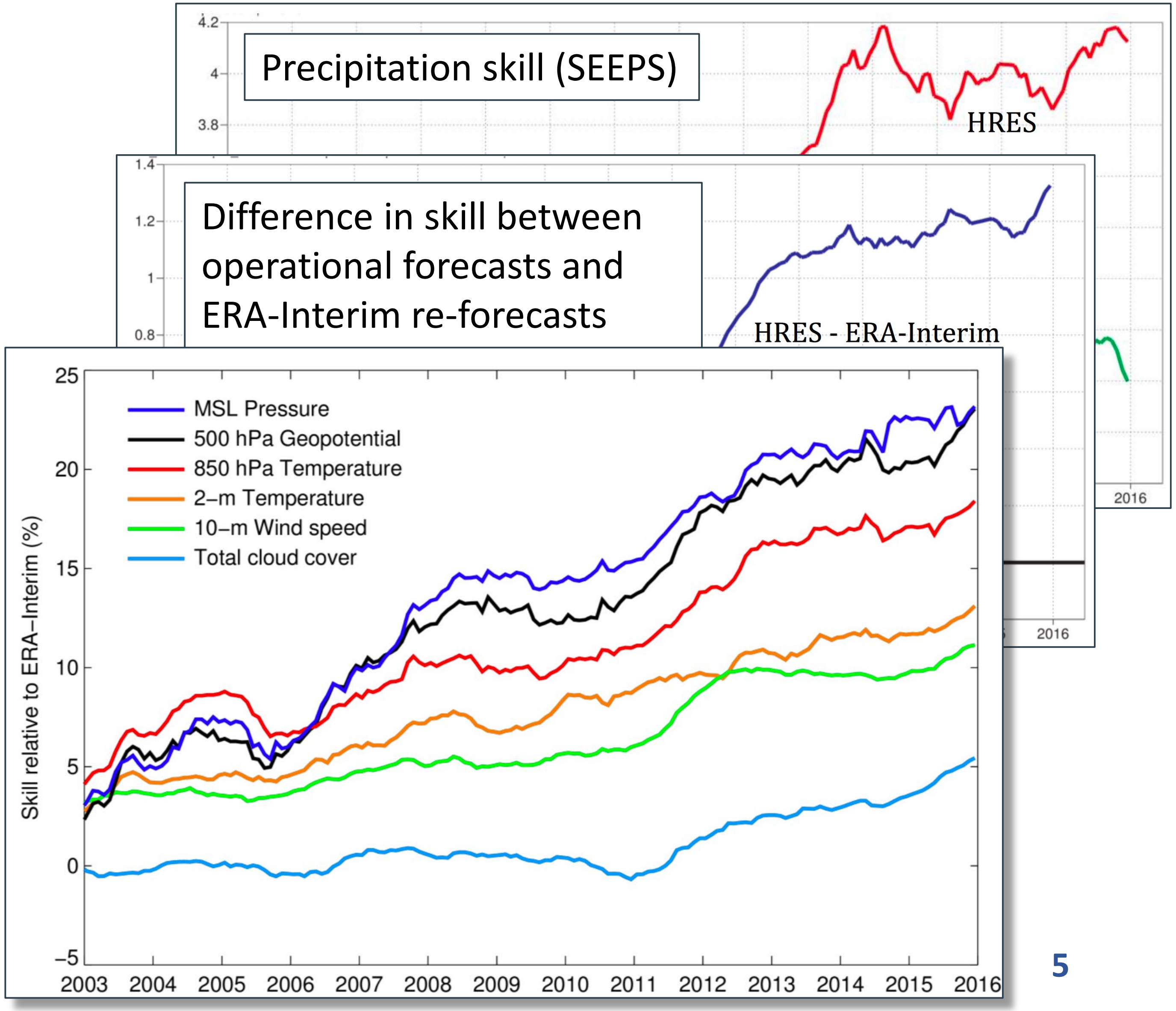
Use of reanalysis to evaluate forecast performance

NWP forecast skill varies due to

- model and DA upgrades
- changes in the observing system
- atmospheric predictability

Comparing with re-forecasts skill can isolate the effect of model/DA upgrades

Reanalysis system must be “similar” to the NWP system



Use of reanalysis in probabilistic forecast products

Global EFI - multiple parameters

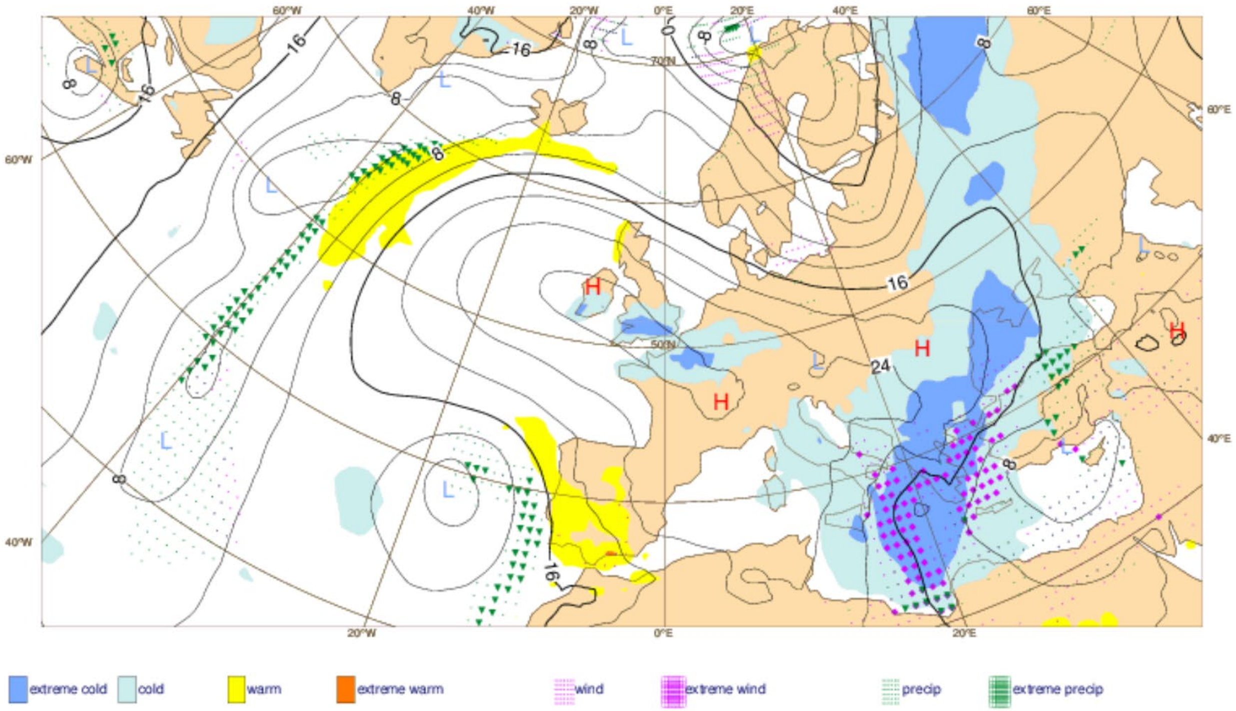
- Forecasts homepage
- Charts
- Datasets
- Quality of our forecasts
- Documentation and support
- Accessing forecasts
- Back to charts

Related charts

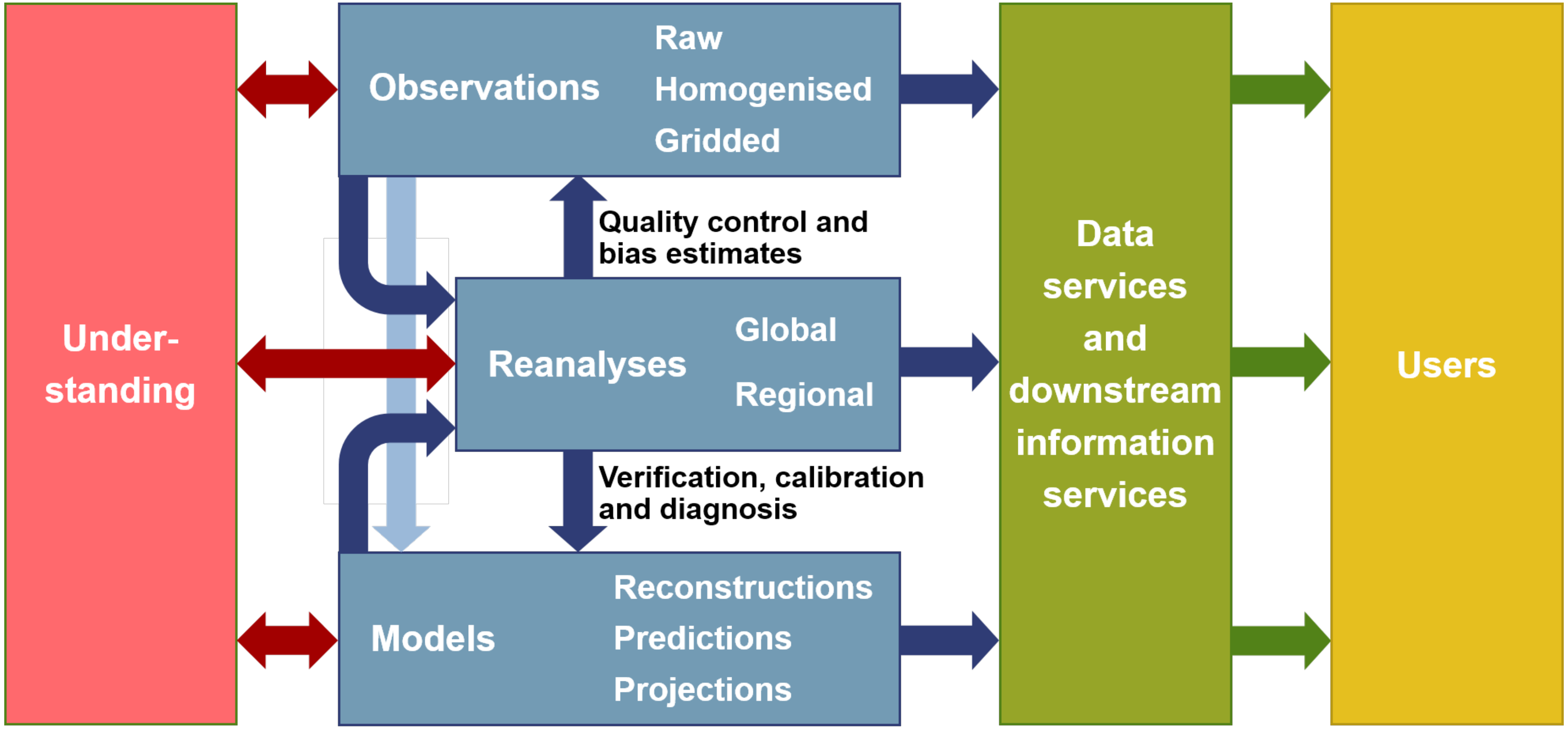
- EFI 2m temperature
- EFI 2m minimum temperature
- EFI 2m maximum temperature
- EFI wind gust
- EFI wind speed
- EFI precipitation
- EFI significant wave height
- EFI snow fall
- EFI cape
- EFI cape shear
- Global EFI - multiple parameters

Base time ▾ Day ▾ Area ▾

Anomalous weather predicted by EPS:Wednesday 30 November 2016 0000 UTC
1000 hPa Z ensemble mean (Wednesday 30 November 2016 1200 UTC)
and EFI values for Total precipitation,maximum 10m wind gust and mean 2m temperature (all 24h)
valid for 24hours from Wednesday 30 November 2016 0000 UTC to Thursday 01 December 2016 0000 UTC



Use of reanalysis for climate services development



Adrian Simmons: Adapted from a 2009 talk, with acknowledgments to Kevin Trenberth and organisers of the 2009 World Climate Conference-3

The EU Copernicus Earth Observation Programme

The Copernicus Sentinels, together with other systems for Earth Observation, provide (or will provide) operational data:

- for atmosphere, ocean and land
- for climate and environmental monitoring

SENTINEL-6 (Jason-CS)
- 2020
- Radar altimeter
- 10 days
- Measure precision sea-surface height for ocean and climate studies

SENTINEL-1
Launch Date: 1A: Launched; 1B: Launched
Payload: All Weather Imaging Radar
Revisit time: 1-6 Days
Applications: Monitoring sea ice and the Arctic, Land Surface motion risks, disaster response

SENTINEL-2
- 2A: Launched; 2B: 2017
- Optical imaging sensor with 13 bands
- 2-5 days
- Monitoring land-use changes, agriculture and ecosystems, volcanoes and landslides

SENTINEL-5
- 2021
- Ultraviolet/visible/near-infrared/short-wave infrared spectrometer on Metop-SG A satellite
- Daily
- Monitoring of air pollution, stratospheric ozone, solar radiation and climate

SENTINEL-3
- 3A: Launched; 3B: 2017
- Radar altimeter, Sea/land surface temperature radiometer, sea/land colour imager
- 1-2 days (imagers); 27 days (altimeter)
- Sea-surface and land-ice topography, sea and land surface temperature and colour

SENTINEL-5 precursor
- 2016
- Ultraviolet/visible/near-infrared/short-wave infrared spectrometer
- Daily
- Monitoring of air pollution, stratospheric ozone, solar radiation and climate

SENTINEL-4
- 2021
- Ultraviolet/visible/near-infrared spectrometer on MTG-S satellite
- Geostationary. Hourly coverage of Europe/North Africa
- Monitoring of air pollution, stratospheric ozone, solar radiation

Copernicus also provides associated services

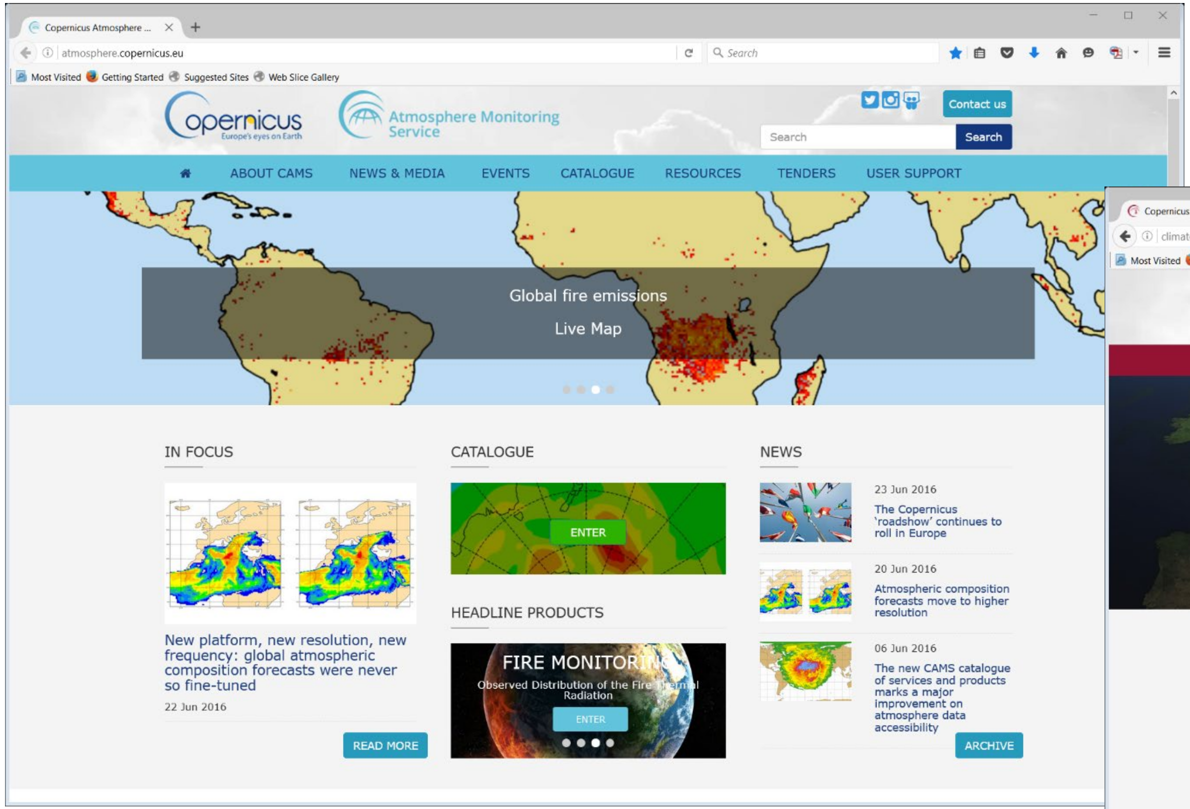
The six Copernicus Information Services

Three services monitoring individual components of the Earth System …

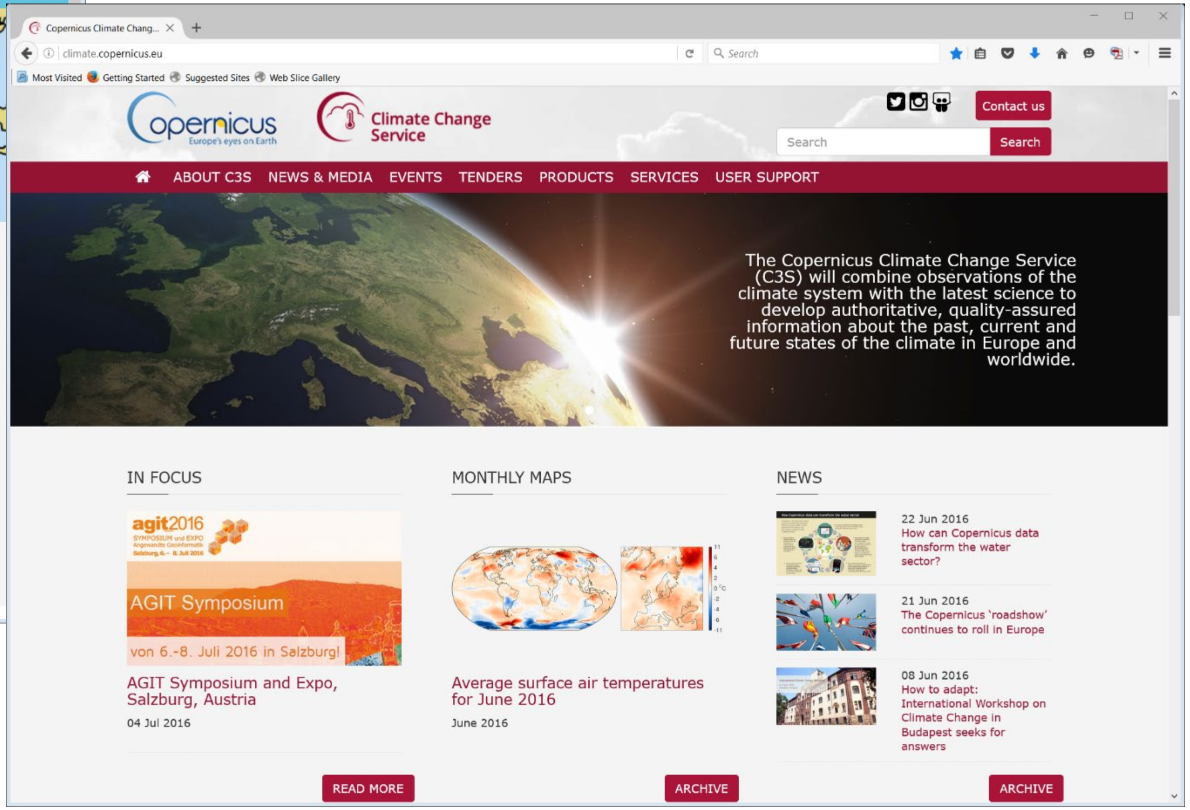
… and three themed cross-cutting services

ECMWF implements two of the services on behalf of the European Commission

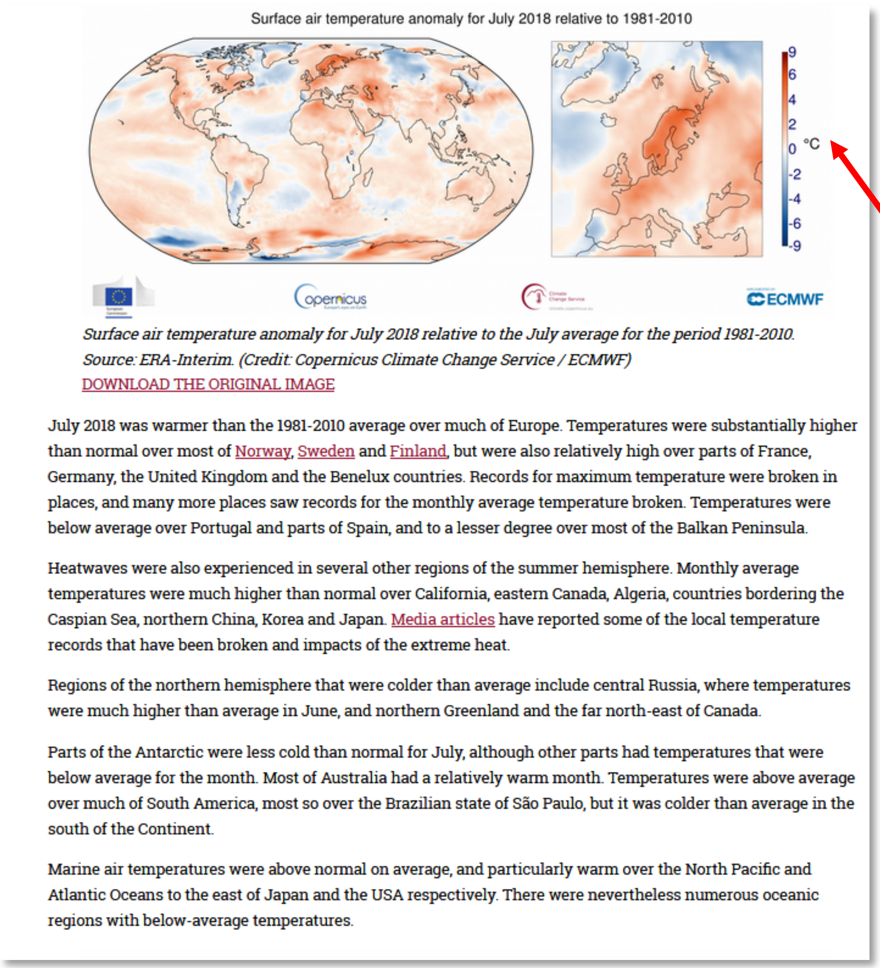
atmosphere.copernicus.eu



climate.copernicus.eu



A Climate Data Store for access to data and tools



Surface air temperature anomaly for July 2018 relative to 1981-2010

Surface air temperature anomaly for July 2018 relative to the July average for the period 1981-2010. Source: ERA-Interim. (Credit: Copernicus Climate Change Service / ECMWF)

DOWNLOAD THE ORIGINAL IMAGE

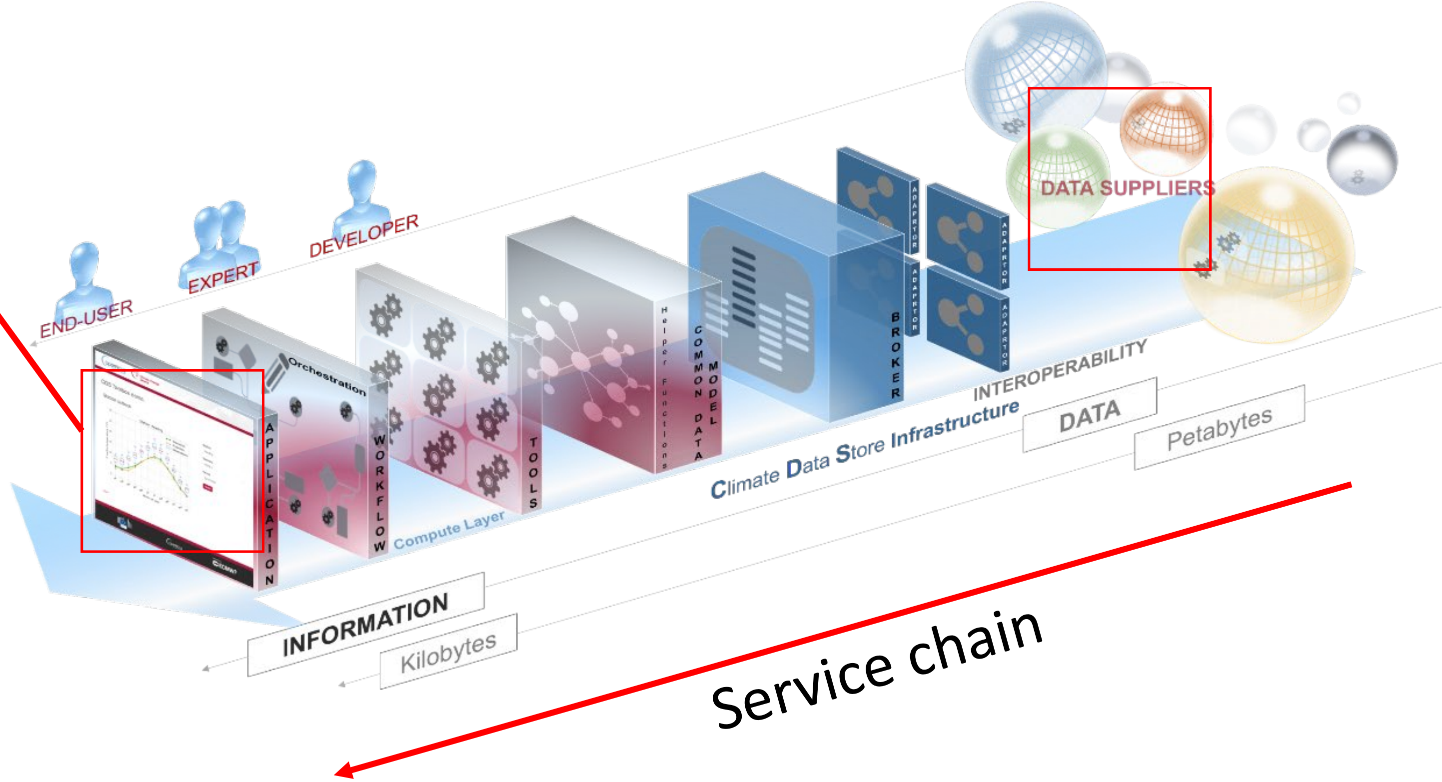
July 2018 was warmer than the 1981-2010 average over much of Europe. Temperatures were substantially higher than normal over most of Norway, Sweden and Finland, but were also relatively high over parts of France, Germany, the United Kingdom and the Benelux countries. Records for maximum temperature were broken in places, and many more places saw records for the monthly average temperature broken. Temperatures were below average over Portugal and parts of Spain, and to a lesser degree over most of the Balkan Peninsula.

Heatwaves were also experienced in several other regions of the summer hemisphere. Monthly average temperatures were much higher than normal over California, eastern Canada, Algeria, countries bordering the Caspian Sea, northern China, Korea and Japan. Media articles have reported some of the local temperature records that have been broken and impacts of the extreme heat.

Regions of the northern hemisphere that were colder than average include central Russia, where temperatures were much higher than average in June, and northern Greenland and the far north-east of Canada.

Parts of the Antarctic were less cold than normal for July, although other parts had temperatures that were below average for the month. Most of Australia had a relatively warm month. Temperatures were above average over much of South America, most so over the Brazilian state of São Paulo, but it was colder than average in the south of the Continent.

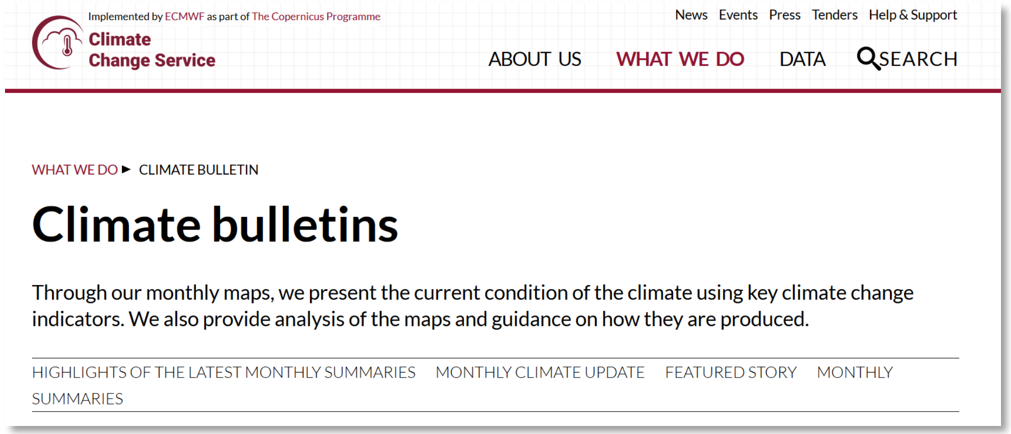
Marine air temperatures were above normal on average, and particularly warm over the North Pacific and Atlantic Oceans to the east of Japan and the USA respectively. There were nevertheless numerous oceanic regions with below-average temperatures.

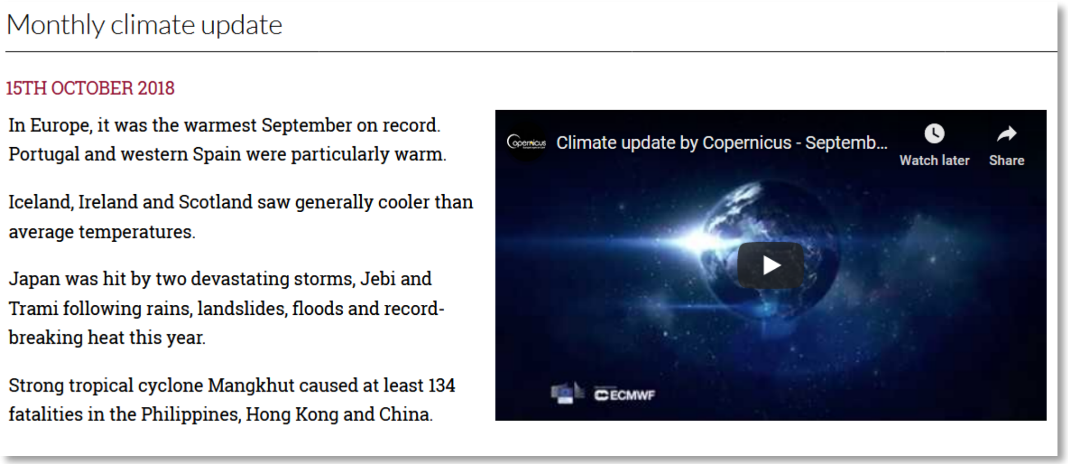


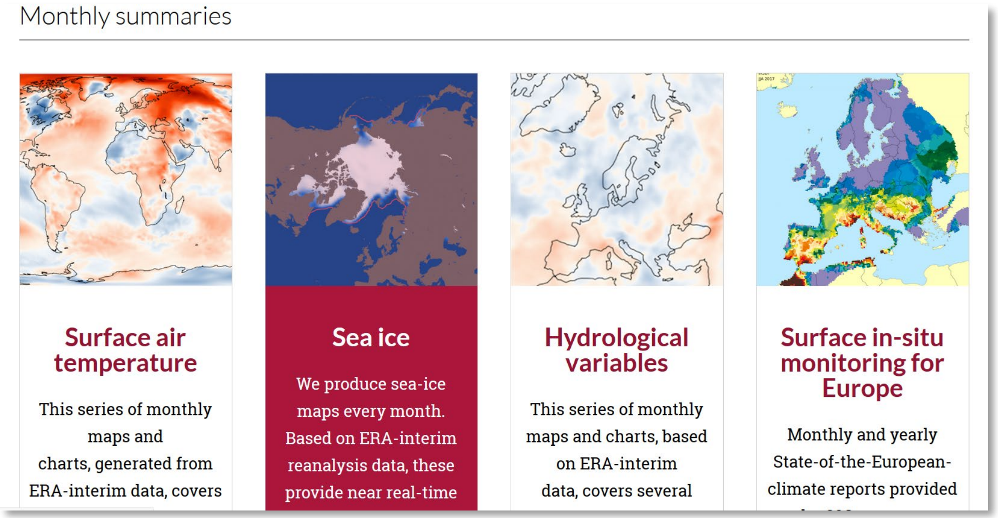
Quality-assured information and tools for scientists, practitioners and policy makers.

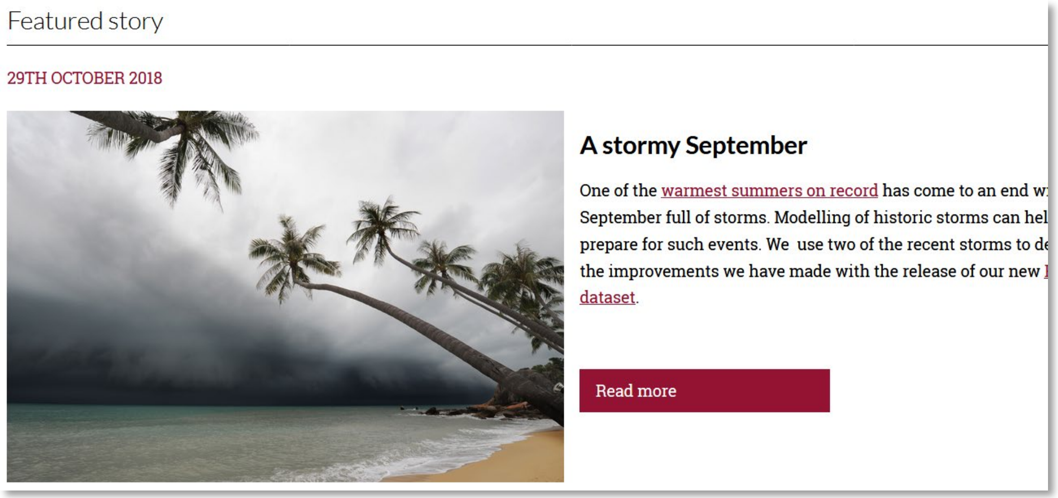
cds.climate.copernicus.eu

Monthly climate bulletins







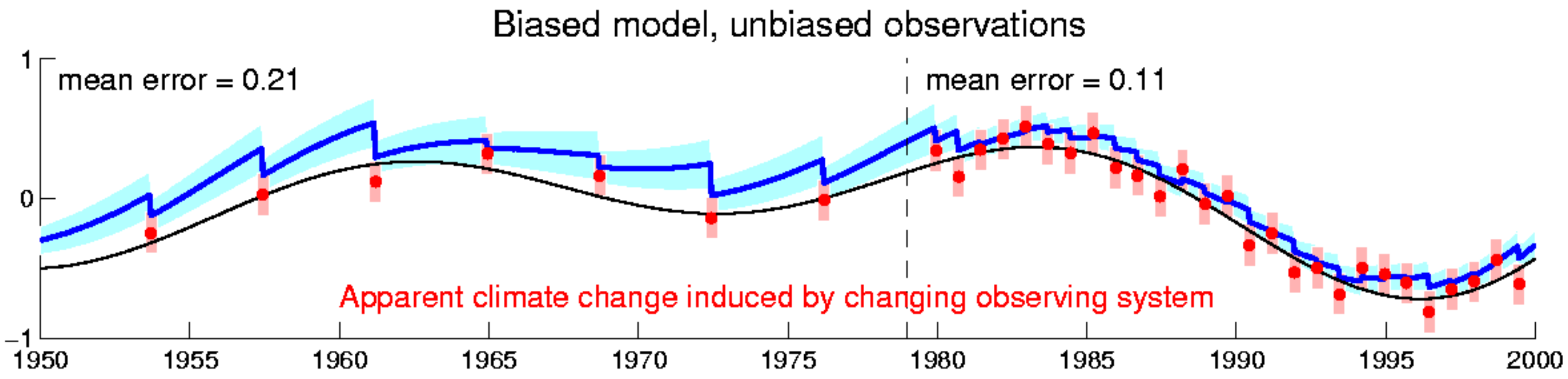


climate.copernicus.eu/climate-bulletins

Is it possible to accurately represent climate trends and variability?

The fundamental problem:

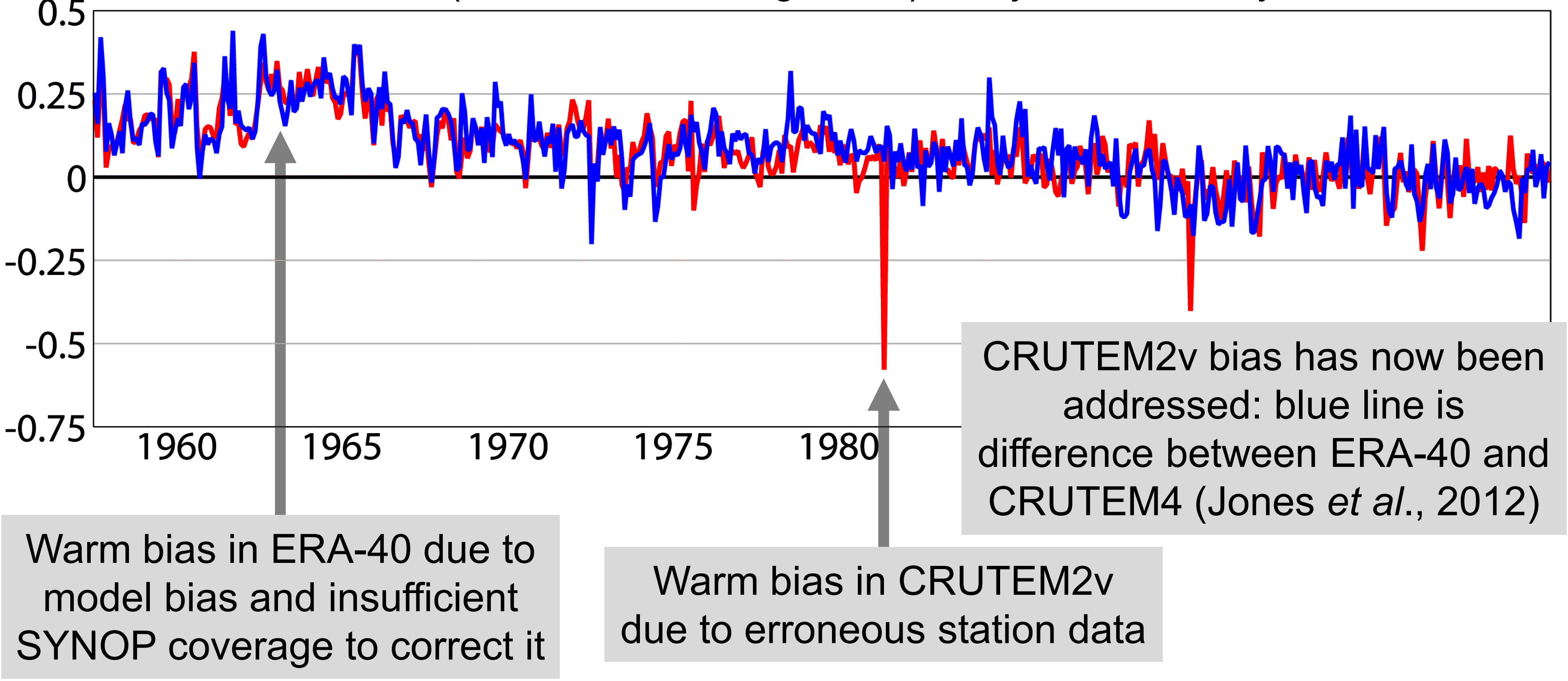
- Observation coverage changes over time
- Models biases are partly corrected by observations



- Observations are also biased
- Data assimilation may exacerbate the problem

Surface air temperature anomalies

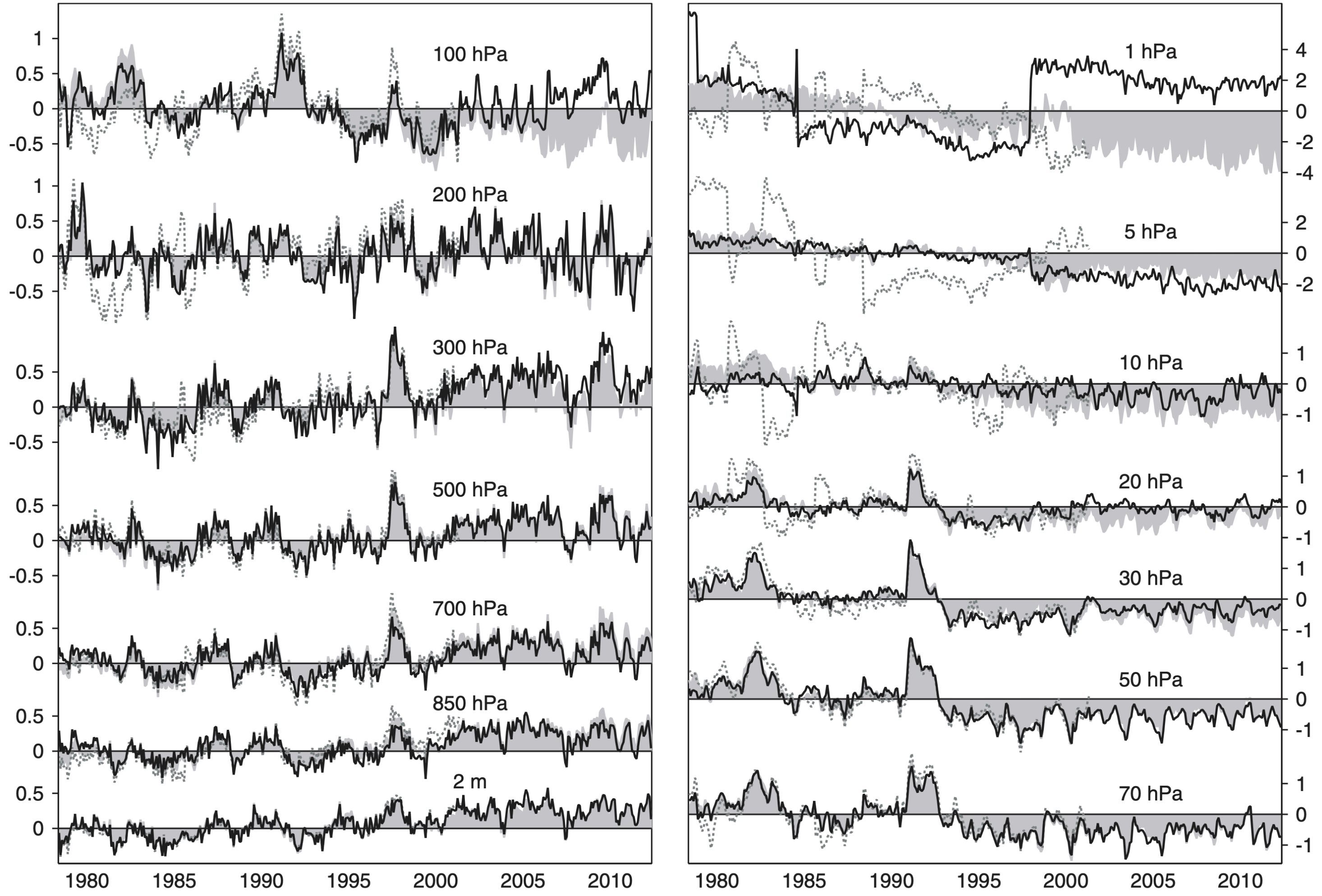
Red line is difference over Europe between ERA-40 analysis of synoptic data and CRUTEM2v (Jones and Moberg, 2003) analysis of monthly station data



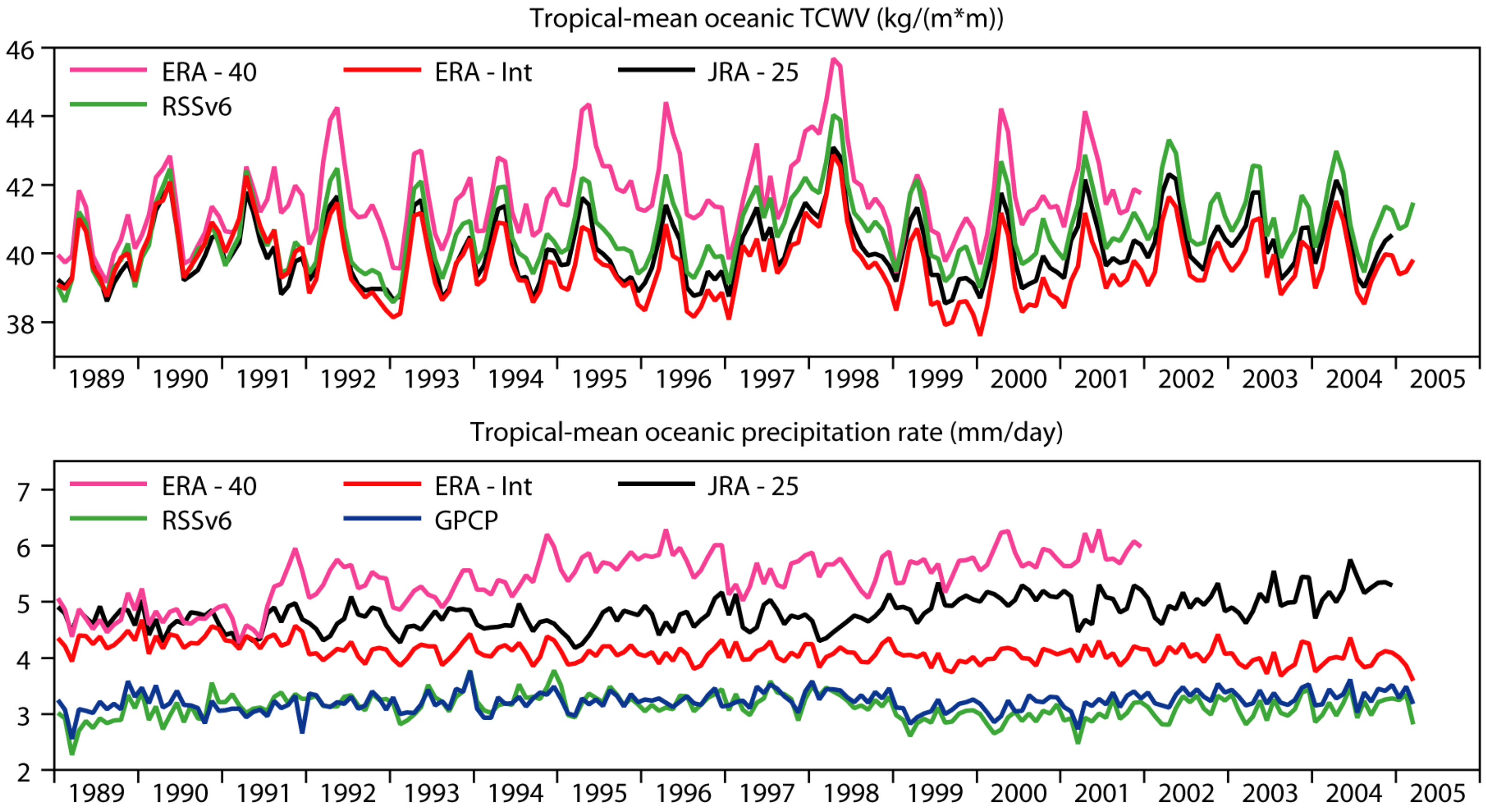
Air temperature anomalies

Simmons et al, 2014
DOI:10.1002/qj.2317

ERA-Interim
ERA-40
JRA-55

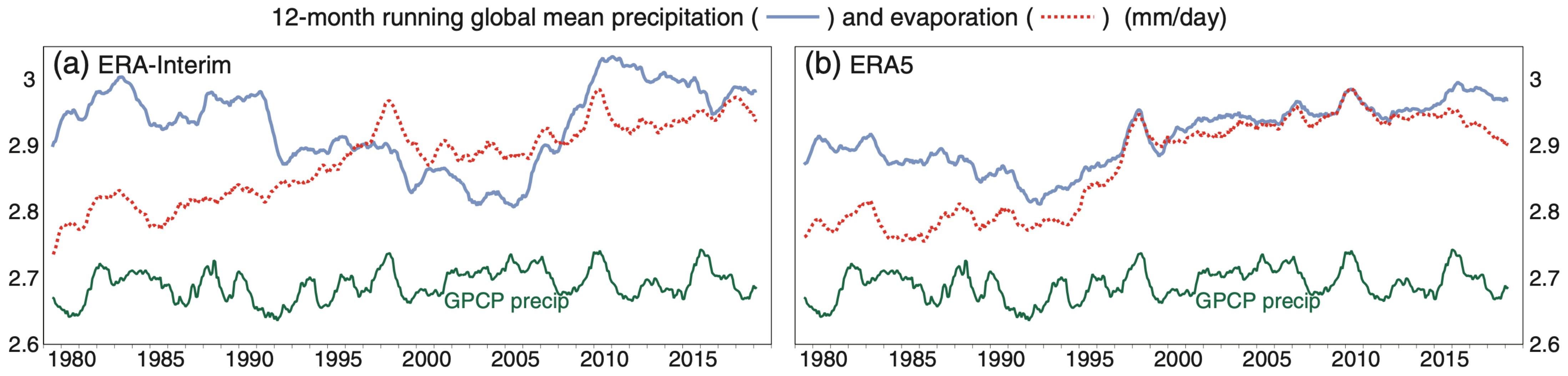


Hydrological cycle



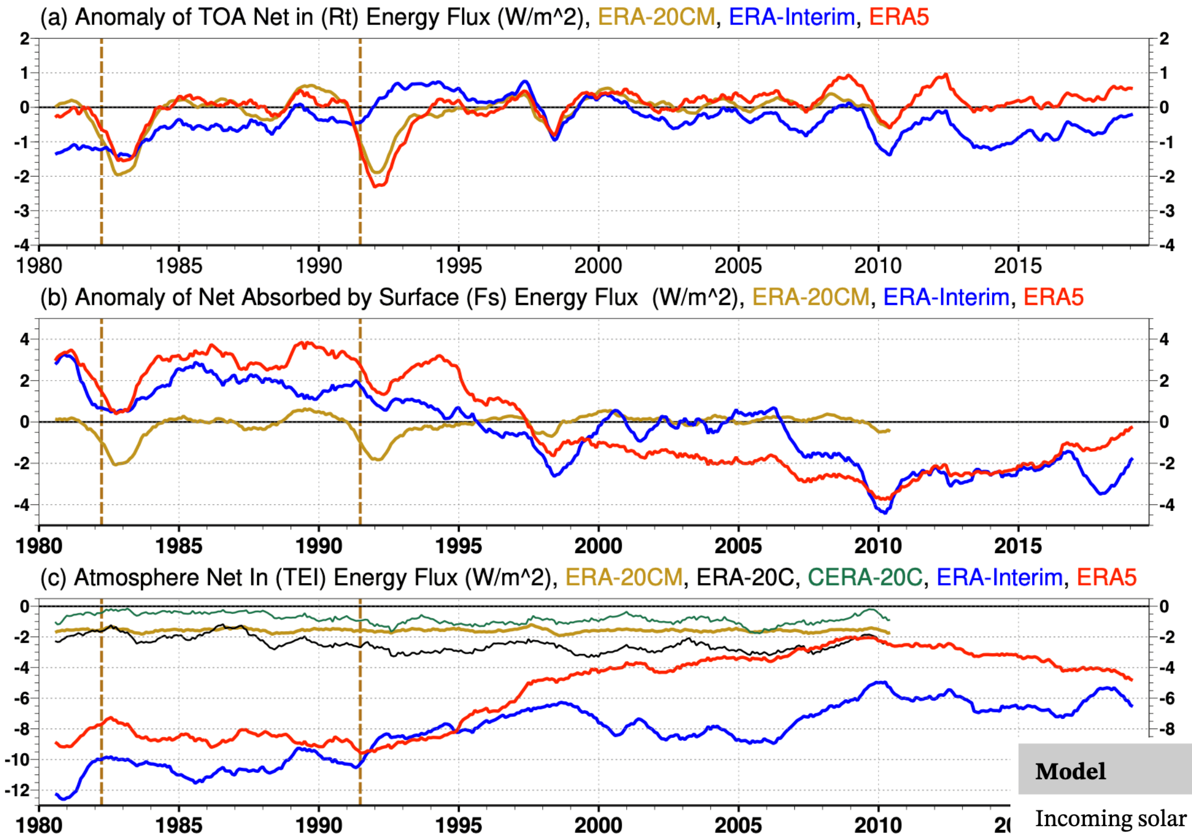
Hydrological cycle

Hersbach et al, 2020
DOI:10.1002/qj.3803



Energy fluxes

Hersbach et al, 2020
DOI:10.1002/qj.3803



Global mean energy budgets (W/m^2)

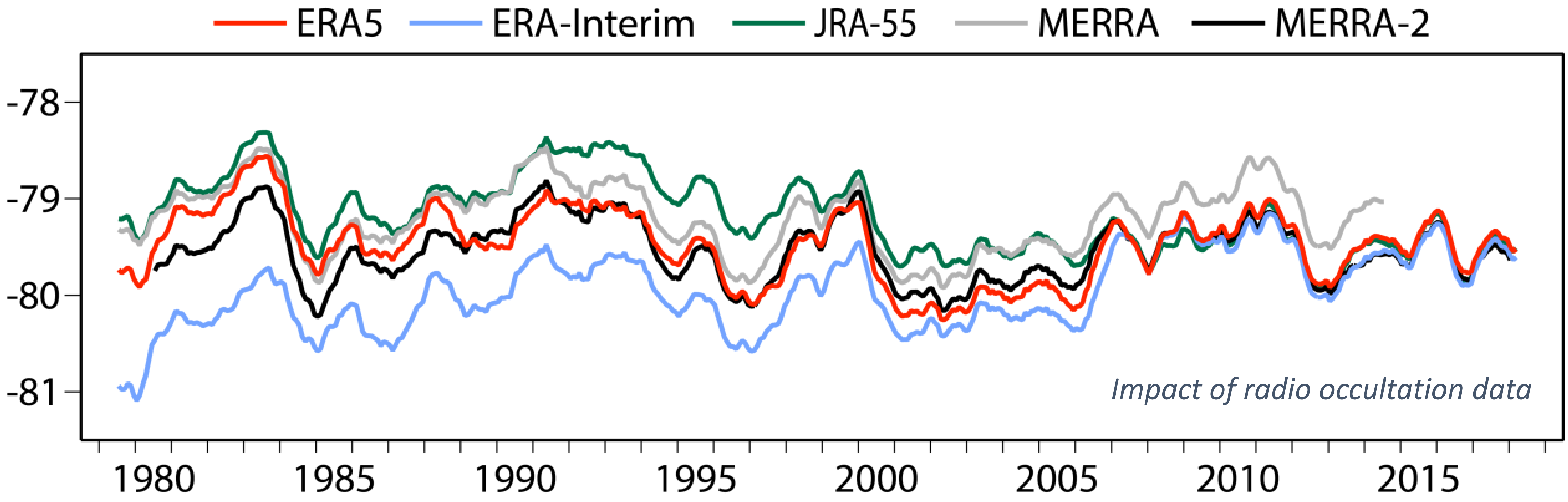
- 03/2000–05/2004 (Trenberth 2009)
- 1989-2008 (ERA-20CM, ERA-I, ERA5)

Model	**Trenberth *et al.* (2009)**	**ERA-20CM**	**ERA-Interim**	**ERA5**
Incoming solar radiation (TSI/4)	341.3	340.4	344.2	340.4
Net absorbed solar radiation (ASR)	239.4	240.9	244.3	242.7
Outgoing long-wave radiation (OLR)	238.5	240.6	245.5	242.2
TOA net radiation in ($\mathbf{R}_T$)	0.9	0.3	−1.2	0.4
Net energy absorbed by surface ($\mathbf{F}_S$)	0.9	1.9	6.9	6.1
Atmosphere net (TEI = $\mathbf{R}_T - \mathbf{F}_S$)	0.0	−1.6	−8.1	−5.6

Progress in representing climate trends and variability

Ho et al 2019

Twelve-month running mean temperature (°C) at 100 hPa averaged over the tropics (20°S to 20°N)

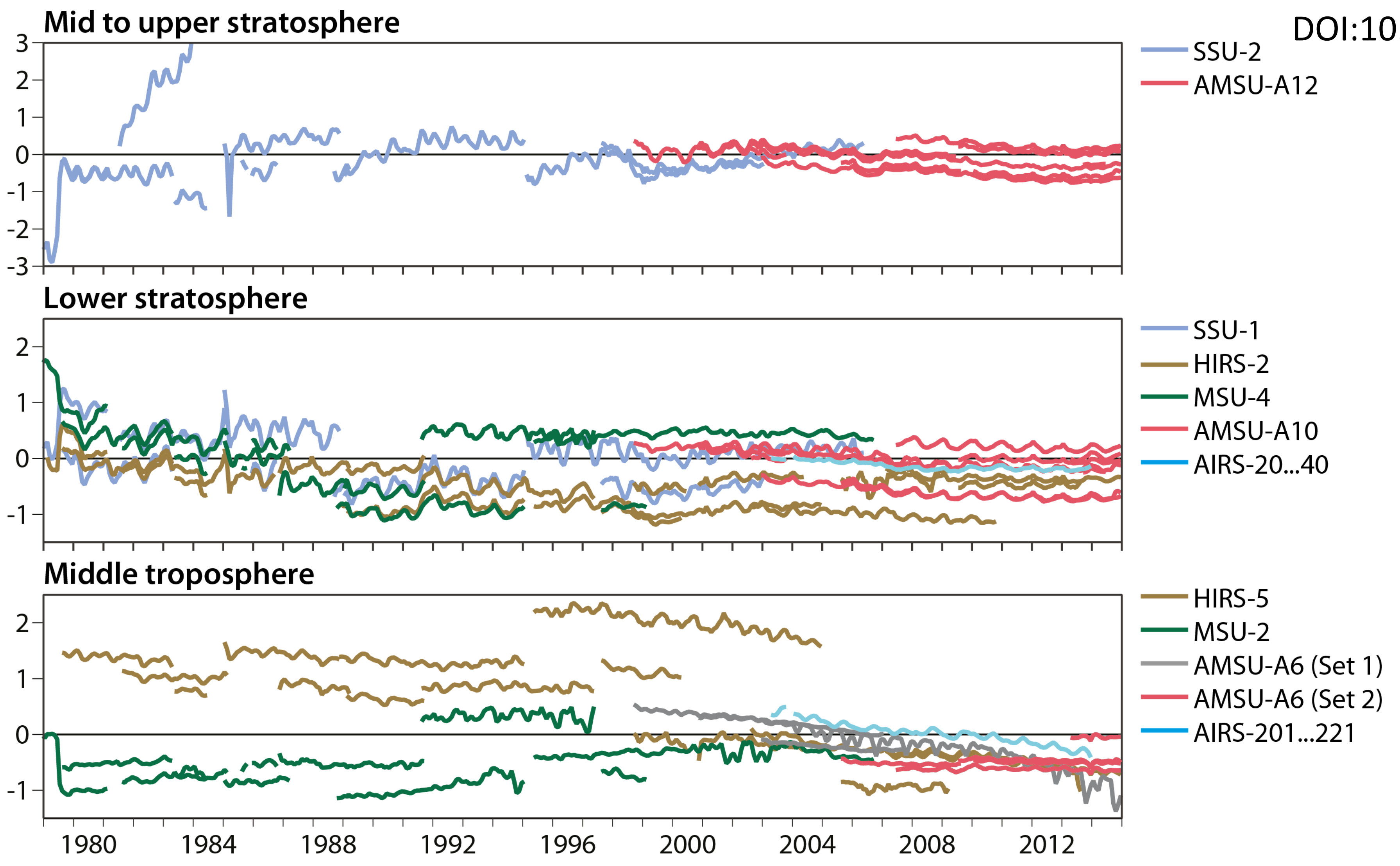


Progress in representing climate trends and variability – what is involved?

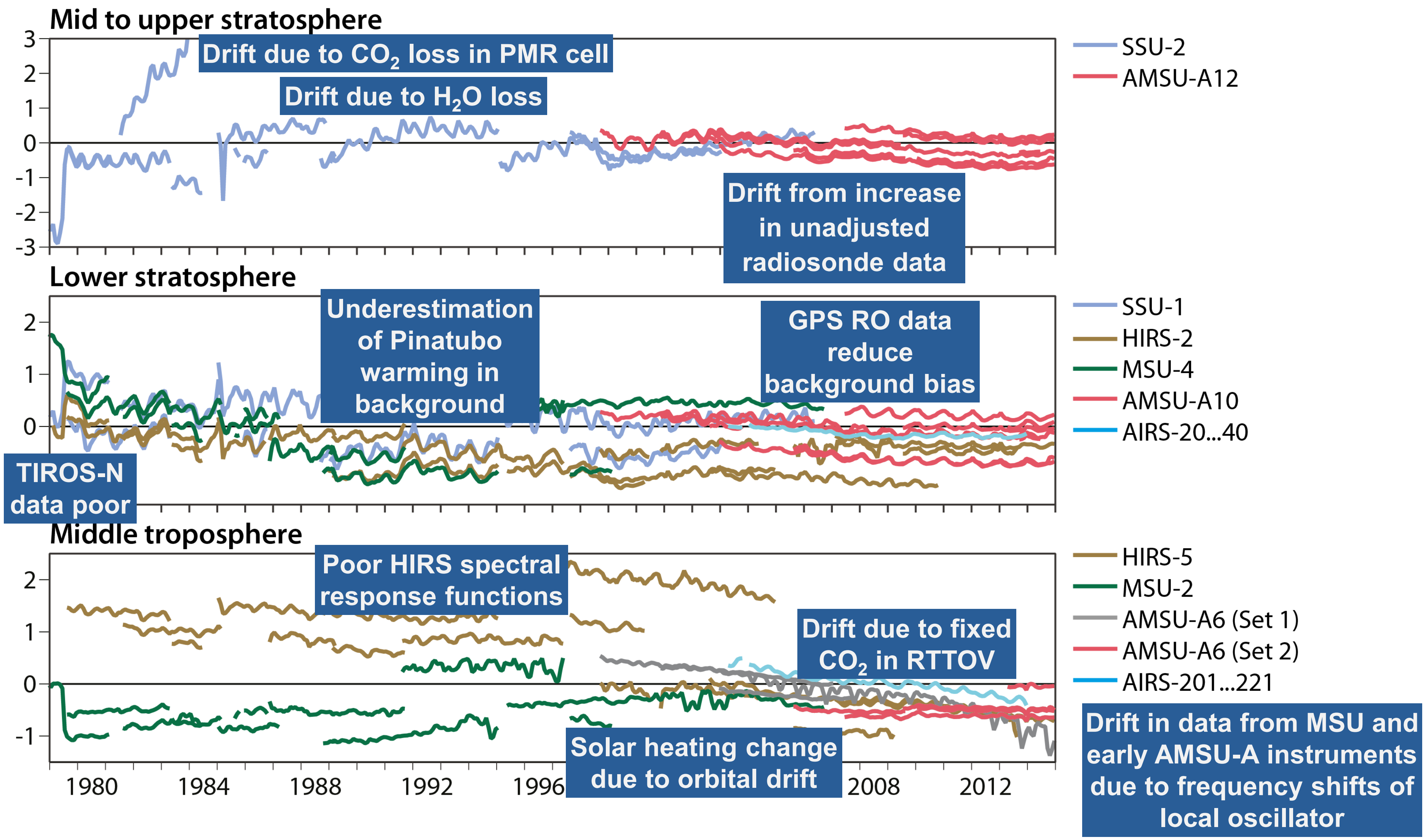
- Reprocessing input observations
- Improving model input (radiative forcing, boundary conditions)
- Addressing biases in forecast models
- Improving observation operators
- Better quality control of observations
- Bias-aware data assimilation (VarBC, weak-constraint 4D-Var)
- Performance monitoring, workflows and practices

Variational bias corrections (K) in ERA-Interim

Simmons et al, 2014
DOI:10.1002/qj.2317



Variational bias corrections (K) in ERA-Interim

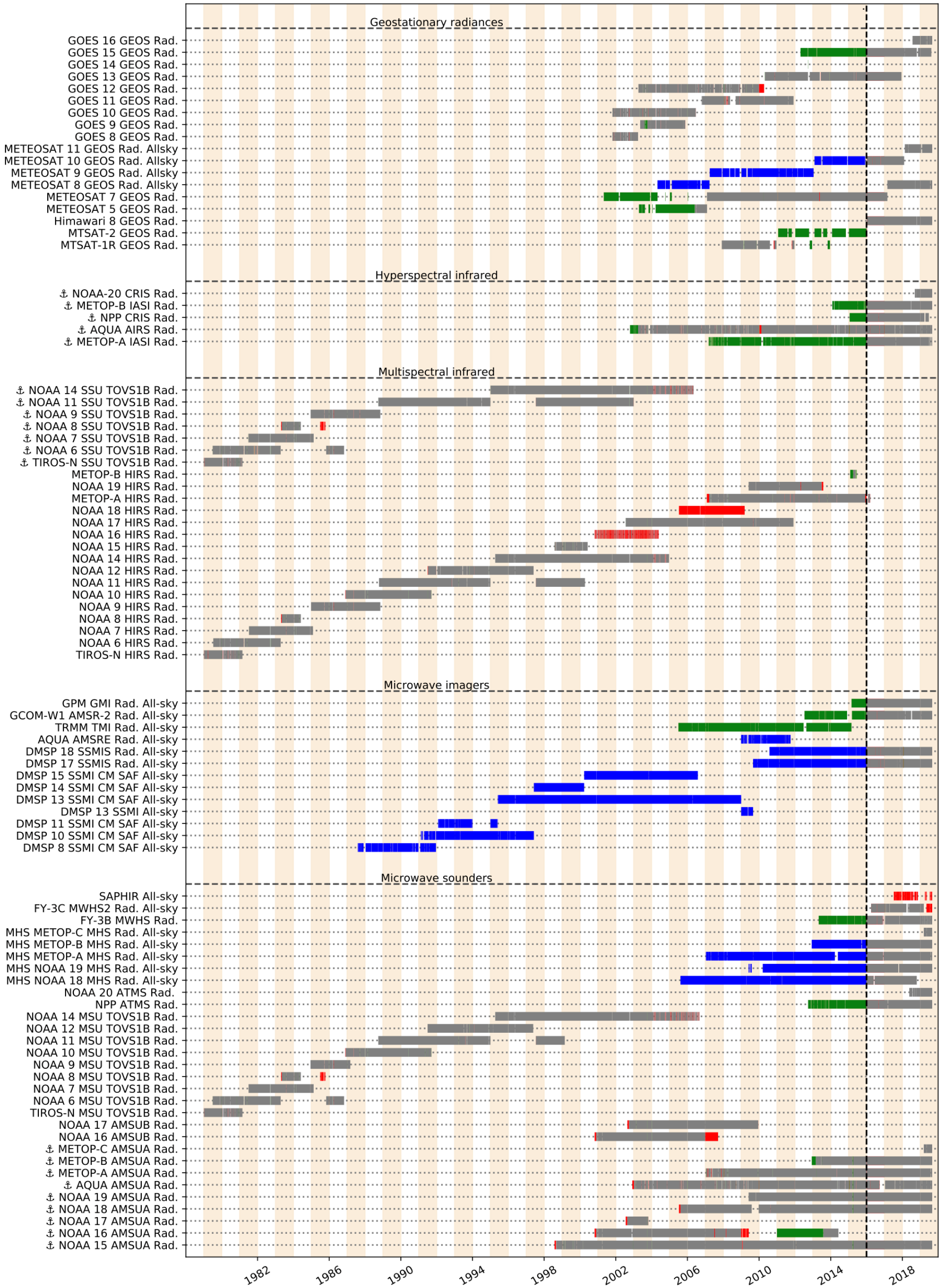


Cao et al. (2009), Dee and Uppala (2009), Kobayashi et al. (2009), Chung and Soden (2011), Nash and Saunders (2013), Saunders et al. (2013), Lu and Bell (2014), Simmons et al. (2014), …

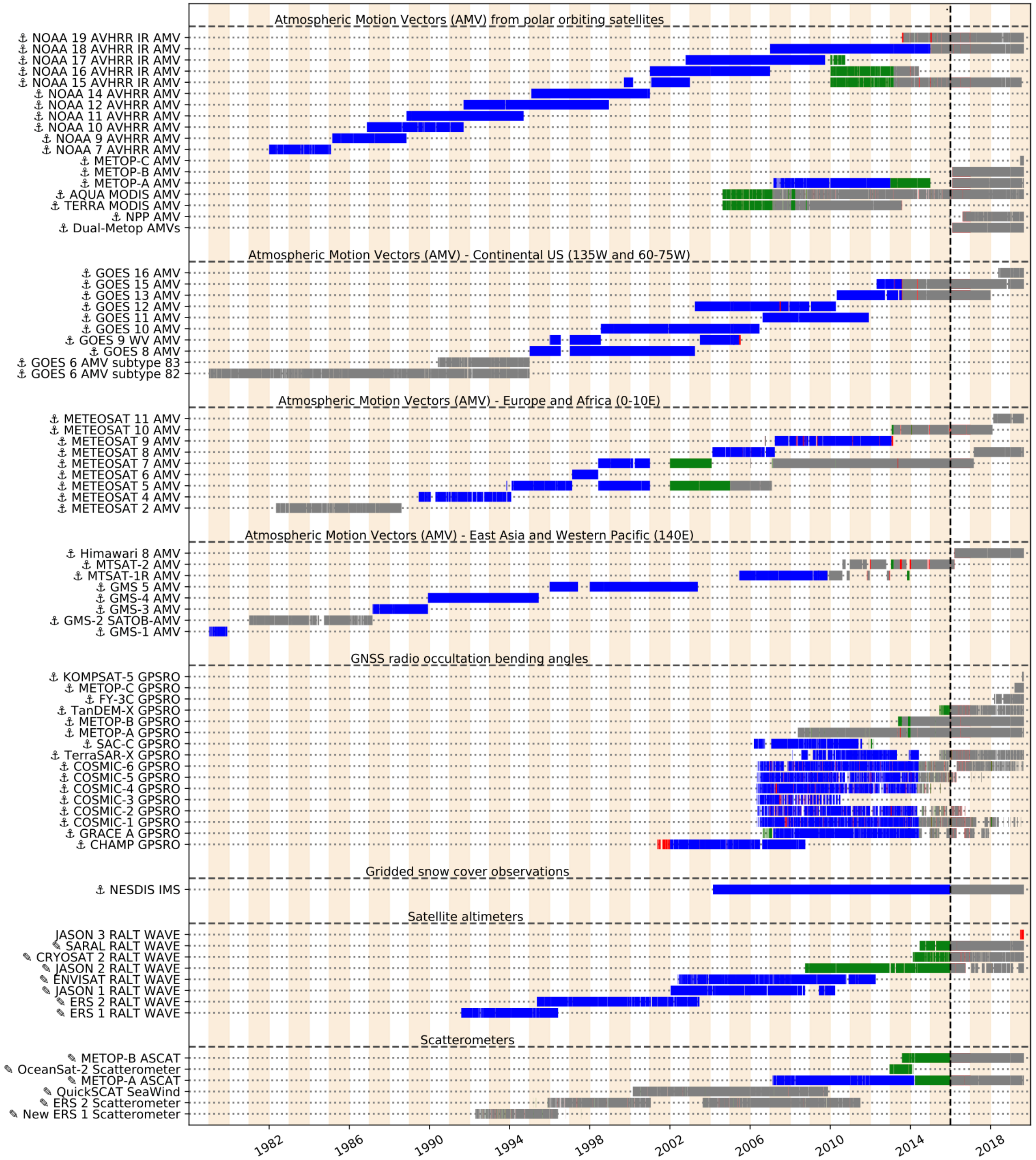
What is new in ERA5?

	ERA-Interim	ERA5
Period	1979 – present	1979 – present, now extended to 1950
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 ensemble
Model input (radiation and surface)	As in ERA-40 *(inconsistent SST and sea ice)*	*Appropriate for climate:* greenhouse gases, volcanic eruptions, sea surface temperature, sea ice
Spatial resolution	79 km globally 60 levels to 10 Pa	31 km globally 137 levels to 1 Pa
Uncertainty estimates		Based on a 10-member 4D-Var ensemble at 62 km
Output frequency	6-hourly analysis fields	Hourly (three-hourly for the ensemble)
Output parameters	84 (sfc) + 25 (wave) + 27 (ua)	205 (sfc) + 46 (wave) + 30 (ua)
Improved observations	Mostly ERA-40, GTS	Various reprocessed CDRs, latest instruments
Variational Bias Correction	Satellite radiances	Radiances, ozone, aircraft temperature, surface pressure, rain rates
Downscaled land product	ERA-Interim land, 79km	ERA5L, 9km

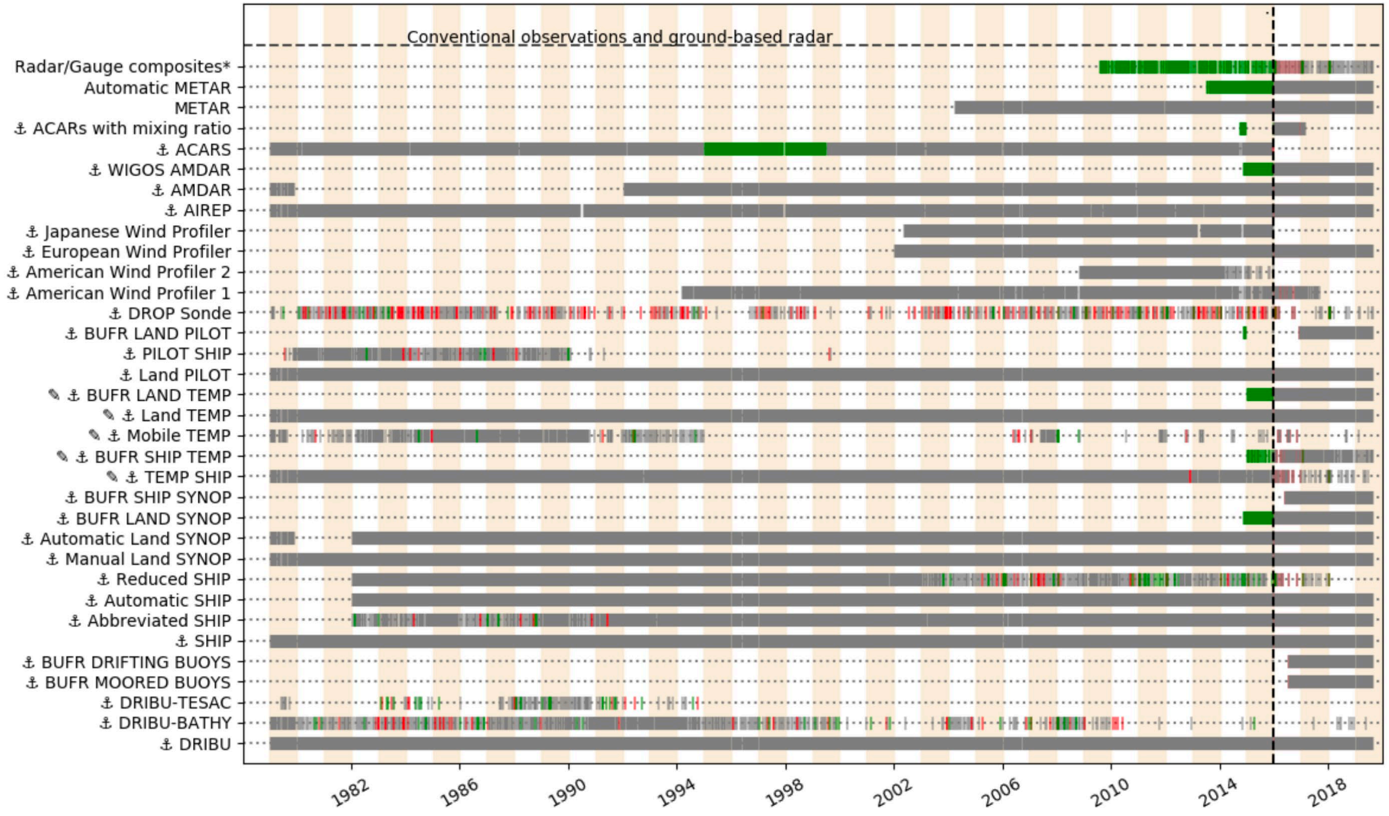
ERA5 input observations *(newly reprocessed in blue)*

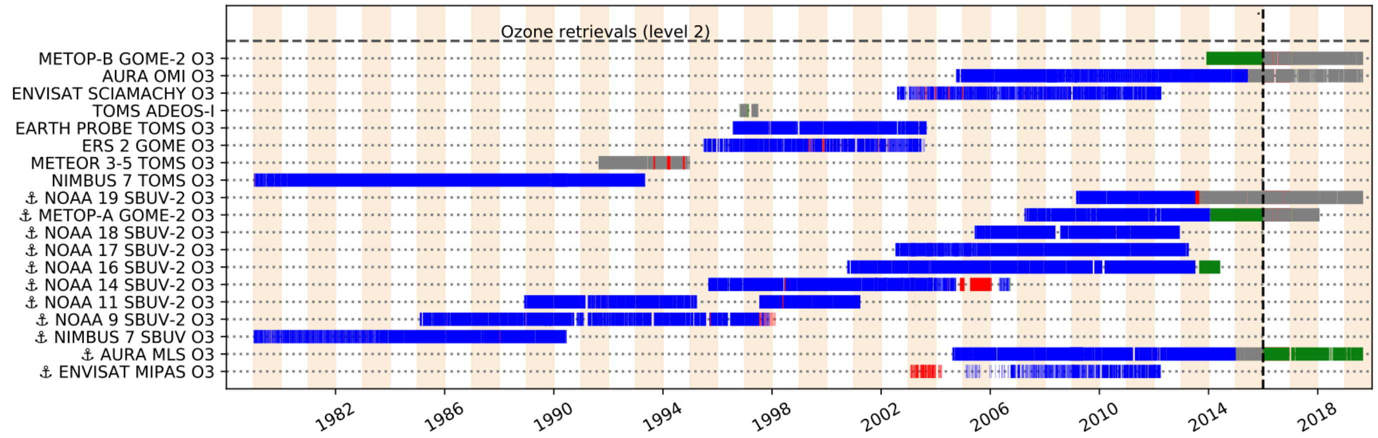


FORECASTS



ERA5 input observations *(newly reprocessed in blue)*

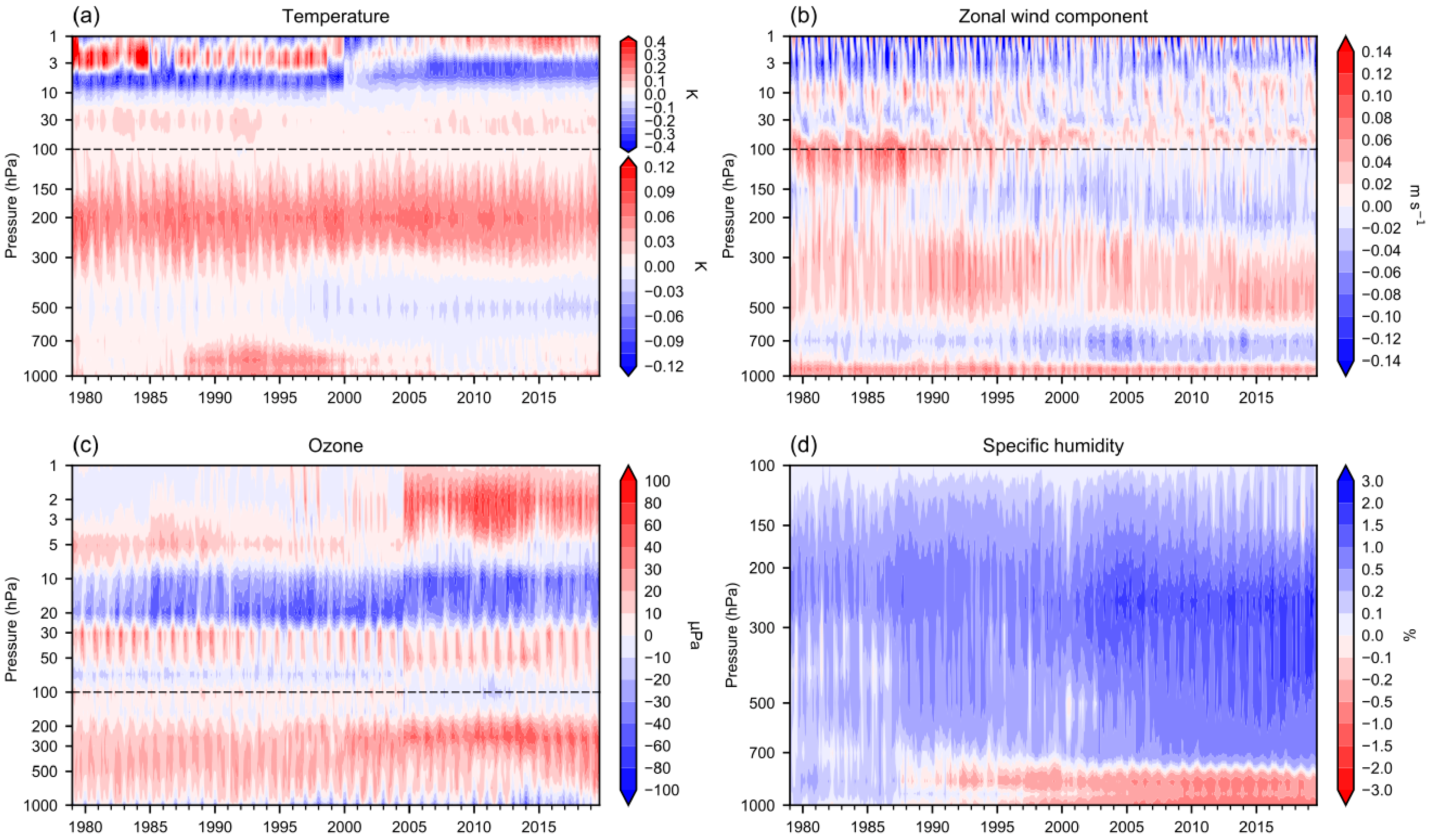




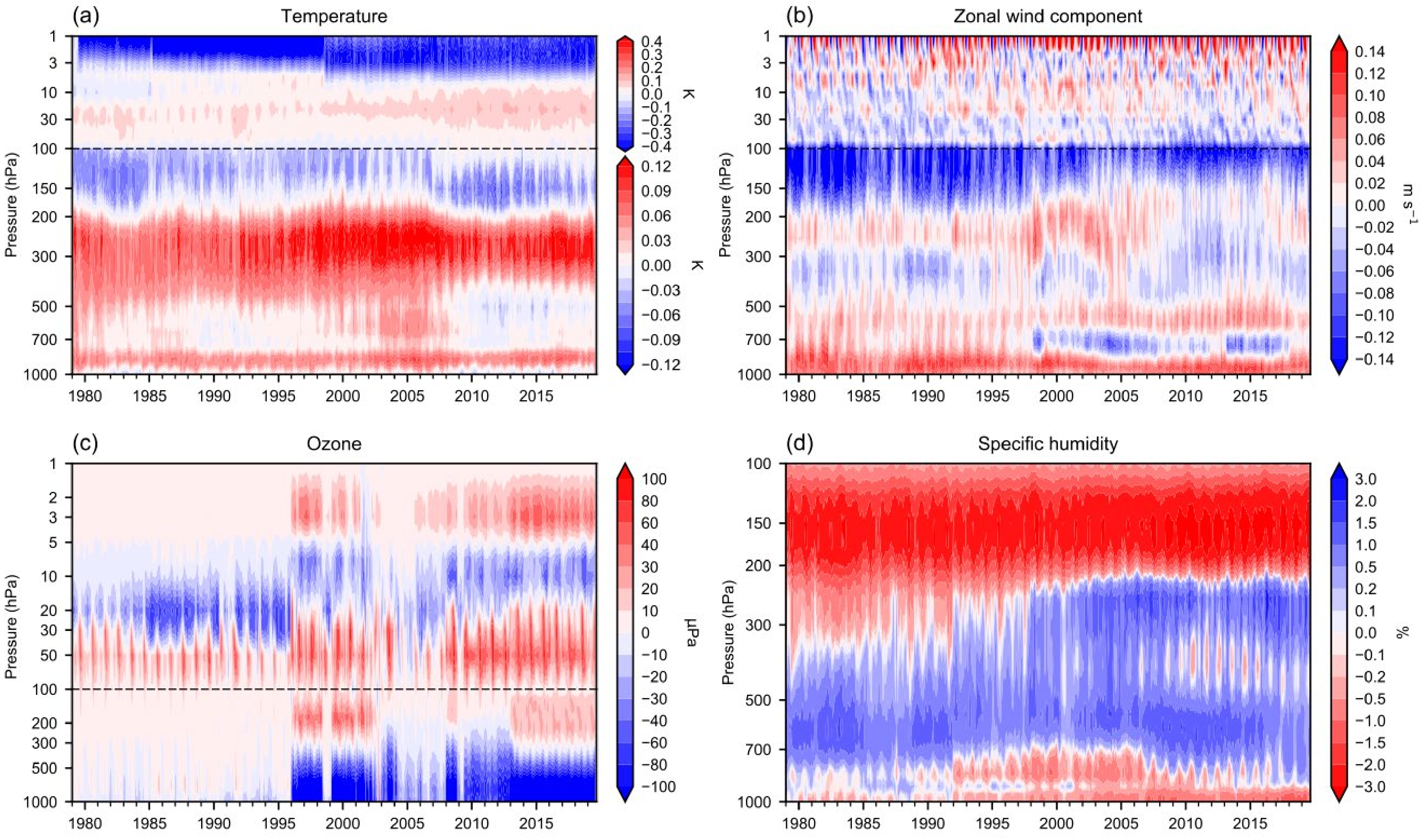
See Hersbach et al. 2020 for details on ERA5 input observations https://doi.org/10.1002/qj.3803

- Preparing input observations for reanalysis is a massive undertaking
- Under Copernicus, many input data records are being reprocessed for use in climate reanalysis
- JCSDA is proposing to develop an observation data store, provide shared access to reanalysis input

ERA5 analysis increments

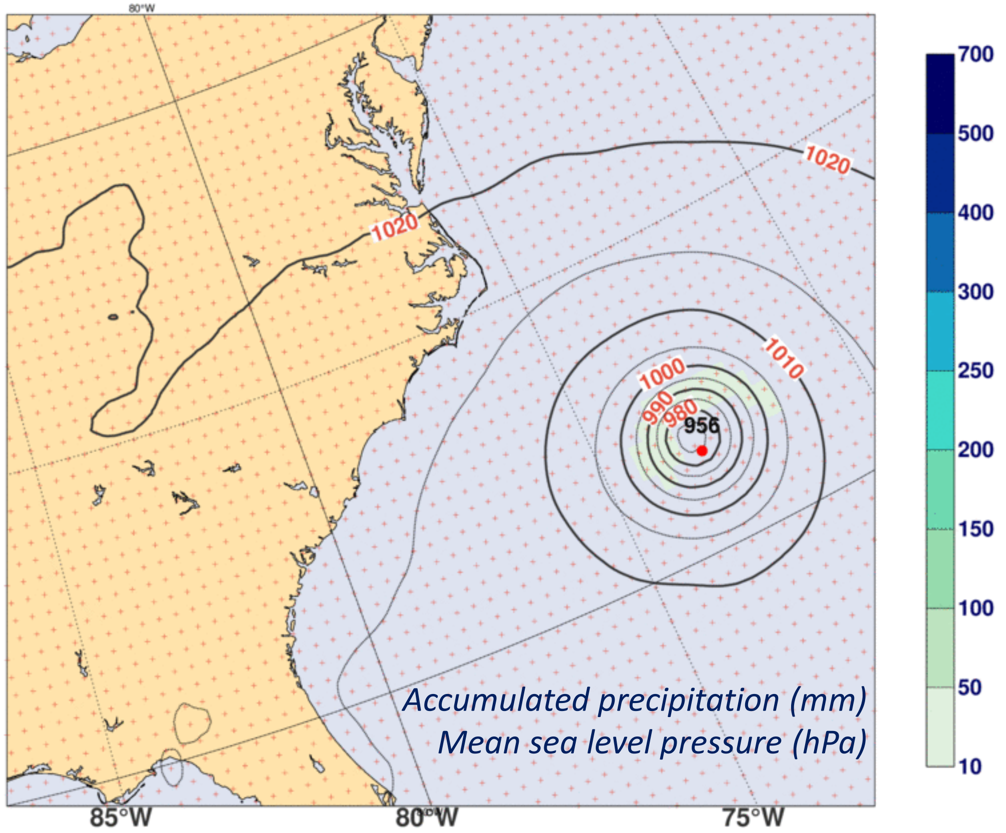


ERA-Interim analysis increments



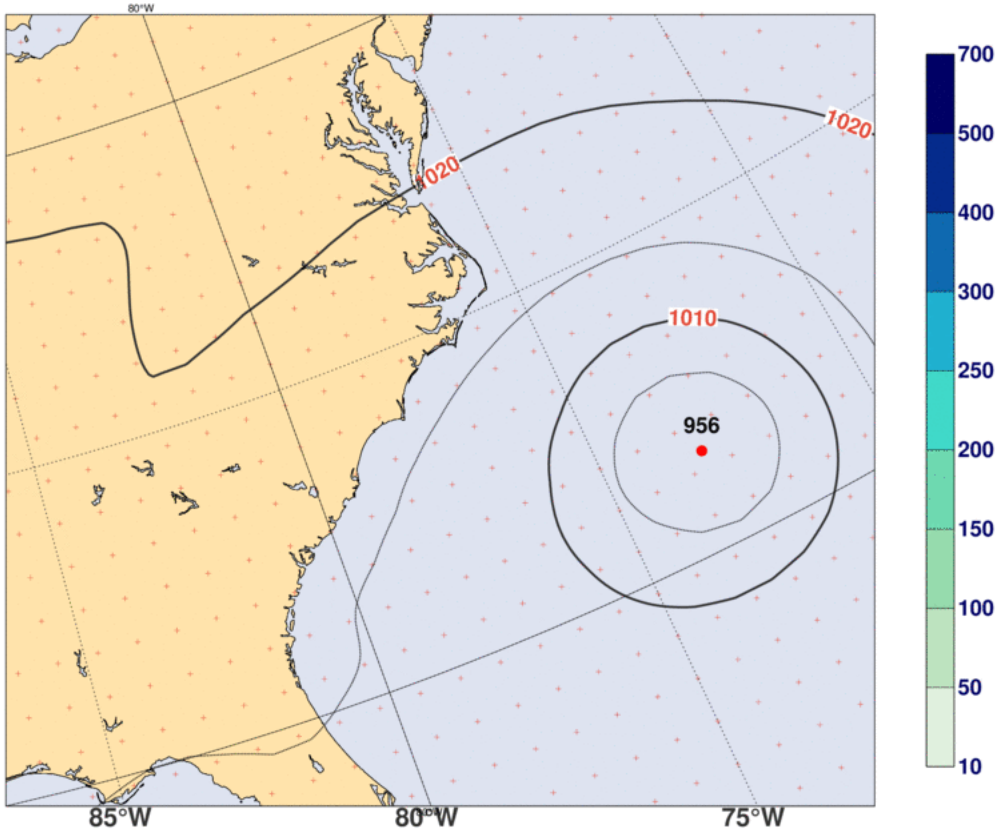
Improved spatial and temporal resolution

Florence Thu 13 Sep 2018, 01 UTC for ERA5



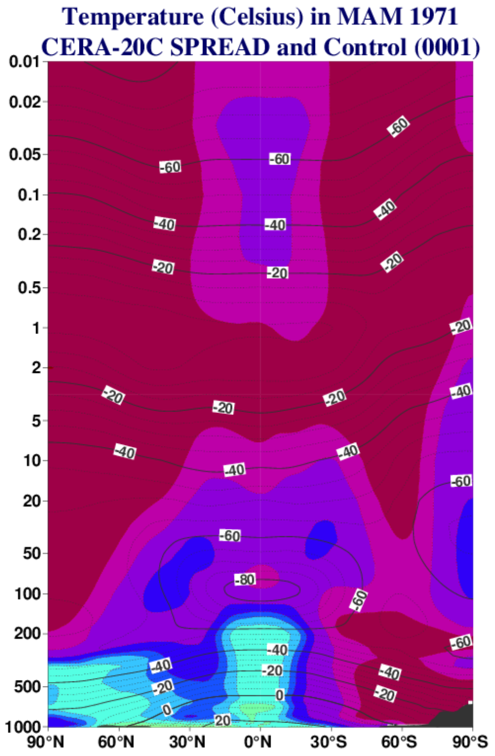
ERA5

Florence Thu 13 Sep 2018, 01 UTC for ERA-Interim

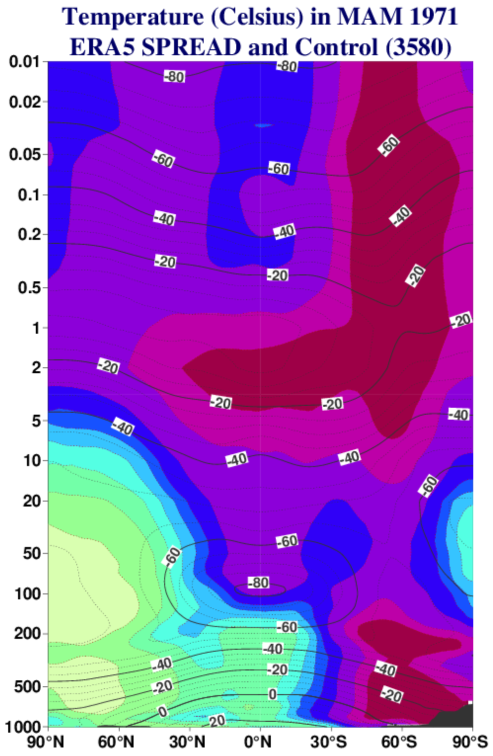


ERA-Interim

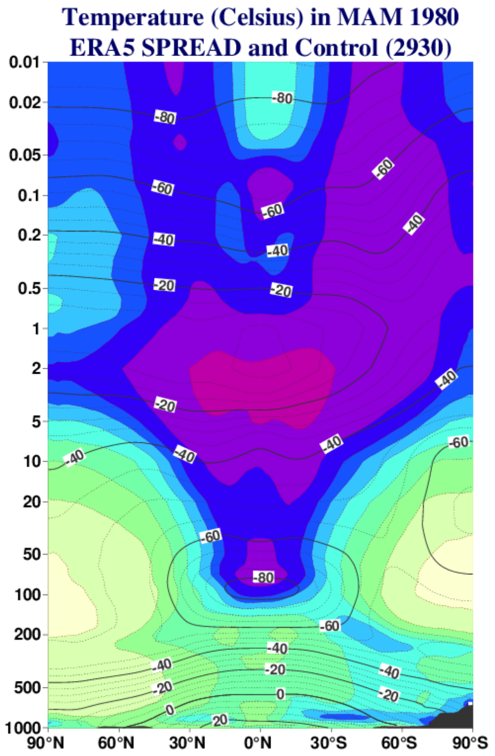
Ensemble spread as a measure of uncertainty



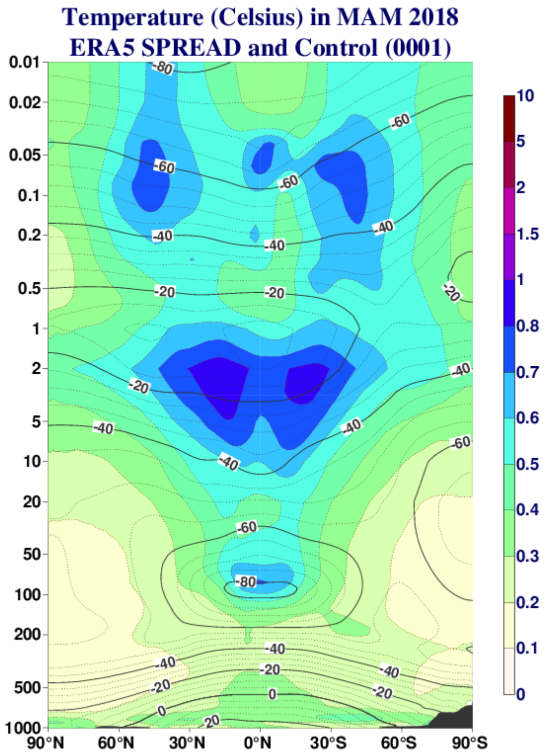
1971 CERA-20C:
Surface pressure, marine wind, only



1971 ERA5:
Upper-air data



1980 ERA5:
Early-satellite era

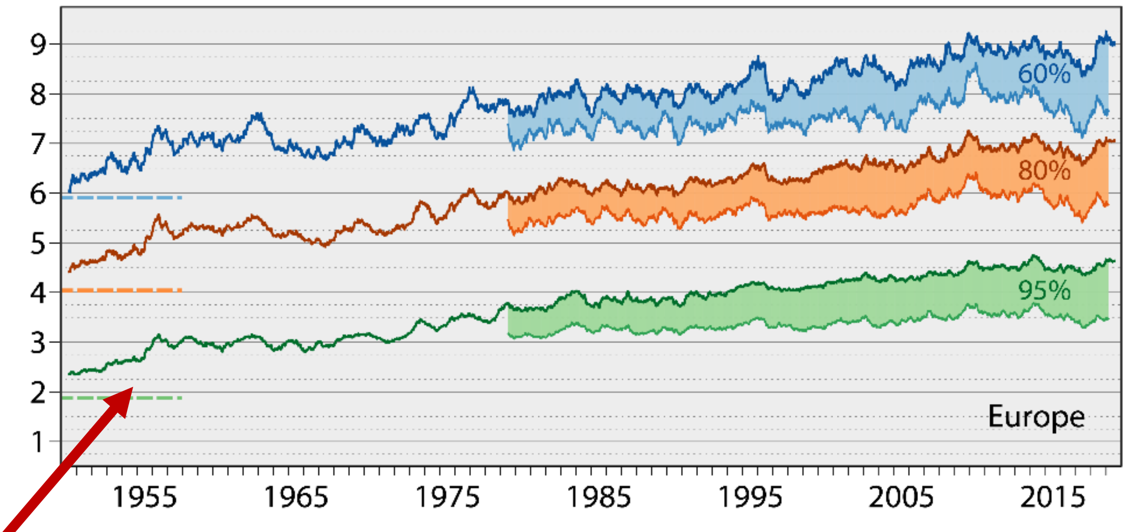


2018 ERA5:
Current observing system

ERA5 extension back to 1950

Range (days) when 365-day mean 500hPa height AC (%) falls below threshold

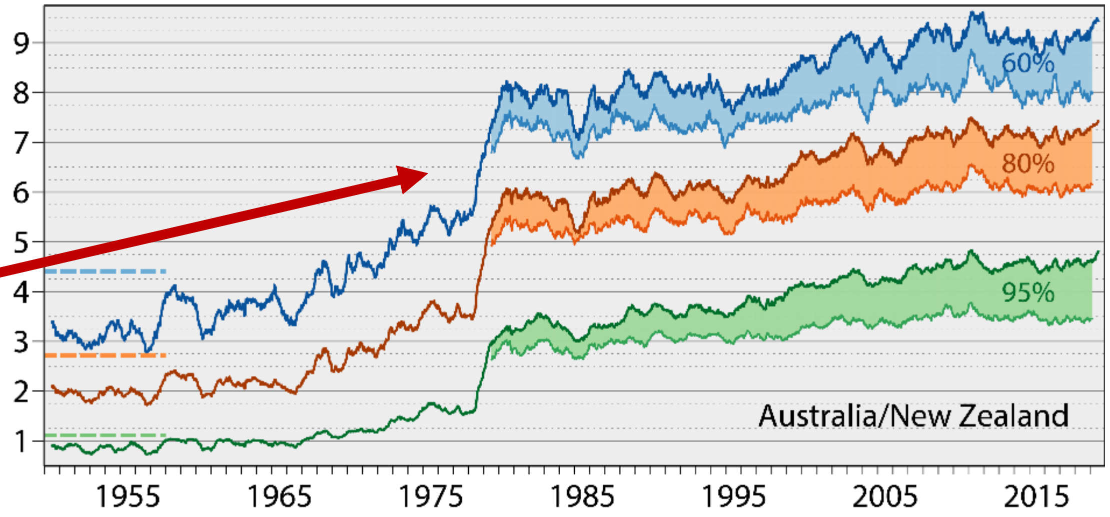
ERA5   ERA-Interim   ECMWF operations 1981



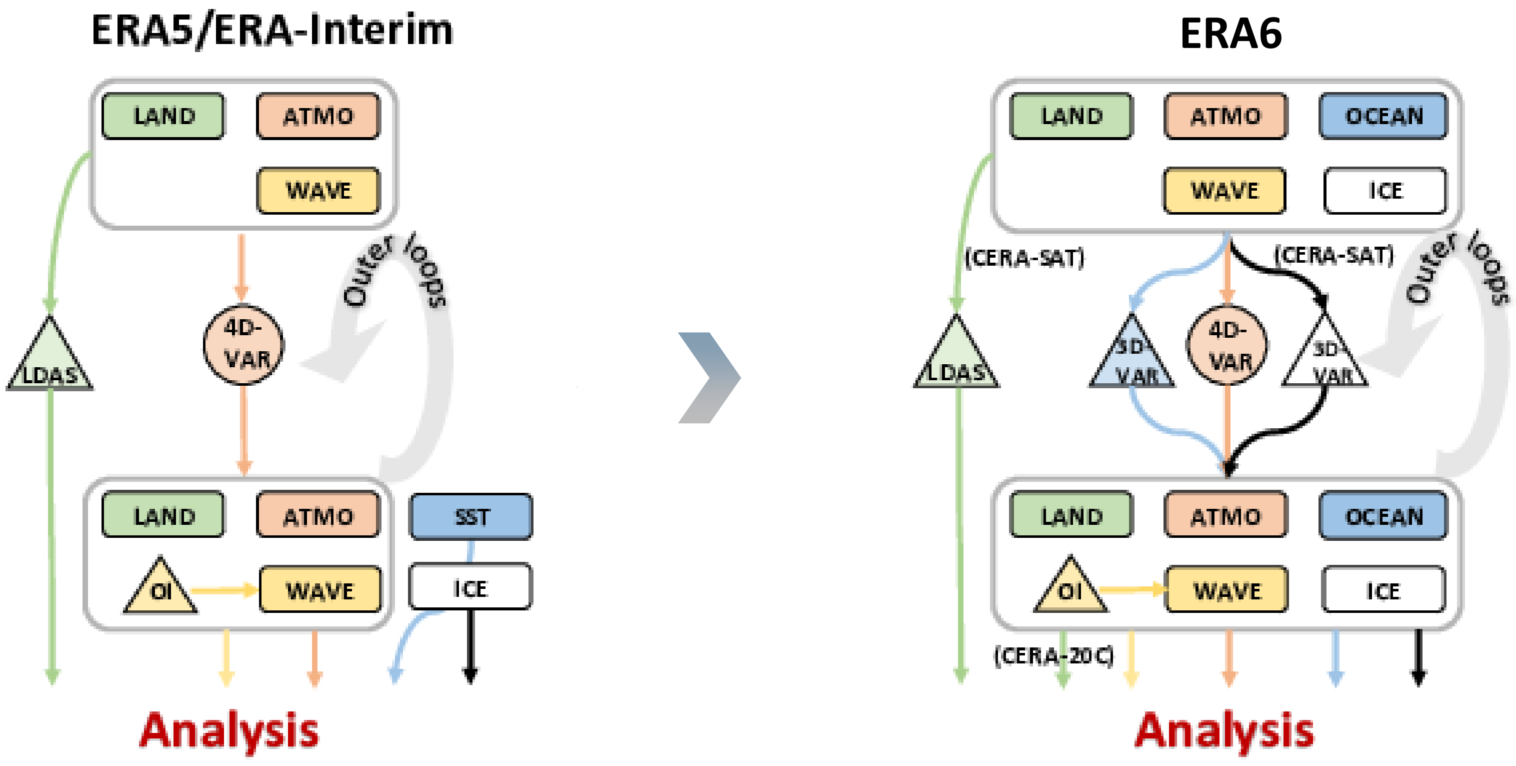
ERA5 1979 onwards:
Re-forecasts from ERA5 are up to 1 day more skilful than ERA-Interim

ERA5 back extension:
NHEM (especially Europe) skill is rather robust, but declines prior to the IGY in 1957-1958

Over SHEM there is a dramatic improvement following the introduction of TOVS satellite data in late 1978.



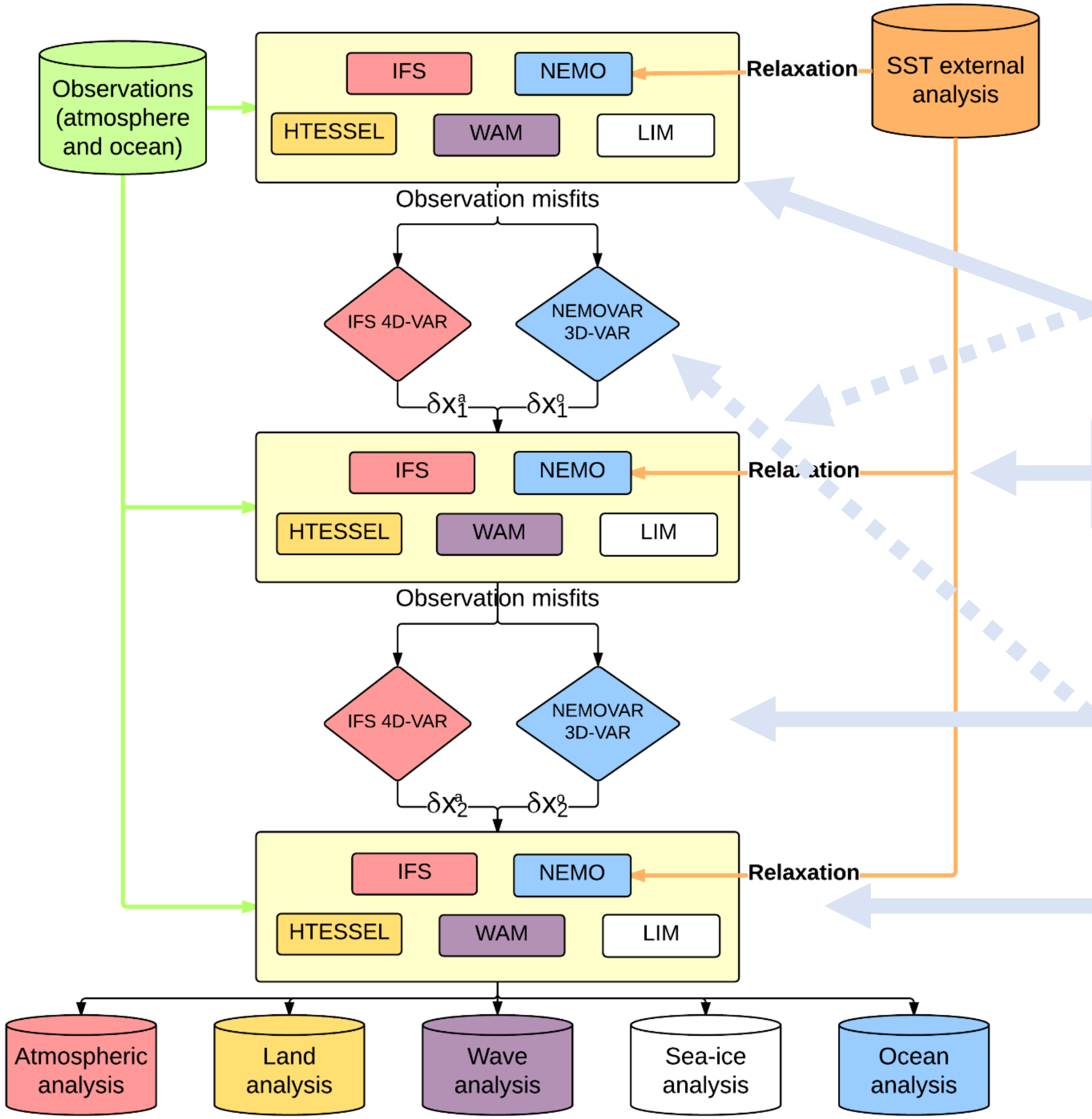
Coming next: Coupling with the ocean and sea ice



The **ERA-CLIM2** project pioneered the development of an **outer-loop coupled** data-assimilation in climate reanalysis

- **CERA-20C:** centennial reanalysis using surface observations only
- **CERA-SAT:** proof of concept for a recent 9-year period using the full observing system at the ERA5 EDA resolution

Coupled atmosphere-ocean analysis (CERA)



Variational approach is implemented as iterative system with inner-loop minimisations and outer-loop calculations of fits to observations

The coupled model is used in each of the outer iterations

SST is computed in NEMO and relaxed to external analysis

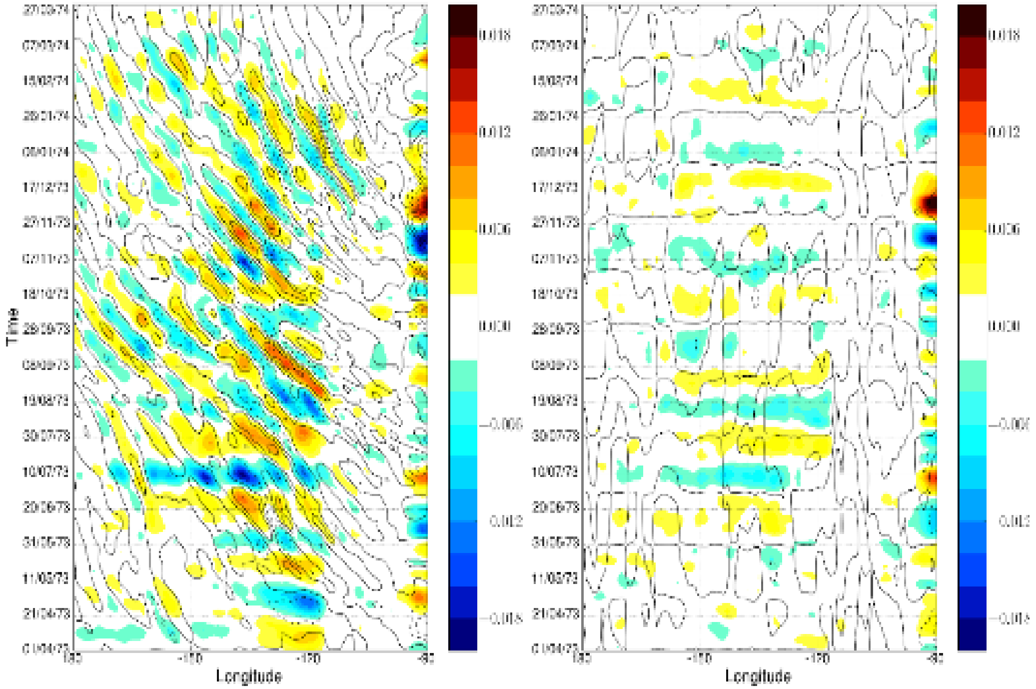
Atmospheric and ocean increments are computed in parallel to correct the initial state in the inner loops

The analysis is dynamically consistent with respect to the coupled model

Analysis is consistent with coupled model

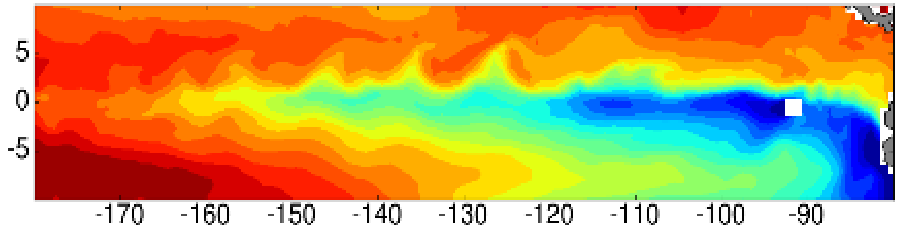
Example: Tropical instability waves

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



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

Courtesy Eric de Boisseson



CERA-20C
- tropical instability waves enabled by ocean dynamics
- atmosphere responds accordingly through surface wind stress

ERA-20C
- monthly SST for boundary condition
- no tropical instability waves or wind stress signals

Laloyaux et al. QJRMS 2016; MWR 2016; JAMES 2018.

Final remarks and outlook

- Copernicus provides sustained funding for reanalysis in Europe – focus on climate
- Copernicus also supports work on improving the observational record:
  - Satellite data rescue and reprocessing activities
  - Coordination and tools for historical data rescue
- The next global reanalysis (ERA6) will be coupled with ocean/sea-ice
- Reanalysis-producing centers have always worked together, especially on observations
- JCSDA can help the US reanalysis collaborative effort by providing:
  - Shared access to observation data, including ERA5 input (R2D2)
  - Observation operators and QC for older instruments (JEDI/UFO)
  - Evaluation tools for observation impact in coupled data assimilation

Extra slides

Baseline: ERA-Interim (until 2016) + ECMWF operations (after 2016)

Baseline

Not used in baseline

Not used in ERA5

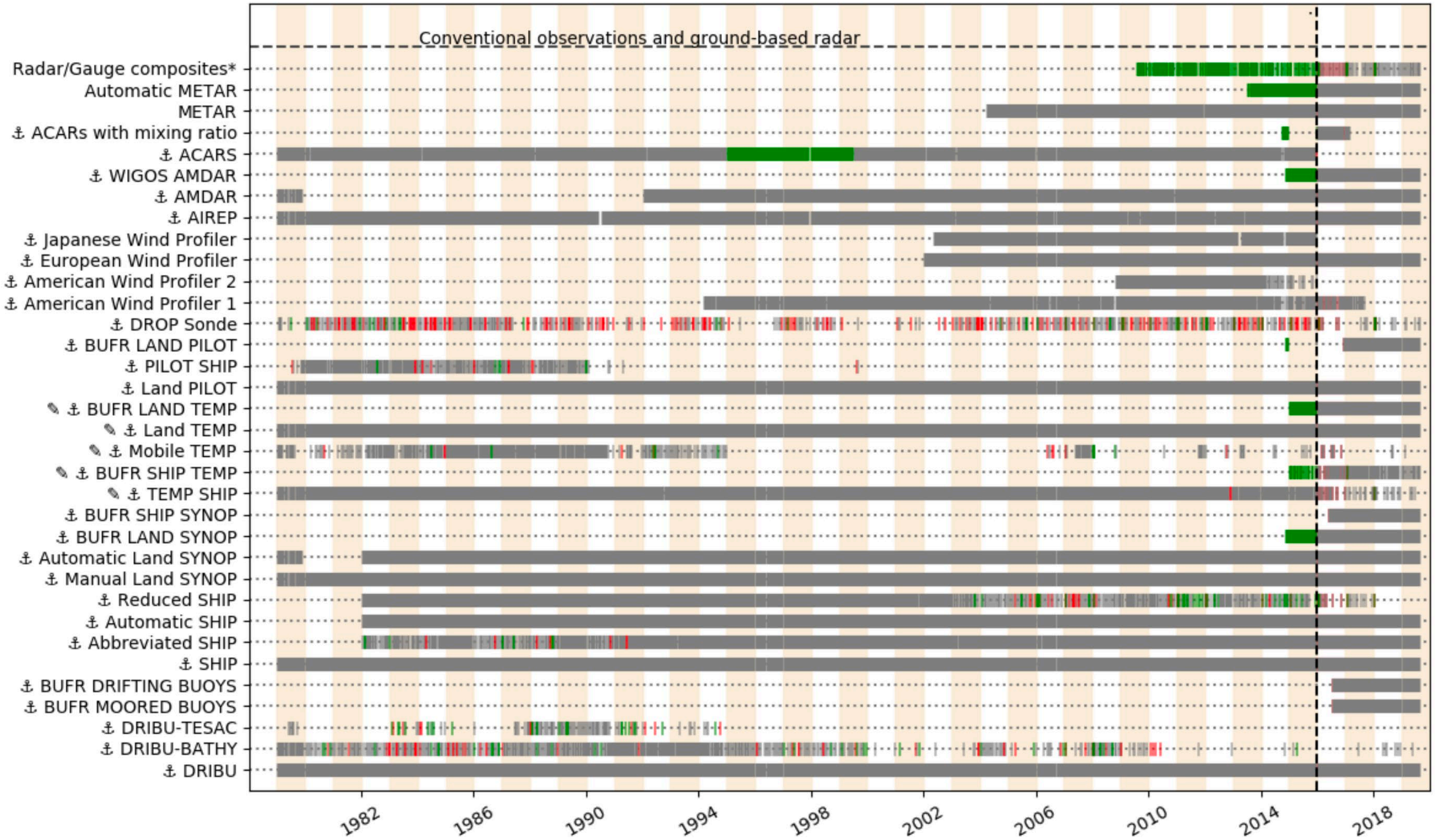
Reprocessed for ERA5

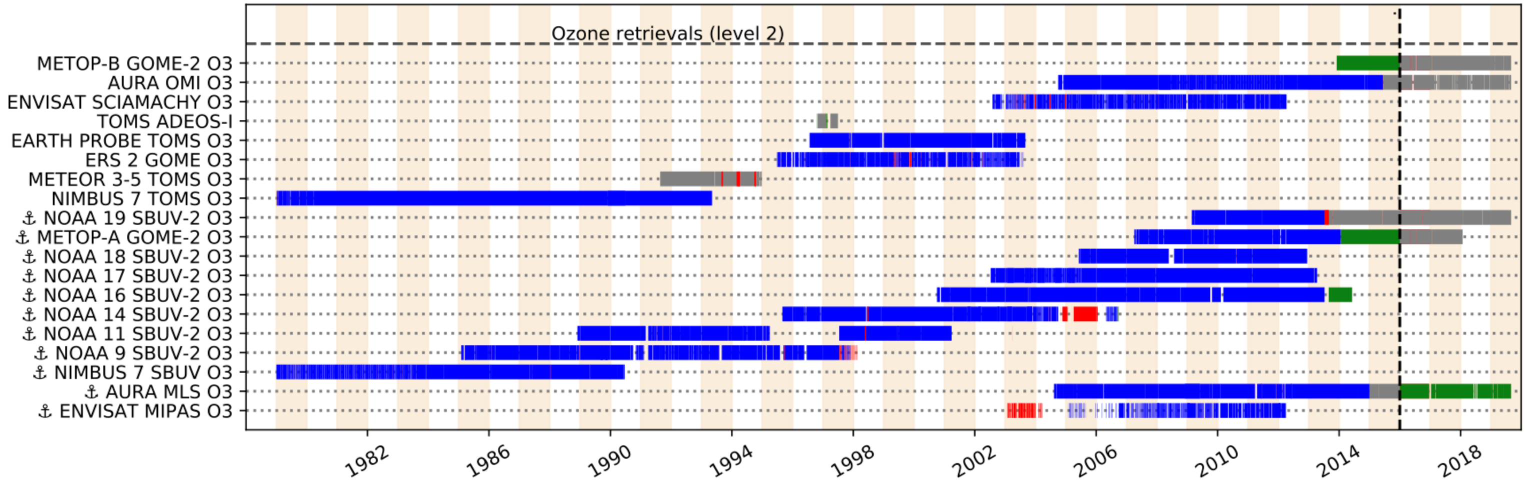
⚓ No bias correction

✎ Prescribed bias correction

VarBC

Radiances
Retrieved ozone
Aircraft temperatures
Surface pressure
Rain rates





Hersbach *et al.* 2020: doi.org/10.1002/qj.3803

Baseline: ERA-Interim (until 2016) +
ECMWF operations (after 2016)

Baseline

Not used in baseline

Not used in ERA5

Reprocessed for ERA5

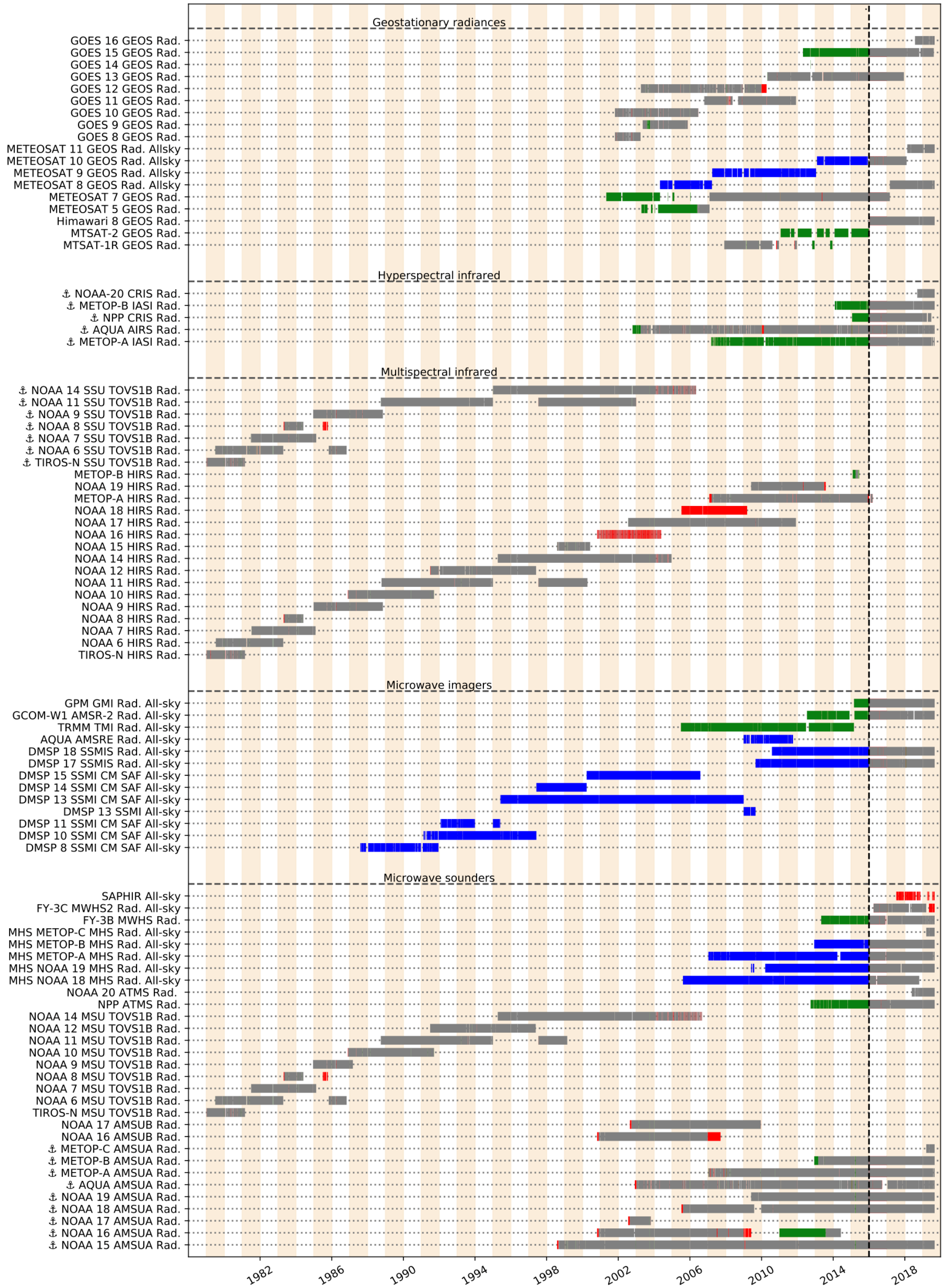
⚓ No bias correction

✎ Prescribed bias correction

VarBC

Radiances
Retrieved ozone
Aircraft temperatures
Surface pressure
Rain rates

Hersbach *et al.* 2020: doi.org/10.1002/qj.3803



Baseline: ERA-Interim (until 2016) +
ECMWF operations (after 2016)

Baseline

Not used in baseline

Not used in ERA5

Reprocessed for ERA5

⚓ No bias correction

✎ Prescribed bias correction

VarBC

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