Coupled reanalysis at ECMWF

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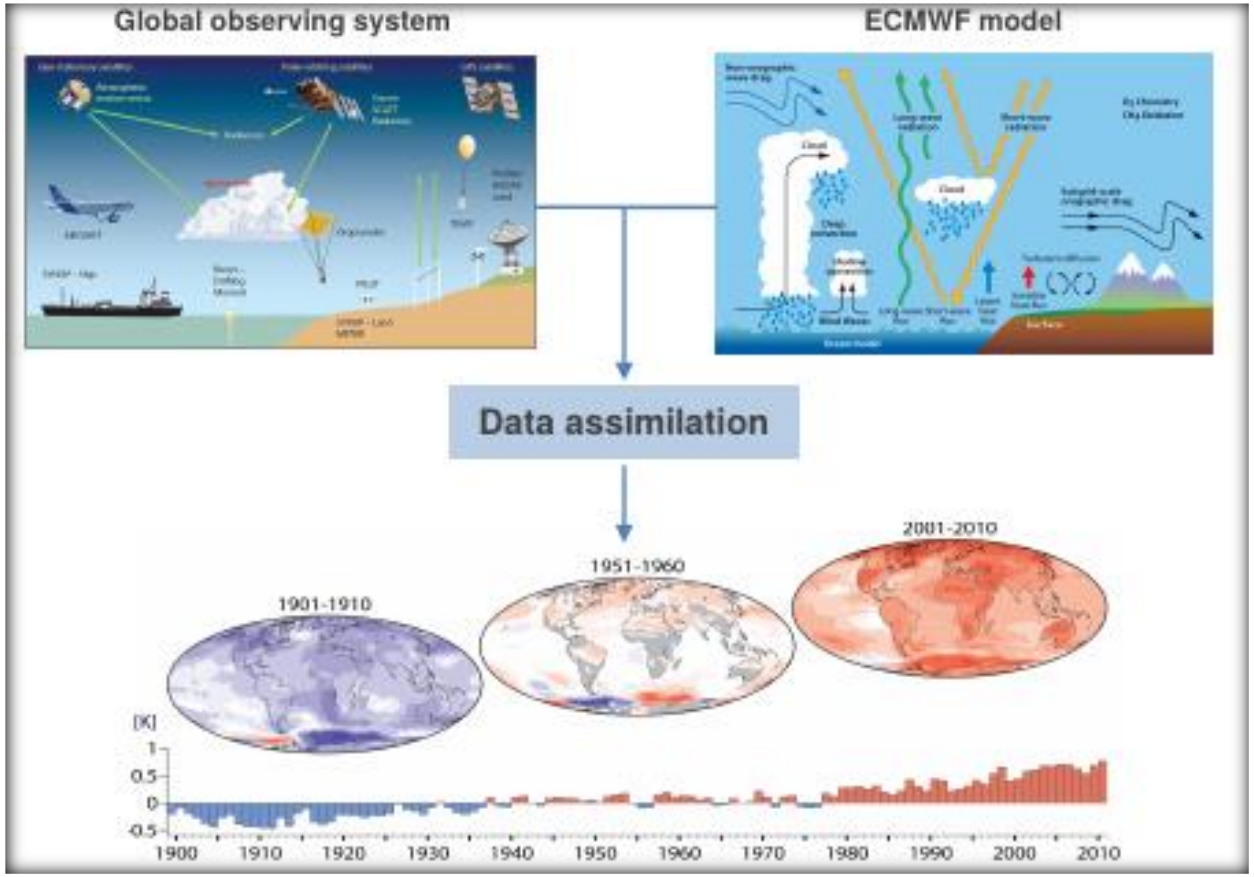
ECMWF

Reanalysis

Reanalysis offers a detailed overview of the past ~~atmosphere~~ Earth system

- **Complete**: combining vast amounts of observations into (global) fields
- **Consistent**: use the same physical model and DA system throughout
- **State-of-the-art**: use the best available observations and model at highest feasible resolution

Reanalysis allows for a close monitoring of the Earth's climate system also where direct observations are sparse.



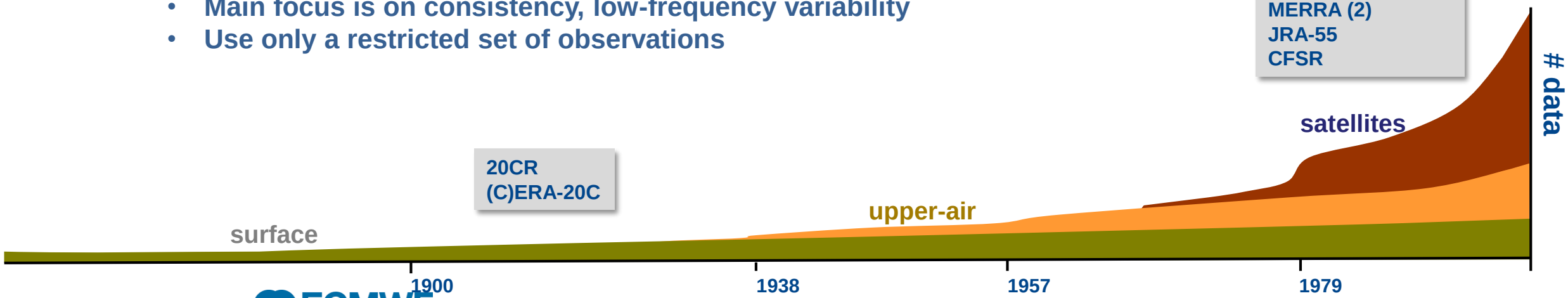
Reanalysis (II)

Reanalyses of the modern observing period (~30-50 years):

- Produce the best state estimate at any given time (as for NWP)
- Use as many observations as possible, including from satellites
- Closely tied to forecast system development and evaluation
- Can support product updates in near-real time

Extended climate reanalyses (~100-200 years):

- As far back as the instrumental record allows
- Pioneered by NOAA-CIRES 20th-Century Reanalysis Project
- Long perspective needed to assess current changes
- Main focus is on consistency, low-frequency variability
- Use only a restricted set of observations



Reanalysis (III) – The ECMWF reanalysis landscape

Atmosphere/land *including ocean waves*

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

Ocean *including sea ice*

2006 ORAS3	2010 - … ORAS4	2016 - … ORAS5

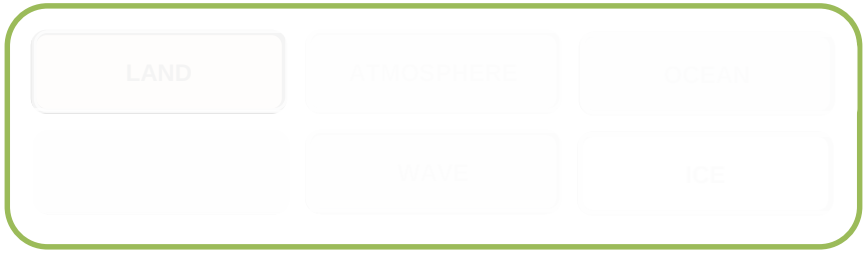
ERA CLIM / ERA CLIM 2

Centennial *Coupled*

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

Enhanced land

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



Atmospheric composition

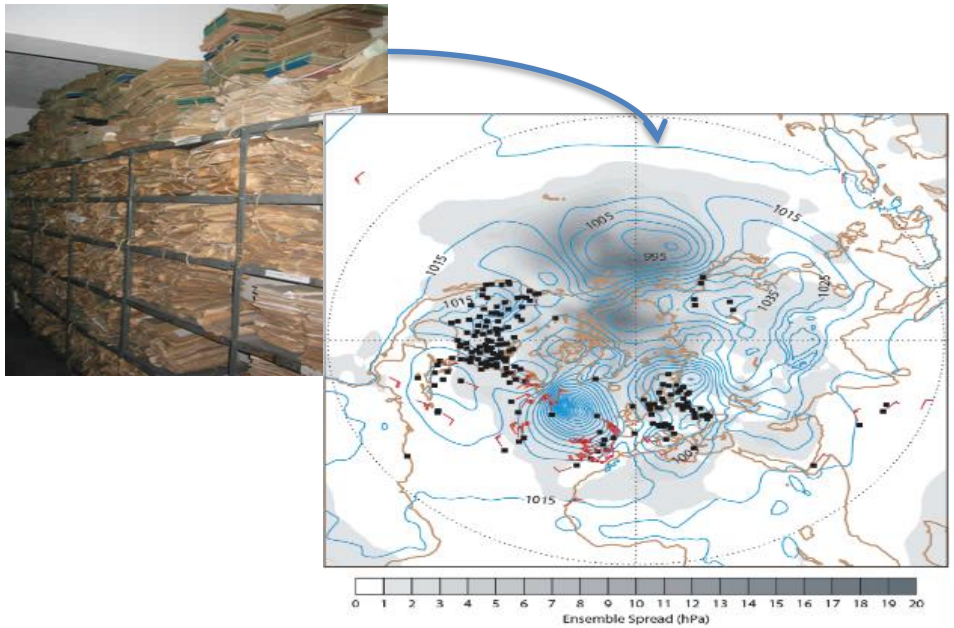
2008 - 2009 GEMS	2010 - 2011 MACC	2017 - … CAMS

Outline - Coupled reanalysis at ECMWF

- Reanalysis – An introduction
- A quick recap – how did we get where we are now?
  - Pioneering work done in the ERA-CLIM and ERA-CLIM2 projects
- A pilot for coupled reanalysis in the satellite era: CERA-SAT
  - Assimilation approach and system setup
  - Preliminary assessment of performance
- Current reanalysis (and related) activities at ECMWF
  - ERA5
  - Copernicus Climate Change Service (C3S)

ERA-CLIM project (2011-2013)

Goal: Preparing input observations, model data, and data assimilation systems for a global atmospheric reanalysis of the 20th century

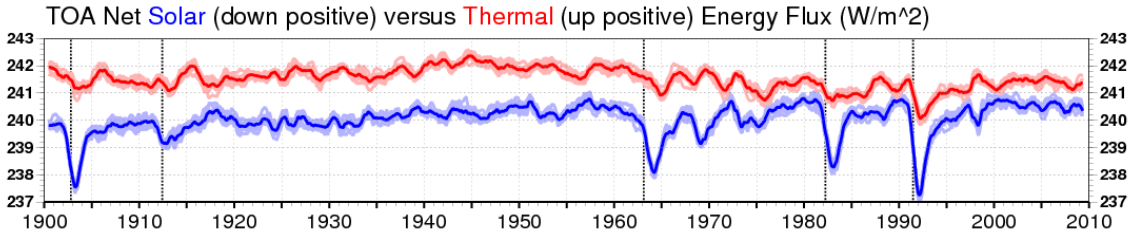


Main components:

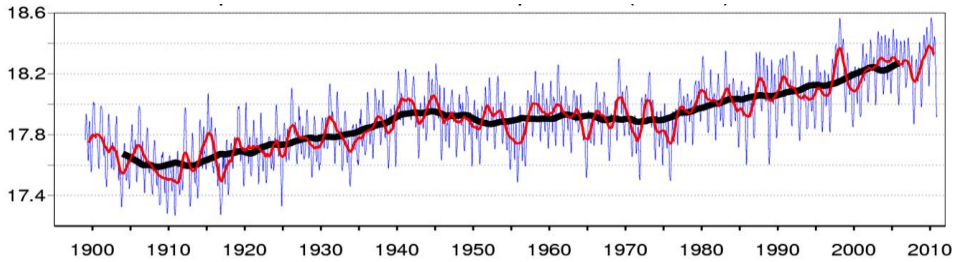
- Data rescue (in-situ upper-air and satellite observations)
- Incremental development of new 20C reanalysis products
- Use of reanalysis feedback to improve the historic data record
- Access to reanalysis data and observation quality information

ERA-20CM

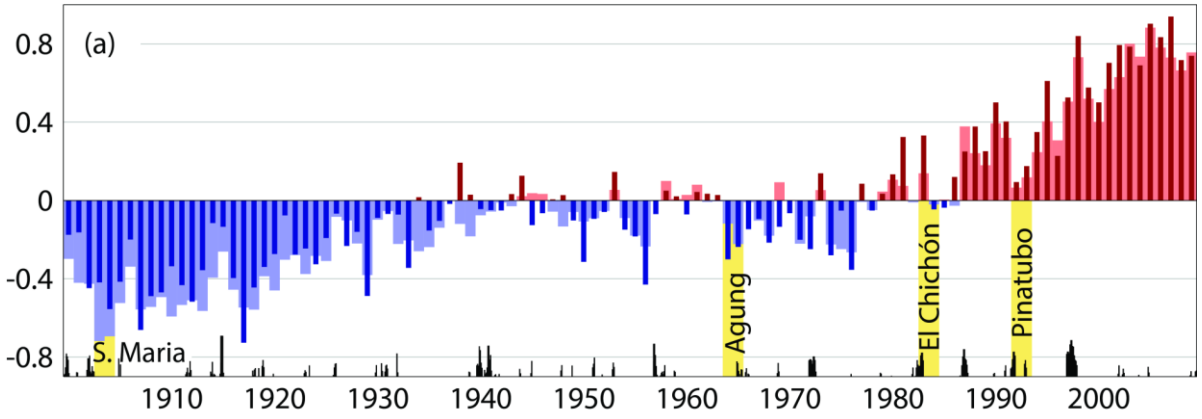
Radiative forcing



HadISST2 SST and sea ice



- ✓ Although there are certainly model biases:
- ✓ **ERA-20CM** gives **good** reference of **low-frequency variability**
- ✓ **Well suited** to **project** global warming and major events **onto other geophysical quantities** not directly provided in the forcing data

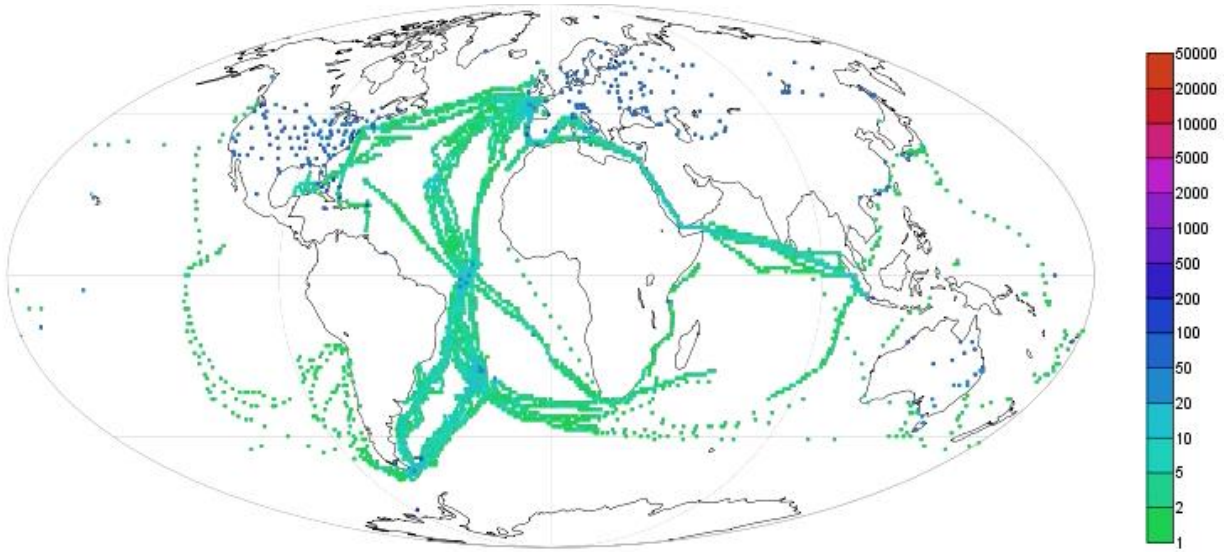


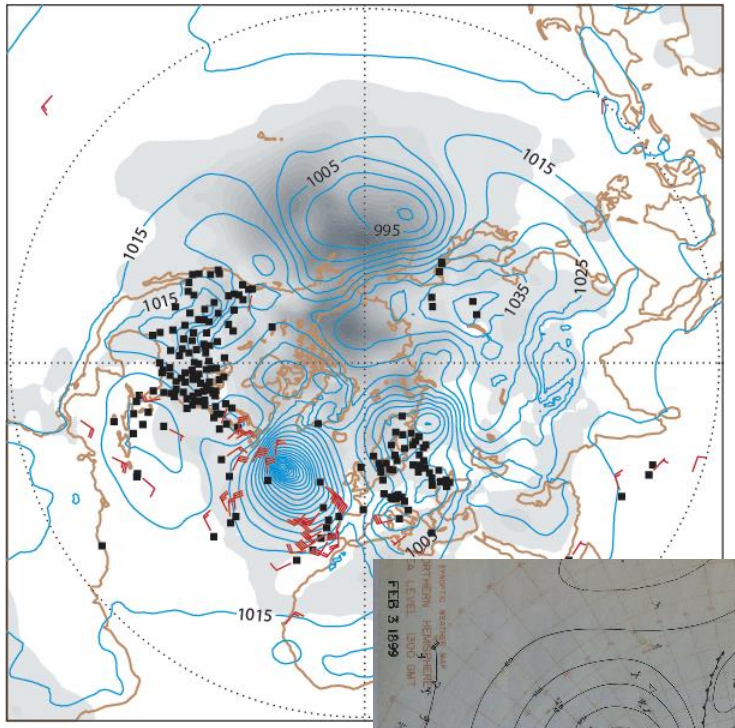
Hersbach et al, QJRMS 2015

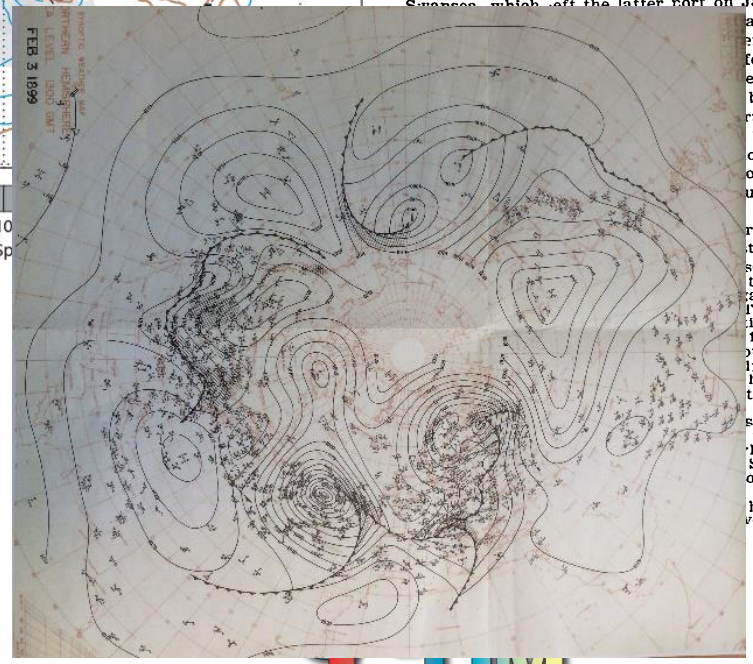
ERA-CLIM project – ERA-20C

Century-long climate reanalysis using surface observations only

ISPD 3.2.6 and ICOADS 2.5.1 pressure observations assimilated in ERA-20C[1]







The New York Times
Published: February 16, 1899
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TERRIFIC STORMS AT SEA

Steamships from All Quarters Report Extremely Rough Voyages.

ALL MORE OR LESS BATTERED

Vessels Sighted in Distress and Abandoned — Blinding Snow and Waves Like Mountains.

All the steamers that came in yesterday were coated with ice from the tops of the masts down to the water line, and all had passed through storms of blinding snow and mountainous waves. The British steamer Ethelgonda, from Bristol and

1) *Poli et al, J. Climate 2016 ;* **ERA-20C Observation Feedback Archive available at www.ecmwf.int/research**

ERA-CLIM2 project (2014 - 2017)

Goal: Production of a consistent 20th-century reanalysis of the coupled Earth-system: *atmosphere, land surface, ocean, sea-ice, and the carbon cycle*

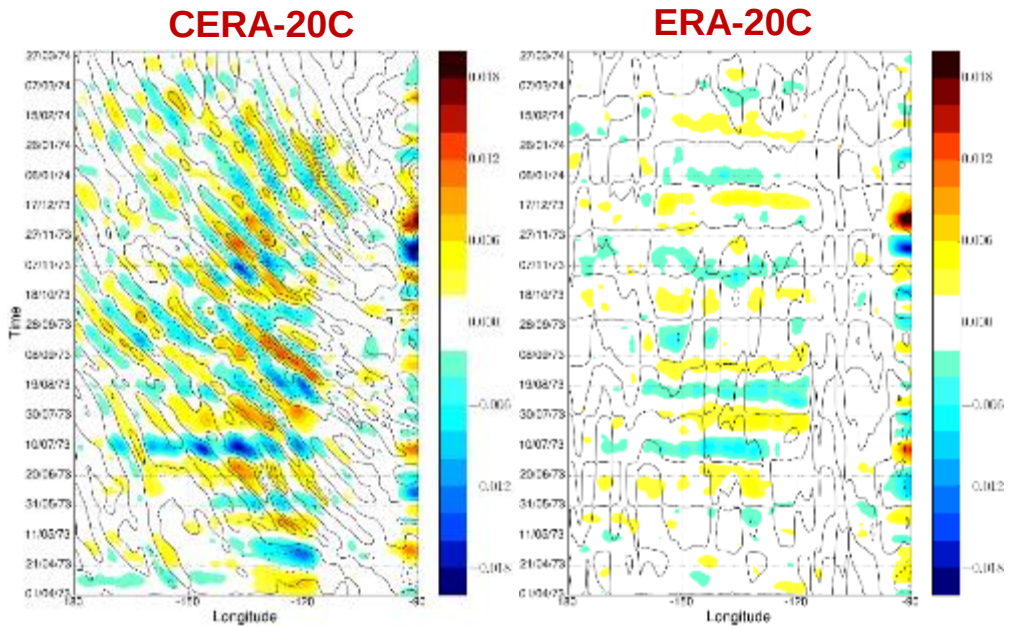
Main components:

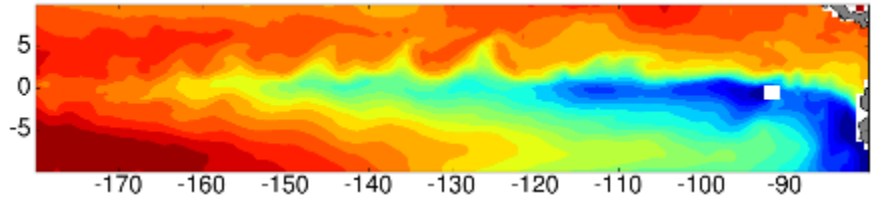
- **Production of coupled reanalyses, for 20C and the modern era**
- **Research and development in coupled data assimilation**
- **Earth system observations for extended climate reanalyses**
- **Evaluation of uncertainties in observations and reanalyses**

ERA-CLIM2 project – CERA-20C

Century-long climate reanalysis using surface observations only (like ERA-20C), but coupled with the ocean and sea ice

Example: Tropical instability waves (westward-propagating waves near the equator)





CERA-20C

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

ERA20C

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

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

Courtesy of Eric de Boisseson

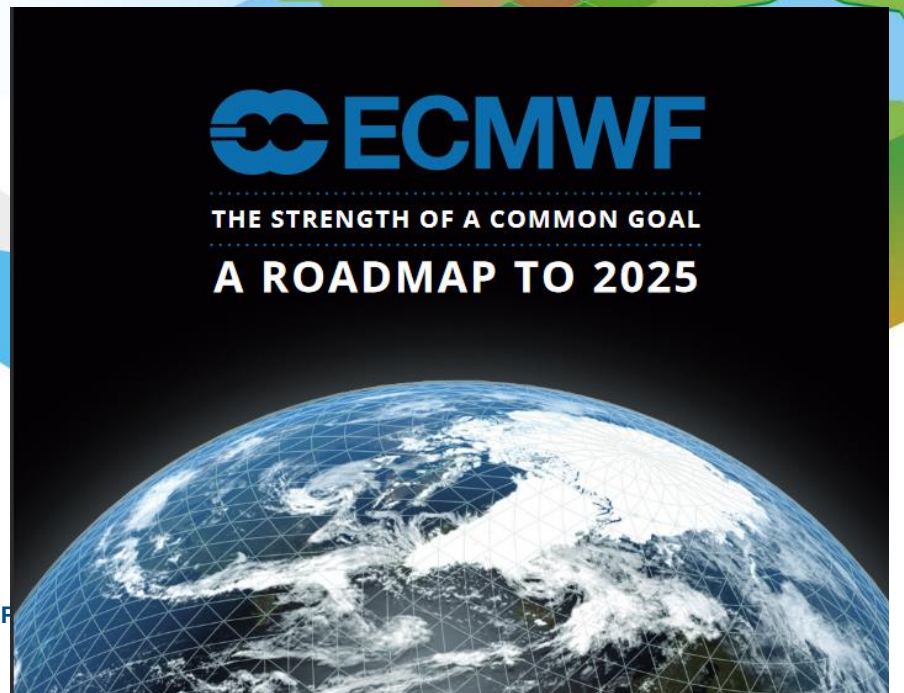
Laloyaux et al. QJRMS; 2016, Laloyaux et. al MWR 2016; Laloyaux et al. JAMES 2018.

ERA-CLIM2 project – CERA-SAT

A pilot for coupled reanalysis of the satellite era, using a higher resolution ocean component and the full, modern observing system

"Whilst Earth system modelling is already in its early stages, its application to data assimilation is very novel and results could be ground-breaking"

Roadmap to 2025



ERA-CLIM2 project – CERA-SAT

Atmosphere/Land

- **Model:** IFS (CY42R1, April 2016)
- **Atmosphere Resolution:** TL319 (~60 Km); 137 levels
- **Assimilation:** 24-hour window 4D-Var
- **Full observing system :** ERA5 observing system
- **Land surface analysis**: Dedicated; Weakly coupled

Ocean/Sea ice

- **Model:** NEMO / LIM2 (CY42r1)
- **Resolution** (1/4 degree; ORCA025) ~30 km; 75 levels
- **Assimilation:** 24-hour window 3D-Var FGAT
- **Observations:** salinity and temperature profiles, SSH, SI analysis (OSTIA L4)

Wave

- **Model:** WAM (CY42R1)
- **Resolution:** 0.5 degree
- **Assimilation:** 24-hour window
- **Observation:** ERA5 observing system

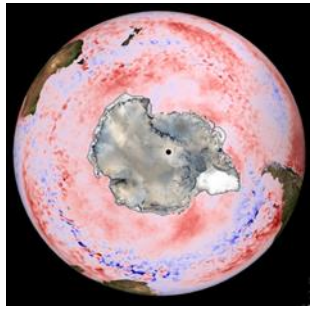
CERA – Outer loop coupled assimilation

Full observing system

- SYNOP, radiosondes, radiances, scatterometer, etc.
- Screen level, snow depth and cover, soil moisture, etc.

Salinity and Temperature

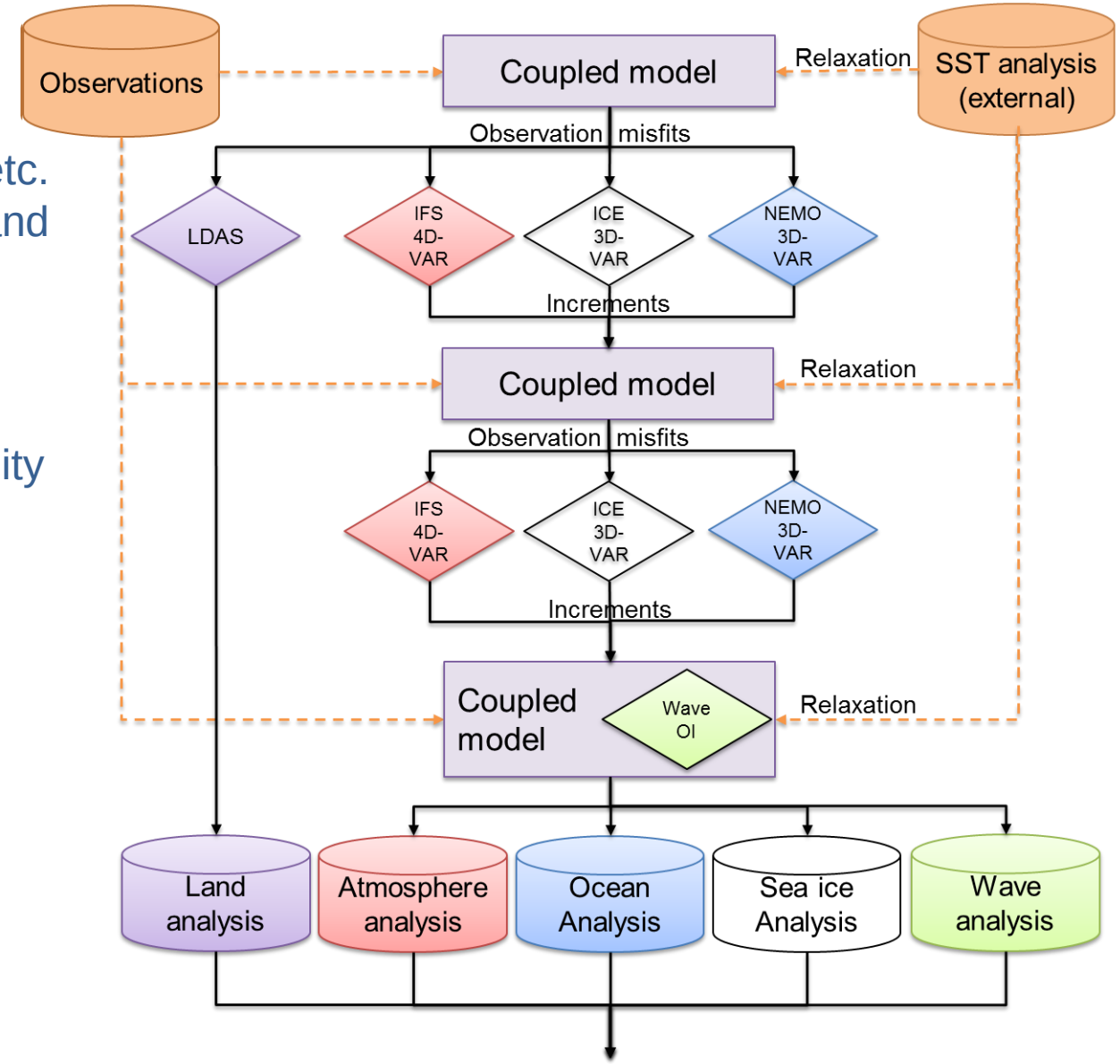
- Subsurface profiles of salinity and temperature
- EN4.1.1 dataset
- Sea surface height



SST and sea ice analysis

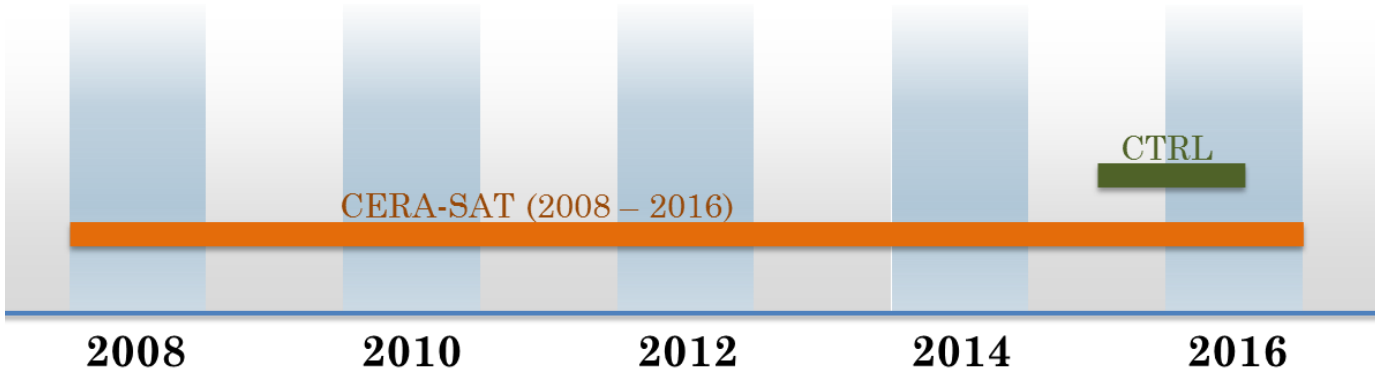
- OSTIA 0.05° product sea ice concentration (L4)

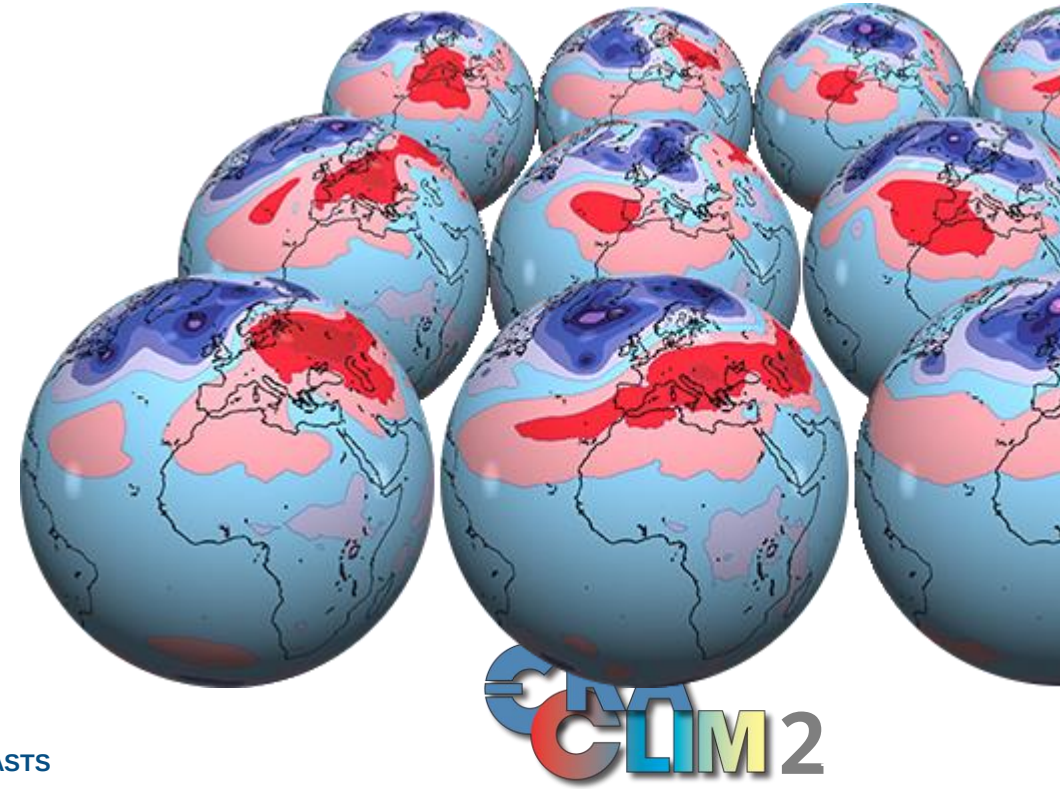
SST nudging



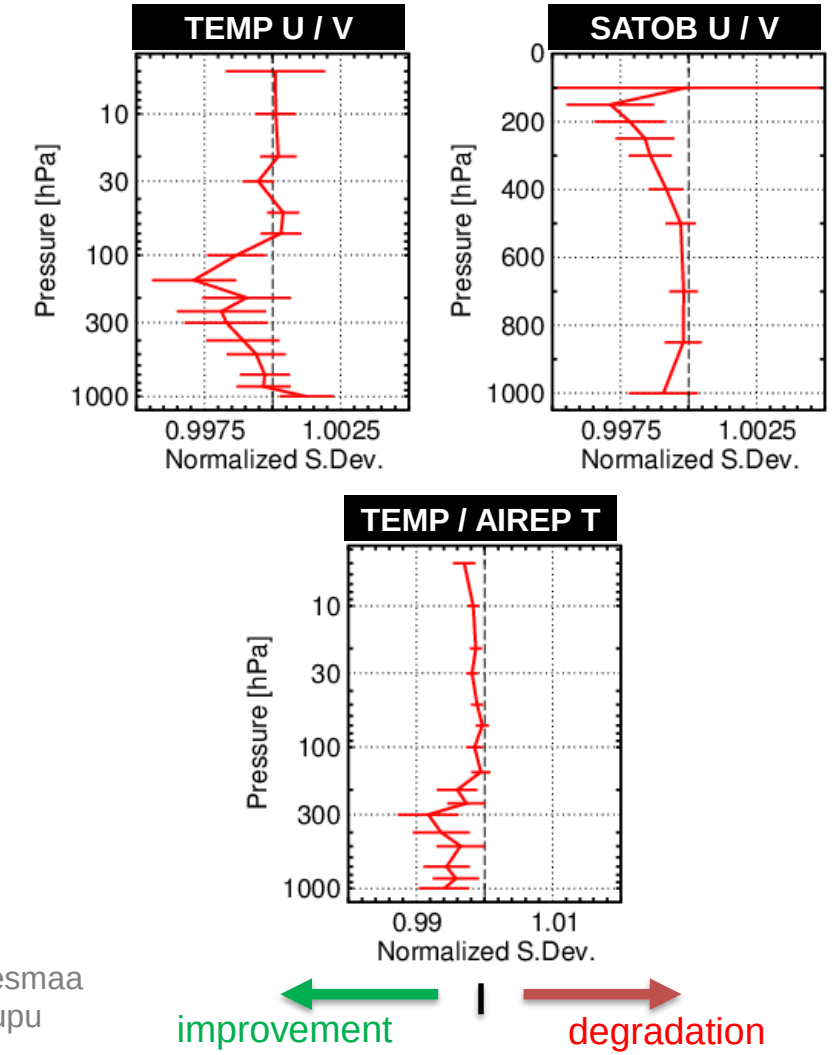
CERA-SAT – A pilot for satellite era coupled reanalysis

- 10-member ensemble of data assimilations (EDA)
- Available between 2008 and 2016 (produced in 4 streams)
- Uncoupled CTRL for assessment studies





CERA-SAT – Improved fit to observations



Courtesy:
Reima Eresmaa
Cristina Lupu

Control-normalized standard deviation of background departure

- Global, 1-year sample (1 Sept 2015 – 31 Aug 2016)
- Improvements in
  - Temperature btw 300—1000 hPa
  - Wind btw 100—300 hPa

Bars indicate 95% confidence intervals

CTRL: Uncoupled, atmosphere/land/wave analysis and forecasts

CERA-SAT – Improved fit to observations

Control-normalized standard deviation of background departure

- global 1-year sample (1 Sept 2015 – 31 Aug 2016)
- Improvements in

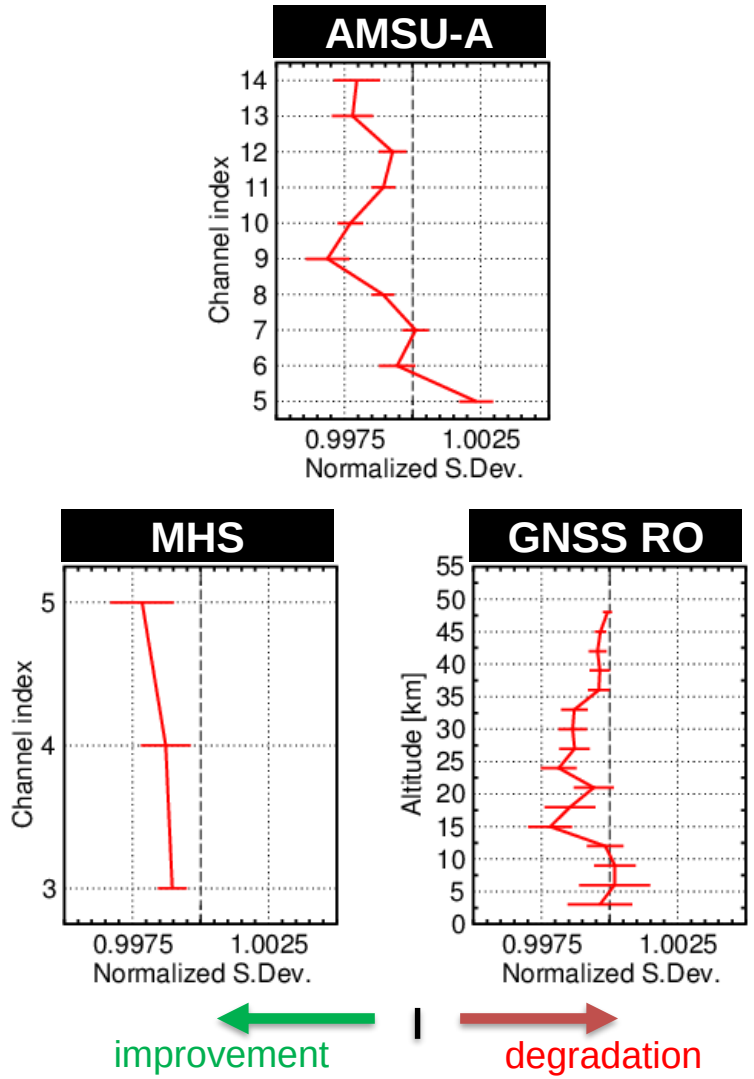
  AMSU-A microwave radiance channels 9—14

  Microwave humidity sounder radiances

  Radio occultation data btw 15—35 km

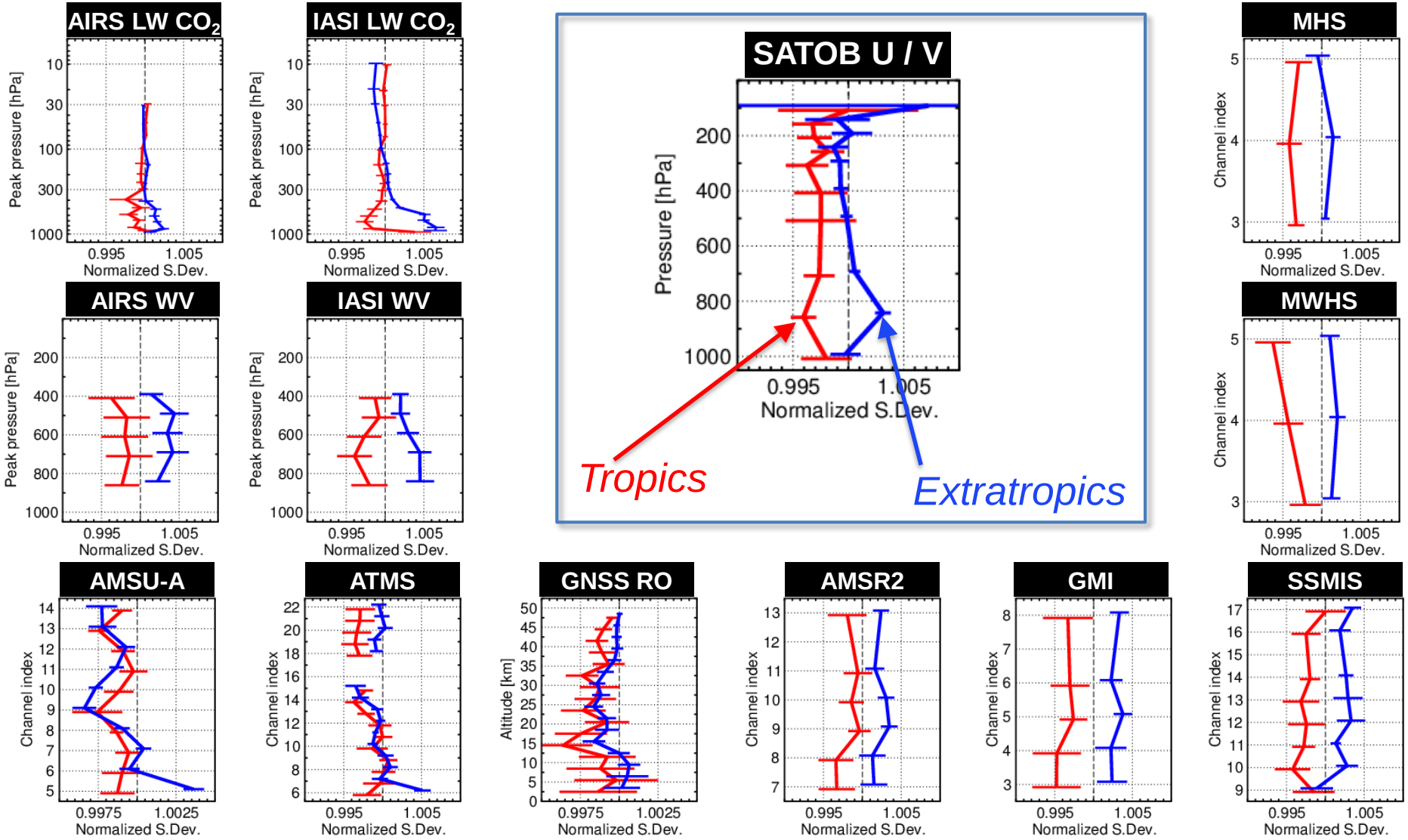
Bars indicate 95% confidence intervals

CTRL: Uncoupled, atmosphere/land/wave analysis and forecasts



Courtesy:
Reima Eresmaa, Cristina Lupu

CERA-SAT – Improved fit to observations (in the Tropics)



Courtesy:
Reima Eresmaa, Cristina Lupu

improvement | degradation

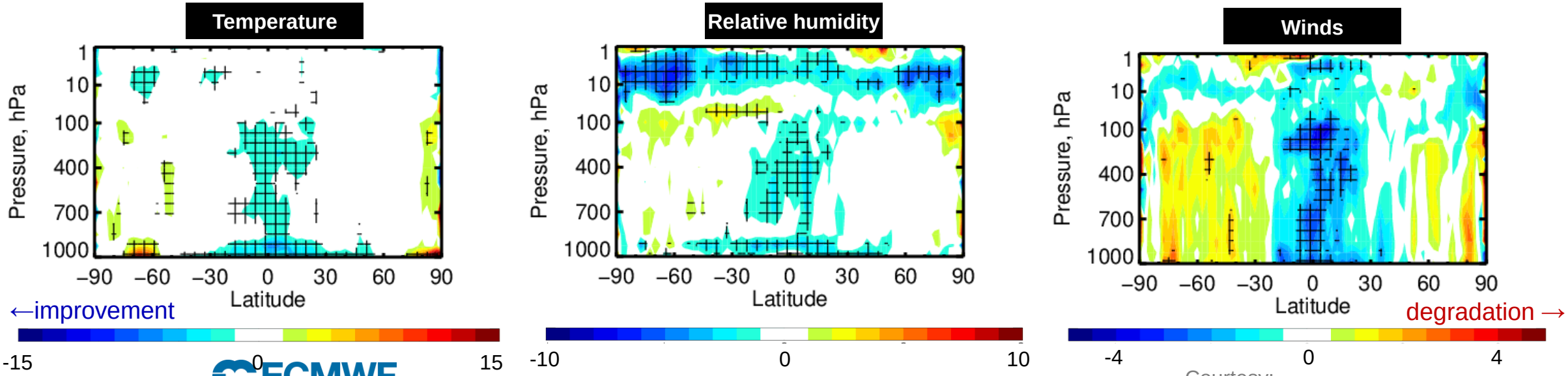
CERA-SAT – Improved forecast performance

Forecast improvements at Day+5 in Tropical regions - against own analysis
Reduction of forecast error standard deviation

- Temperature: 1.5% - 3%
- Relative humidity: 1% - 2%
- Vector winds: 4% - 5%

CTRL: Uncoupled, atmosphere/land/wave analysis and forecasts

Difference in standard deviation of error
(May 2015 – Aug 2016, own analysis)



Courtesy:
Reima Eresmaa, Cristina Lupu

CERA-SAT – Improved forecast performance

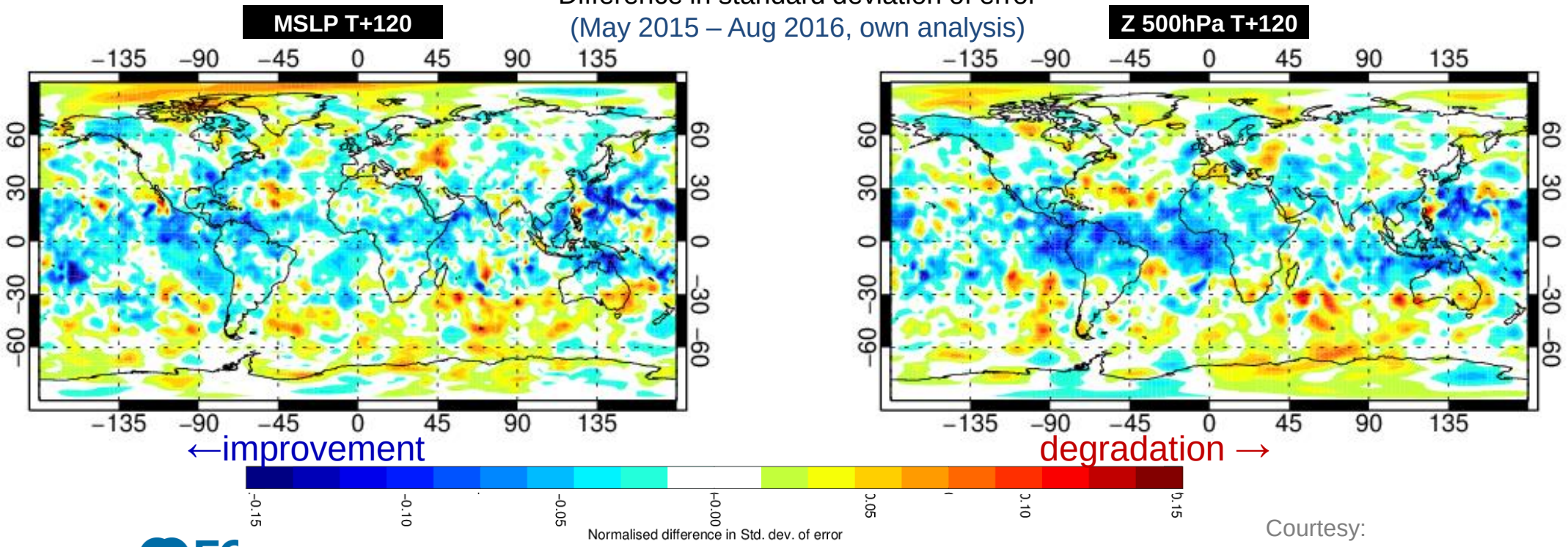
Forecast improvements at Day+5 in Tropical regions - against own analysis

Reduction of forecast error standard deviation

- Tropics pressure about 5 -10 %
- Tropics Z500 about 5 - 10 %

CTRL: Uncoupled, atmosphere/land/wave analysis and forecasts

Difference in standard deviation of error
(May 2015 – Aug 2016, own analysis)

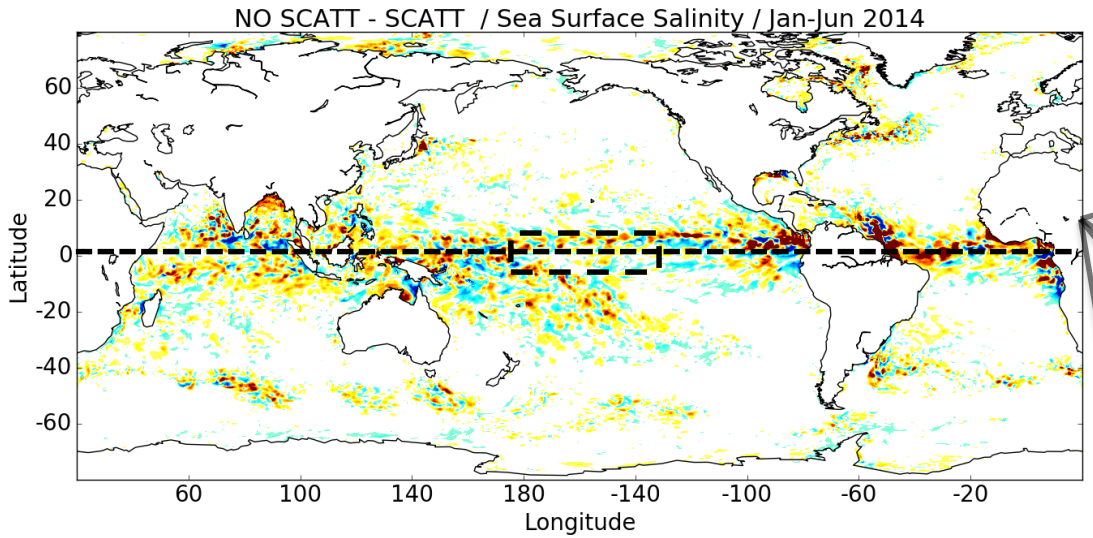


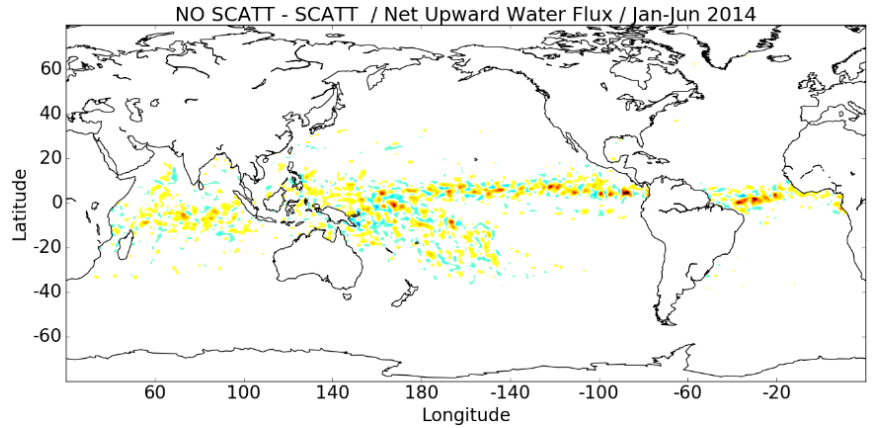
Courtesy:
Reima Eresmaa, Cristina Lupu

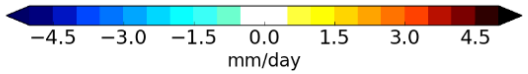
Coupled assimilation – Scatterometer denial experiments

Assimilation of scatterometer winds benefits ocean salinity

Reduction of salinity background and analysis departures



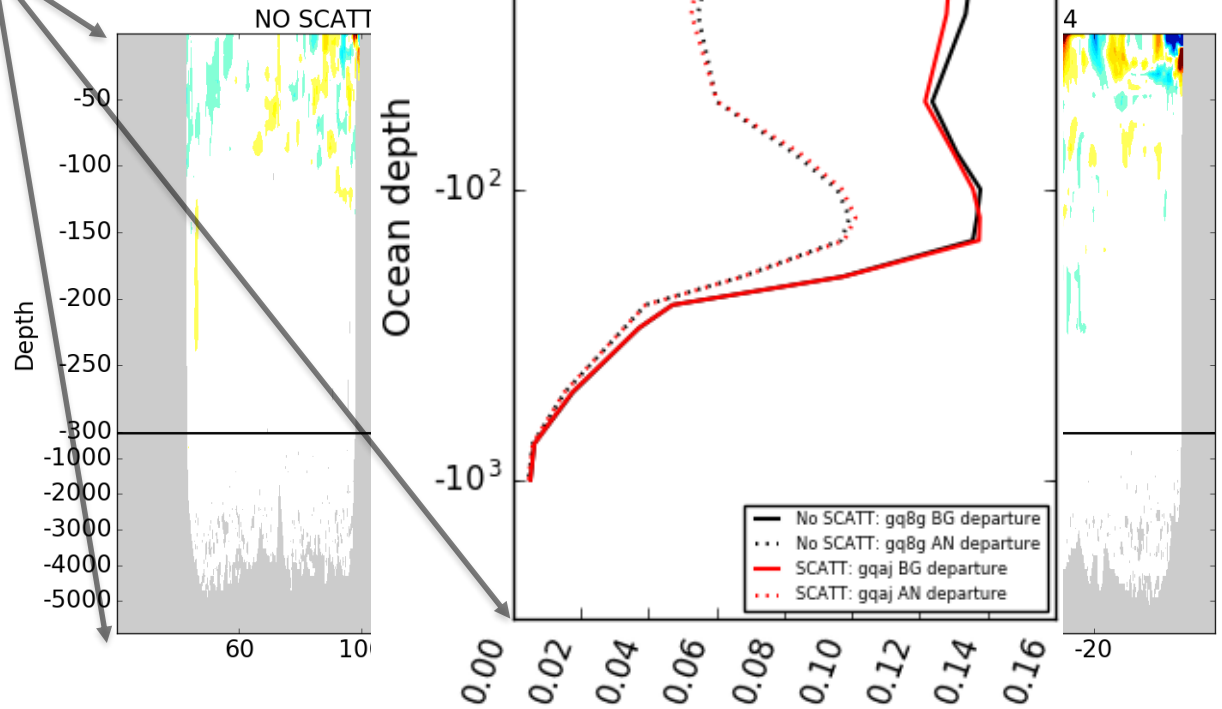




Courtesy:
Giovanna De-Chiara

Scatt. winds assimilated

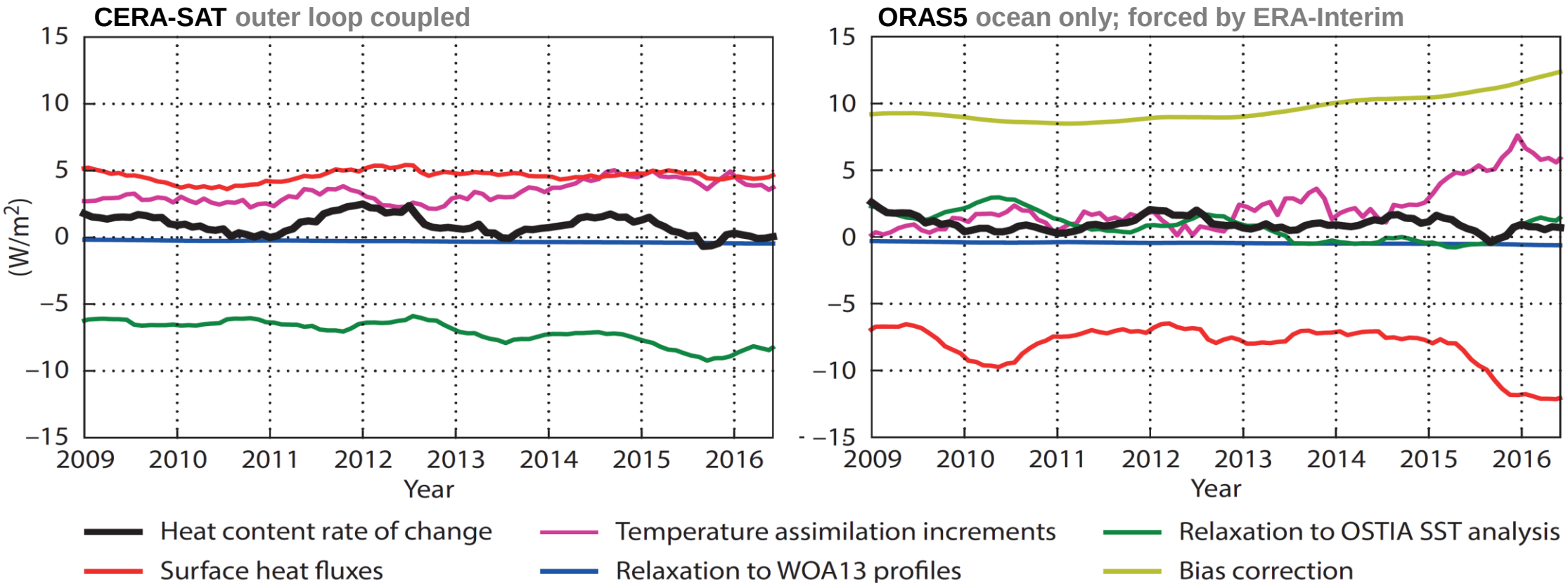
No scatt. winds assimilated



CERA-SAT – Global ocean heat budget

Global ocean heat budget decomposition - Comparing CERA-SAT and ORAS5

- Total global heat content rate of change (**Black**) very similar
- Although contributions from individual sources differ significantly



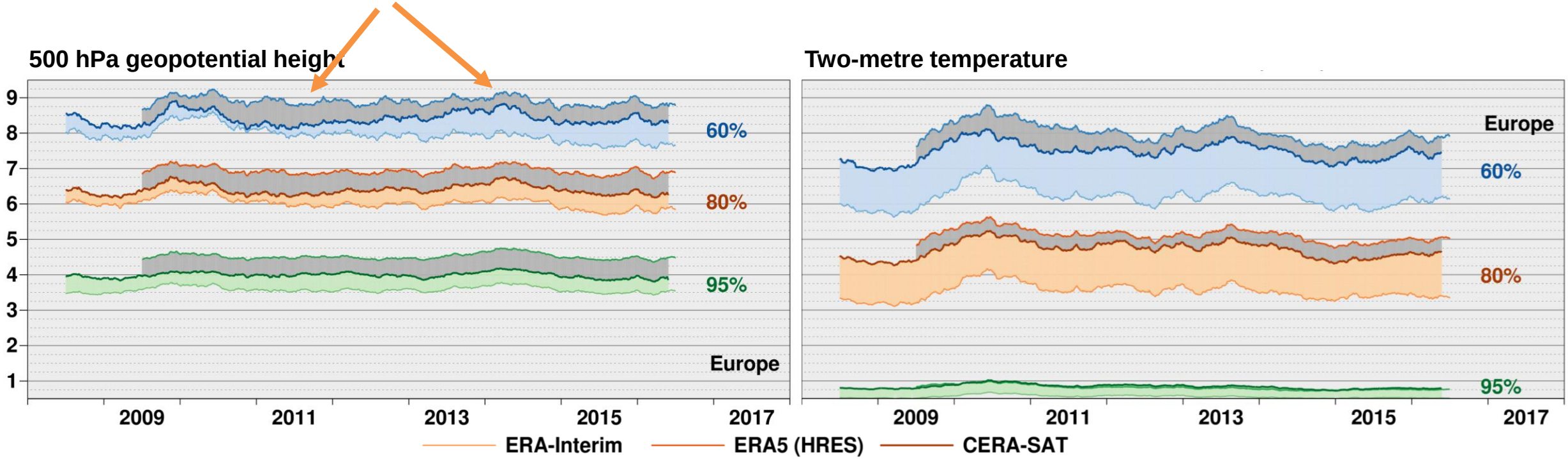
Courtesy of Eric de Boisseson

CERA-SAT – place among other ECMWF reanalyses

Forecast performance for Europe - compared to operational ECMWF reanalyses

Number of days after which AC (%) falls below threshold

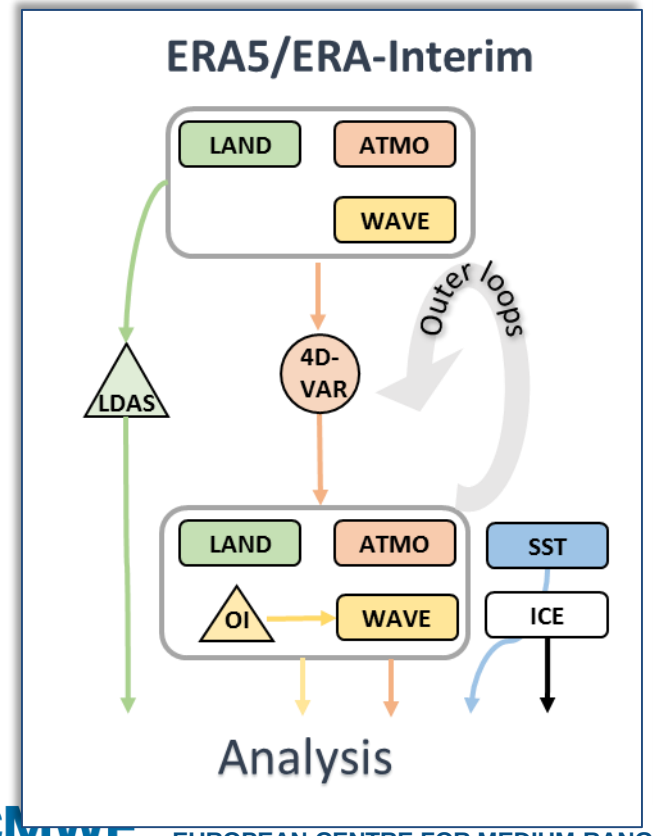
- CERA-SAT outperforms ERA-Interim
- CERA-SAT underperforms w.r.t. ERA5
- Note the temporal variations



CERA-SAT vs. ERA5

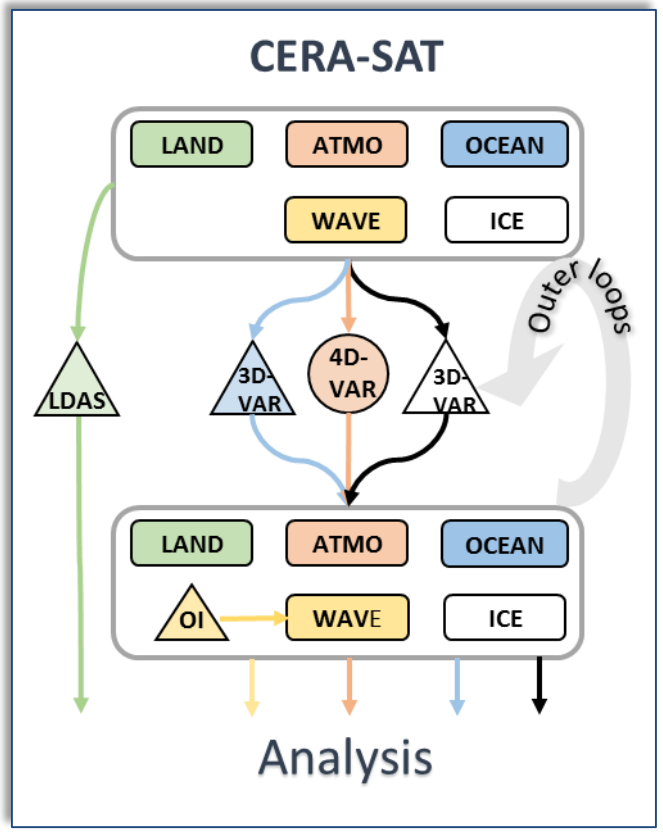
State-of-the-art, operational reanalysis

- High resolution (TL639)
- 12-hour assimilation window
- ‘Uncoupled’ – atmosphere/land/wave only



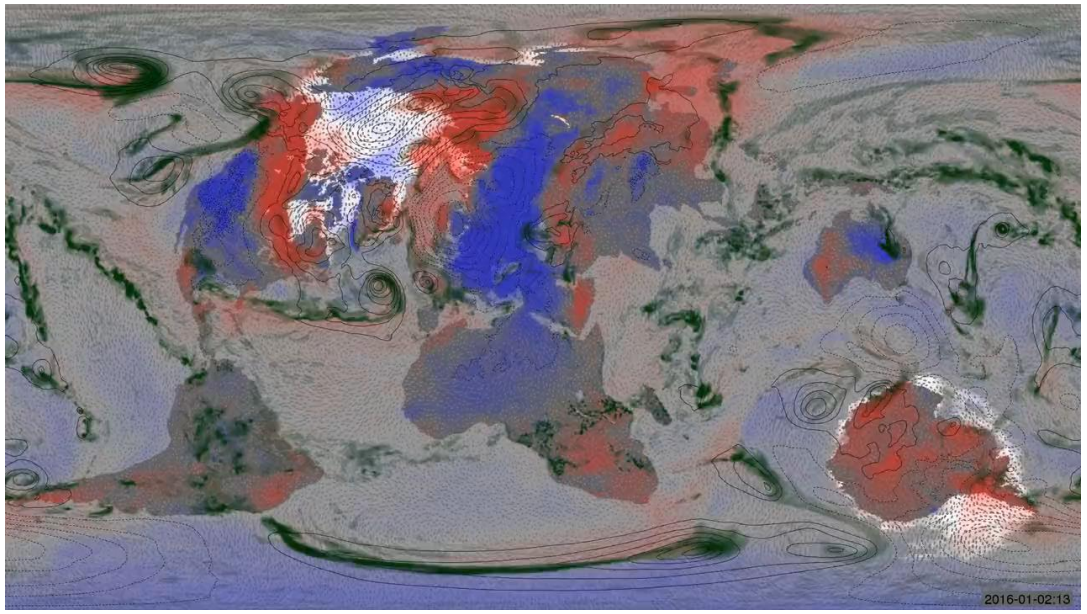
Experimental, pilot reanalysis

- Moderate resolution (TL319)
- 24-hour assimilation window
- Outer loop coupled



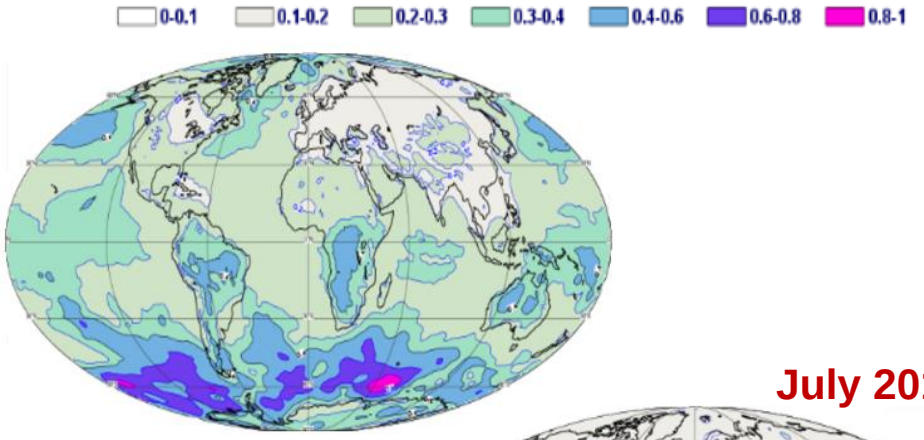
ERA5 – State of the art reanalysis

Hourly data throughout and more parameters



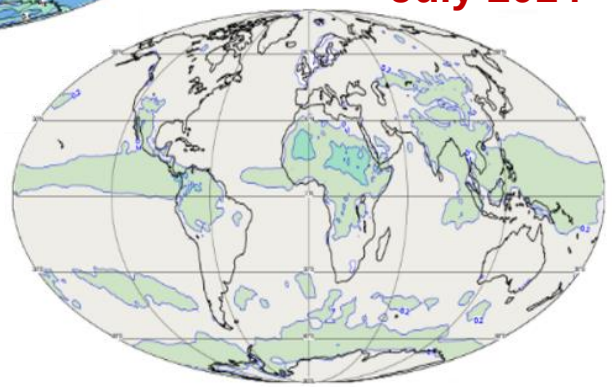
Uncertainty estimate

Spread in Surface Pressure (hPa)



January 1979

July 2014



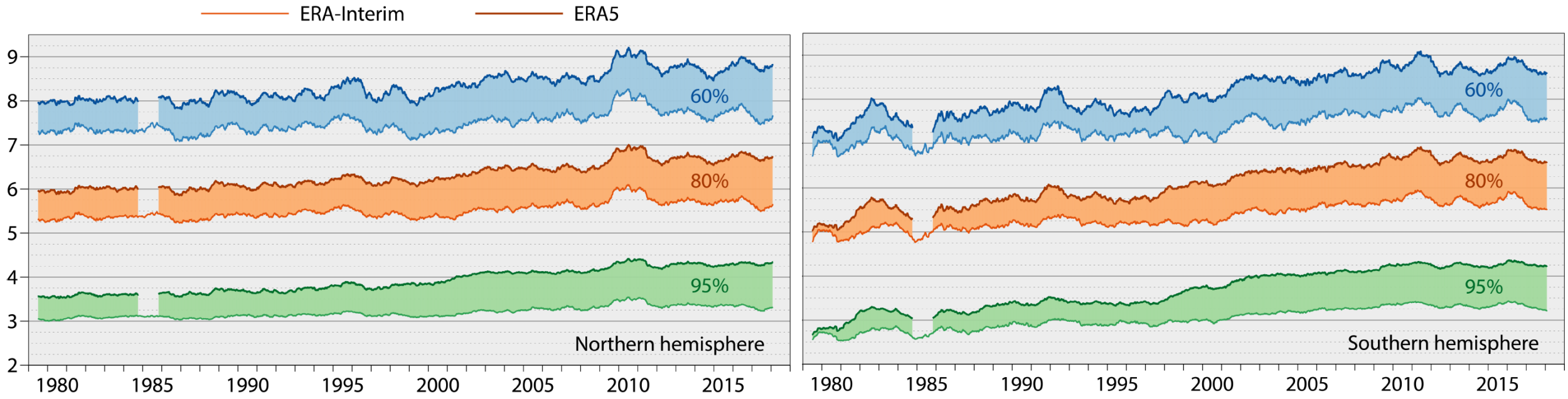
ERA5 – State of the art reanalysis

	ERA-Interim	ERA5
Period	1979 – present	Initially 1979 – present, later addition 1950-1978
Streams	1979-1989, 1989-present	Parallel streams, one/two per decade
Assimilation system	2006, 4D-Var	2016 ECMWF model cycle (41r2), 4D-Var
Model input (radiation and surface)	As in operations, *(inconsistent sea surface temperature)*	***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		Based on a 10-member ***4D-Var ensemble*** at 62 km
Land Component	79km	ERA5L, 9km (separate, forced by ERA5)
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 correction	Satellite radiances, radiosondes predetermined	Also ozone, aircraft, surface pressure, newly predetermined for radiosondes.

ERA5 – State of the art reanalysis

Forecast performance for Northern / Southern hemisphere - compared to ERA-Interim

Number of days after which AC (%) falls below threshold



C3S – Climate data store

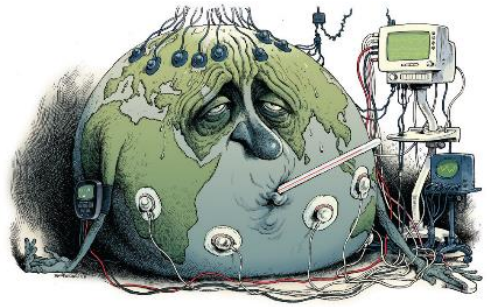
Scientific basis:

- Essential Climate Variables as defined by GCOS
- GCOS Status Report and Implementation Plan
- IPCC, CMIP

Observations	Global estimates of ECVs from satellite and in-situ observations	Reprocessed CDRs, reference observations	Support for data rescue, climate data collections	Climate Indicators
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	

C3S – Climate indicators

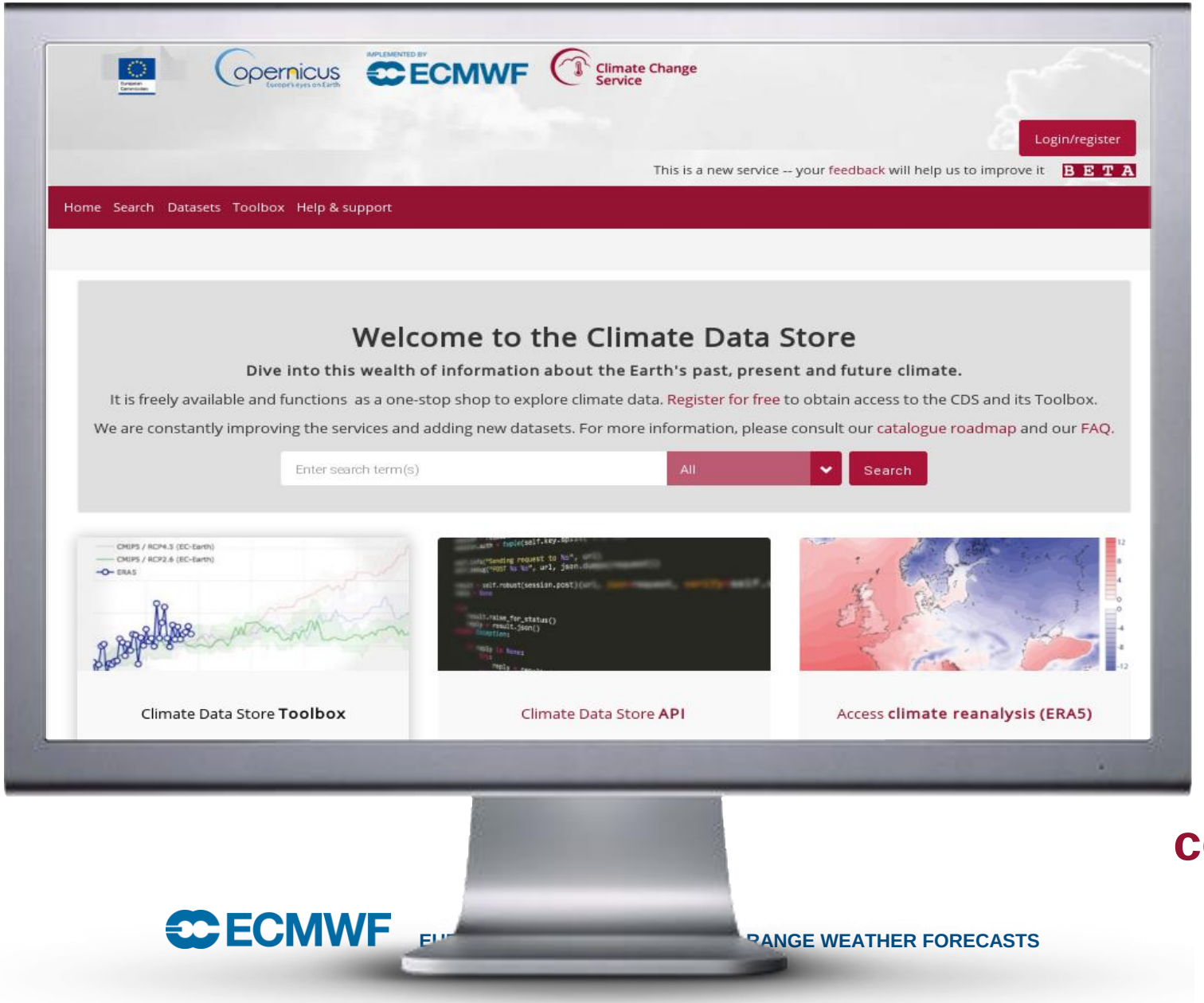
Surface temperature	↑
Greenhouse gases	↑
Rain	–
Sea Ice	↓
Glaciers	↓
Sea Level	↑
Soil Moisture	↓



Credit: Victor & Kennel, Nature Climate Change, 2014.

Copernicus Europe's eyes on Earth | European Commission | ECMWF

C3S – Climate Data Store



The CDS contains **observations**, global and regional **climate reanalyses**, global and regional **climate projections** and **seasonal forecasts.** It also contains generic and **sectoral climate indicators.**

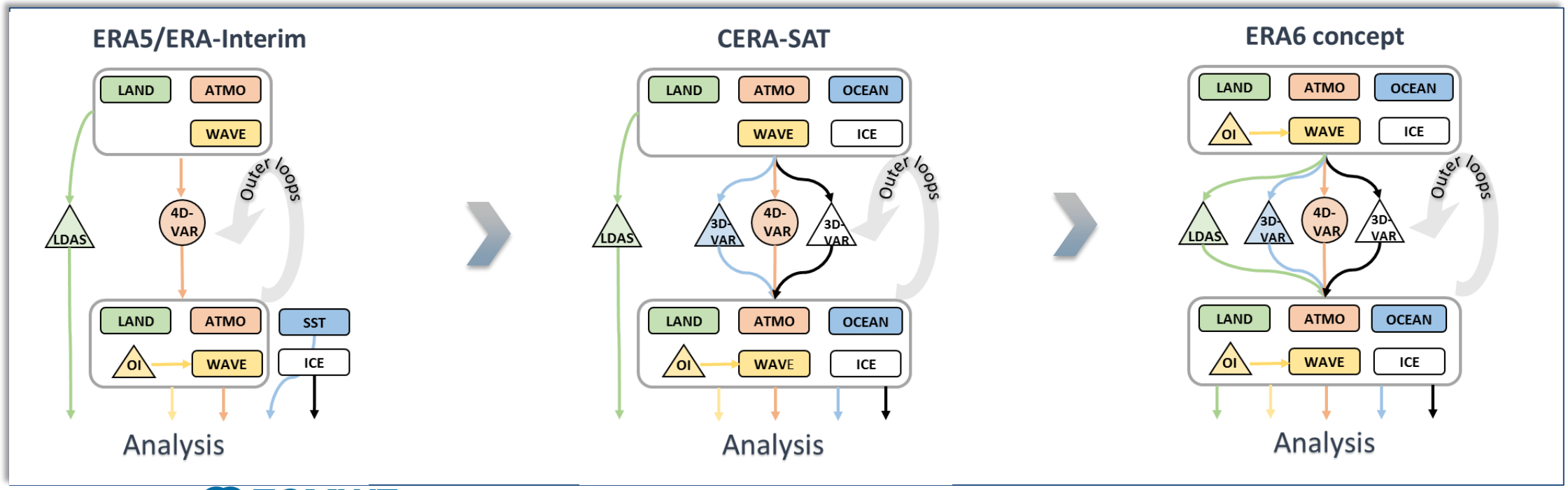
The CDS is designed as a **distributed system**, providing improved access to **existing datasets** through a **unified web interface.**

cds.climate.copernicus.eu

Where next?

C3A provides for operational production of reanalyses, envisioning a regular upgrade cycle

- Centennial reanalyses based on limited historical observations
- Reanalyses of the modern era
- Based on ECMWF operational models (following operational drive towards coupling)

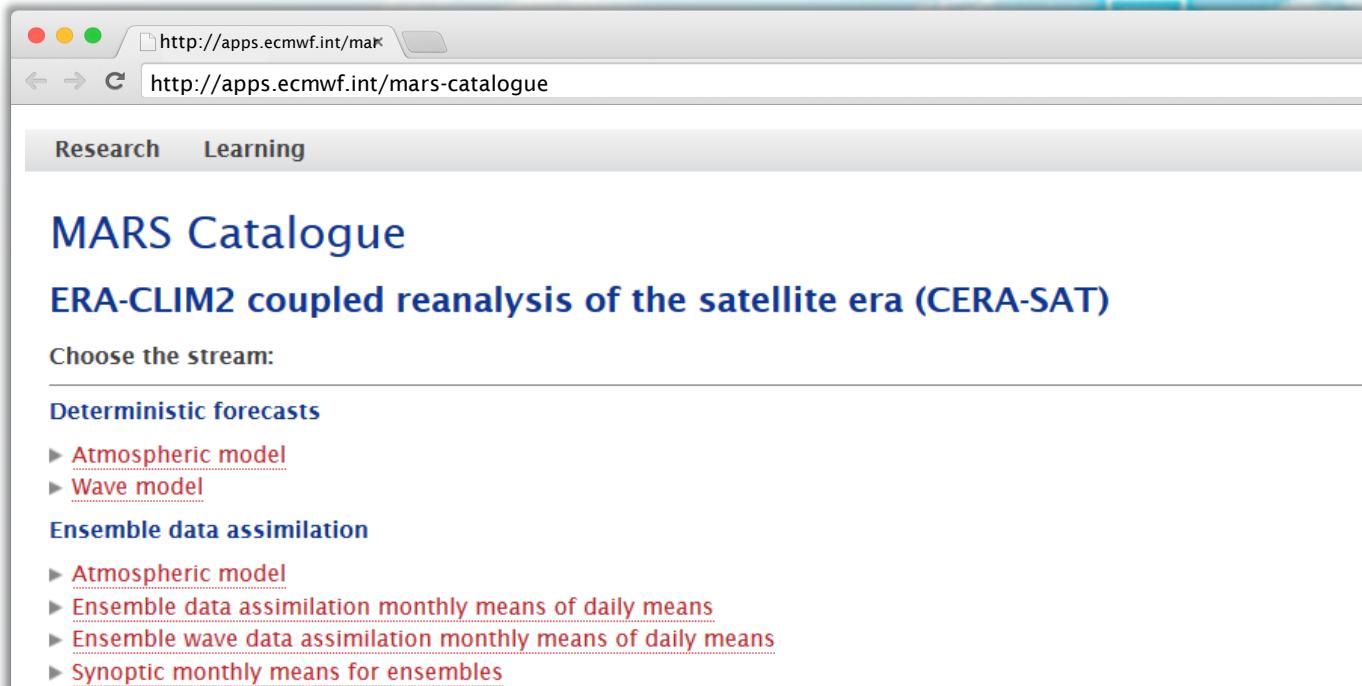


Final remarks

Reanalysis activities at ECMWF have produced a sizable body of experience –and data sets- regarding Earth system assimilation in the context of limited, historical observations systems (CERA-20C) as well as for modern-day assimilation scenarios (CERA-SAT).

State of the art –uncoupled – operational reanalysis production is now undertaken at ECMWF by the Copernicus Climate Change Service (C3S). Future, coupled reanalyses are envisioned within C3S, leveraging operational model developments towards Earth system assimilation as well as external reprocessing and data rescue efforts.

For now, the vanguard of coupled reanalysis at ECMWF is represented by CERA-SAT, publicly available through MARS.




Thank you

Ensemble spread – Coupled vs. uncoupled

10-member ensemble spread for Temperature

- Lower ensemble spread in coupled experiment
- June 2015 – May 2016
- Signal consistent in time (no apparent seasonality or change in time)

Hypothesis: Nudging to external SST analysis in coupled setup is stricter (too strict?) than SST perturbation in uncoupled.