State-of-the-art Global Atmospheric Reanalysis at ECMWF

Jean-Noël Thépaut, Head of C3S

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Climate Change

European Commission | Copernicus Europe's eyes on Earth

ECMWF

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Overview

- Copernicus Services
- ERA5 configuration and performance
- Final remarks and outlook

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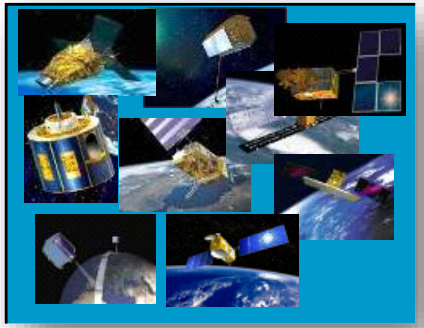
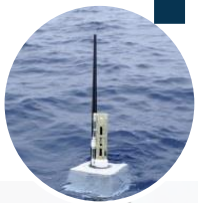
Copernicus Architecture

6 services use Earth Observation data to deliver …



Sentinels

Contributing missions



…added-value products

in-situ

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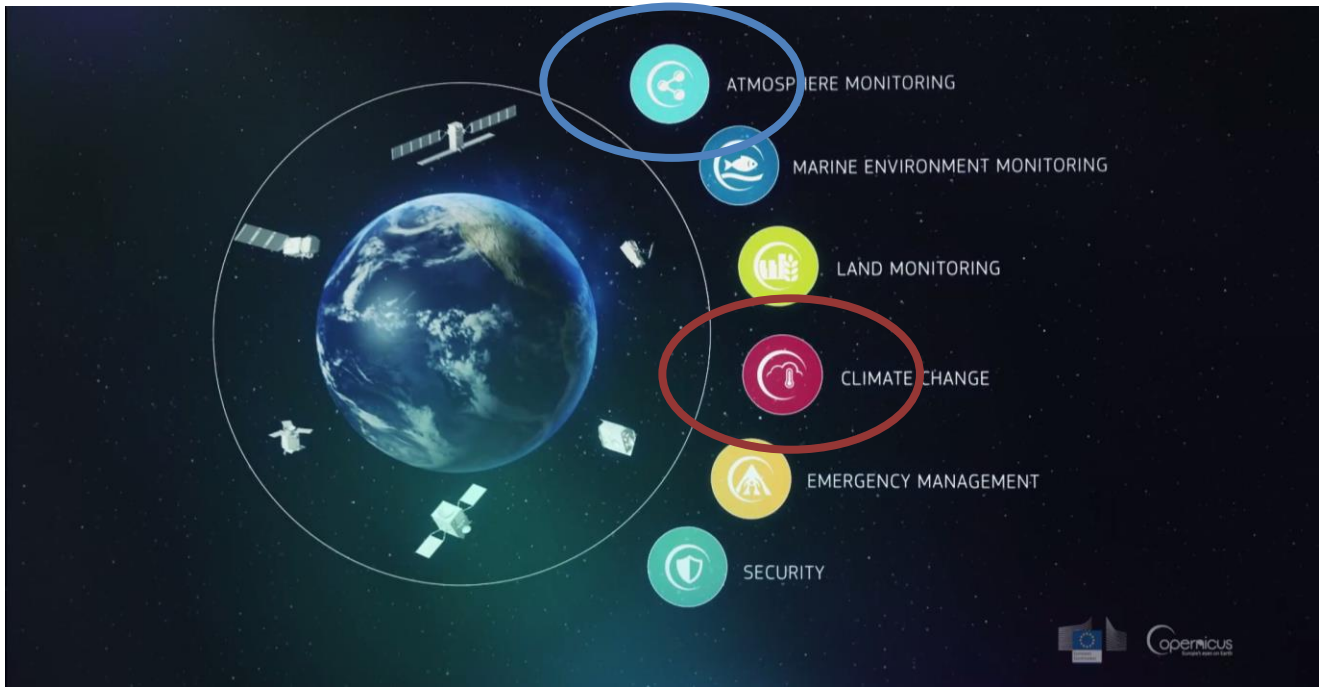
Copernicus: Earth observations and information services



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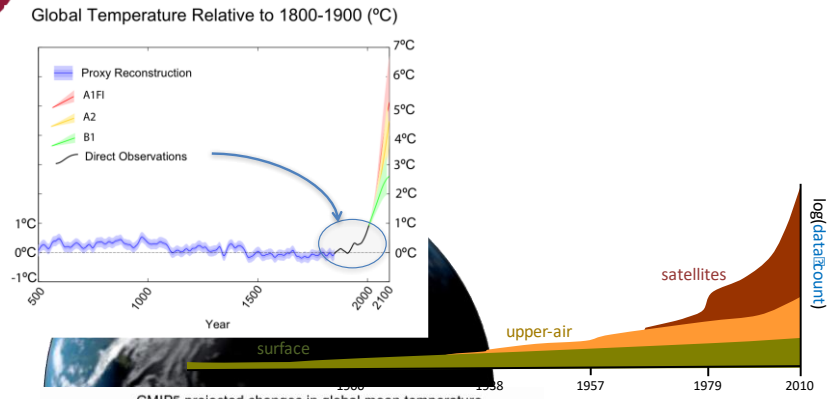
The C3S mission

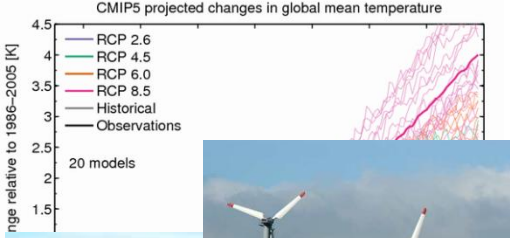
To support European adaptation and mitigation policies by:

- Providing consistent and authoritative information about climate (past, present, future)
- Building on existing capabilities and infrastructures (nationally, in Europe and worldwide)
- Stimulating the market for climate services in Europe

Climate Change Service: Solutions

Climate Change





- **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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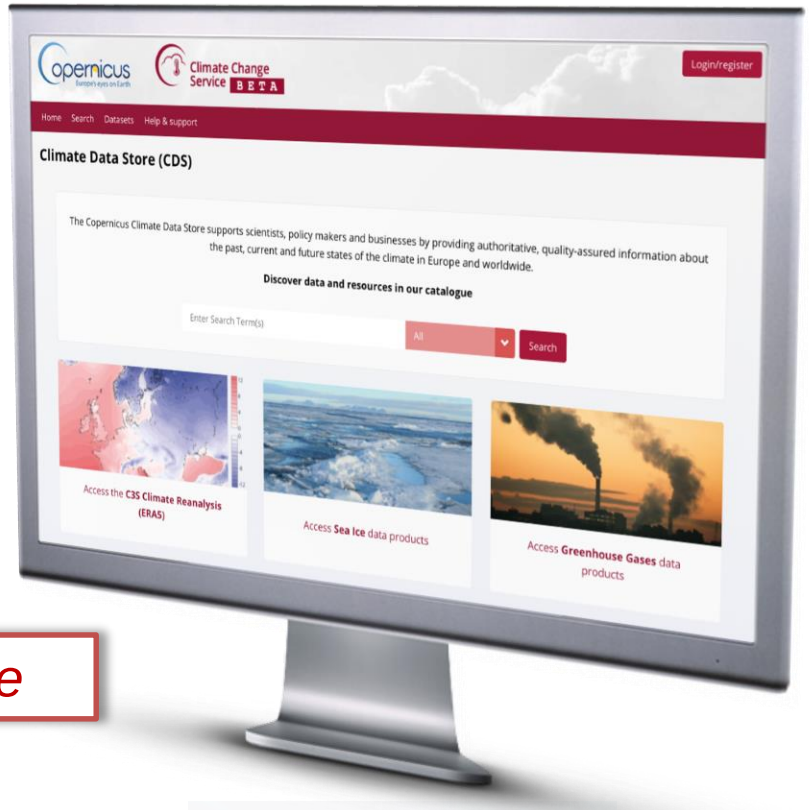
What C3S offers to its users

- Access to climate data
- Tools needed to use the data
- Information on sectoral impacts
- Quality assurance
- User support and training
- Climate change assessments
- Outreach and communication



A one-stop Climate Data Store

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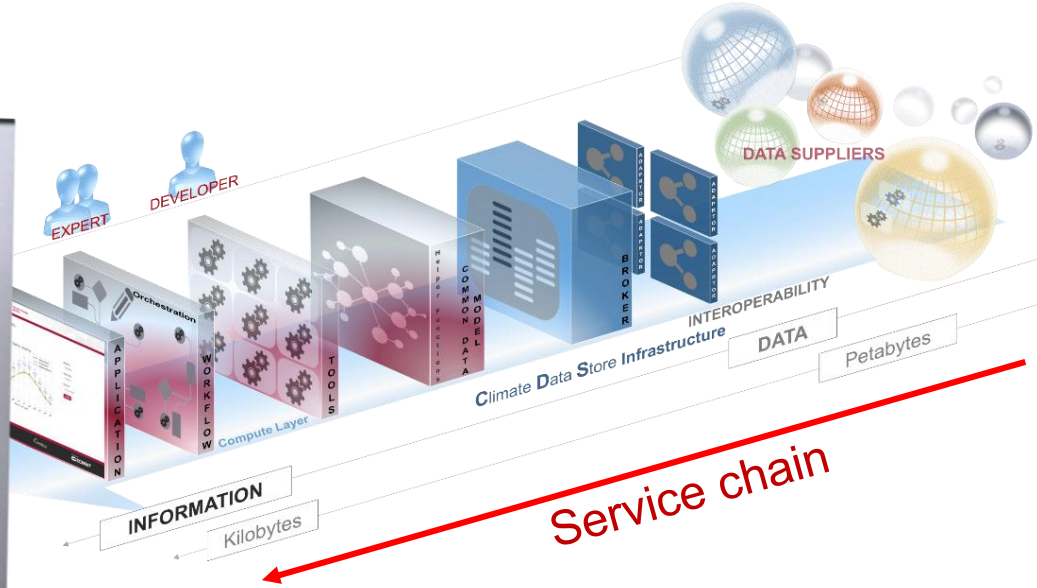
CDS toolbox, workflows and applications



Quality assured information and tools for users: scientists, consultants, decision makers.

cds.climate.copernicus.eu

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Climate Data Store content

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 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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Overview

- Copernicus Services
- ERA5 configuration and performance
- Final remarks and outlook

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ECMWF has a long experience with reanalysis

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 CLIM2

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

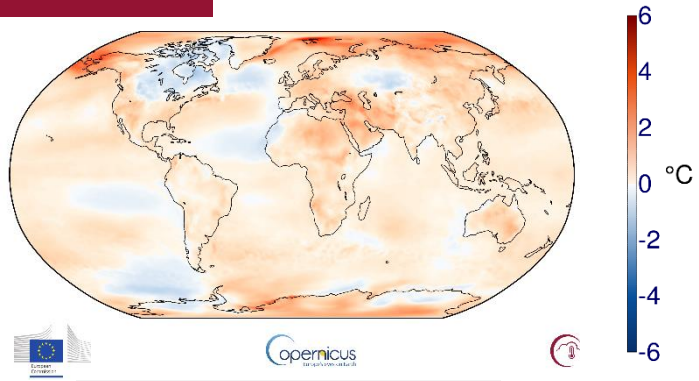
2008 - 2009 GEMS	2010 - 2011 MACC	2017 - … CAMS

C3S Global Reanalysis

ERA5 is in production at ECMWF

ERA5 is replacing ERA-Interim
In 2015-2018 ERA-Interim had about ***40,000 users***

To date ERA5 is publicly available from 1979-2018 (**40 years!**)



T2m, **Feb 2018 - Jan 2019**
relative to 1981-2010

Improvements compared to ERA-Interim:

- Benefit from 10 years model development
- Much higher resolution; **31km** versus 80km
- More and better input data
- Hourly output
- Uncertainty estimate (at 62km)

CDS Public Release plan for 2019:

- **Currently:** updates 2-months behind real time
- **soon:** updates 2-5 days behind real time: ERA5T
- **Next:** access to ERA5 observations
- **End 2019:** 1950-1978.

Climate reanalysis

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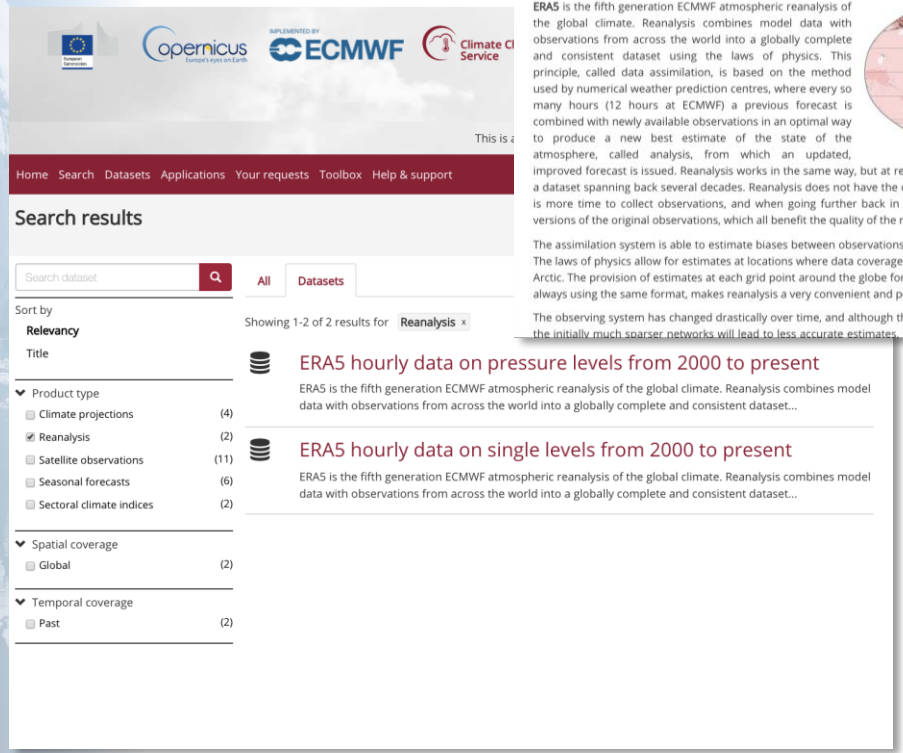

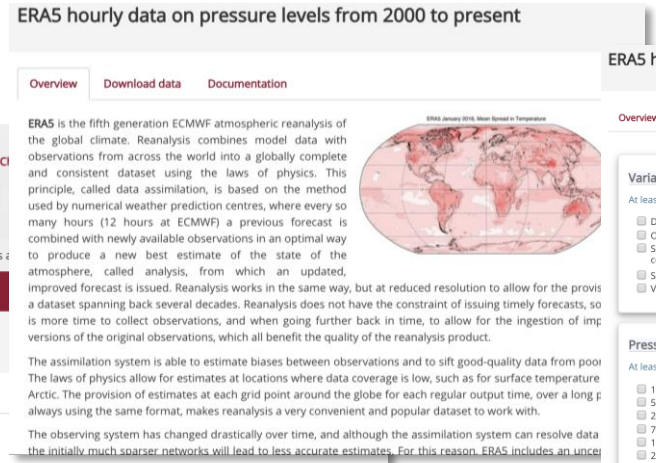

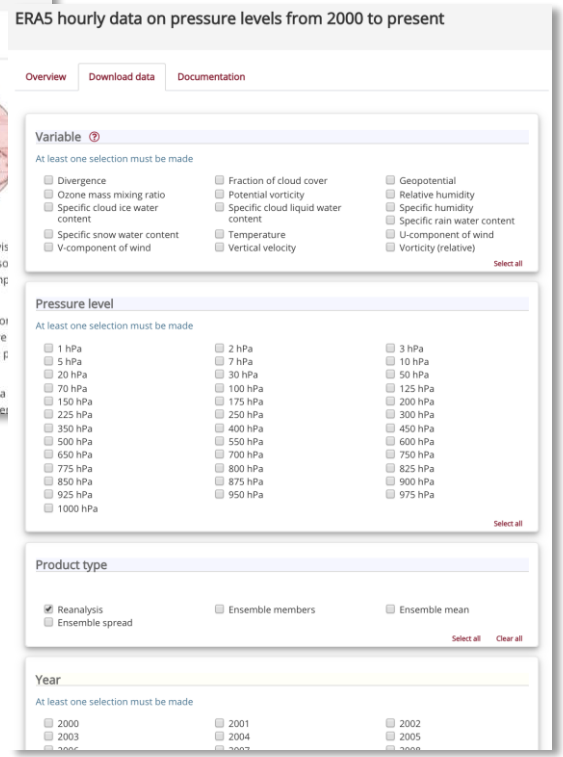

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What is new in ERA5?

	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

The ERA5 observing system

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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

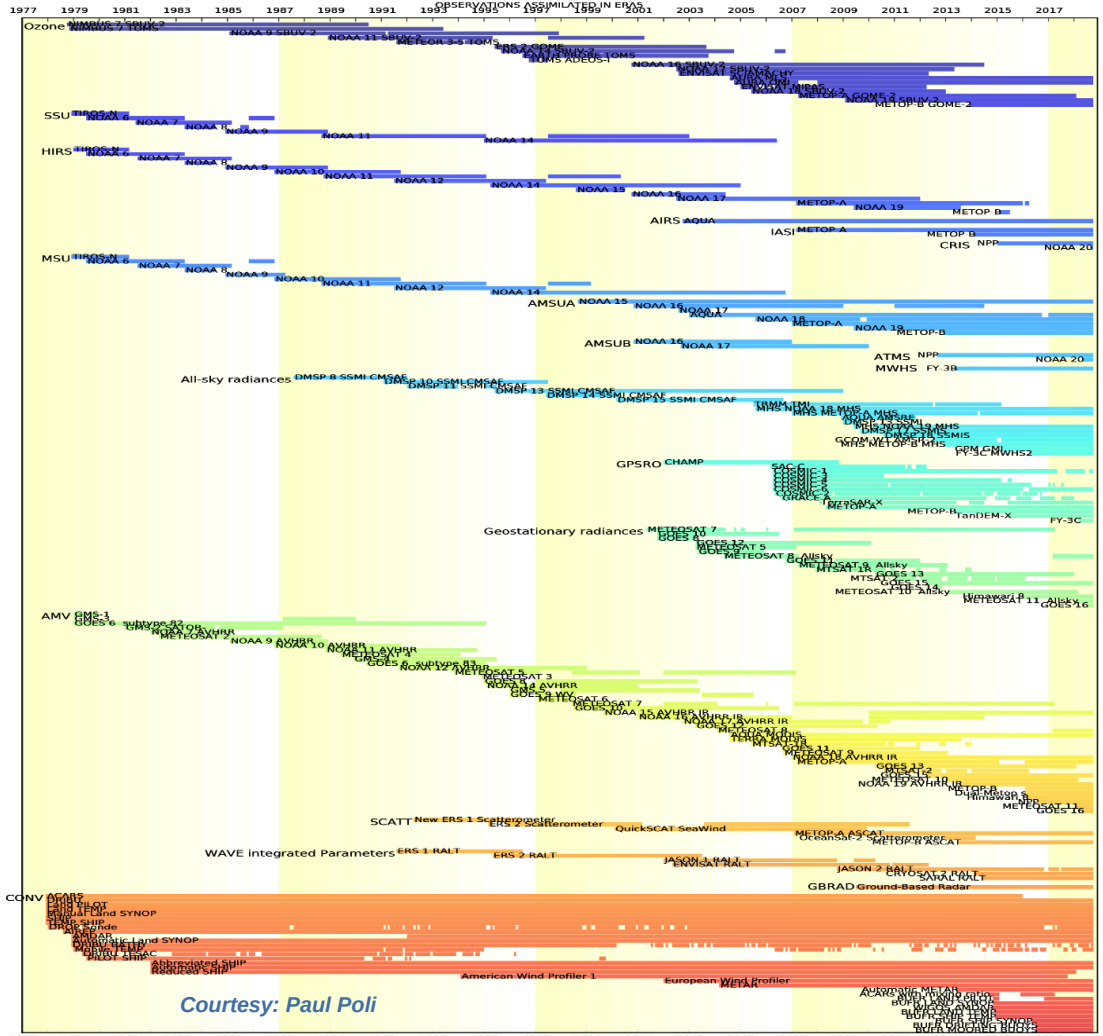
Wave Height: ERS-1,ERS-2, Envisat, Jason

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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ERA5 data usage compared to ERA-Interim

ERA5 data usage has increased from 0.75 (1979) to 21 million/day (2018)

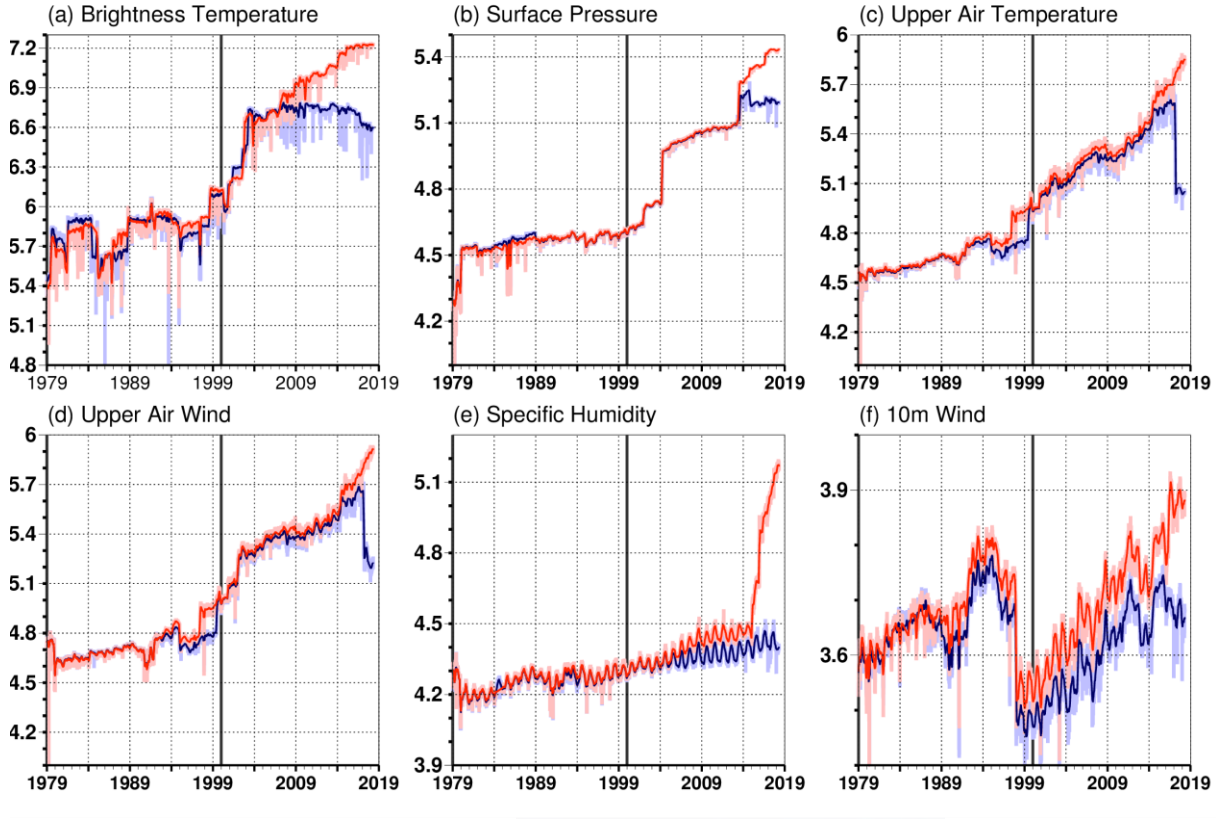
Over 200 types of reports:

- 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 (like the ongoing transition to BUFR format for conventional data)

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



Skill from re-forecasts as a measure for the accuracy of reanalysis products

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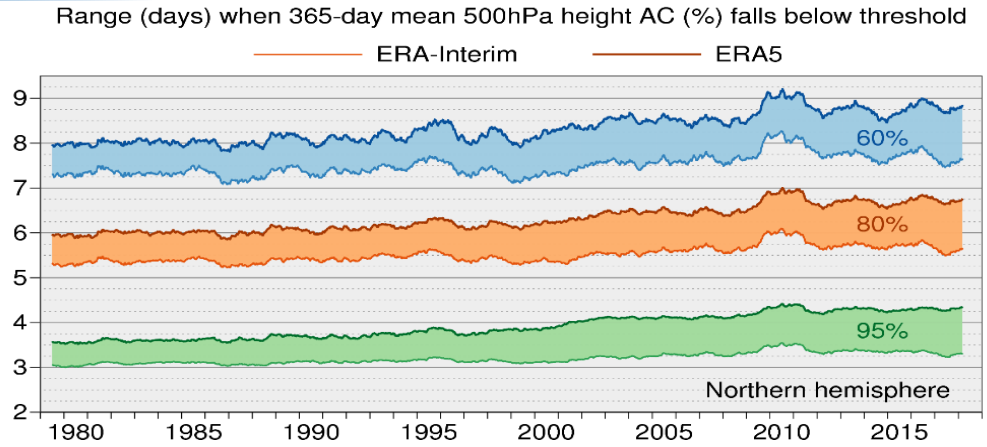

Re-forecasts from ERA5 have higher skill than those from ERA-Interim

The (forecast) model is an integral part of the assimilation system

- It provides the 'glue' between observations
- which are scattered across space, time and geophysical variables

- Also: better analyses produce better forecasts

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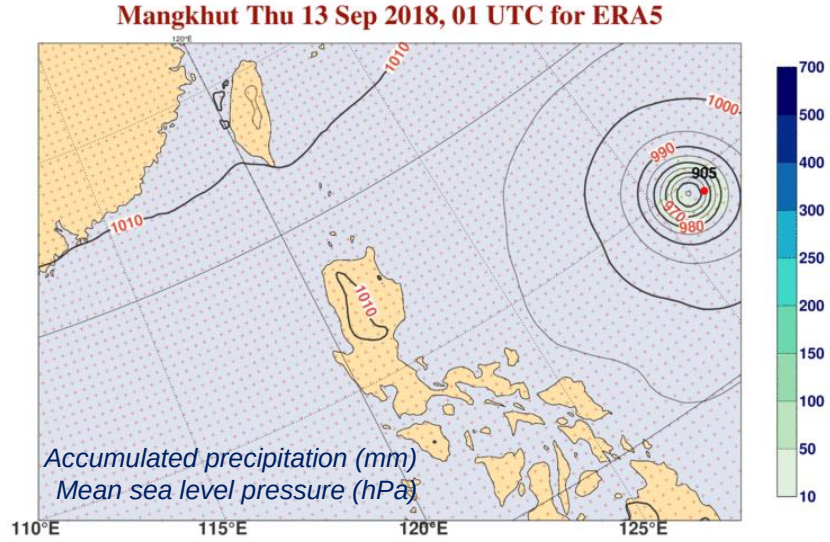
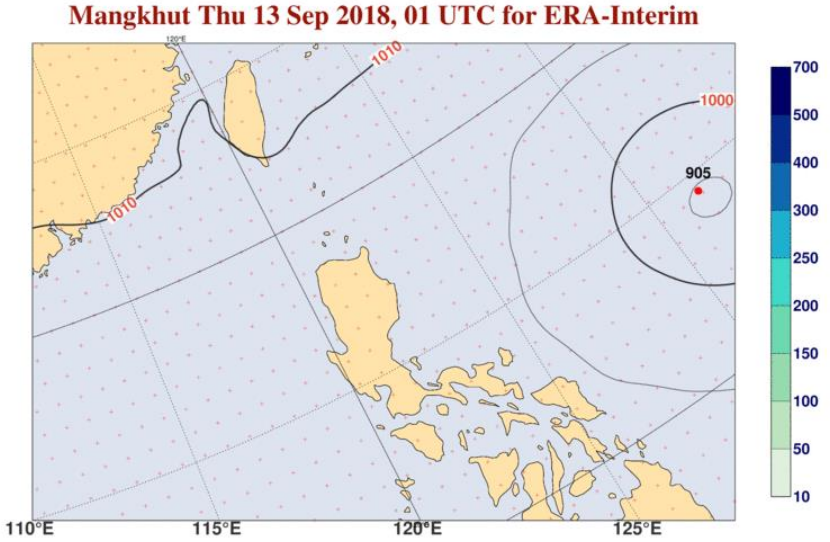
Better model, more and better observations, higher resolution, hourly output



Accumulated precipitation (mm)
Mean sea level pressure (hPa)

ERA5



ERA-Interim

Freja Vamborg, Hans Hersbach

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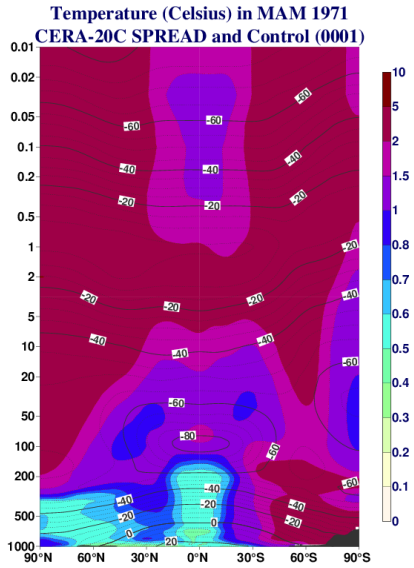
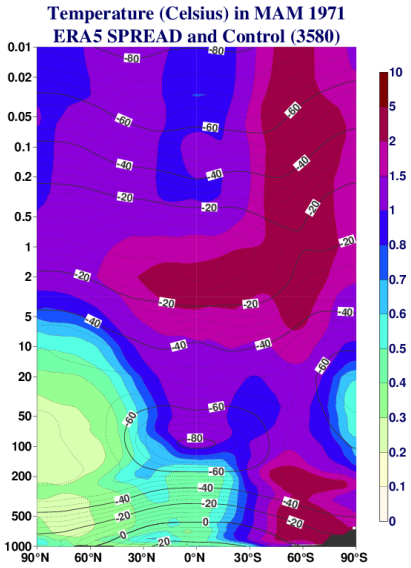
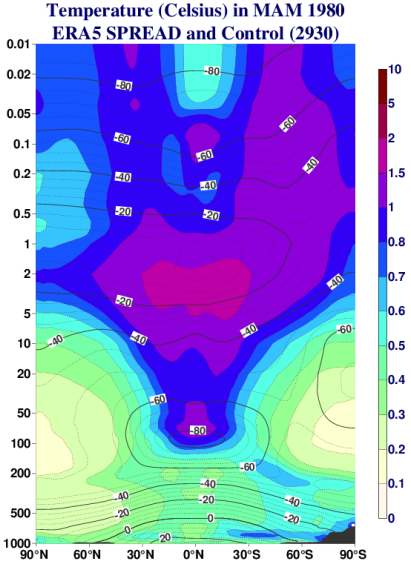
Ensemble spread as a measure for the *synoptic* ERA5 uncertainty



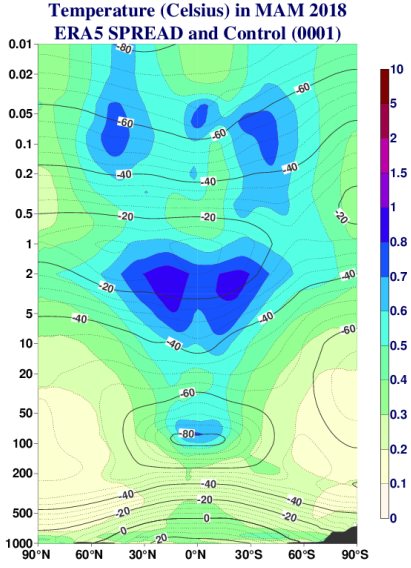
1971 CERA-20C:
Surface pressure, marine wind, only



1971 ERA5:
Upper-air data



1980 ERA5:
Early-satellite era



2018 ERA5:
Current observing system

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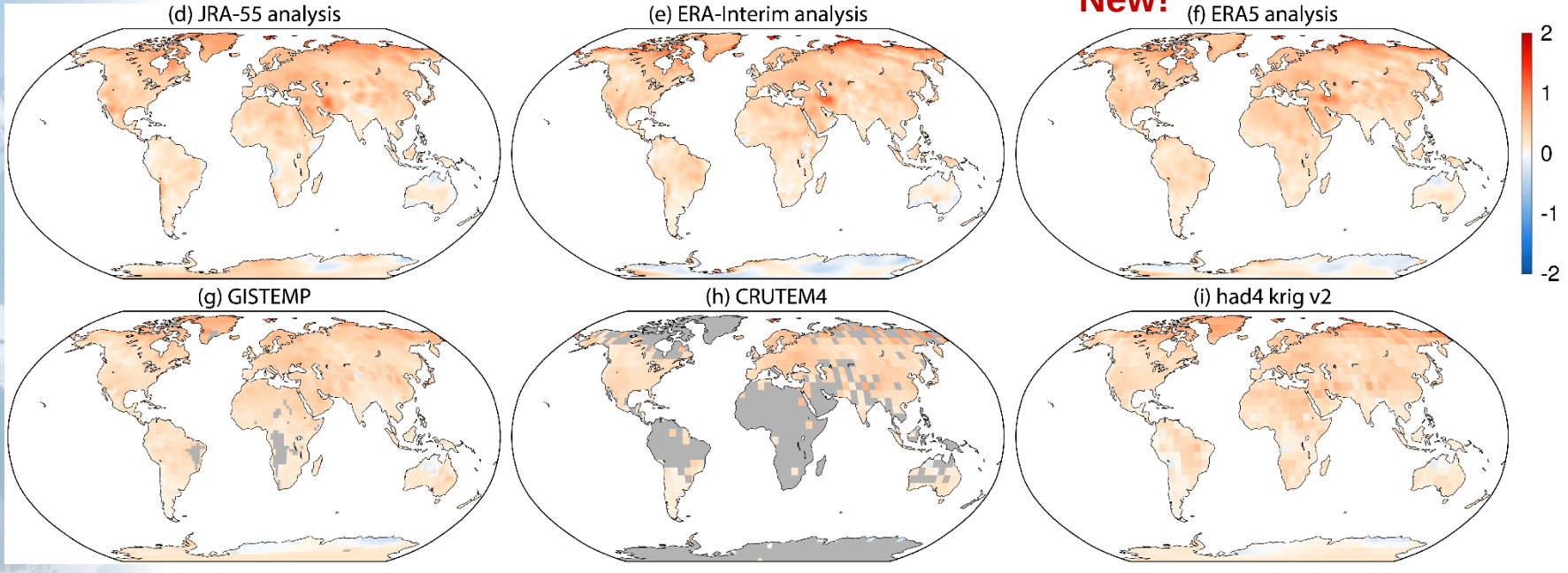
Linear trend in surface air temperature over land

Kelvin/Decade for 1979-2017 (~0.18 globally)



Adrian Simmons

There is a good general consensus between various products (including ERA5), although there are differences in the details.

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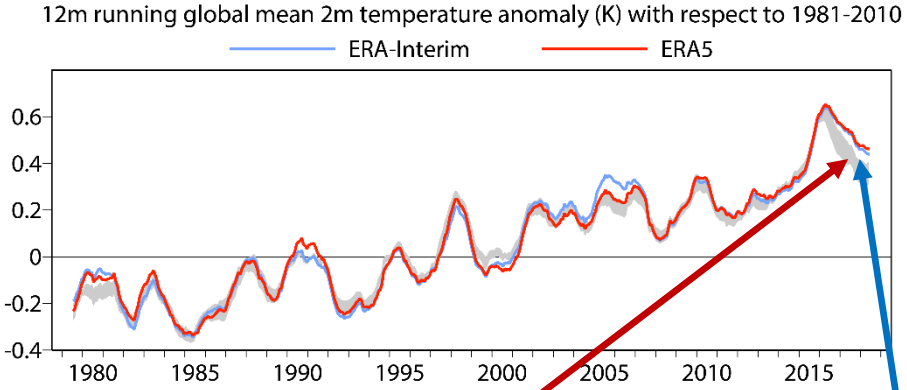
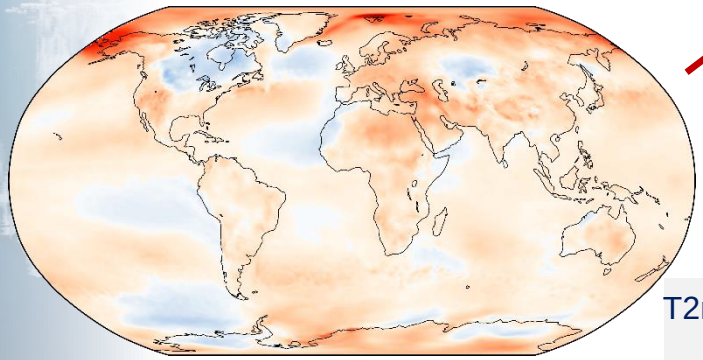
More refined monitoring of the climate

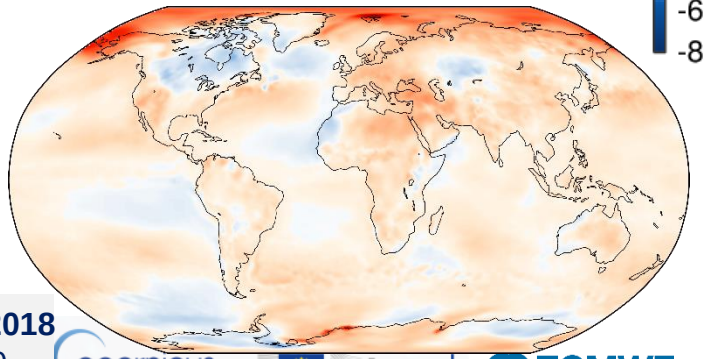
https://climate.copernicus.eu/climate-bulletins

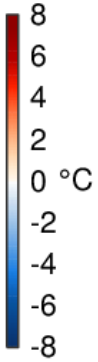


ERA5



ERA-Interim





T2m, **Dec 2017 – Nov 2018**
relative to 1981-2010

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Dedicated land reanalysis – what's new?

ERA5-Land

- Rerun of a single stand-alone simulation of the land component
- No data assimilation
- Uncoupled run with the atmosphere

  - Physics of the IFS in cy45r1 (includes all modeling used in ERA-Interim/Land)
  - Surface dynamical downscaling (allows capturing details associated to processes as topographic forcing)
  - Daily lapse-rate correction
  - Revision of soil thermal conductivity and water balance,
  - Bug-fixes (rain over snow, infinitesimal fraction of convective rainfall, accumulation fluxes of CO2, etc.)
  - Potential evapotranspiration fluxes bugged in ERA5, corrected in ERA5-Land and added to the catalogue,

  - Uncertainty estimation based on a 10-member ensemble
  - More customized data set for users in different economic sectors

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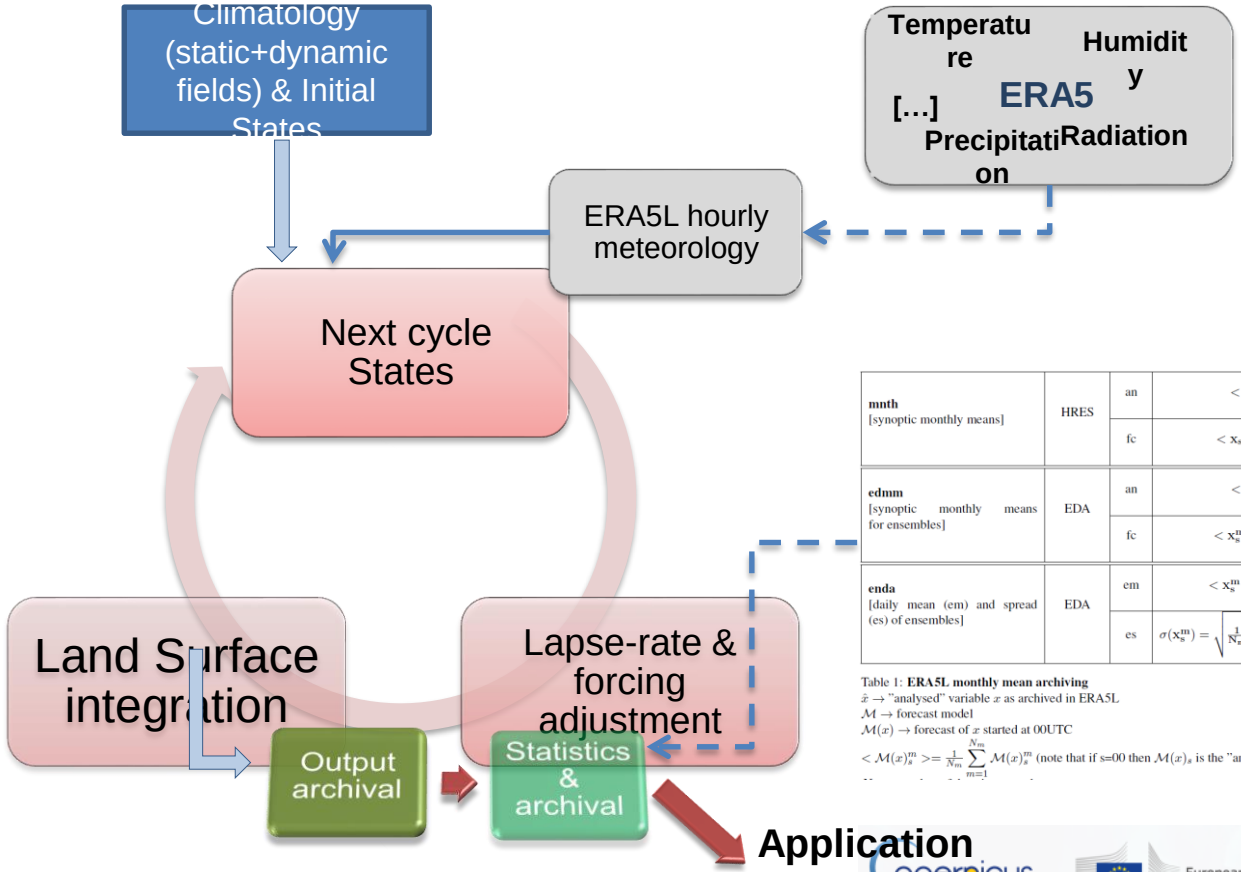
ERA5-Land in a simple diagram



mnth [synoptic monthly means]	HRES	an	$< \hat{x}_h >= \frac{1}{N_d} \sum_{d=1}^{N_d} \hat{x}_{d,h}$
		fc	$< x_s >= \frac{1}{N_d} \sum_{d=1}^{N_d} \mathcal{M}(x)_{d,s}$
edmm [synoptic monthly means for ensembles]	EDA	an	$< \hat{x}_h^m >= \frac{1}{N_d} \sum_{d=1}^{N_d} \hat{x}_d^m$
		fc	$< x_s^m >= \frac{1}{N_d} \sum_{d=1}^{N_d} \mathcal{M}(x)_{d,s}^m$
enda [daily mean (em) and spread (es) of ensembles]	EDA	em	$< x_s^m >= \frac{1}{N_m} \sum_{m=1}^{N_m} < x_s >^m$
		es	$\sigma(x_s^m) = \sqrt{\frac{1}{N_m} \sum_{m=1}^{N_m} [\mathcal{M}(x)_s^m - < \mathcal{M}(x)_s^m >]^2}$

Table 1: **ERA5L monthly mean archiving**
$\hat{x} \rightarrow$ "analysed" variable x as archived in ERA5L
$\mathcal{M} \rightarrow$ forecast model
$\mathcal{M}(x) \rightarrow$ forecast of x started at 00UTC
$< \mathcal{M}(x)_s^m >= \frac{1}{N_m} \sum_{m=1}^{N_m} \mathcal{M}(x)_s^m$ (note that if s=00 then $\mathcal{M}(x)_s$ is the "analysis")

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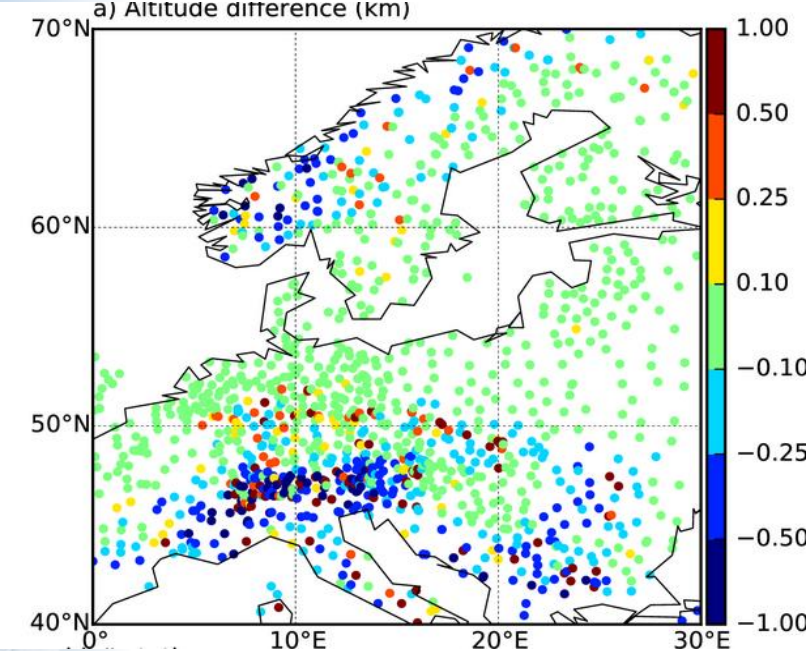
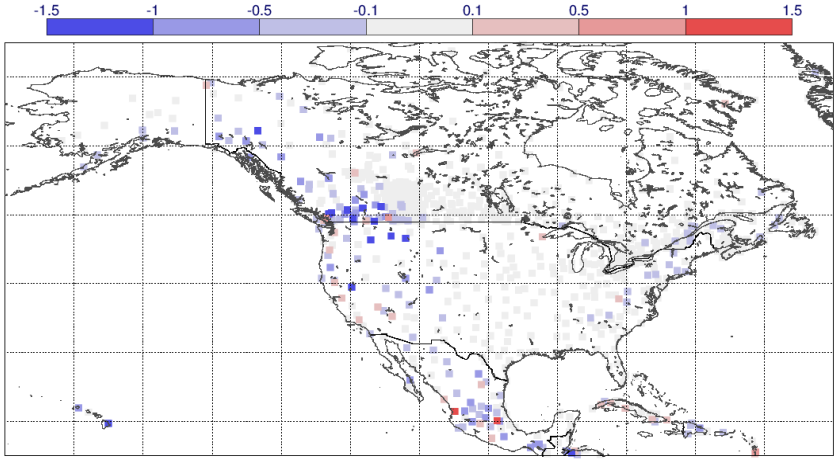
Lapse-rate adjustment

- **Correct for differences in orography due to different model resolutions.**



Δh (km)

T2m
RMSE(corrected)- RMSE(no corrected) (K)



See details in oral presentation: E. Dutra et al. (9.40am): "Land surface downscaling using a spatially and temporally varying lapse rate"

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ERA5-Land specs compared to…

	ERA-Int	Era-Int/Land	ERA5	ERA5-Land
Period covered	Jan 1979 – NRT(*)	Jan 1979 – Dec 2010	Jan 1950 - NRT	Jan 1950 - NRT
Spatial resolution	~79km / 60 levels	79 km	~32 km / 137 levels	~9 km
Model version	IFS (+TESSEL)	HTESSEL cy36r4	IFS (+HTESSEL)	HTESSEL cy45r1
LDAS	cy31r1	NO	cy41r2	NO
Uncertainty estimate	-	-	Based on a 10-member 4D-Var ensemble at 62 km	Based a 10-member atmospheric forcing at 31 km
Output frequency	6-hourly Analysis fields	6-hourly Analysis fields	Hourly (three-hourly for the ensemble)	Hourly (three-hourly for the ensemble)

ERA-Int/Land vs ERA5-Land Inventory of fields

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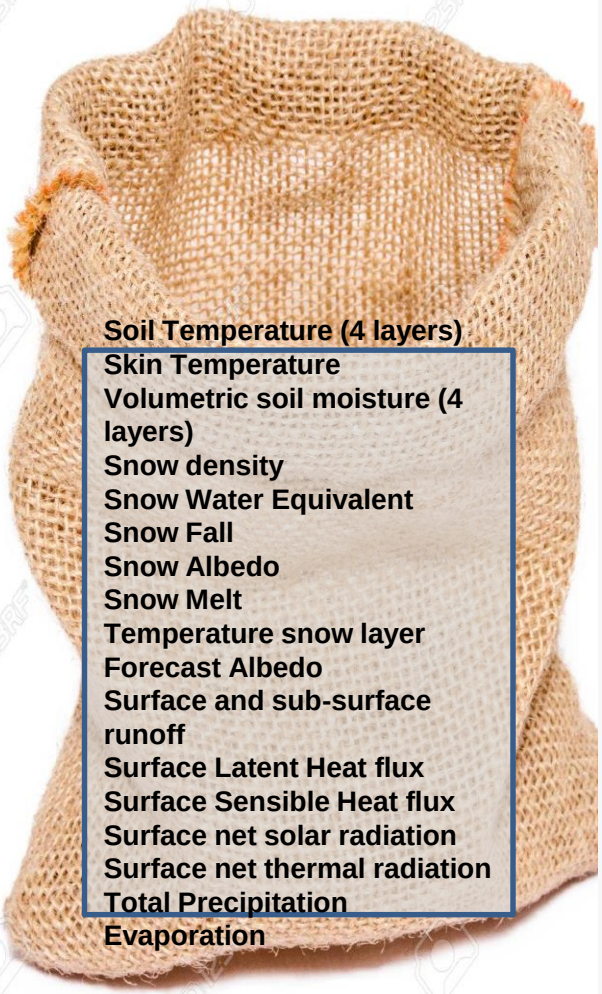

Soil Temperature (4 layers)
Skin Temperature
Volumetric soil moisture (4 layers)
Snow density
Snow Water Equivalent
Snow Fall
Snow Albedo
Snow Melt
Temperature snow layer
Forecast Albedo
Surface and sub-surface runoff
Surface Latent Heat flux
Surface Sensible Heat flux
Surface net solar radiation
Surface net thermal radiation
Total Precipitation
Evaporation

2m temperature & dew point
Accumulated CO2 (Reco, GPP, NEE)
Lakes (Bottom Temperature, Ice depth, ice Temperature, mix-layer depth, mix-layer temperature, shape factor, total layer temperature)
LAI (low/high vegetation)
Runoff
Skin reservoir content
U,V surface wind components
Surface Pressure
Snow Depth
Snow cover fraction
Snow evaporation
Canopy evaporation
Soil evaporation
Vegetation transpiration
Surface solar radiation downwards
Surface Thermal radiation downw

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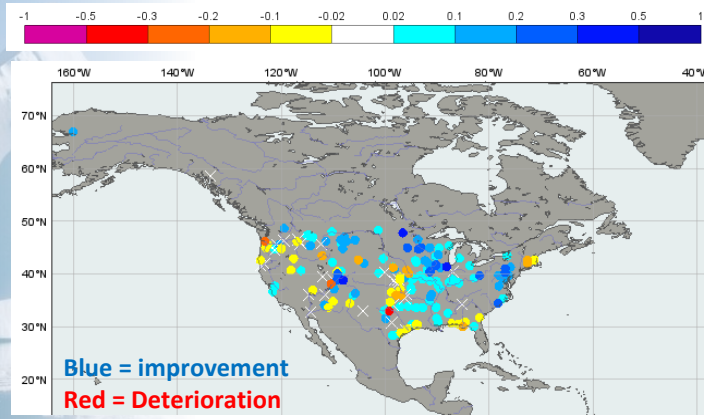
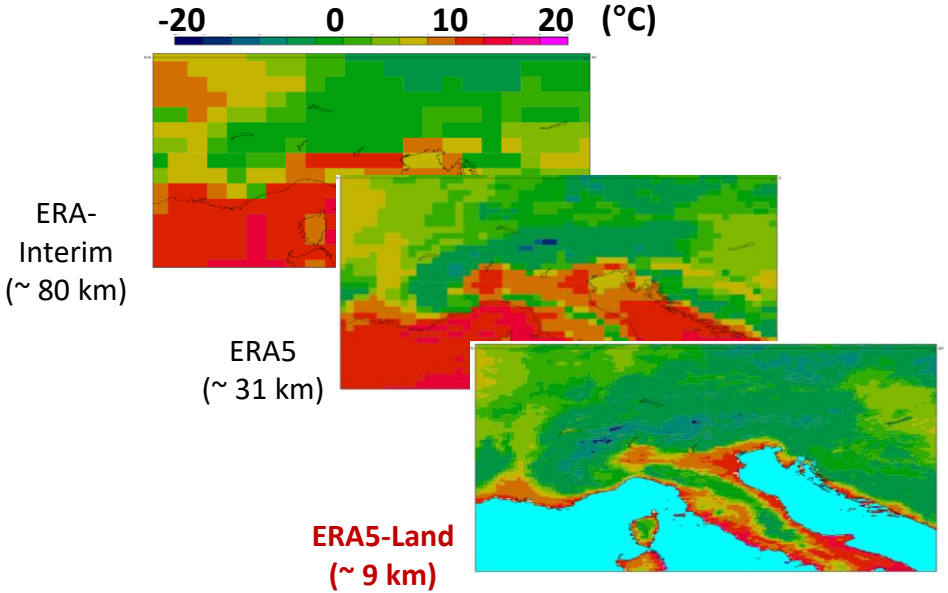
ERA5-Land, a high-resolution downscaling of the land-surface component



Discharge time series correlation difference ERA5-Land vs. ERA5



ERA5-Land is currently in production.
To become available via the C3S Climate Data Store in 2019

Joaquin Munoz-Sabater

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Copernicus C3S High-resolution Regional Reanalysis

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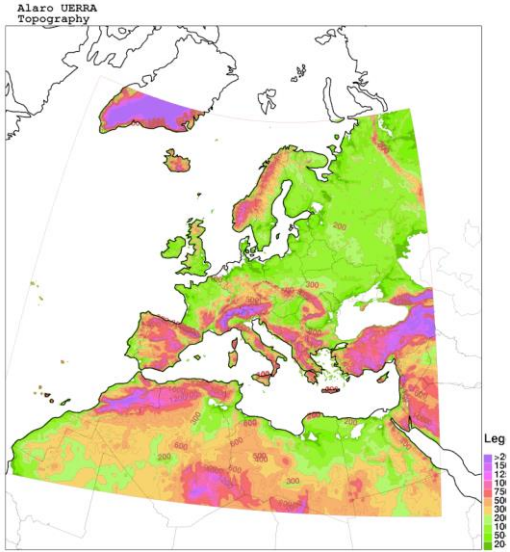
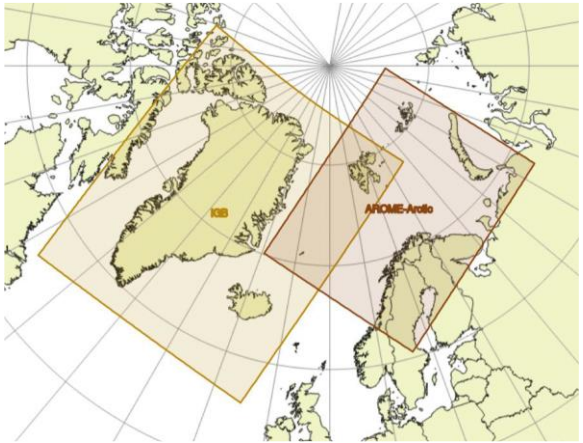
European area



5.5 km, 106 levels, Harmonie/Aladin, hydrostatic
Surface analysis at 5.5 km – no downscaling
Plus 10 ensemble members at 11km
Will start from the early 1980s

SMHI, Météo-France - MET Norway

Arctic area



2.5 km, 65 levels, Harmonie/Arome non-hydrostatic

Reanalysis period July 1997 – June 2021 (24 years)

Special emphasis on handling of “cold surfaces”: snow, sea ice, glaciers

Met Norway , the Nordic countries and Météo-France.

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Overview

- Copernicus Services
- ERA5 configuration and performance
- Final remarks and outlook

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Final remarks and outlook

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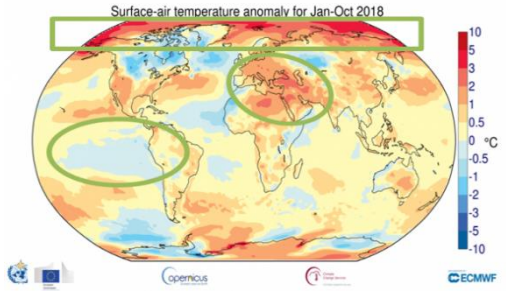
ERA5 is available from 1979 and is replacing ERA-Interim.

- Much higher resolution, better model, better and more observations
- To include timely updates (**ERA5T)** with a latency of 2-5 days

WMO climate statement: past 4 years warmest on record

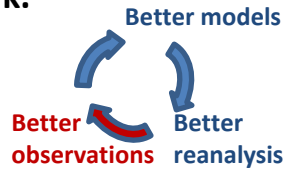


Reanalysis provides a physically complete view of the recent climate.

- Reanalysis is now fully integrated into international assessments of climate change as delivered by, for example, the WMO, and the European State of the Climate.

The ongoing production of ERA5 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 outsourced providers:
  - satellite reprocessing (EUMETSAT), data rescue, consolidation of historical datasets
  - 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:

- A **centennial global reanalysis** going back to 1851 (to start around 2021)
- A full-observing-system coupled reanalysis **ERA6** (to start around 2023)
- A joint **CAMS/C3S** reanalysis with coupled chemistry, from 1979, with timely updates
- Future **regional reanalysis** by third parties. Possibly centennial.

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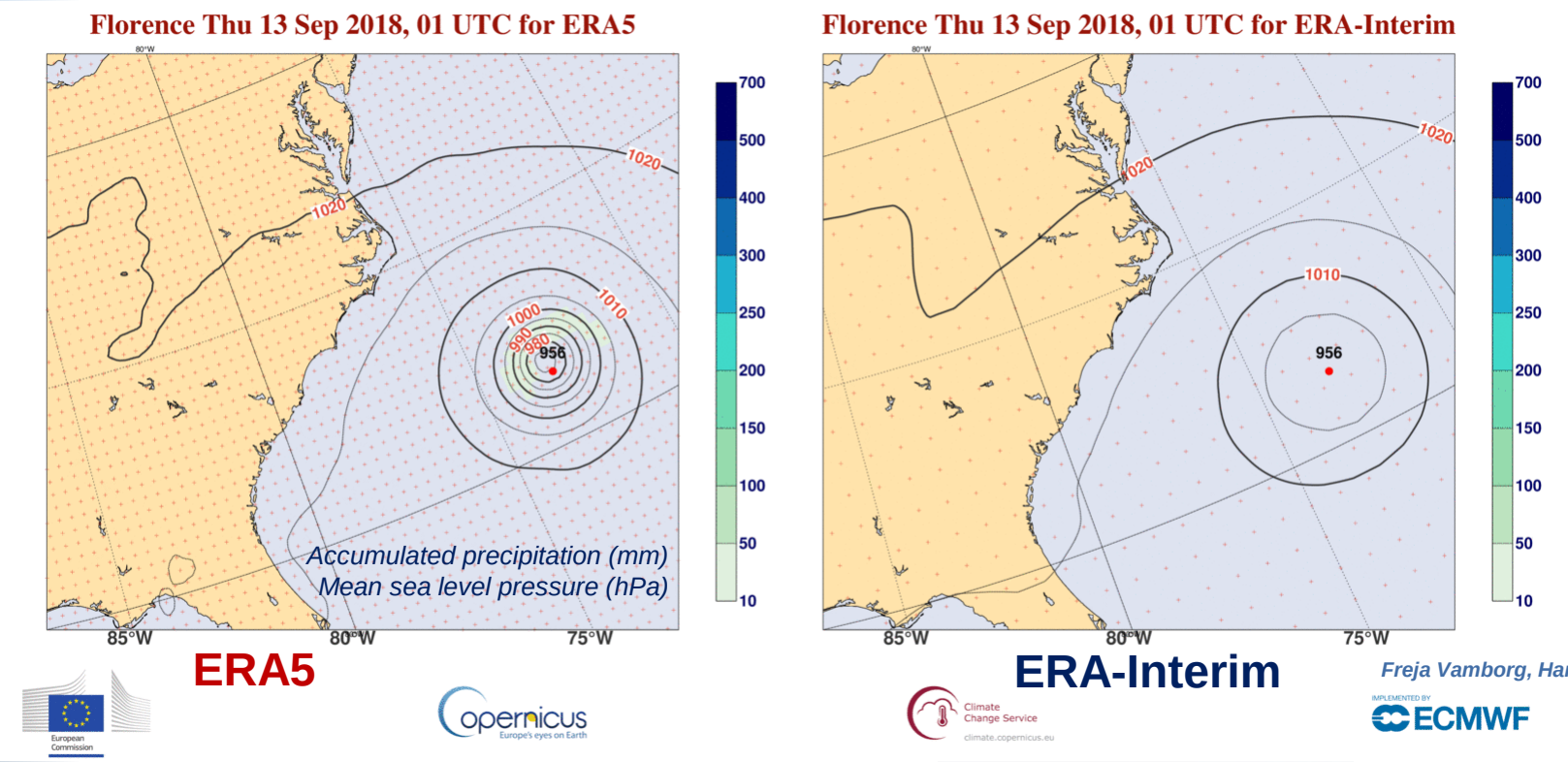
Visit: climate.copernicus.eu !

Thank You!



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