Climate Change

Copernicus European Regional Reanalysis

BMIP workshop, 09/04/2021

Semjon Schimanke et al.

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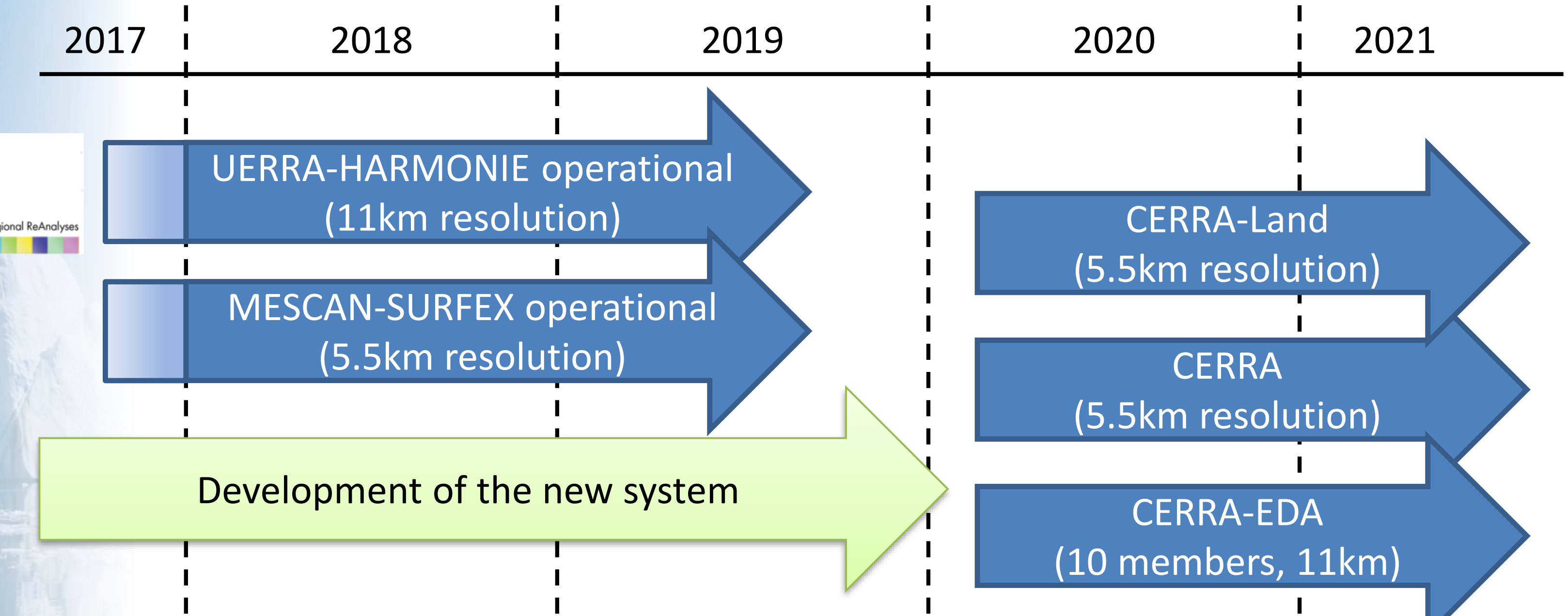
Overview

1. UERRA/CERRA – data and availability
2. Comparison UERRA-CERRA-ERA5
3. Training material
4. The reanalysis systems

Time line of service and system details



- 11 km (565x565 grid points), 65 levels
- Surface/soil analysis 5.5 km (MESCAN-SURFEX)
- 1961 – July 2019

- CERRA: 1069x1069 grid points, 106 levels
- CERRA-Land: precipitation analysis and surface/soil analysis
- Starts in the September 1984

SCREEN CAPTURE WELCOME

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1. UERRA/CERRA – data and availability

Available data – UERRA

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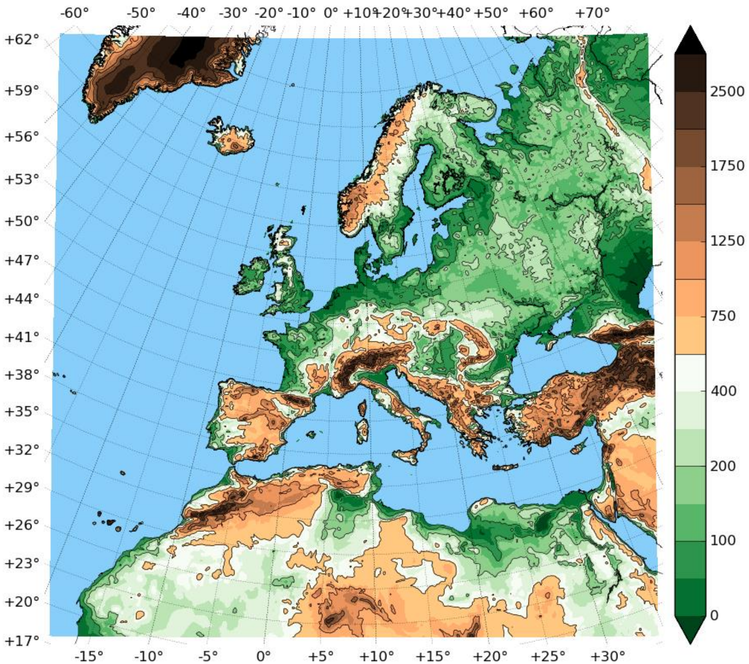
- Modell domain covers entire Europe
- Period 1961 – July 2019

- 31 surface parameters,
  9 parameters on pressure levels,
  7 parameters on height levels,
  4 parameters on model levels
  2 parameters on soil levels

- Additional output from MESCAN-SURFEX (surface and soil)

Complete list in the user guide available in the CDS:
https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-uerra-europe-single-levels?tab=doc



Model domain illustrated with model topography and land-sea mask

Relevant data for ocean modelling

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UERRA

- 10m wind speed
- 10m wind direction
- 2m temperature
- 2m relative humidity
- Short and long wave radiation
- Rain and snow
- Mean sea-level pressure
- (Cloud cover)
- Gustiness

CERRA (additional)

- Momentum fluxes
- More radiation parameters

Available time steps - UERRA

	1978-12-02							1978-12-03																											
Forecast starting at	17	18	19	20	21	22	23	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	0	1	2	3
1978-12-02 0 UTC																																			
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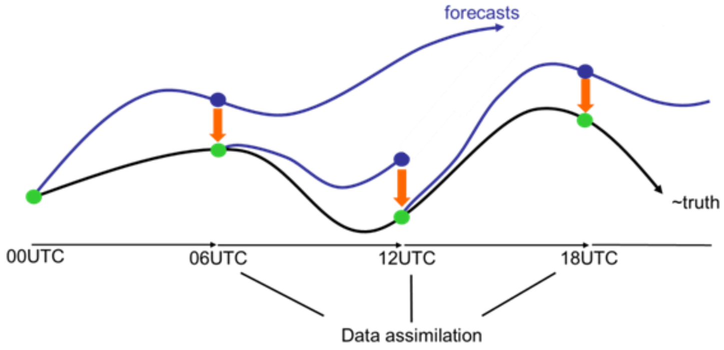
1978-12-03 12 UTC																																			
1978-12-03 18 UTC																																			
1978-12-04 0 UTC																																			
Number of available time steps								4	1	1	2	1	1	4	1	1	3	1	1	4	1	1	2	1	1	4	1	1	3	1	1				

- 4 analysis per day
- Hourly resolution from the forecast model
- Maximum forecast lengths is 30 hours



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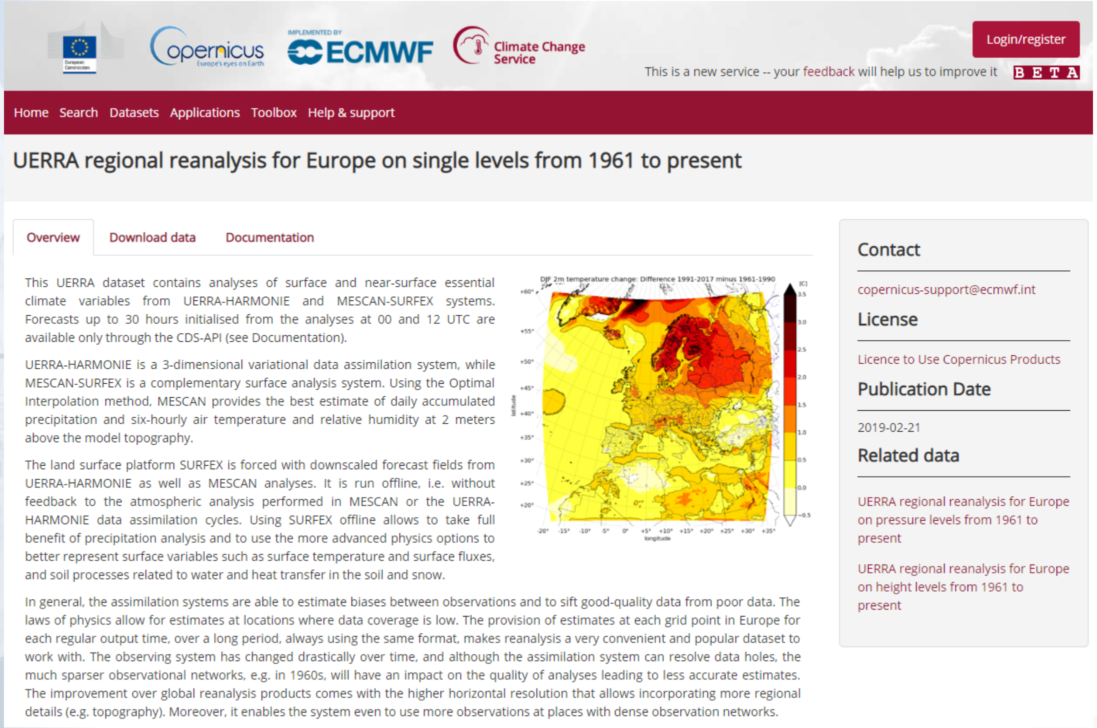
Data access via CDS

https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-uerra-europe-single-levels?tab=overview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UERRA regional reanalysis for Europe on single levels from 1961 to present

Overview Download data Documentation

This UERRA dataset contains analyses of surface and near-surface essential climate variables from UERRA-HARMONIE and MESCAN-SURFEX systems. Forecasts up to 30 hours initialised from the analyses at 00 and 12 UTC are available only through the CDS-API (see Documentation).

UERRA-HARMONIE is a 3-dimensional variational data assimilation system, while MESCAN-SURFEX is a complementary surface analysis system. Using the Optimal Interpolation method, MESCAN provides the best estimate of daily accumulated precipitation and six-hourly air temperature and relative humidity at 2 meters above the model topography.

The land surface platform SURFEX is forced with downscaled forecast fields from UERRA-HARMONIE as well as MESCAN analyses. It is run offline, i.e. without feedback to the atmospheric analysis performed in MESCAN or the UERRA-HARMONIE data assimilation cycles. Using SURFEX offline allows to take full benefit of precipitation analysis and to use the more advanced physics options to better represent surface variables such as surface temperature and surface fluxes, and soil processes related to water and heat transfer in the soil and snow.

In general, the assimilation systems are able to estimate biases between observations and to sift good-quality data from poor data. The laws of physics allow for estimates at locations where data coverage is low. The provision of estimates at each grid point in Europe for each regular output time, over a long period, always using the same format, makes reanalysis a very convenient and popular dataset to work with. The observing system has changed drastically over time, and although the assimilation system can resolve data holes, the much sparser observational networks, e.g. in 1960s, will have an impact on the quality of analyses leading to less accurate estimates. The improvement over global reanalysis products comes with the higher horizontal resolution that allows incorporating more regional details (e.g. topography). Moreover, it enables the system even to use more observations at places with dense observation networks.

Contact

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Publication Date

2019-02-21

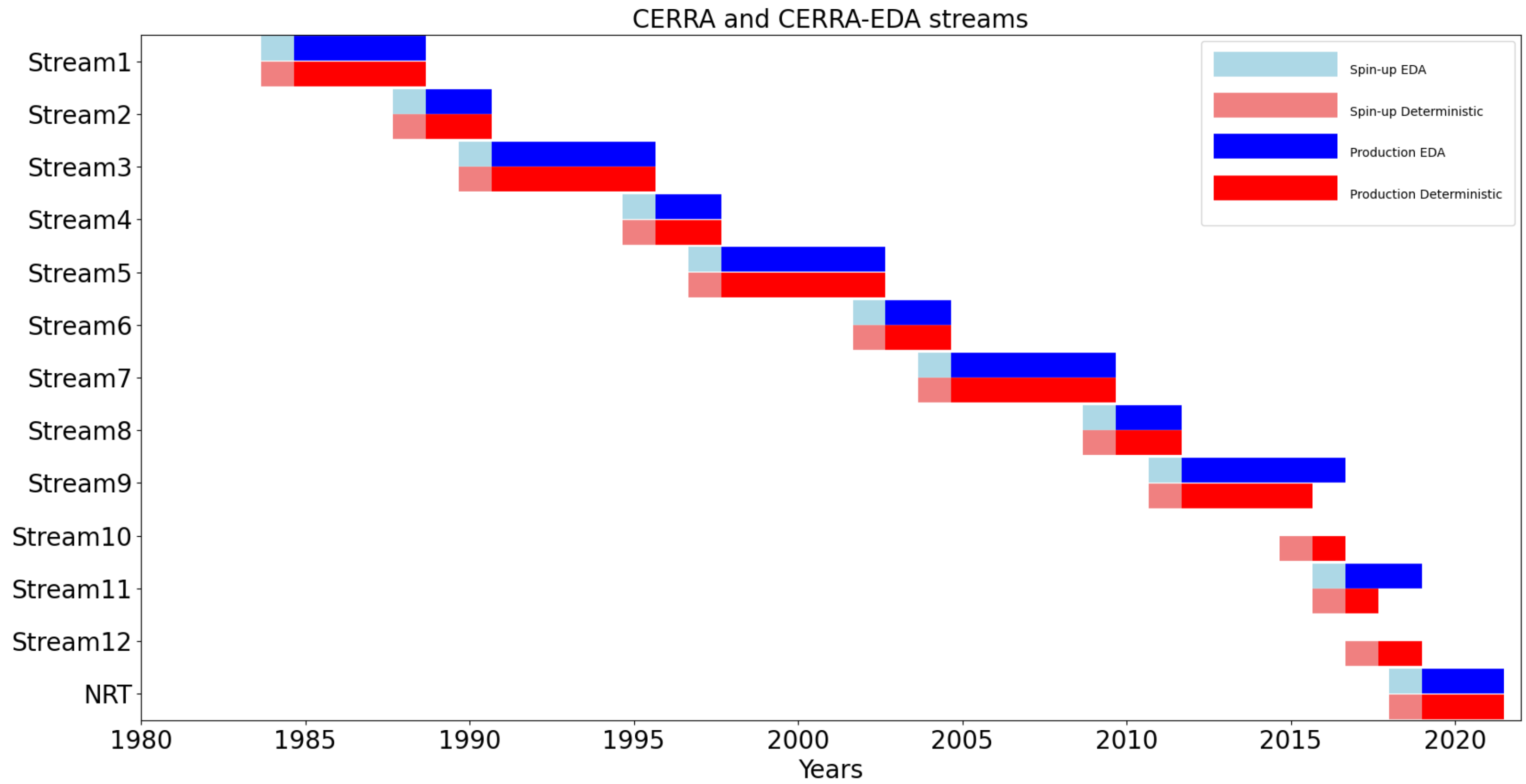
Related data

UERRA regional reanalysis for Europe on pressure levels from 1961 to present

UERRA regional reanalysis for Europe on height levels from 1961 to present

- All data is freely available!
- All you need is to register!
- Almost 500 TB of data

Streams



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Available time steps - CERRA

		2009-12-09																								2009-12-10																							
Day	Time of the analysis in UTC	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
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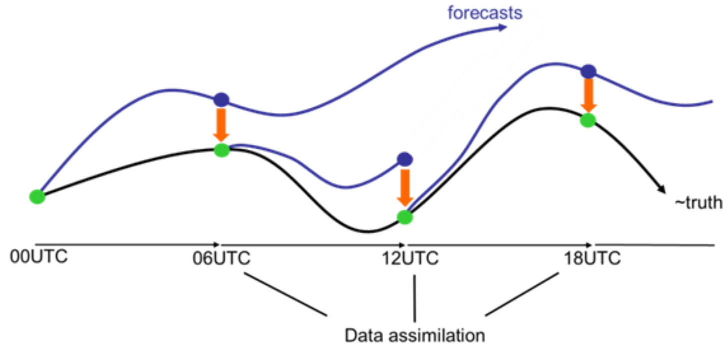
2009-12-10	15 UTC																																																
2009-12-10	18 UTC																																																
2009-12-10	21 UTC																																																
Number of available time steps																										5	2	2	5	2	2	5	2	2	5	2	2	5	2	2	5	2	2	5	2	2	5	2	2

- 8 analysis per day
- Hourly resolution from the forecast model
- Maximum forecast lengths is 30 hours



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CERRA surface parameters

	Name	Unit	GRIB code	Analysis 0, 3, 6, 9, ...	Forecast 1,2,3,...	Height
1.	2m relative humidity	%	260242	yes	yes	2m
2.	Total column integrated water vapour	kg/m^2	260057	yes	yes	vertically integrated above the surface
3.	Total precipitation	kg/m^2	228228	-	yes	surface
4.	10m wind speed	m/s	207	yes	yes	10m
5.	10m wind direction	degrees	260260	yes	yes	10m
6.	10m wind gust speed	m/s	49	-	yes	10m
7.	Surface air maximum temperature	K	201	-	yes	2m
8.	Surface air minimum temperature	K	202	-	yes	2m
9.	2m temperature	K	167	yes	yes	2m
10.	Skin temperature	K	235	yes	yes	surface
11.	Albedo	%	260509	yes	yes	surface
12.	Evaporation	kg/m^2	260259	-	yes	surface
13.	Time-integrated surface latent heat flux	J/m^2	147	-	yes	surface
14.	Time-integrated surface sensible heat flux	J/m^2	146	-	yes	surface
15.	Time-integrated surface direct solar radiation	J/m^2	260264	-	yes	surface
16.	Time-integrated surface net solar radiation	J/m^2	176	-	yes	surface
17.	Time-integrated surface solar radiation downwards	J/m^2	169	-	yes	surface
18.	Time-integrated surface net thermal radiation	J/m^2	177	-	yes	surface
19.	Time-integrated surface thermal radiation downwards	J/m^2	175	-	yes	surface

	Name	Unit	GRIB code	Analysis 0, 3, 6, 9, ...	Forecast 1,2,3,...	Height
20.	Clear-sky net short-wave downward flux at the surface	J/m^2	210	-	yes	surface
21.	Clear-sky net long-wave downward flux at the surface	J/m^2	211	-	yes	surface
22.	Momentum flux at the surface U-component	N/m^2	260062	-	yes	surface
23.	Momentum flux at the surface V-component	N/m^2	260063	-	yes	surface
24.	Mean sea level pressure	Pa	151	yes	yes	surface
25.	Surface pressure	Pa	134	yes	yes	surface
26.	High cloud cover	%	3075	yes	yes	above 5000m
27.	Low cloud cover	%	3073	yes	yes	surface-2500m
28.	Medium cloud cover	%	3074	yes	yes	2500m-5000m
29.	Total cloud cover	%	228164	yes	yes	above ground
30.	Snow density	kg/m^3	33	yes	yes	surface
31.	Snow depth		3066	yes	yes	surface
32.	Snow depth water equivalent	kg/m^2	228141	yes	yes	surface
33.	Snow fall water equivalent	kg/m^2	228144	-	yes	surface
34.	Land-sea mask	dimension-less	172	yes	-	surface
35.	Orography	gpm	228002	yes	-	surface
36.	Surface roughness	m	173	yes	yes	surface

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C E R R A parameters on pressure levels

	Parameter	Unit	GRIB code	Analysis 0, 3, 6, 9, …	forecast 1,2,3,…
1.	Cloud cover	%	260257	-	yes
2.	Specific cloud liquid water content	kg/kg	246	-	yes
3.	Specific cloud ice water content	kg/kg	247	-	yes
4.	Specific rain water content	kg/kg	75	-	yes
5.	Specific snow water content	kg/kg	76	-	yes
6.	Turbulent kinetic energy	J/kg	260155	-	yes
7.	Relative humidity	%	157	yes	yes
8.	Temperature	K	130	yes	yes
9.	U-component of wind	m/s	131	yes	yes
10.	V-component of wind	m/s	132	yes	yes
11.	Geopotential	m^2/s^2	129	yes	yes

2. UERRA-CERRA-ERA5 comparison

Verification – UERRA vs. ERAint

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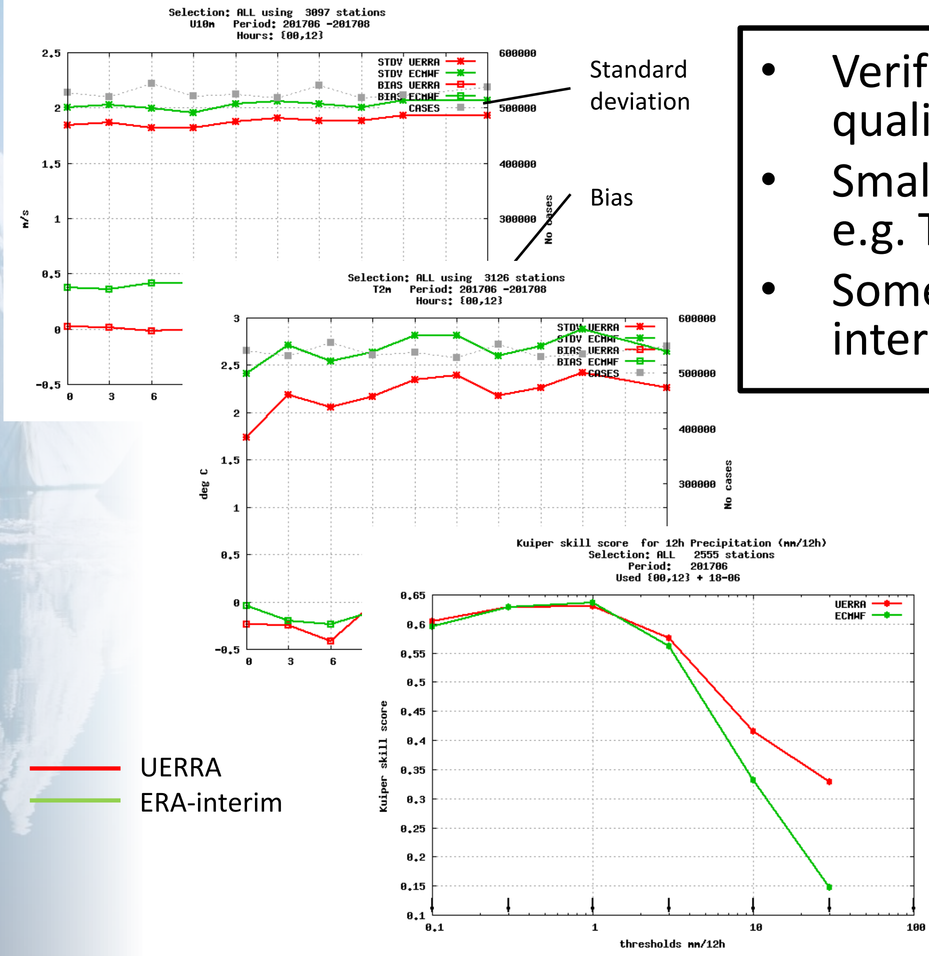
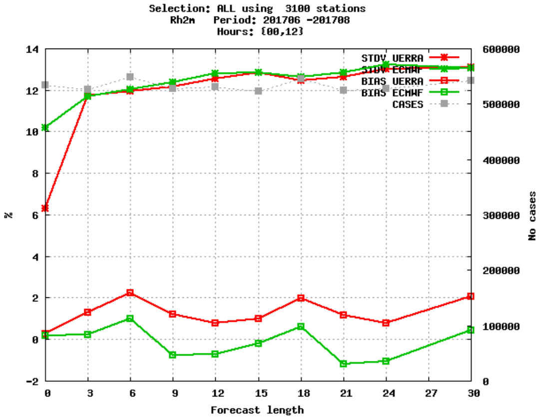
- Verification tools are part of the quality control during the production
- Smaller bias and std than ERA-interim, e.g. T2m, wind speed, precipitation
- Some parameters not better than ERA-interim, e.g. RH2m





UERRA

ERA-interim

DJF windspeed in ERA5 and UERRA

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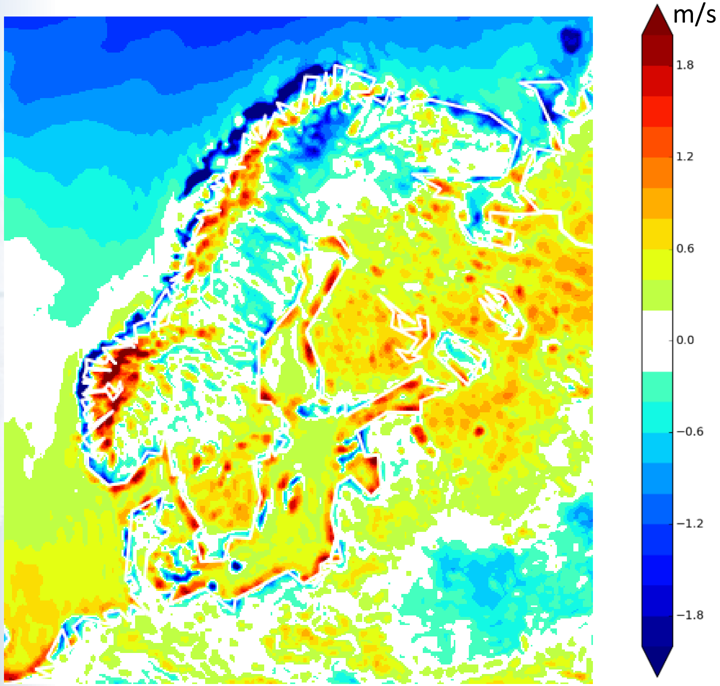
Wind speed differences between ERA5 and UERRA



- Differences mainly smaller than 1m/s
- Most differences are related to topography and the coastline

Quality of wind speed

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	Observations	ERA5	UERRA	CERRA
Mean [m/s]	6.01	5.95	6.14	6.18
Mean abs. error (MAE)		0.84	0.59	0.60
Average standard deviation [m/s] (STD)	3.19	2.72	3.14	3.17
Mean abs. STD		0.57	0.30	0.28
RMSE		1.95	1.89	1.74
Correlation		0.85	0.85	0.88

Assessment is based on hourly data for a 1996 – 2018 at 28 Swedish coastal stations.

Demonstration: storm Gudrun, southern Sweden, January 2005

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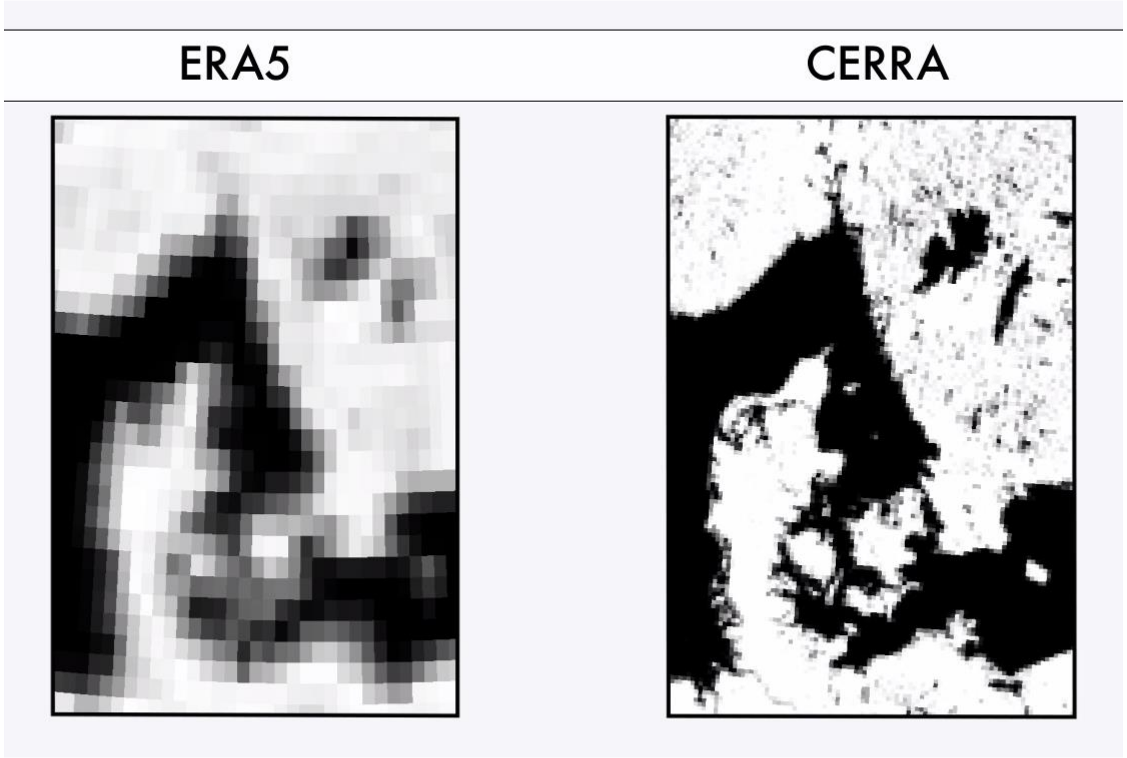
Some facts:

- Most severe storm ever registered in Southern Sweden in terms of power outages and forest devastations (75 million cubic meter of lumber)
- Seven people died

Source: https://www.elinstallatoren.se/2020/02/sa-minns-vi-stormen-gudrun-det-var-fel-att-ge-sig-ut-och-jobba-i-den-blasten/

More information also on Wikipedia (https://en.wikipedia.org/wiki/Cyclone_Gudrun)

Land-Sea-mask



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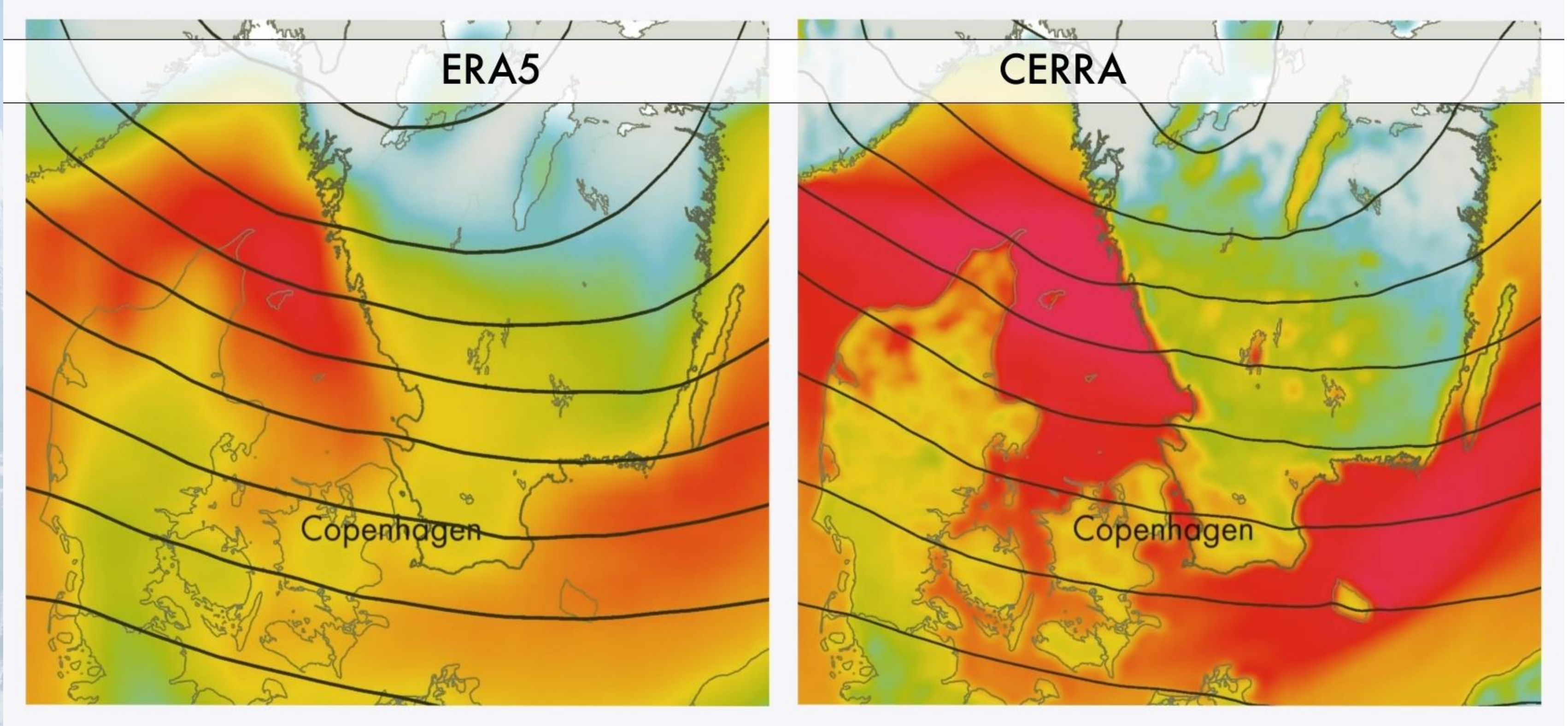
Storm Gudrun in January 2005



Wind speed in 10m

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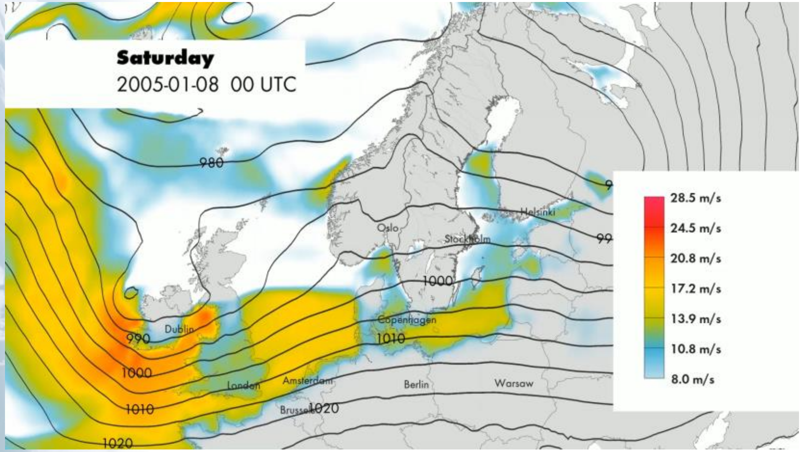
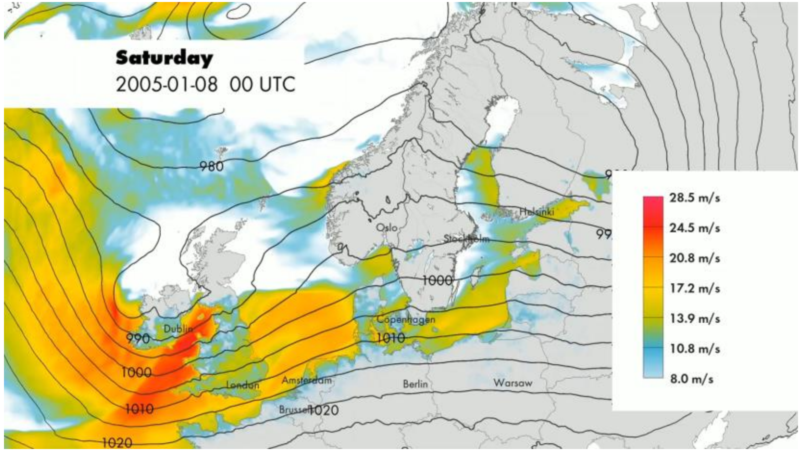
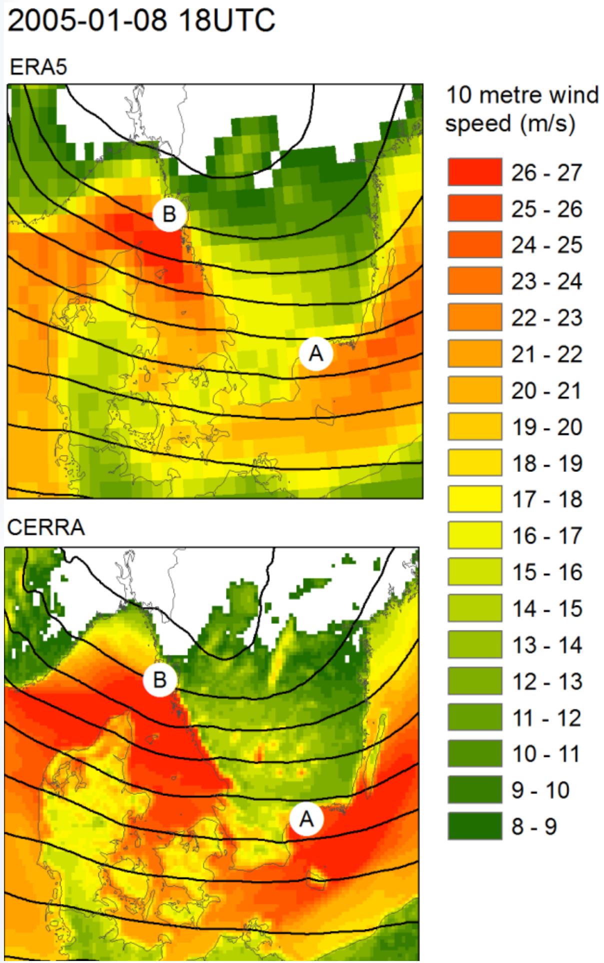
Storm animations





Demonstration: storm Gudrun, southern Sweden, January 2005



- 10m wind speed at the culmination of the storm at 18 UTC 08/01/2005
- General higher wind speeds in CERRA compared to ERA5 – at least over the ocean
- More realistic features related to topography and land-sea mask, e.g.
  - higher wind speed over lakes, e.g. lakes Vättern and Bolmen stick out in CERRA
  - Lower and more realistic wind speed over the island Bornholm in CERRA. That is related to a higher surface roughness.

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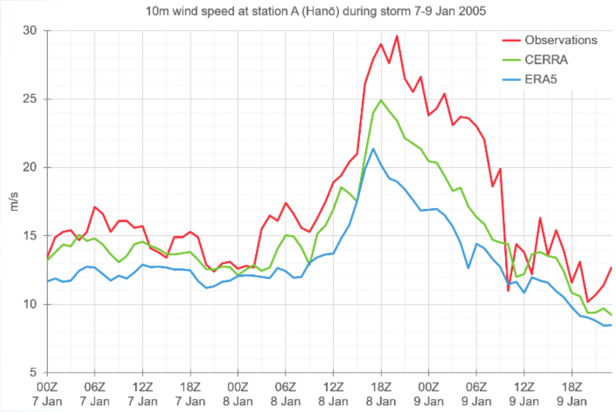
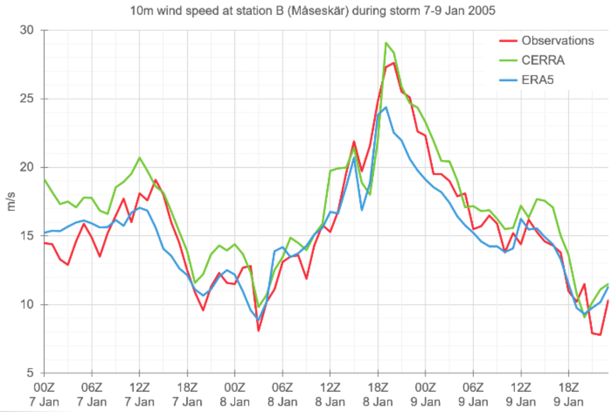
Demonstration: storm Gudrun, southern Sweden, January 2005





- For many Swedish stations we see a better fit to observations in CERRA
- Corresponding to previous figure usually too low wind speed in ERA5

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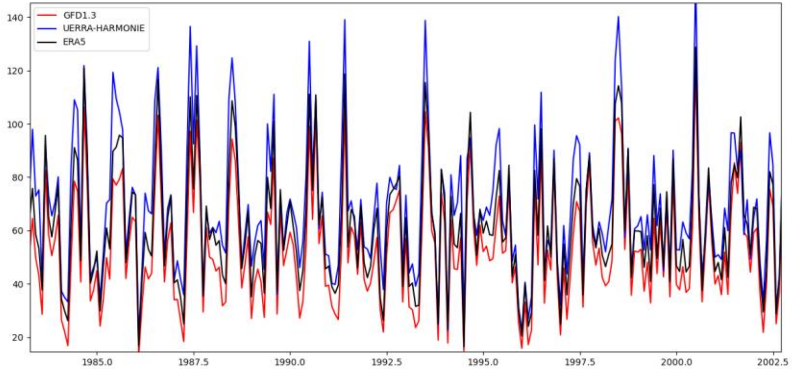
Precipitation in the Baltic Sea area

	Monthly mean [mm/m2]	correlation with HGFD	RMSE with HGFD	correlation with E-OBS	RMSE with E-OBS
HydroGFD3	54,5	---	---	0,985	4,573
E-OBS	52,2	0,985	4,573	---	---
UERRA	68,1	0,927	16,516	0,956	17,607
ERA5	61,4	0,990	7,603	0,987	9,923



T2m: Daily cycle and maximum

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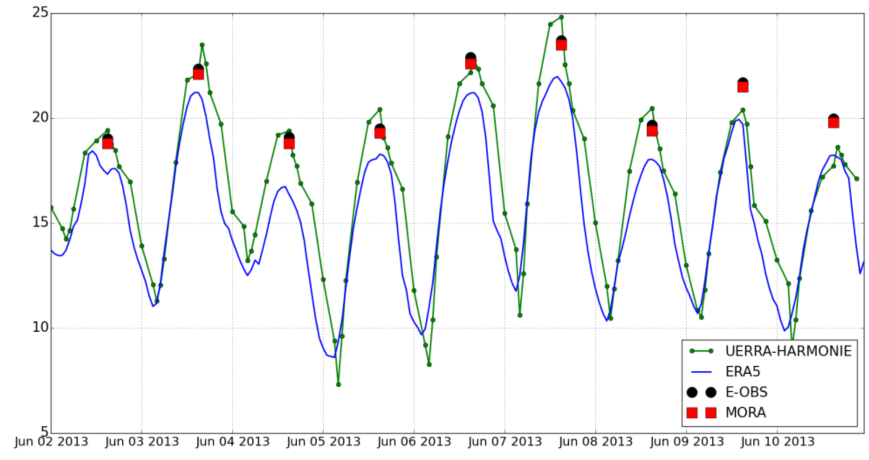
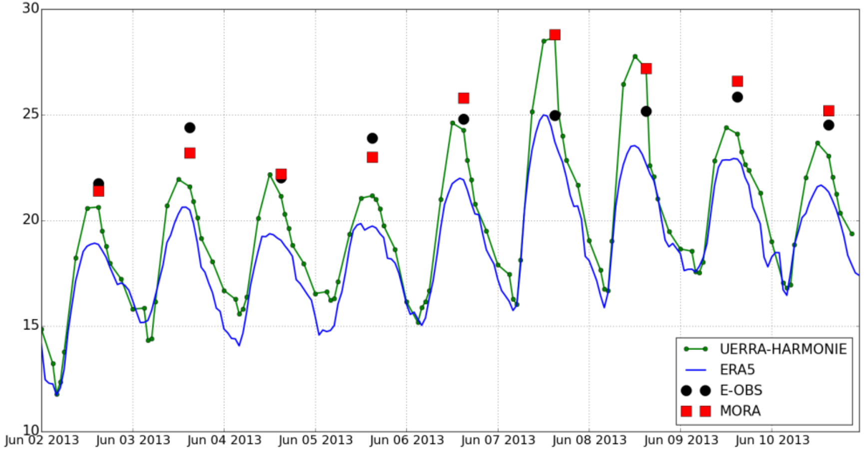
Växjö (Sweden)



Grazzanise (Italy)



- Random sample, nine days in June 2013
- Växjö region is quite flat and homogenous
- UERRA-HARMONIE has general higher daily maximum temperatures than ERA5

- Grazzanise has a more complex terrain
- UERRA-HARMONIE has general higher daily maximum temperatures than ERA5
- Clear difference between gridded (E-OBS) data and direct measurements

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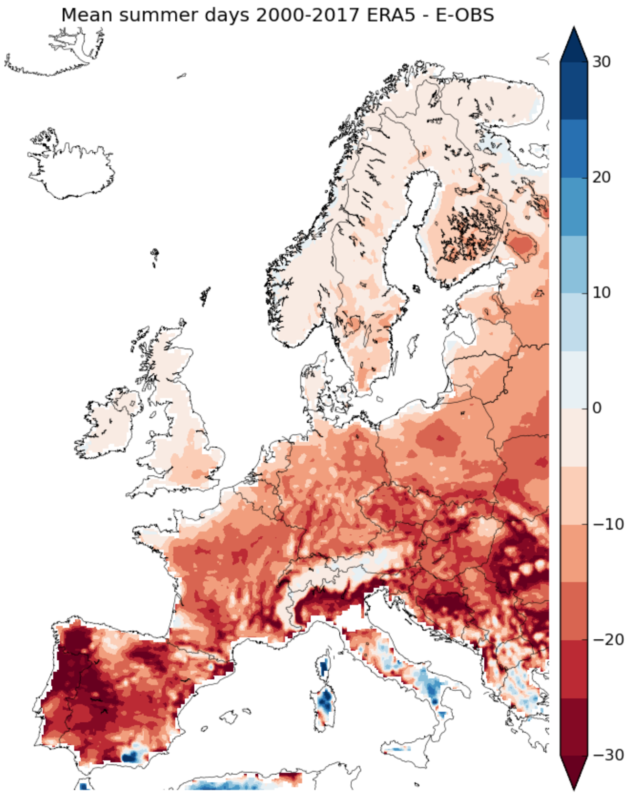
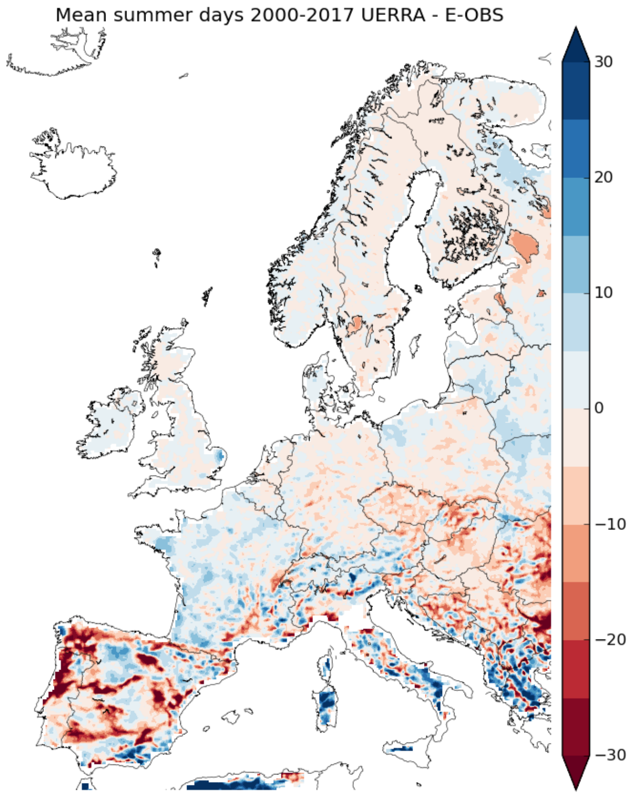
Summer days = Tmax > 25C





JJA 2m-temperature in ERA5 and UERRA

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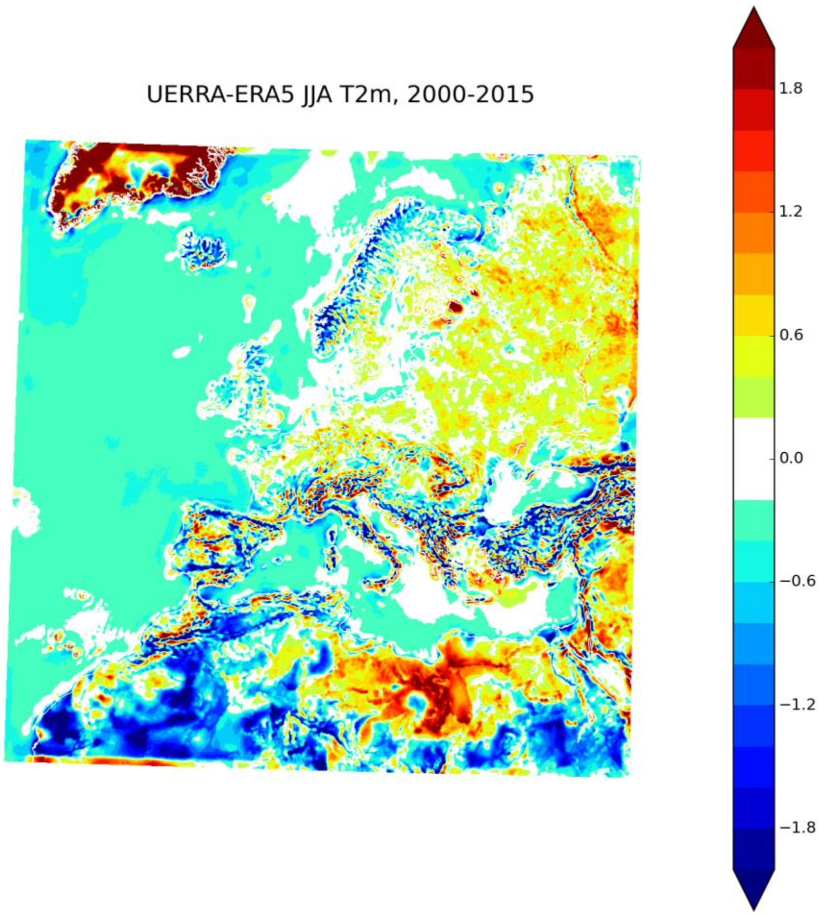

- Small differences over the ocean and flat areas
- Strong effect of topography
- Uncertainty in northern Africa is large

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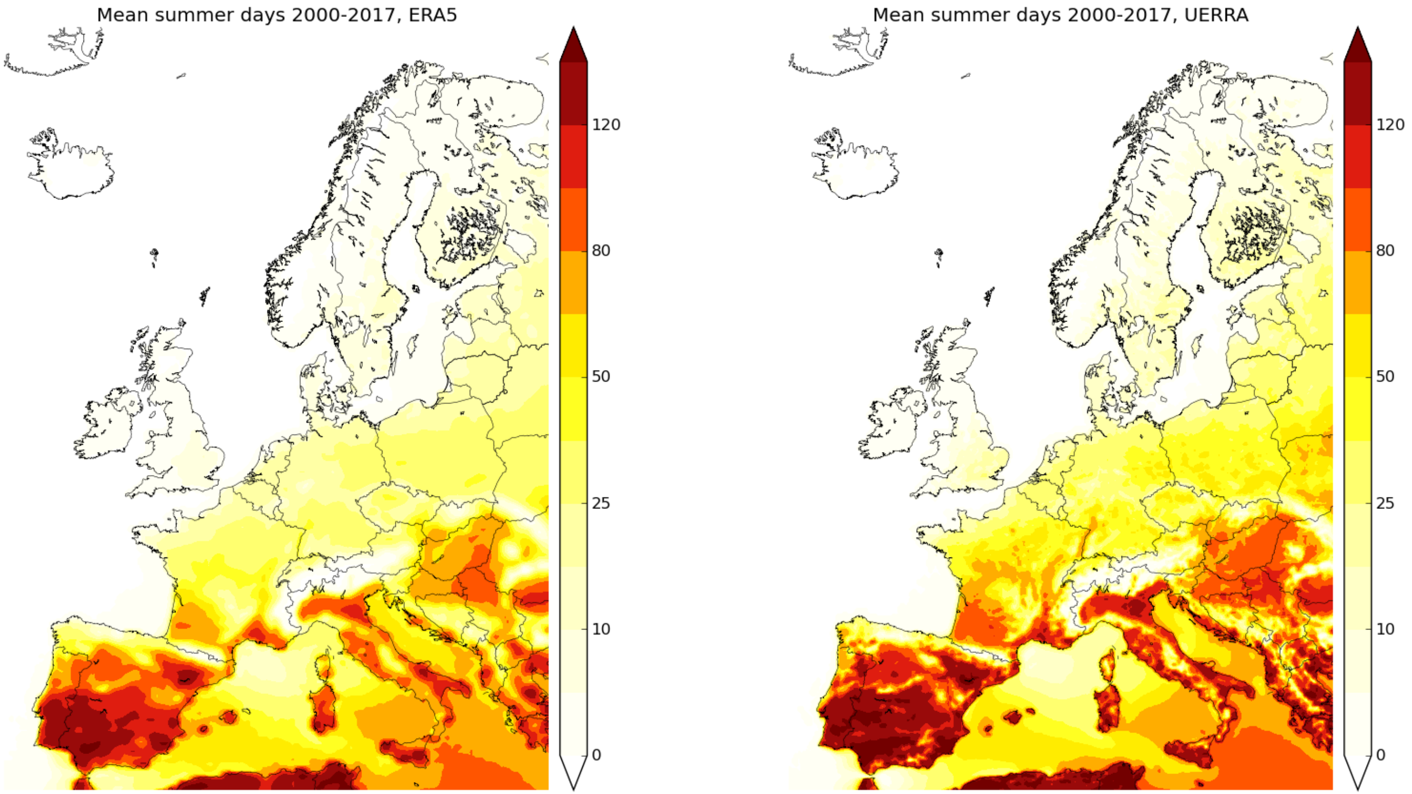
Summer days = Tmax > 25C



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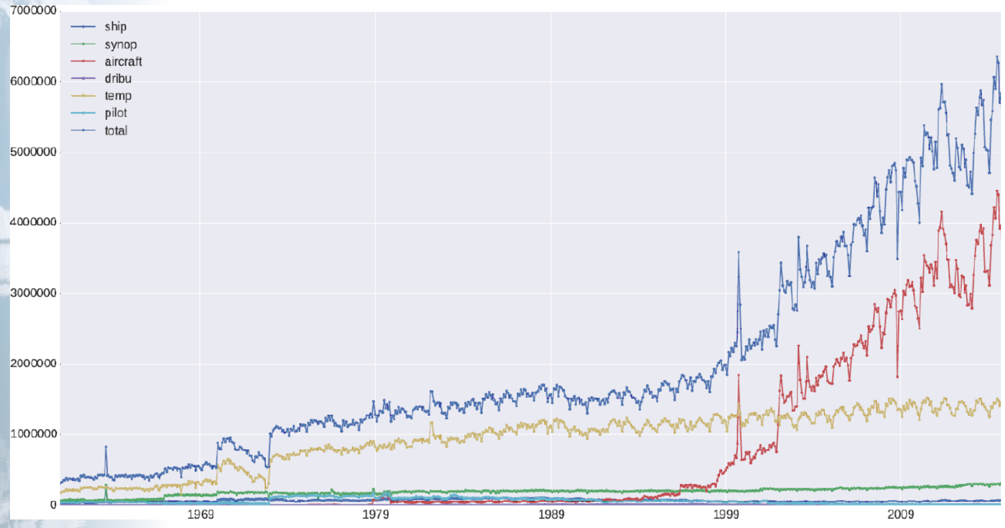
H o m o g e n e i t y

Number of observations



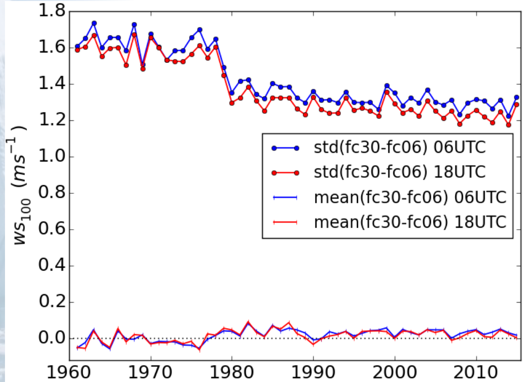
1969 1979 1989 1999 2009

Risks for inhomogeneity

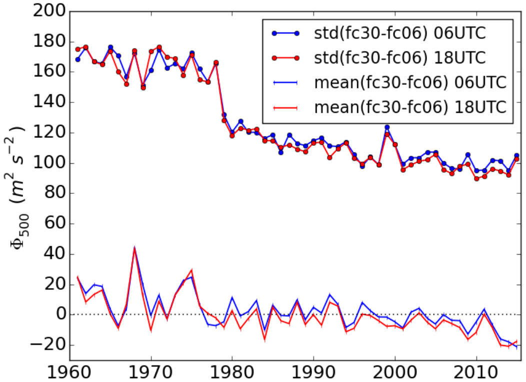
- Switch of lateral boundary data
  - 1961-1978 ERA40
  - 1979-2019 ERA-interim
- Increasing numbers of observations in time, especially aircraft data

Homogeneity

100m wind speed



500 hPa geopotential



Yearly averages of the standard deviation and mean of the forecast difference fc30-fc06 during winter (DJF).
Left: 100m wind speed. Right: 500 hPa geopotential. Curtesy Adam von Kraemer.

Investigations of the [forecast skill](#)(differences between fc30 and fc6):

- Forecast skill effects accuracy of the first guess and has herewith consequences on the data quality
- Increase of quality with the switch to ERA-interim and increasing numbers of observations (upper air)

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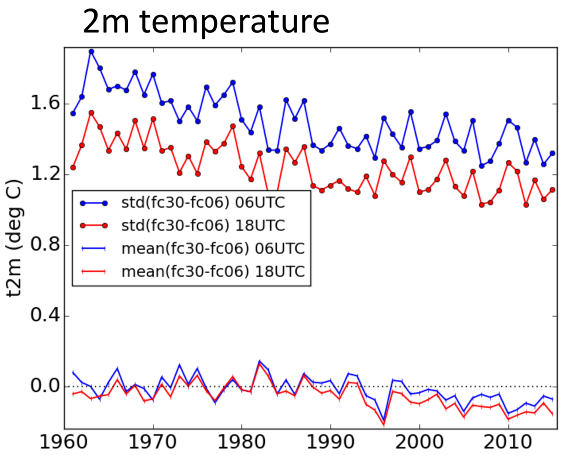
Homogeneity



Yearly averages of the standard deviation and mean of the forecast difference fc30-fc06 during winter (DJF).
Curtesy Adam von Kraemer.

Investigations of the forecast skill (differences between fc30 and fc6):

- Less change of quality for surface parameters
- Surface parameters are less affected due to a more constant number of surface observations throughout time

Demonstration: snow depth in the Alpine region

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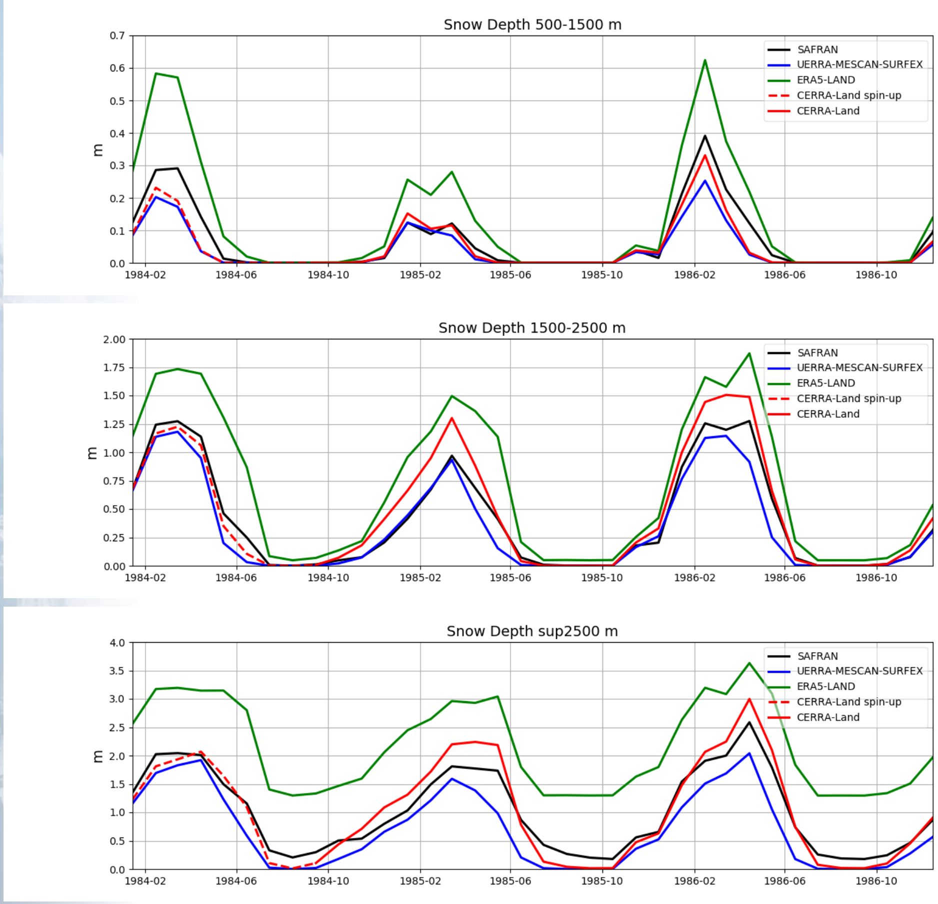

- SAFRAN data can be considered as a dataset close to the truth
- The regional products CERRA-Land and MESCAN-SURFEX outperform ERA5-Land, which overestimates the snow depth

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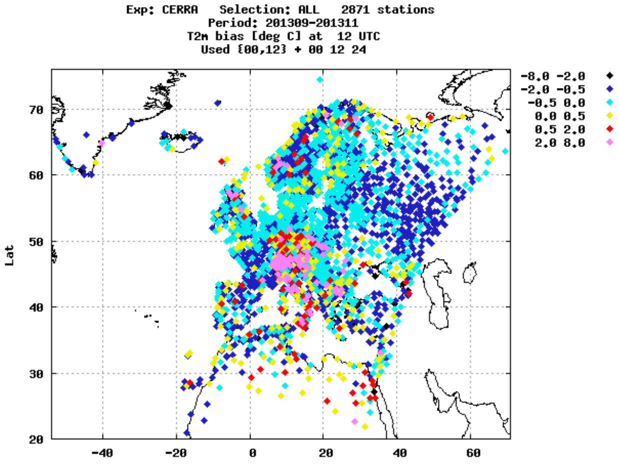
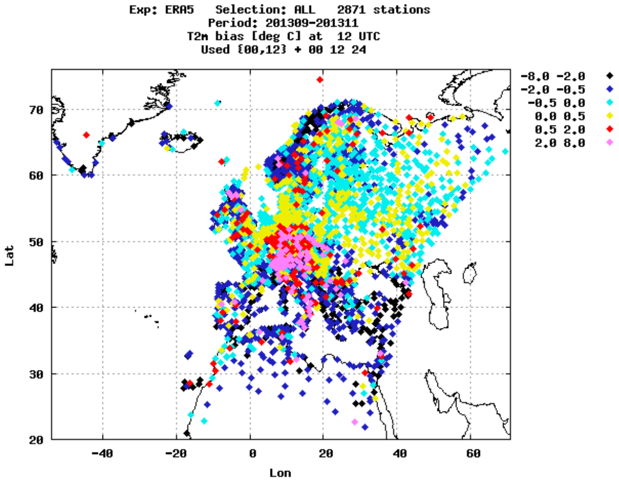
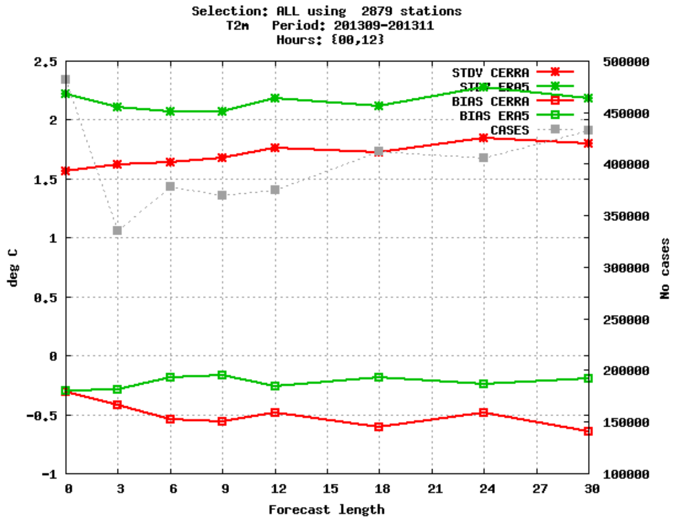
HARMONIE verification - CERRA







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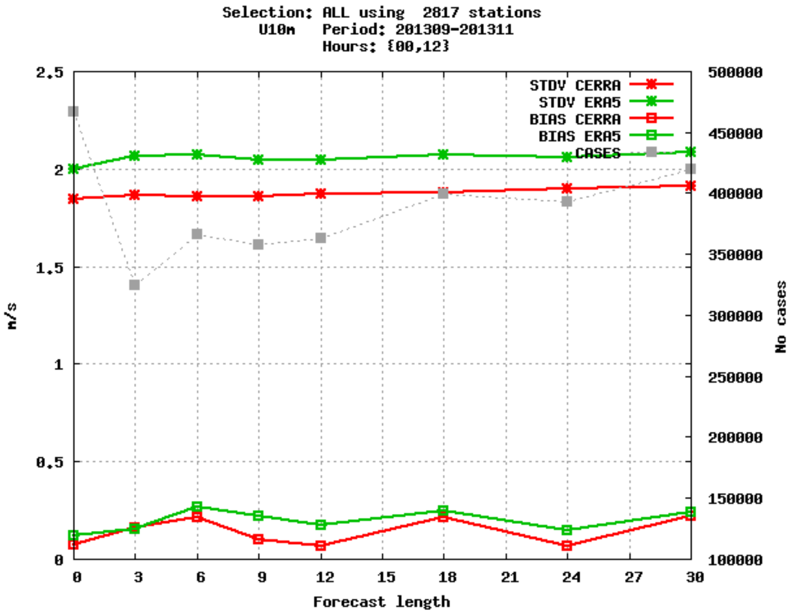
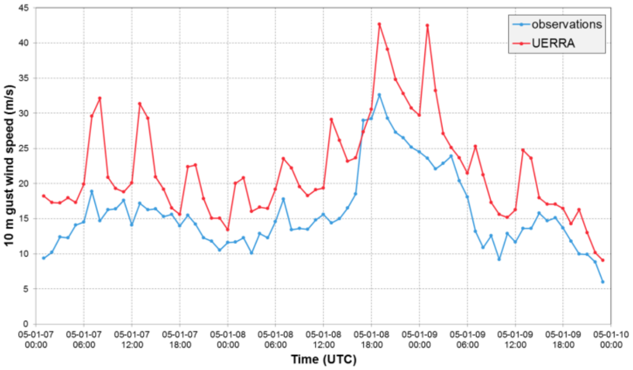
HARMONIE verification - CERRA



Known short comings

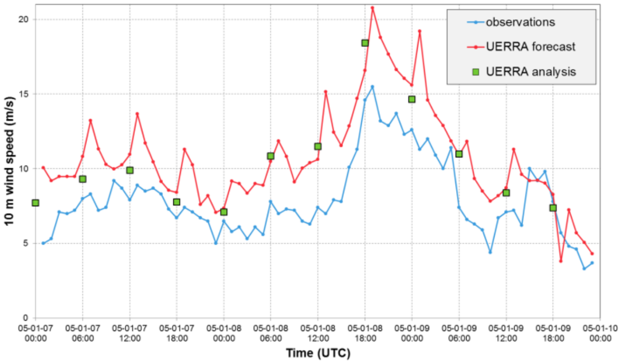
Gust wind speed

10m gust wind speed at station Växjö A (southern Sweden).
Hourly forecast from 2005-01-07 to 2005-01-09 (storm Gudrun).



10m wind speed

10m wind speed at station Växjö A (southern Sweden).
Forecast and analysis from 2005-01-07 to 2005-01-09 (storm Gudrun).

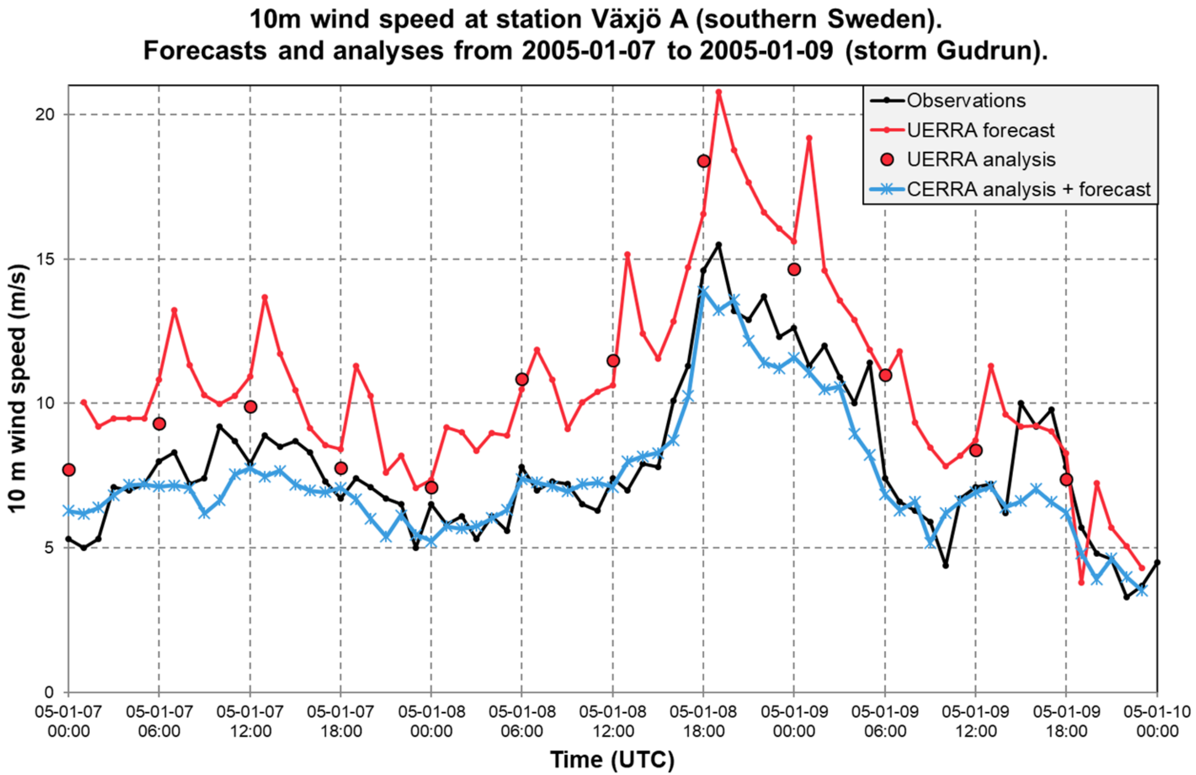


Windspeed during Gudrun

- Wind at a station in southern Sweden during a major storm
- Shown are fc1-6 (and fc0)

➔ Clearly unrealistic jumps
➔ Affected are forecasts lengths 1h and 2h

Climate Change



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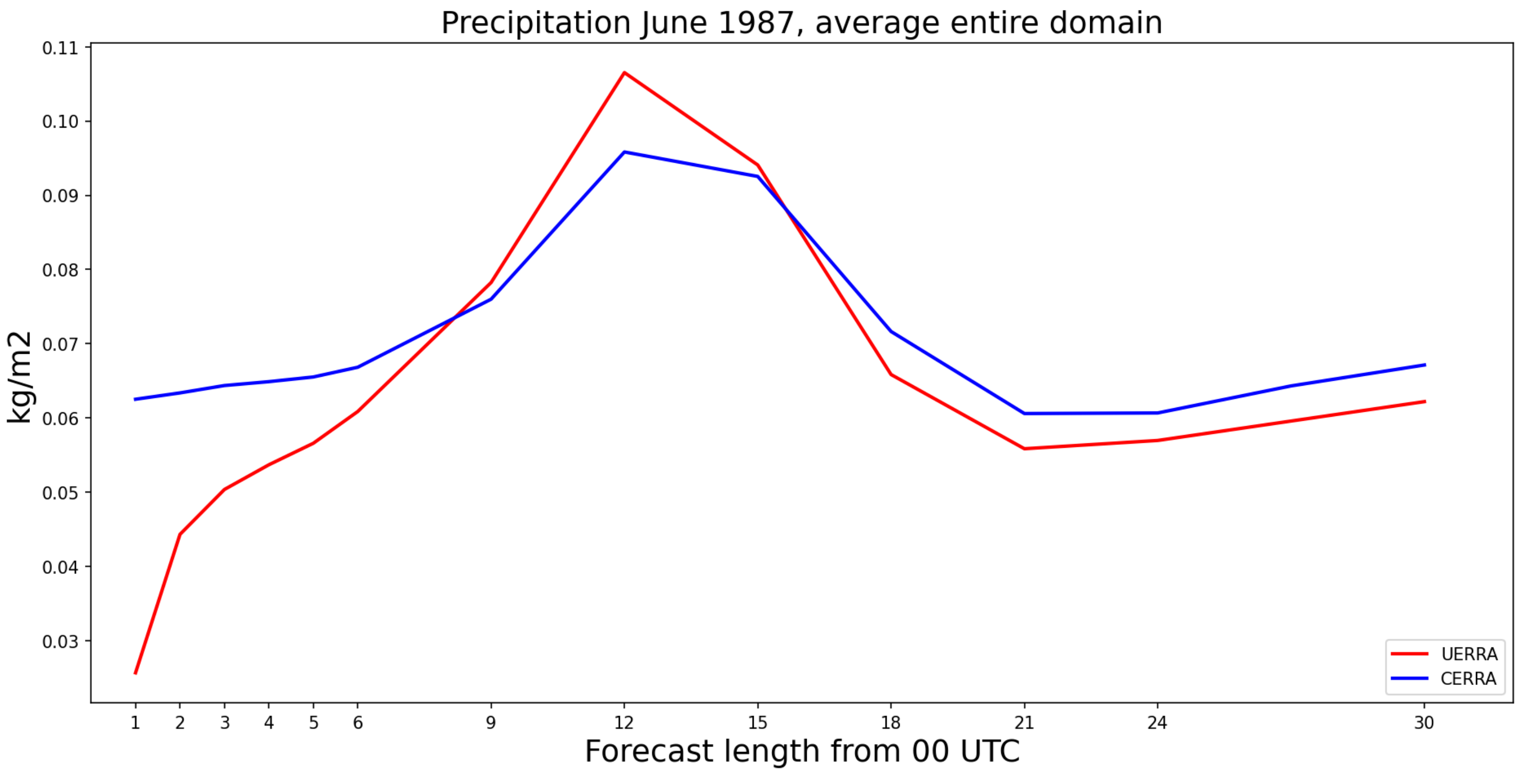
Spin-up precipitation



Climate Change

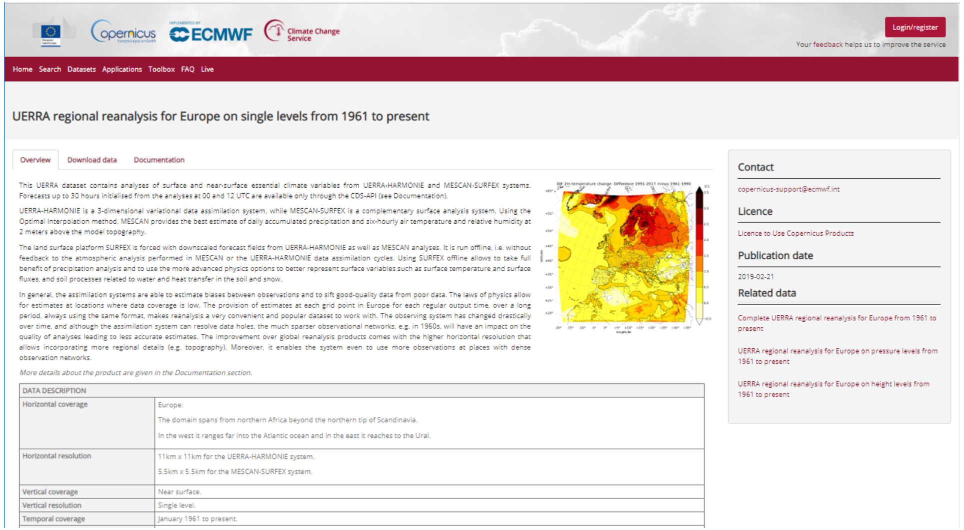
3. Training material

Climate Change

Documentation

Landing page

CDS



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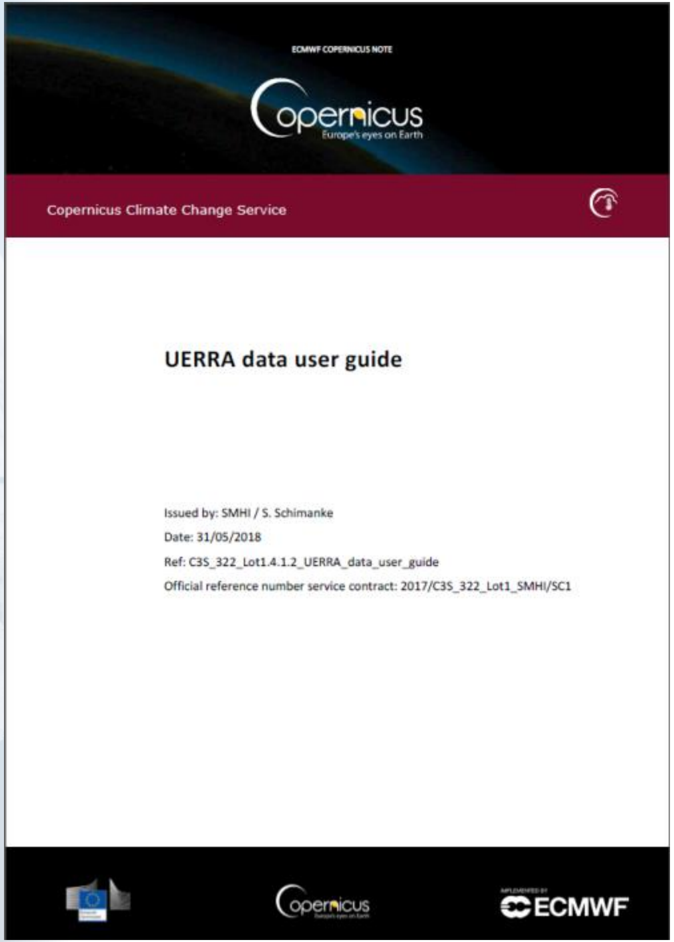
Change

Documentation


ECMWF COPERNICUS NOTE

Copernicus
Europe's eyes on Earth

Copernicus Climate Change Service

UERRA data user guide

Issued by: SMHI / S. Schimanke

Date: 31/05/2018

Ref: C3S_322_Lot1.4.1.2_UERRA_data_user_guide

Official reference number service contract: 2017/C3S_322_Lot1_SMHI/SC1

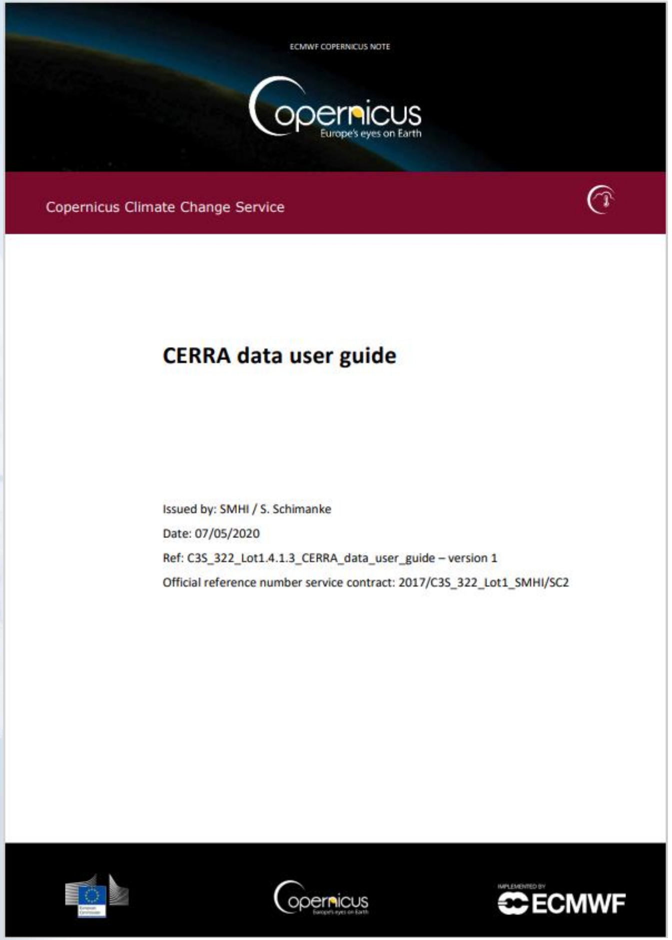
UERRA user guide

- Most comprehensive information
  (53 pages)

- Version 3.3 online

Climate Change

Documentation


ECMWF COPERNICUS NOTE

Copernicus Climate Change Service

CERRA data user guide

Issued by: SMHI / S. Schimanke

Date: 07/05/2020

Ref: C3S_322_Lot1.4.1.3_CERRA_data_user_guide – version 1

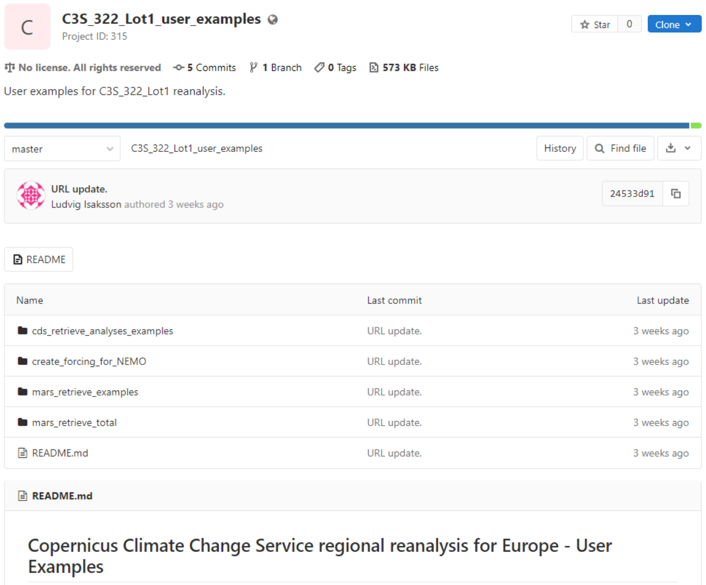
Official reference number service contract: 2017/C3S_322_Lot1_SMHI/SC2

CERRA user guide

- Information on CERRA, CERRA-EDA and CERRA-Land
  (41 pages)
- Detailed information on the grids
- Prepared for the CDS, not available yet

GitHub

- Server with example scripts (python) https://github.com/UserLearningServices-C3S/regionalreanalysis-UERRA
- Get data from CDS/MARS
- Prepare forcing data for NEMO-Nordic



GitHub script

https://github.com/UserLearningServices-C3S/regionalreanalysis-UERRA

Create forcing data for NEMO-Nordic

These scripts are an example of how the UERRA data can be used for input to other model systems, in this case the NEMO-Nordic (a regional ocean model).

The objectives of the scripts

These scripts will:

1. download the needed,
2. extract the region needed for NEMO-Nordic,
3. convert the units as needed for NEMO-Nordic,
4. save the final files as netCDF.

Instructions

Basically, users have only to adopt the "Configure section" in the main script - Create_NEMO_forcing_from_UERRA.py

1. Set the dates your are interested in.
2. Define directories for downloaded data, the final data, and a directory for temporary files.

Then, all you have to do is to run the main script... Create_NEMO_forcing_from_UERRA.py

Good to know

The scripts need some time to run. Especially the downloading of data from the MARS archive takes time. Here, we are talking about days if you want to produce forcing data for longer periods (several years). A rough estimate is about six hours for each year. However, this depends

Conversions:

- Blend analyses and forecasts
- Change units
- Accumulated fluxes
- Compute specific humidity
- Compute wind components based on speed and direction

Lessons in the ULS

Copernicus User Learning Services (ULS)

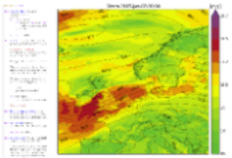
https://climate.copernicus.eu/user-learning-services

Climate Data Store: Introduction to using the regional reanalysis for Europe (UERRA)

★ 5.0 • Lessons • User Learning Service • 20 min

The request will be: data = ct.catalogue.retrieve('reanalysis-**uerra**-europe-single-levels', { 'origin': '**uerra_harmonie**', 'variable': ['10m_wind_speed', 'mean_sea_level_pressure'], 'year': '2005', 'month': '01', 'day': '08', 'time': '12:00', }) The resulting data will become an array 'data', where data[0] is wind speed and data[1] is

CDS • UERRA • Toolbox

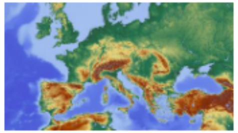


Regional reanalysis for Europe (UERRA): data retrieval and plotting

★ 5.0 • Lessons • User Learning Service • 40 min

data in python with matplotlib, The following section provides examples of how to write a python script that plots **UERRA** data....MS Windows., The GRIB and netCDF formats, Note: **UERRA** complete dataset, As mentioned, the complete **UERRA** dataset (which also contains all forecast data) is only available for download

visualization • UERRA • API

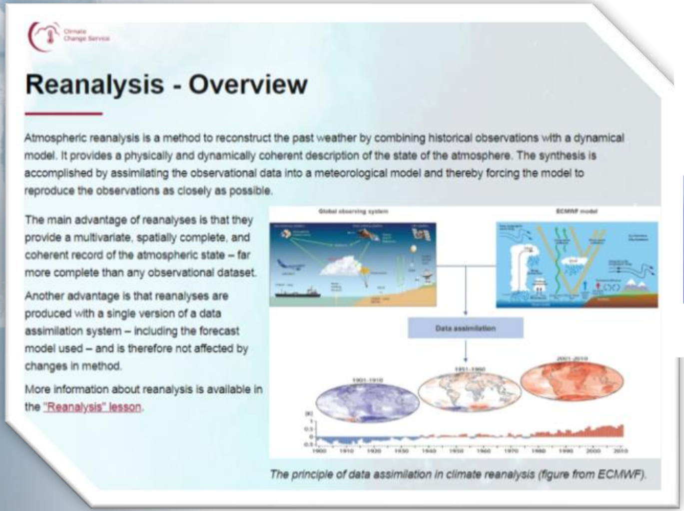


Copernicus regional reanalysis for Europe

★ 4.5 • Lessons • User Learning Service • 20 min

Before running these scripts it is recommended to explore the available data and the corresponding MARS requests via Web-MARS: **UERRA**-HARMONIE data in Web-MARS MESCAN-SURFEX data in Web-MARS Then modify the time, parameters, levels etc. in the scripts to match your specific needs., **UERRA** data

ULS



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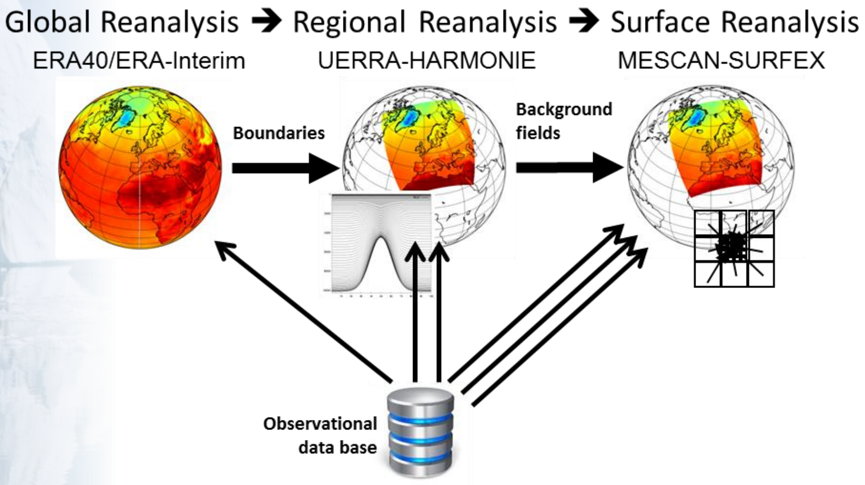
4. The reanalysis systems

The system



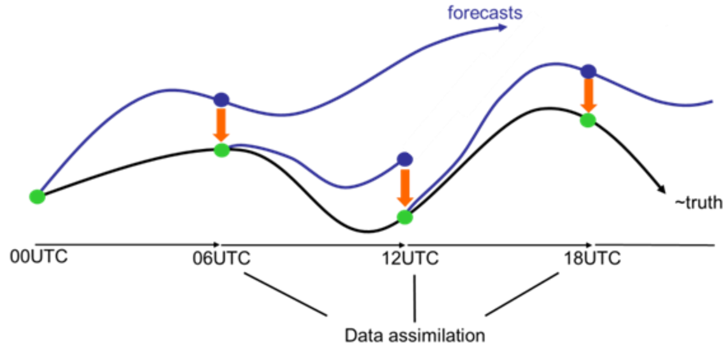
- UERRA system
  - HARMONIE cycle 38h1, ALADIN physics
  - ERA40/ERA-interim as lateral boundary
  - Assimilation of conventional observations
  - 4 cycles per day, forecast lengths 6h and 30h
  - 11km resolution (565x565) and 65 vertical levels

- MESCAN-SURFEX
  - Optimal interpolation (OI)
  - 5.5km resolution

Available time steps

	1978-12-02							1978-12-03																											
Forecast starting at	17	18	19	20	21	22	23	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	0	1	2	3
1978-12-02 0 UTC																																			
1978-12-02 6 UTC																																			
1978-12-02 12 UTC																																			
1978-12-02 18 UTC																																			
1978-12-03 0 UTC																																			
1978-12-03 6 UTC																																			
1978-12-03 12 UTC																																			
1978-12-03 18 UTC																																			
1978-12-04 0 UTC																																			
Number of available time steps								4	1	1	2	1	1	4	1	1	3	1	1	4	1	1	2	1	1	4	1	1	3	1	1				

- 4 analysis per day
- Hourly resolution from the forecast model
- Maximum forecast lengths is 30 hours



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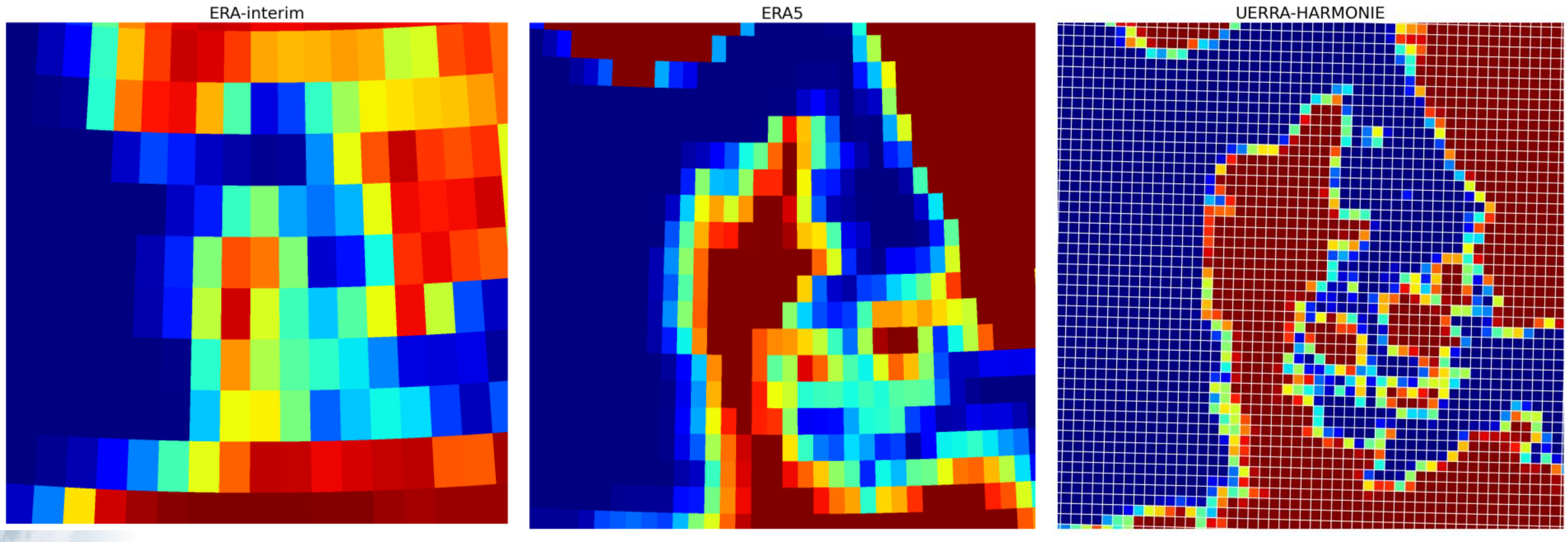
Added value compared to global RA

Land-sea masks

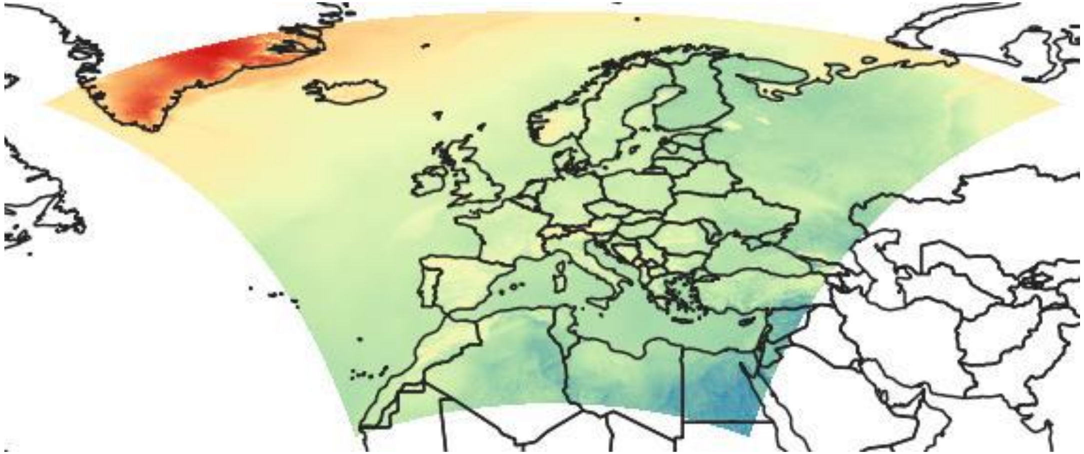


~80km

~31km

11km

Lambert conformal conic projection



CERRA proj string:

+proj=lcc +lat_1=50 +lat_2=50 +lat_0=50 +lon_0=8 +x_0=0 +y_0=0 +a=6371229 +b=6371229 +units=m +no_defs

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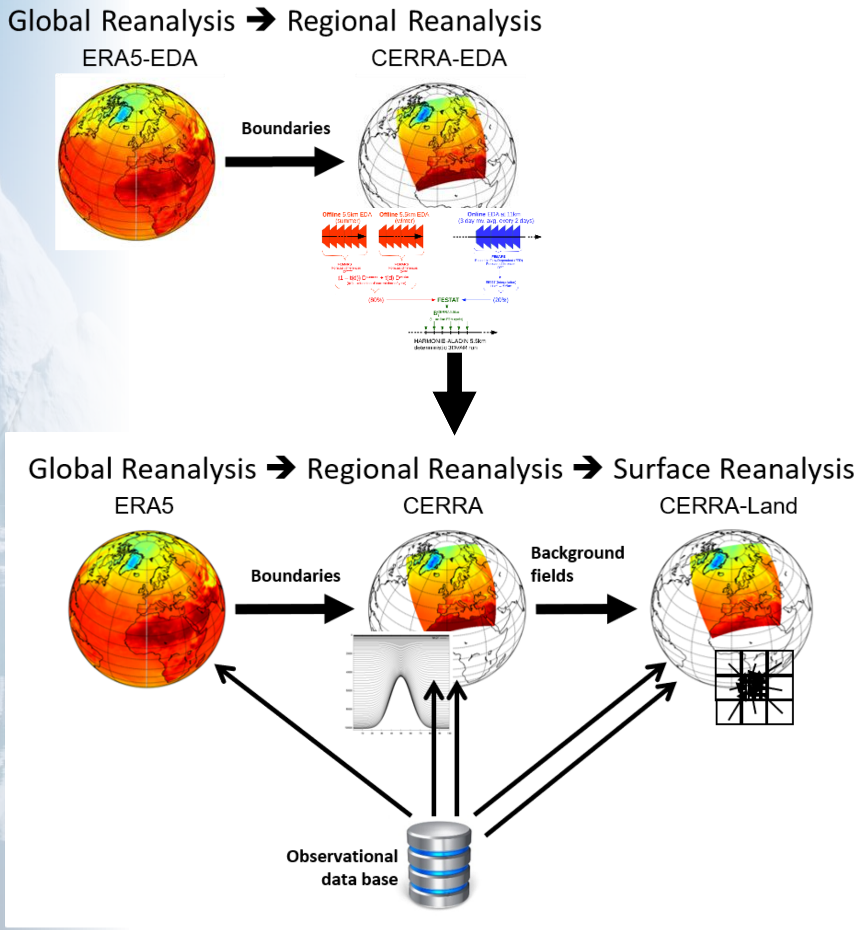
The systems – an overview



- CERRA system
  - HARMONIE cycle 40h1.2, ALADIN physics (partly back phased from cy42)
  - 3D-VAR for upper air observations and OI at the surface
  - Estimation of background errors from CERRA-EDA
  - ERA5 as lateral boundary
  - Assimilation of conventional observations, satellite radiances (MSU, AMSU-A+B, and IASI), GB-GNSS, RO-GNSS, AMV and scatterometer winds
  - 8 cycles per day, forecast lengths 6h and 30h
  - 5.5km horizontal resolution (1069x1069) and 106 vertical levels
- CERRA-EDA (same as CERRA beside)
  - 10 members
  - 11km horizontal resolution
  - 4 cycles per day with 6 hourly forecasts
- CERRA-Land
  - Daily precipitation analysis and soil model (SURFEX 8.1)
  - 5.5km resolution

Model systems: differences

UERRA system	CERRA system
HARMONIE cycle 38h1 (ALADIN physics)	HARMONIE cycle 40.1h/42 (ALADIN physics)
SURFEX 7.3	SURFEX 7.3 with updates from SURFEX 8.0
ERA40 and ERA-interim as LBC	ERA5 as LBC
4 cycles per day	8 cycles per day
No satellite data	Satellite radiances, e.g. IASI, MSU, AMSU
---	Usage of ERA5 ODB files, e.g. blacklisting information
---	More obs-data, e.g. GBGNSS

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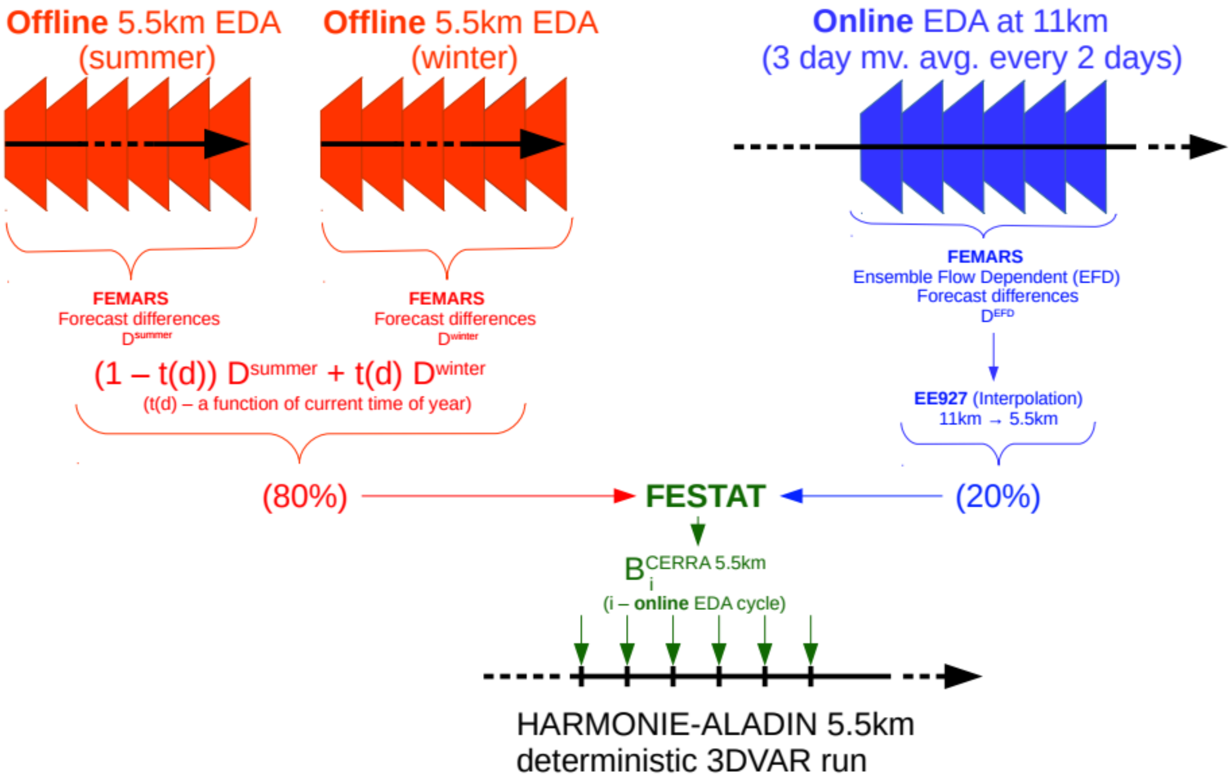
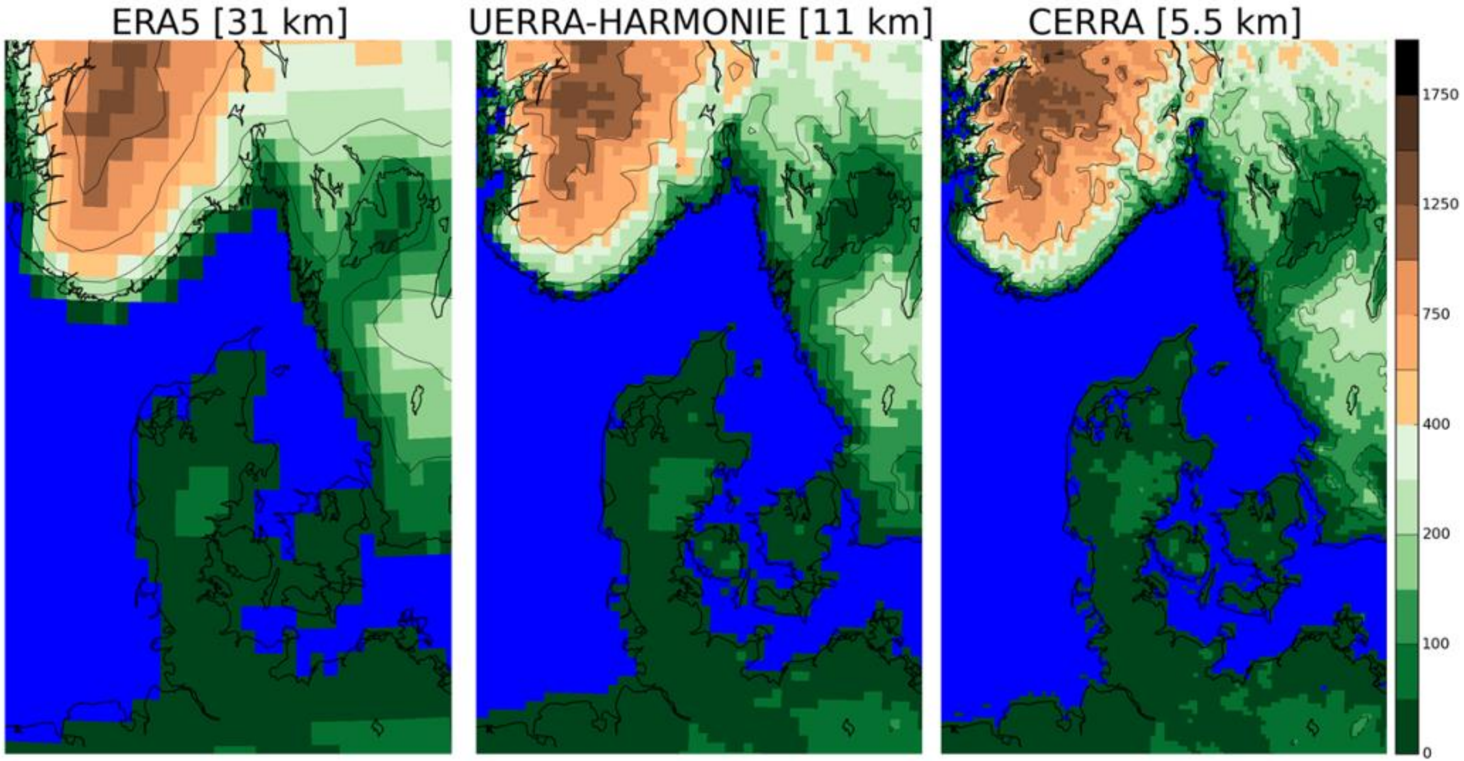
Impact of CERRA-EDA



Climate Change



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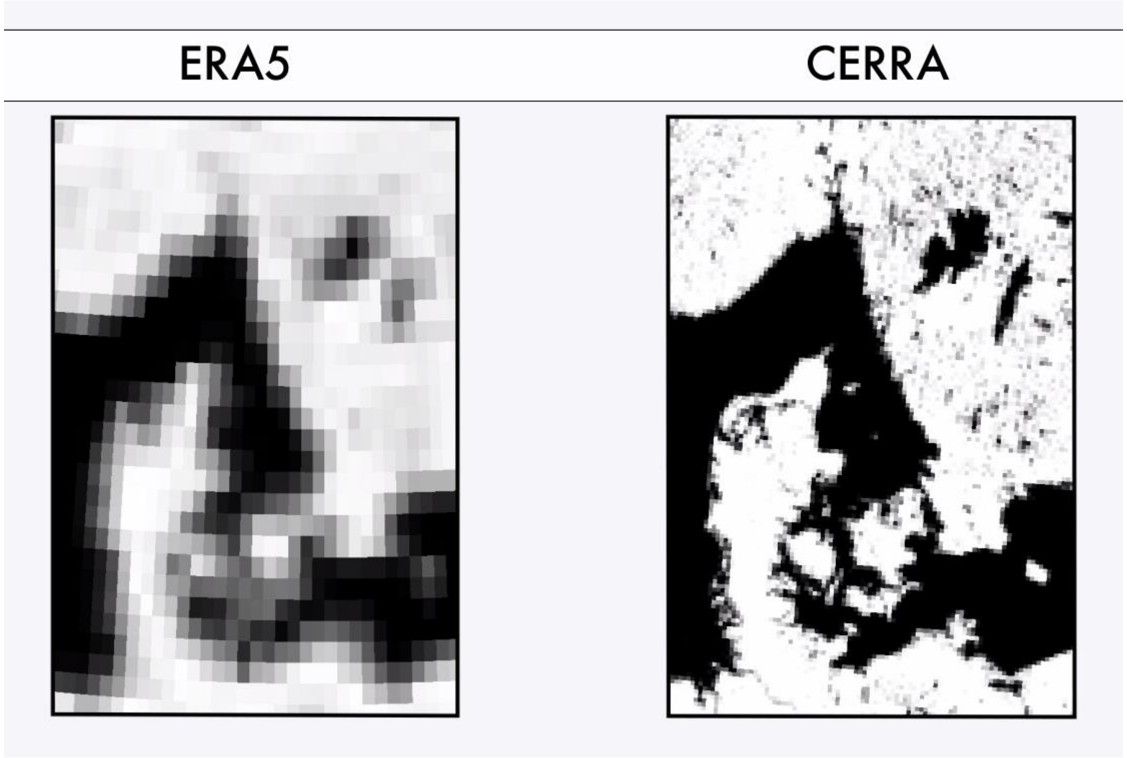
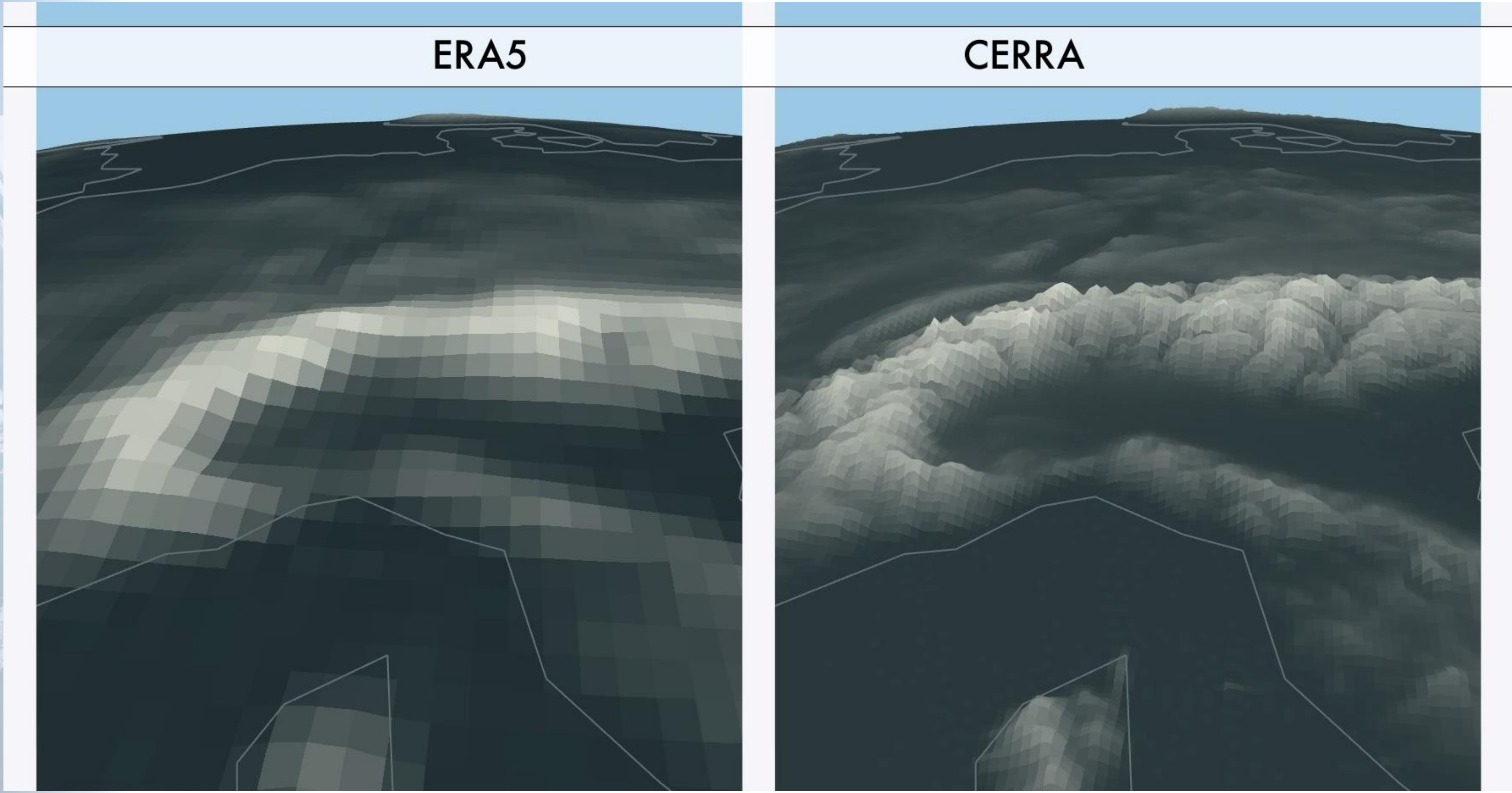
L a n d - S e a - m a s k

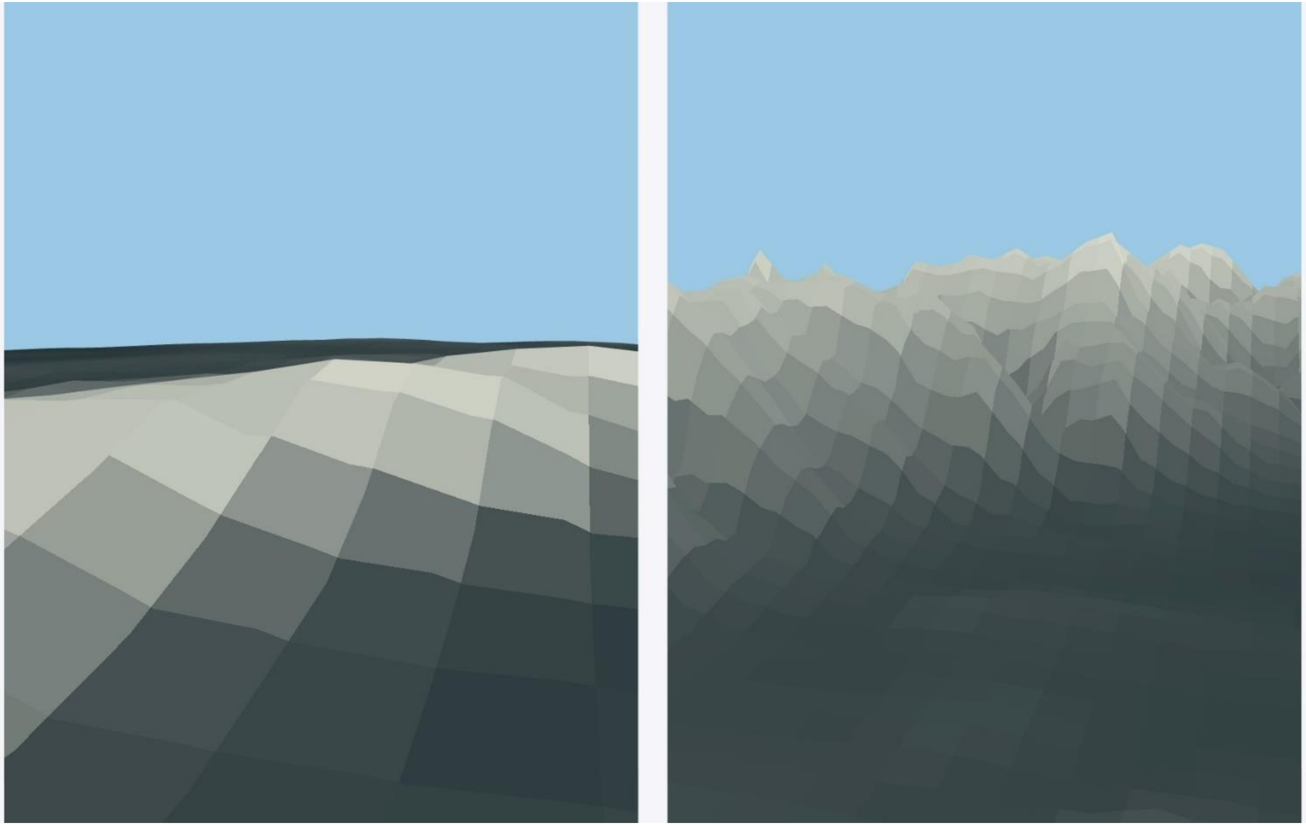


Climate Change

Topography



Topography II



Additional (type of) Observations used in CERRA compared with ERA5

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- GNSS-ZTD and 24-h total precipitation – not assimilated in ERA5

- Additional near-surface observations (T2m, RH2m, and snow water equivalent for the surface assimilation and geopotential for the upper air assimilation) from Finland, France, Greenland, Iceland, Norway and Sweden. (Compared to GTS these data are more complete, e.g. data rescue activities at institutes, and quality controlled.)

- In CERRA some data are processed differently than in ERA5, which is supposed to add some value:

  - shorter thinning distance with full radiance pixels in CERRA. No pre-thinning along field of view or scanning angles before screening. This gives relatively more radiance data in CERRA compared to the ERA5 system.

  - GNSS-RO reprocessed dataset (period 2001-NRT) produced from SAF at DMI. This dataset is supposed to have a higher quality compared to the original data which is used for ERA5. The higher signal to noise ratio also allows us to use data closer (down to 3 km) to the surface resulting in relatively more data being used.

  - We use special datasets for SST and sea-ice concentrations in the Baltic Sea. These datasets are reanalysis products for the Baltic Sea based on the models RCO (Rossby Climate Ocean model), a regional NEMO setup, and the Baltic Monitoring and Forecasting Centre model (HBM). (The RCO reanalysis is an SMHI product, see e.g. https://doi.org/10.1002/jgrc.20384; NEMO and HBM data were fetch from the Copernicus Marine Service: https://marine.copernicus.eu/)

More detailed description of surface (physiographic) dataset

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- What details of the surface are better in CERRA (and differently described) than in ERA5, and why is seen as added value?

- CERRA uses Harmonized World Soil Database at 1km resolution, ERA5 uses FAO for soil texture at 10km resolution.

- The representation of vegetation is based on a more detailed classification in CERRA (ECOCLIMAP 1km) as compared to ERA5 which uses the BATS classification (no urban area for instance).

- CERRA uses decadal maps and ERA5 uses monthly vegetation maps (e.g. LAI per type of vegetation).

- CERRA-Land uses a 1km map of Soil Organic Carbon areas (improves soil temperature profiles in permafrost regions). To our knowledge, such information is not used in ERA5 or ERA5-Land.

  - Decharme et al., 2016: Impacts of snow and organic soils parameterization on northern Eurasian soil temperature profiles simulated by the ISBA land surface model, The Cryosphere, 10, 853–877, 2016, doi:10.5194/tc-10-853-2016