Climate Change

Cutting-edge climate applications built upon atmospheric reanalysis: a user’s perspective

Chiara Cagnazzo
European Centre for Medium-Range Weather Forecasts (ECMWF)

Key Messages

- Significant advances and evolution of reanalysis have made them one key dataset in many climate sector applications

- Continuous analysis of user requirements to inform the evolution of reanalysis

In this presentation:

Applications based on ERA5 & implications for next generation Copernicus Climate Change Service(C3S) reanalyses

Address key questions about the use and the evolution of reanalysis systems, from Climate Service Application perspective

This presentation

- Who the users are
- How reanalysis are used
- Why they are fit for purpose
- Current requirements

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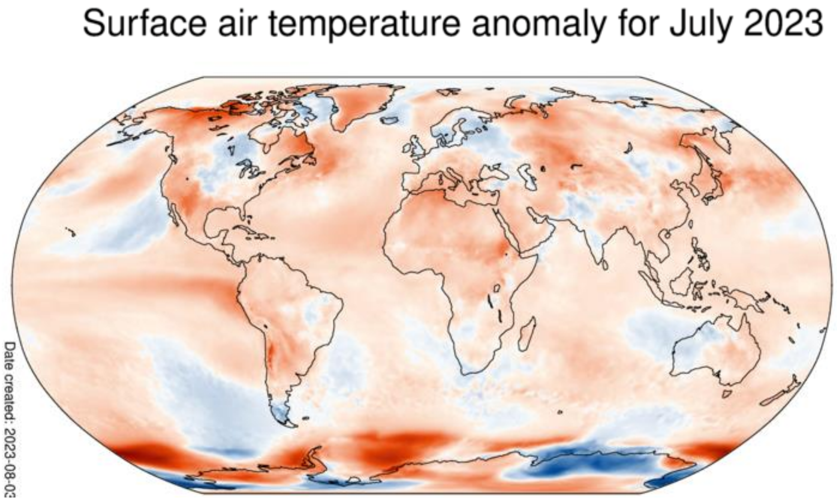
C3S Global reanalysis: ERA5

ERA5: A full-observing-system global reanalysis for the atmosphere, land and ocean waves



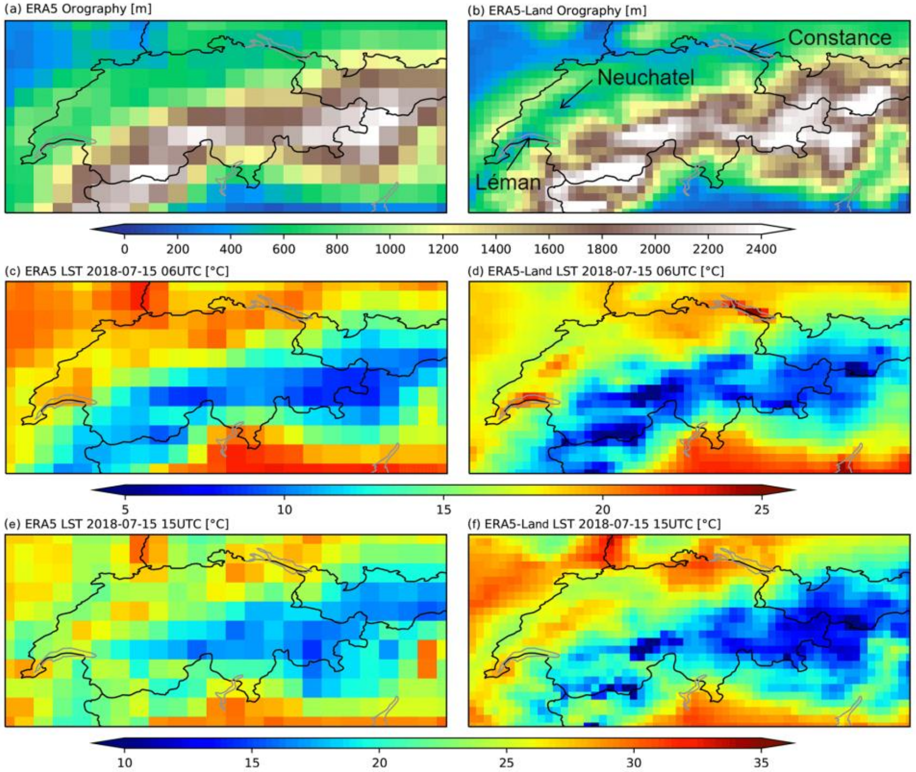
ERA5 Surface air temperature anomaly for July 2023 relative to the July average for the period 1991-2020.

- Most popular dataset in the CDS (over 100,000 Users)
- About **100 TB** daily downloads
- No gaps in space/time, integrator of all observations
- Over 100 billion observations used so far
- Hourly snapshot 31 km resolution up to about 80 km height
- Available from **1940 onwards**
- Daily updates 5 days behind real time
- It relies on external gridded products: SST and sea-ice cover; GHGs, aerosols, TSI, (diagnostic) ozone

https://doi.org/10.1002/qj.3803

Global reanalysis: ERA5 Land

ERA5 Land: Dynamically downscaled land product at 9 km, 1950 onwards



- A dedicated dataset to support land applications, including latest land-model developments
- Added value of higher resolution and lapse rate correction
- Hourly snapshot 9 km resolution

https://doi.org/10.5194/essd-13-4349-2021

Reanalysis users' statistics

List of top 10 datasets

Product
reanalysis-era5-single-levels
reanalysis-era5-pressure-levels
reanalysis-era5-land
reanalysis-era5-complete
reanalysis-era5-single-levels-monthly-means
reanalysis-era5-land-monthly-means
reanalysis-era5-pressure-levels-monthly-means

From I. Rozum

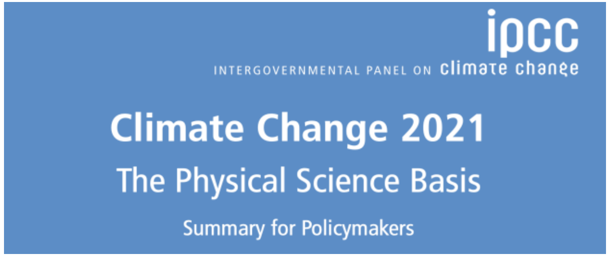
Datasets Top 8 (Running or queued)

1. ERA5-Land hourly data from 1950 to present
2. ERA5 hourly data on single levels from 1940 to present
3. ERA5 hourly data on pressure levels from 1940 to present
4. Complete ERA5 global atmospheric reanalysis
5. CERRA sub-daily regional reanalysis data for Europe on single leve...
6. Seasonal forecast monthly statistics on single levels
7. ERA5.1 complete global atmospheric reanalysis from 1979 to pres...
8. Seasonal forecast daily and subdaily data on single levels

ERA5

Most popular dataset in the CDS (**100k+** Users)

Hersbach et al., 2020 (QJRMS) → ˜8,500 citations https://doi.org/10.1002/qj.3803



C3S is presented as an **exemplar of climate service in IPCC AR6 WG1** report where **ERA5 is mentioned over 240 times**.

From C. Buontempo

A Community of Users

- Researchers
- Professional consultants
- Big data experts
- Journalists, policy makers
- General public


Energy
Agriculture and Food Security
Health
Insurance
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The evolution of climate reanalysis at ECMWF

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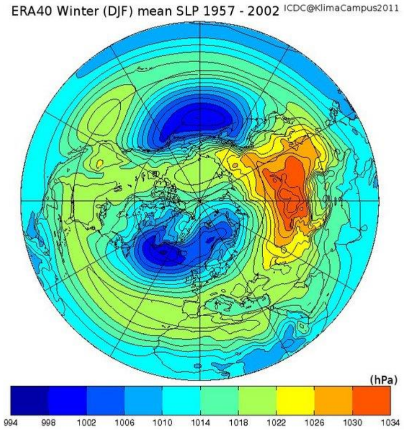
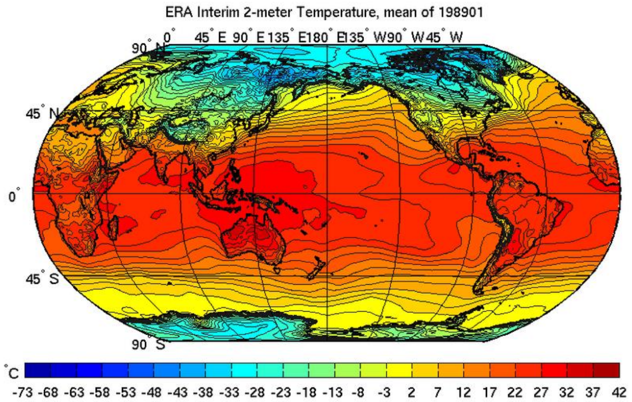
ERA40

- DA: 3DVAR
- Time span: 1957-2002
- Resolution: T159 (N80)
- Levels in the vertical: 60 top @0.1 mb
- Cycle: IFS CY23r4
- NRT: no



ERA Interim

- DA: 4DVAR
- Time span: 1979-2019
- Resolution: T255 (N128)
- Levels in the vertical: 60 top @0.1 mb
- Cycle: CY31r2
- NRT: no



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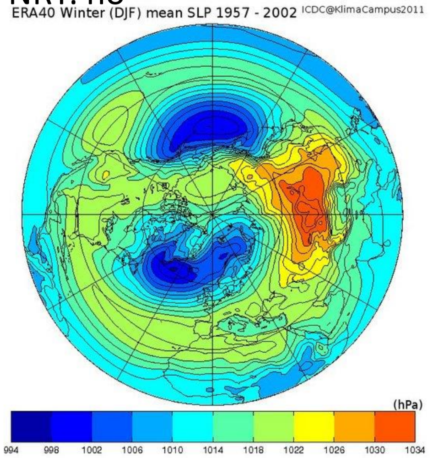

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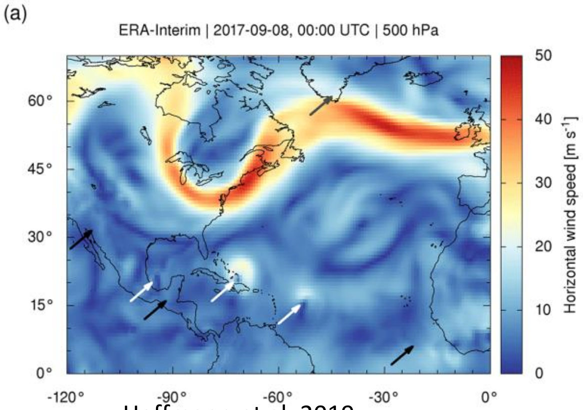
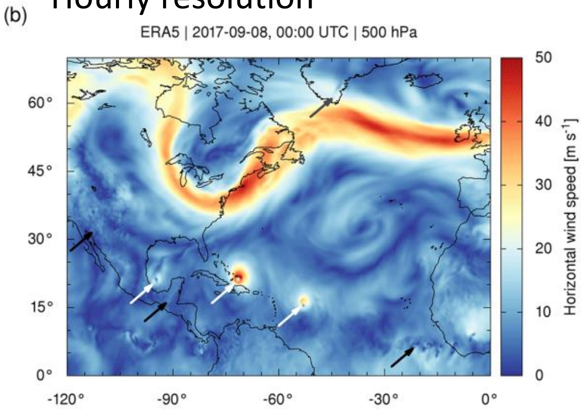


Hoffmann et al, 2019

ERA5

- DA: 4DVAR
- Time span: 1940-present
- Resolution: 31 km globally, 62km for the Ensemble of Data Assimilations (EDA)
- Levels in the vertical: 137 top @0.01 m
- Cycle: CY41r2
- NRT: yes (5 days delay)
- Hourly resolution



The evolution of climate reanalysis at ECMWF

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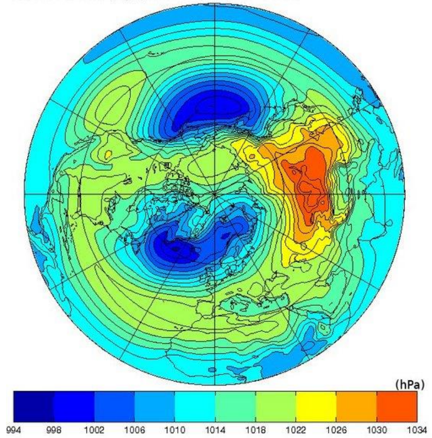

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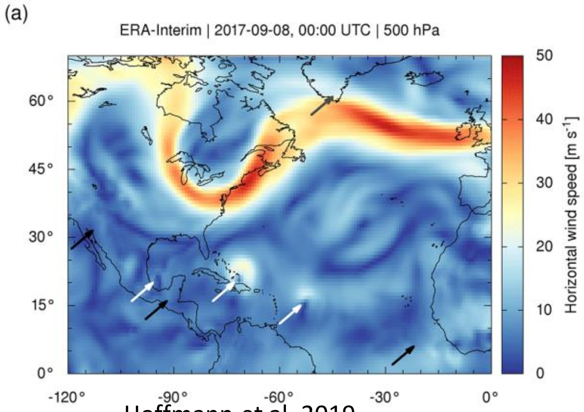

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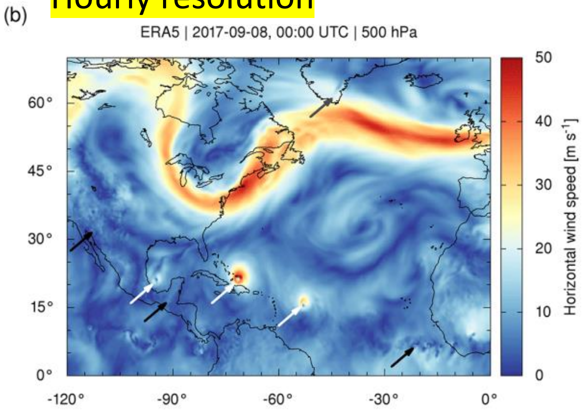

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What is ERA5 reanalysis used for ?

- To obtain an accurate three-dimensional synoptic-scale situation
- To obtain statistics for the climate-related extremes
- To compare the current situation with a consistent 30-year climate of the past
- To estimate the variability of the mean state and long term changes
- To provide initialization, boundary conditions and drive impact models
- To train ML weather prediction models

A few examples…

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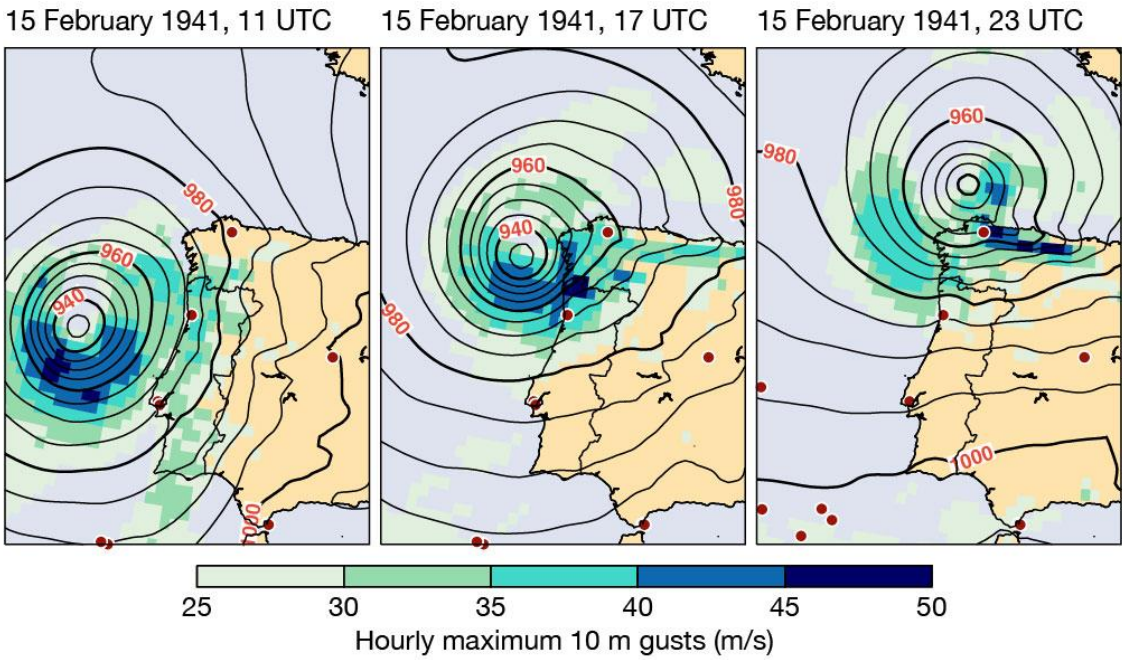
An accurate three-dimensional synoptic-scale situation



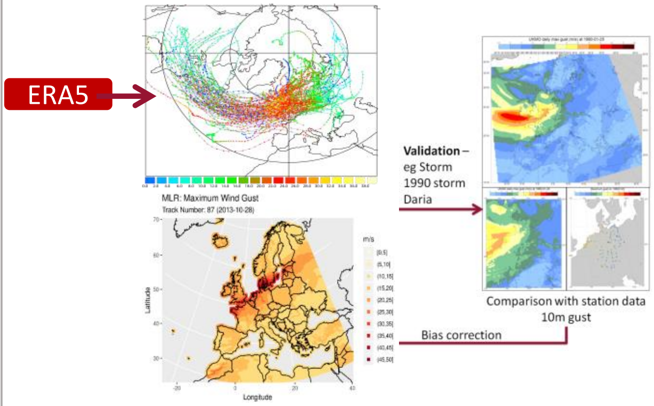
From 1940 ERA5 provides a good estimate of the actual synoptic situation for large regions

→ Representation of a severe storm over the Iberian Peninsula 82 years ago, which led to significant damage and disruption over Portugal and northwest Spain

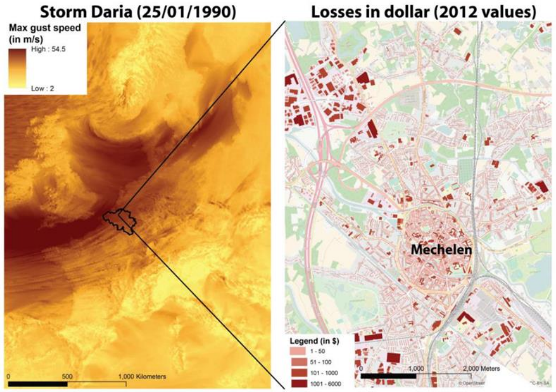
Windstorm service & Insurance sector

Climate Change

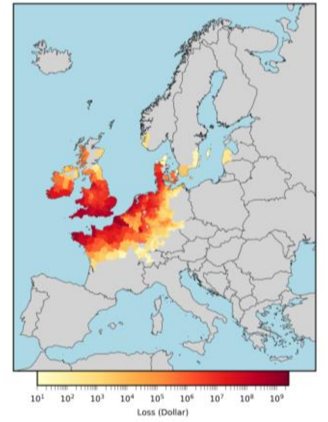
Storm track, footprints

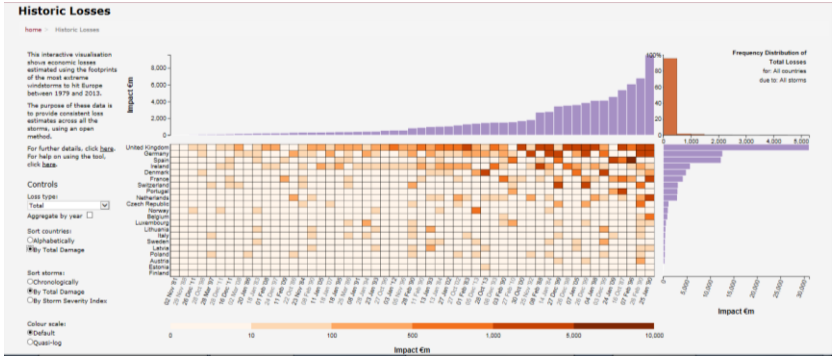


Wind storm loss model

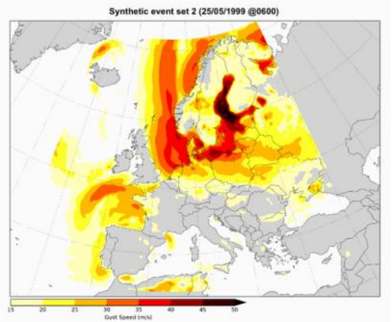


Estimated losses





- Catalogue of wind storms and losses
- Risk and vulnerability information to support insurers
- Indicators provide wind storm and loss indices on yearly basis to provide overview of evolving climate
- Catalogue of synthetic events: physically realistic set of plausible windstorm events based on the modelled climatic conditions



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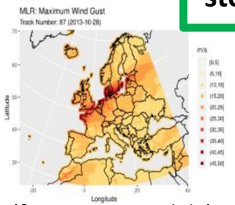
Windstorm service & Insurance sector

ERA based storm footprints



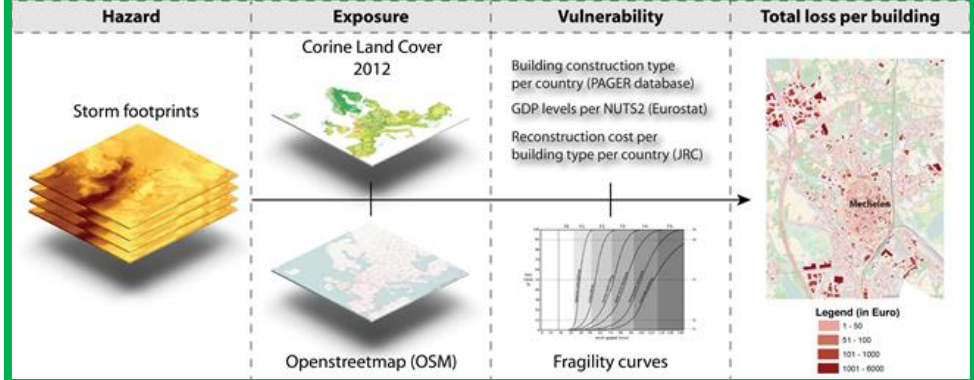
(from previous slide)

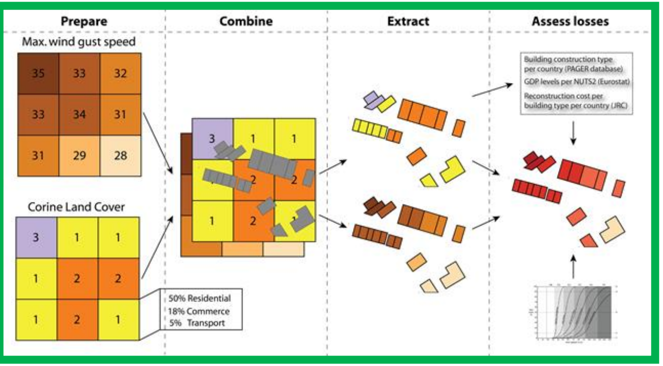
Exposure / Vulnerability

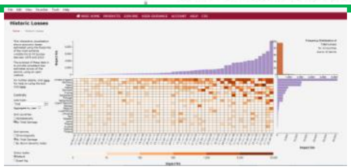
- CORINE – 45 land classes
- PAGER – 106 construction types – aggregated to 6 types
- Fragility curves applied for these 6 types
- Fragility to vulnerability curves via reconstruction costs
- GDP per NUTS3 region applied

Process for Loss Assessment

- Datasets clipped to NUTS3 regions before loss calculations applied
- Loss per hazard (max gust speed) from fragility curves
- Loss ratio multiplied by reconstruction cost per building type
- Losses adjusted by GDP per region
- Validate losses vs actuals







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Revised risk and loss estimates

An accurate three-dimensional synoptic-scale situation

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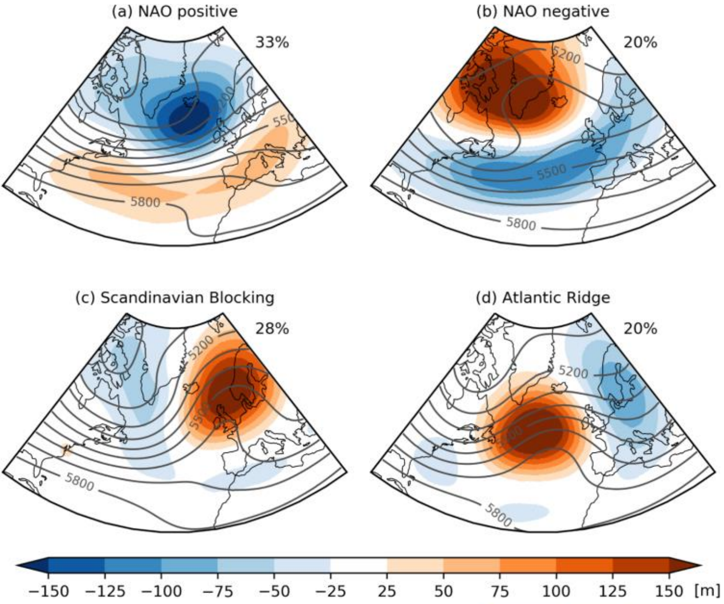
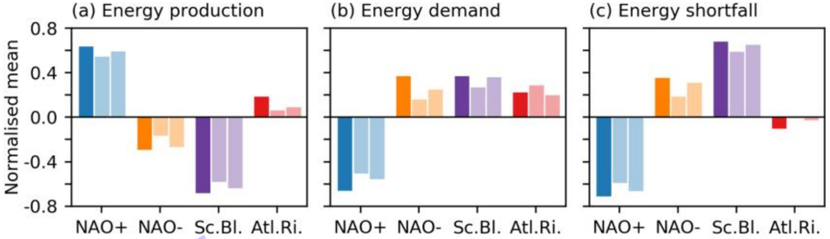
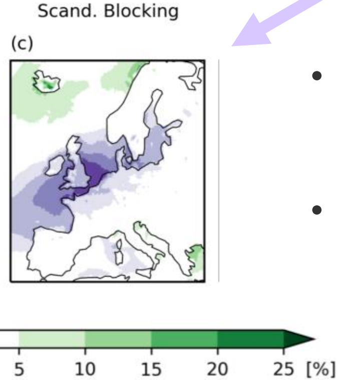
Van der Wield et al., 2019







Four regimes of atmospheric circulation in the North Atlantic-European domain. Colours show the 500 hPa height anomaly (m), contour lines show the 500 hPa height (m, interval 100 m). The percentage values denote the percentage of total days categorised in each regime. Figure based on ERA5 data (DJF, 1979–2018).

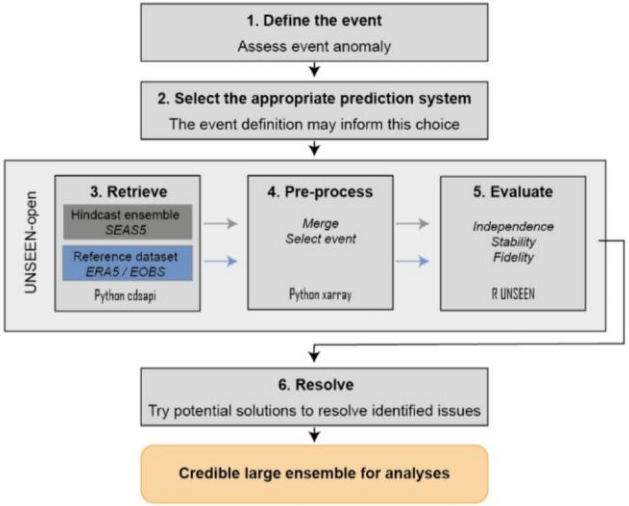
- Winter-time large-scale weather regimes capture the day-to-day variability of energy variables in Europe
- Days with blocked circulation regimes have lower than normal renewable power production, higher than normal energy demand and higher than normal energy shortfall

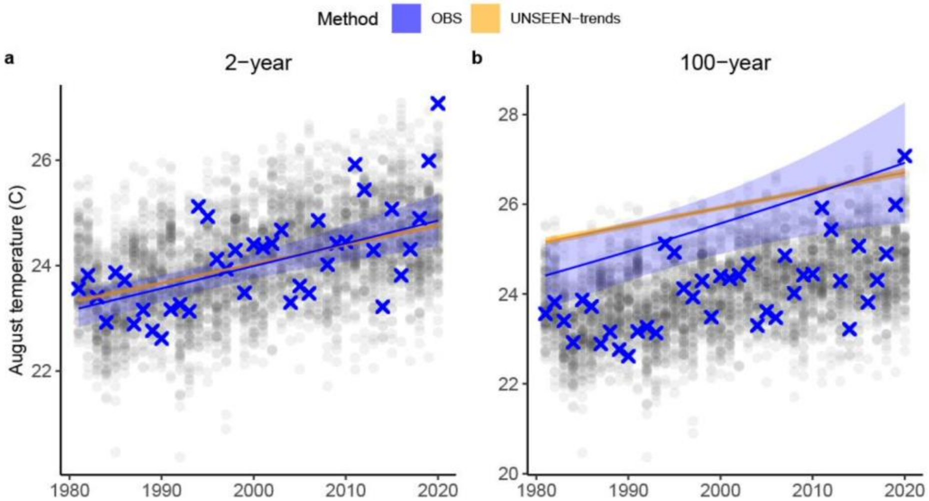
→ Too short for EE study, use of large ensembles simulations

UNSEEN: An open workflow to study unseen weather extremes

UNSEEN-open is an open source project using the global SEAS5 and ERA5 datasets.
It makes evaluation of model simulations and extreme value analysis easy in order to anticipate climate extremes beyond the observed record

Approach: By treating model ensemble members as different, but equally palusible versions of the past→ the sample size of historical weather events can be increased to study rare extreme events





Kelder et al., 2020; 2021

ERA5 ec-point: a new and innovative statistical post-processing technique

Climate Change

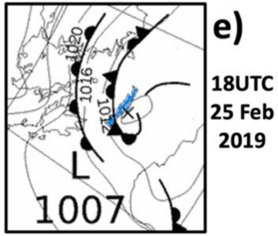
ERA5 ecPoint products are the first ever (probabilistic) global reanalysis products for point scales

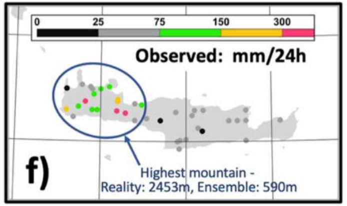
For each gridbox, it includes percentiles (1, 2,..99) of:

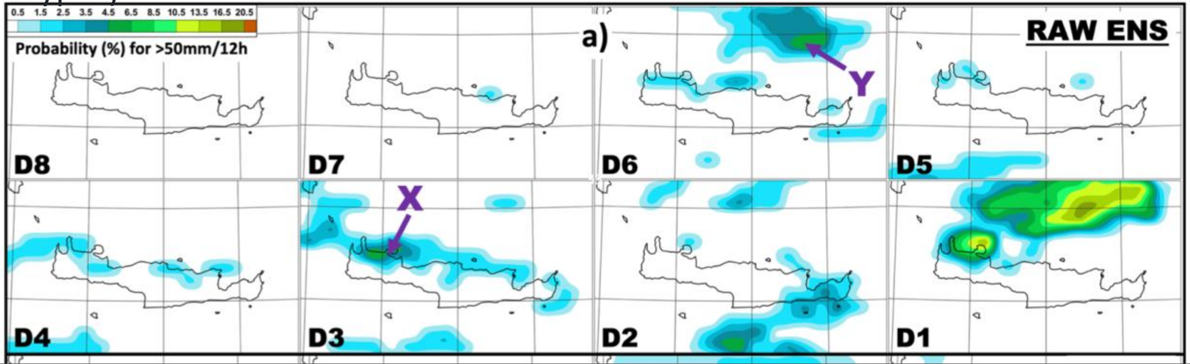
- 24-h rainfall & minimum, maximum and mean 2m temperature
- 12-h rainfall & mean 2m temperature

Values stored are fully compatible with in-situ measurements (i.e. from raingauges and thermometers), whilst the raw ERA5 output refers to average values for the modelled grid scale - i.e. over regions measuring about 31km by 31km

All ecPoint products explicitly incorporate the expected sub-grib variability, and bias correction for gridbox means (which both vary according to grid-box weather types)







Hewson and Pillosu, 2021

ERA5 ec-point: a new and innovative statistical post-processing technique

Highlander Data Delivery System

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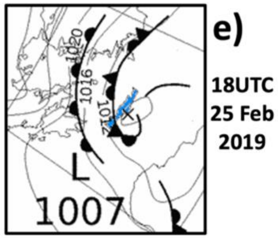

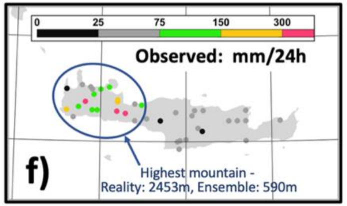

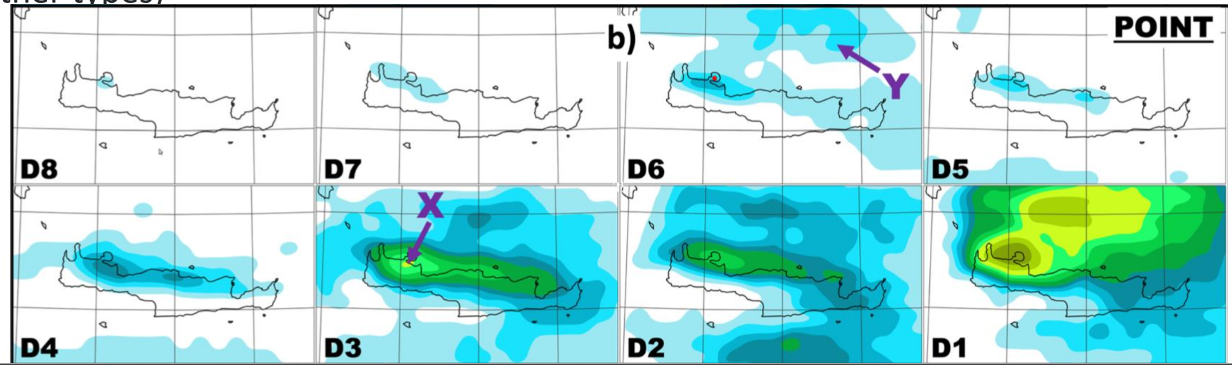

Hewson and Pillosu, 2021

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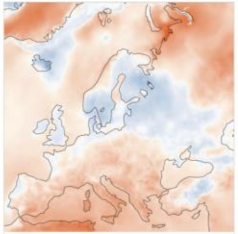
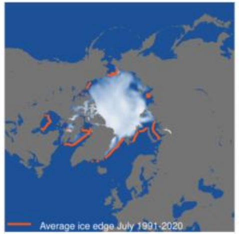
Monitoring the current climate w.r.t. 30-year climate of the past

Monthly summaries



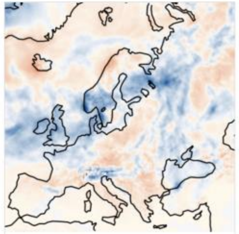
Surface air temperature

This series of monthly maps and charts, generated from ERA5 data, covers global and European surface air temperatures.



Sea Ice

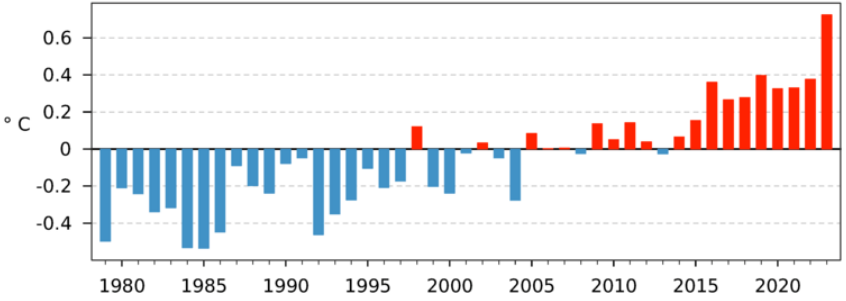
We produce sea ice maps every month. Based on ERA5 reanalysis data, these provide near real-time monitoring of the polar ice caps.



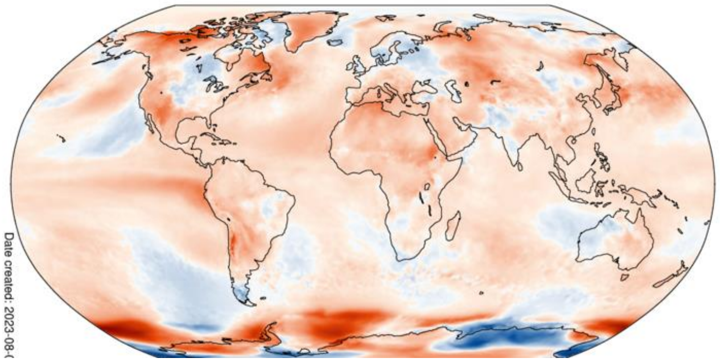
Hydrological variables

This series of monthly maps and charts, based on ERA5 data, covers several variables: precipitation, humidity, and soil moisture for Europe and the extra-tropical regions.

July global surface air temperature anomalies



Surface air temperature anomaly for July 2023

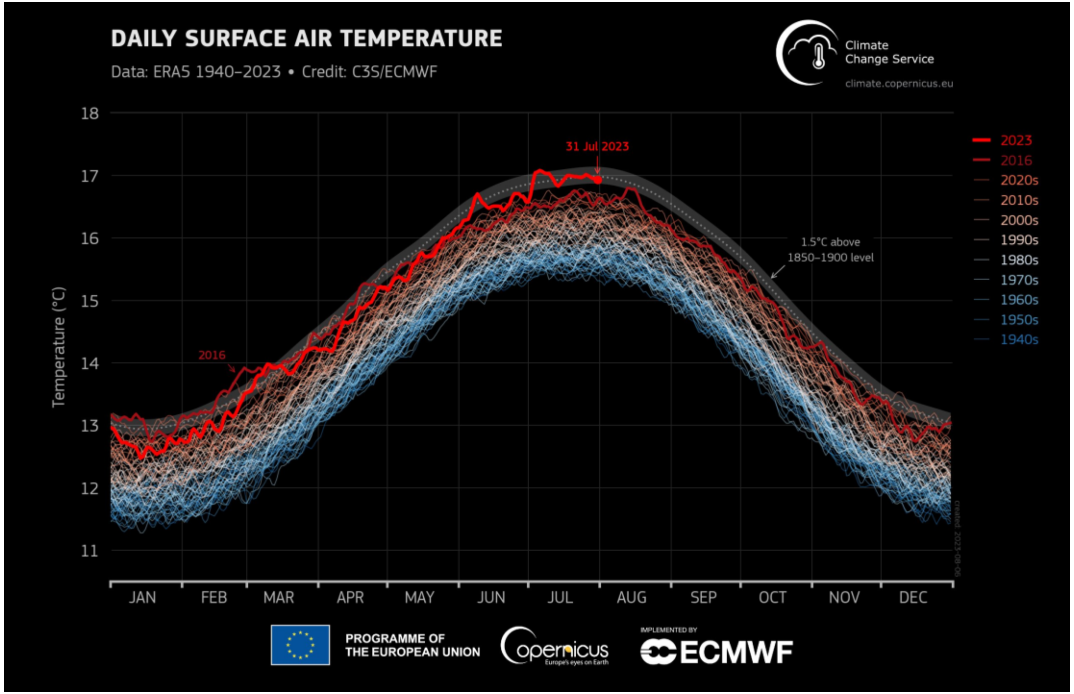


Global-mean surface air temperature anomalies relative to 1991-2020 for each July from 1979 to 2023

https://climate.copernicus.eu/surface-air-temperature-july-2023

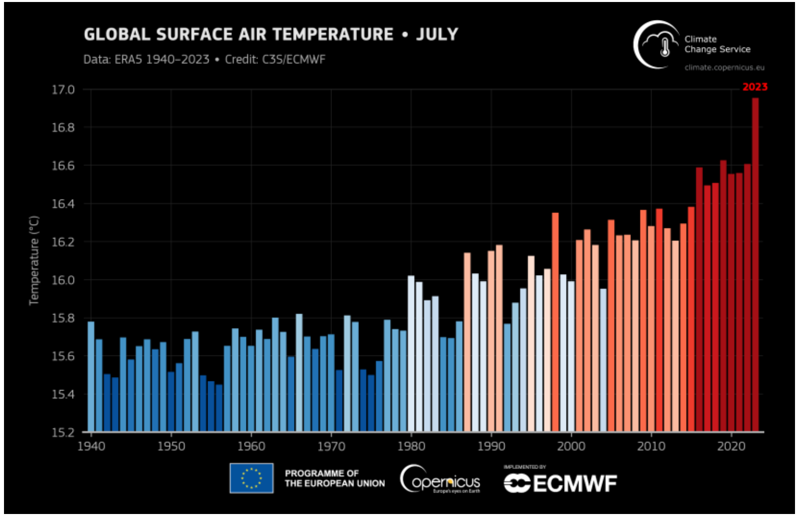
Monitoring the current climate w.r.t. 30-year climate of the past

Climate Change



ERA5 global daily surface air temperature (°C) from 1 January 1940 to 31 July 2023. The dotted line and grey envelope represent the 1.5°C threshold above preindustrial level (1850–1900) and its uncertainty.

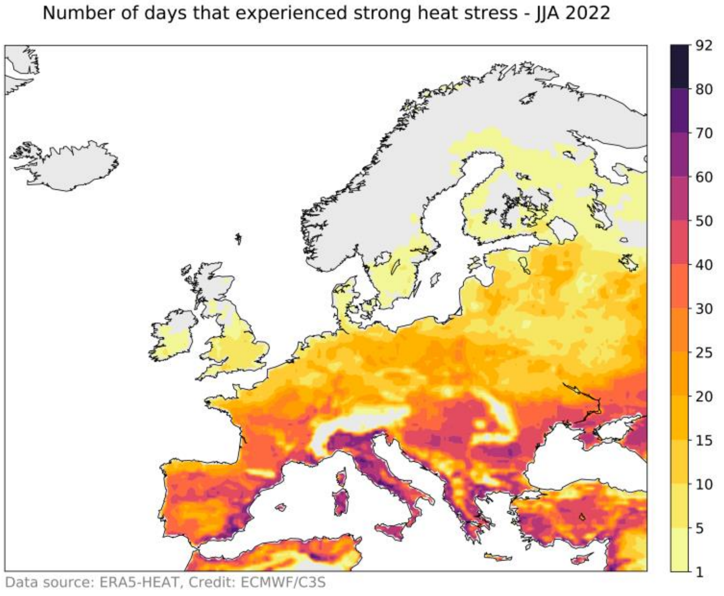
<u>July:</u>
warmest month on ERA5 global record
around 1.5°C warmer than the 1850-1900 average



https://climate.copernicus.eu/july-2023-warmest-month-earths-recent-history

EUROPEAN STATE OF THE CLIMATE

2022



Copernicus Climate Change Service European State of the Climate | 2022 PROGRAMME OF THE EUROPEAN UNION Copernicus ECMWF

Hydrological reanalyses: see C. Proudhomme presentation

ESOTC 2022 highlights: Extreme Heat and Drought

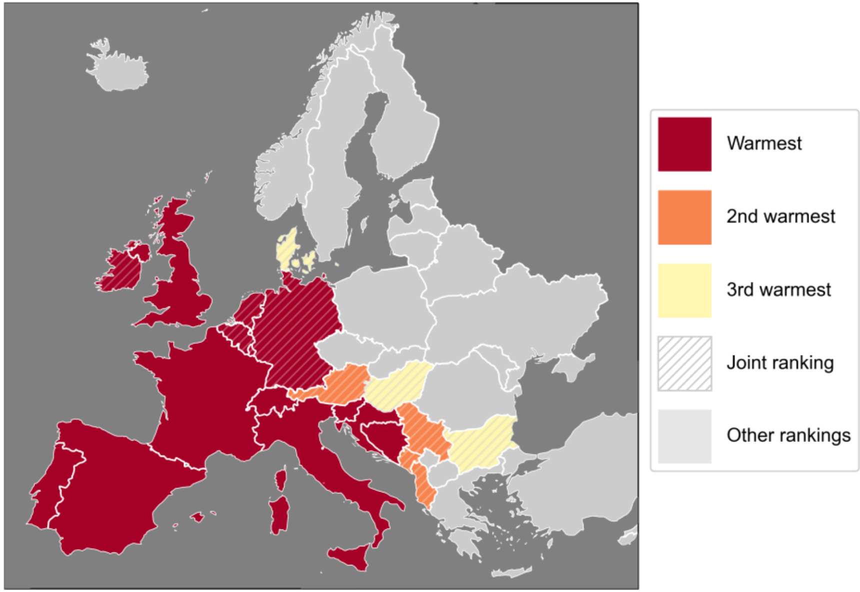
https://climate.copernicus.eu/esotc/2022

Role of atmospheric reanalysis in Climate Monitoring

- Last eight years all more than 1°C warmer than the pre-industrial level
- 2022
    - 1.2°C warmer than pre-industrial level
    - fifth warmest
    - 4th-8th warmest years are very close together
- The average temperature over Europe in 2022 was the highest on record for both August and summer (June – August) by substantial margins.
- August this year exceed the values recorded in August 2018 by of 0.8°C. The whole summer was 0.4°C warmer than the then record-breaking summer of 2021.

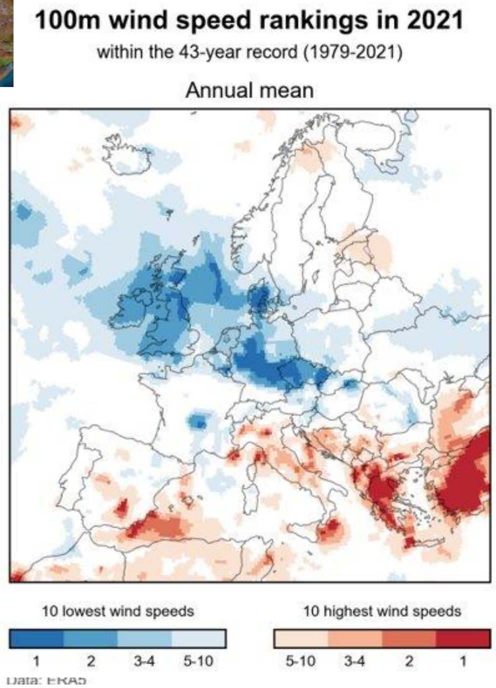
Ranking of 2022 annual mean temperature by country

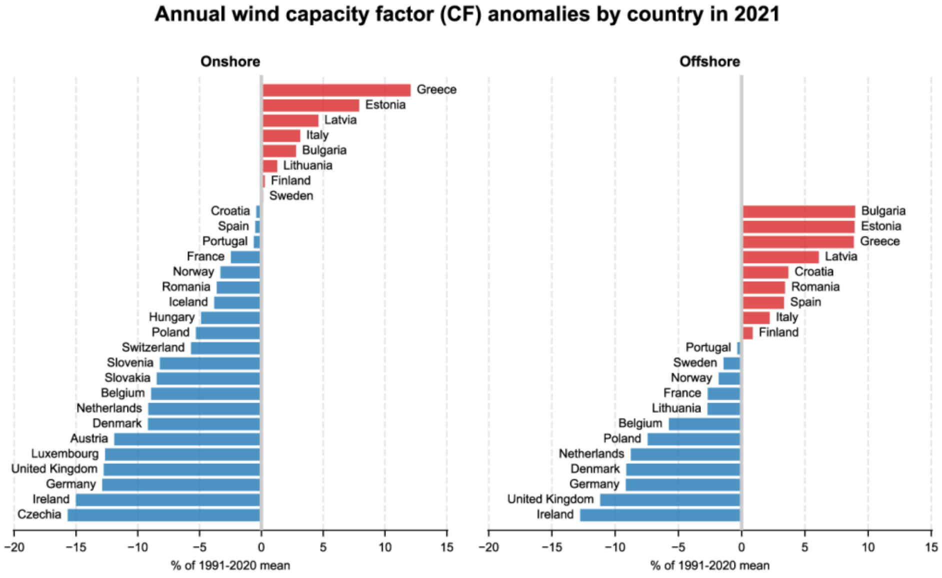
Rankings based on ERA5 data for 1950-2022 • Credit: C3S/ECMWF



Climate mean and variability for the energy sector

Climate Change



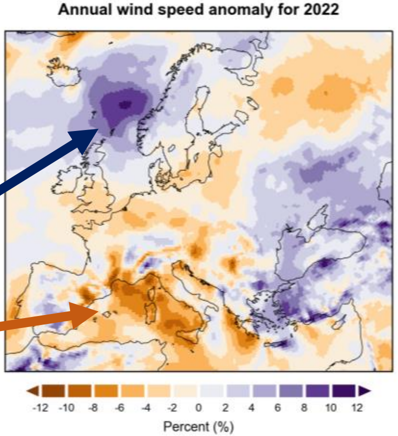


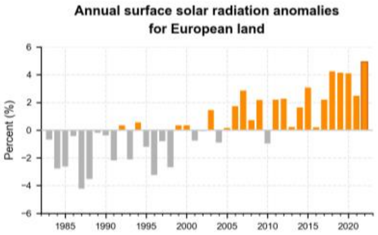
Wind speed and wind capacity factor derived from ERA5 reanalysis dataset

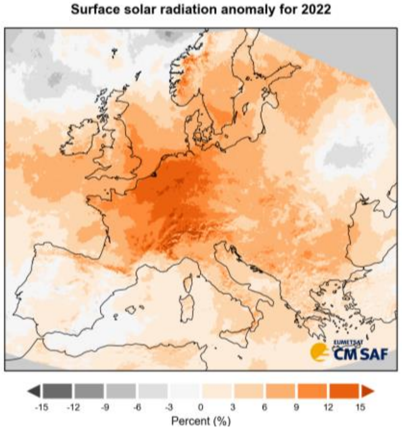
Climate mean and variability for the energy sector

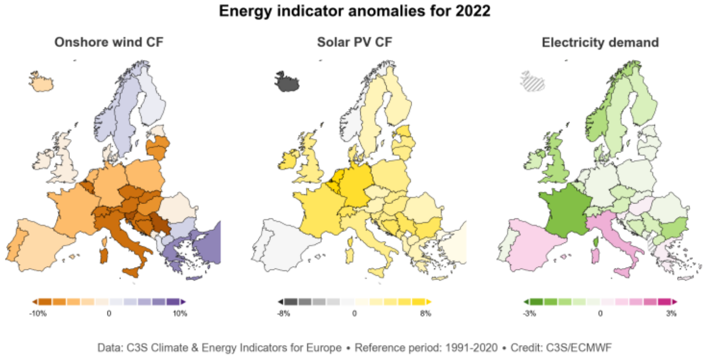
Winds stronger than average

Winds weaker than average









Copernicus Climate Change Service
European State of the Climate | 2022

YEAR 2022

- Potential power generation from onshore wind was below average across most of Europe.
- Potential solar photovoltaic power generation was above average across most of Europe.
- Electricity demand was above average in most of southern Europe, because of high summer temperatures and highe demand for air conditioning

C3S Operational Energy Service

Climate Change

Past to the present day → **Near Future** → **Mid Century to End Century**

https://climate.copernicus.eu/operational-service-energy-sector

A multi-variable, multi-timescale view of the climate and energy systems

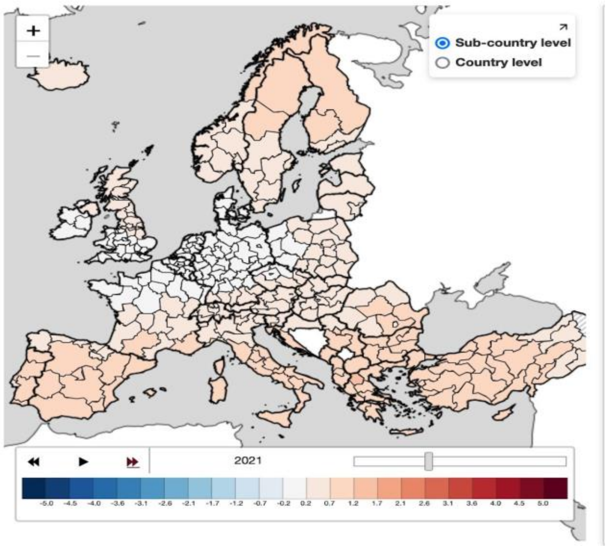
C3S Operational Energy Service

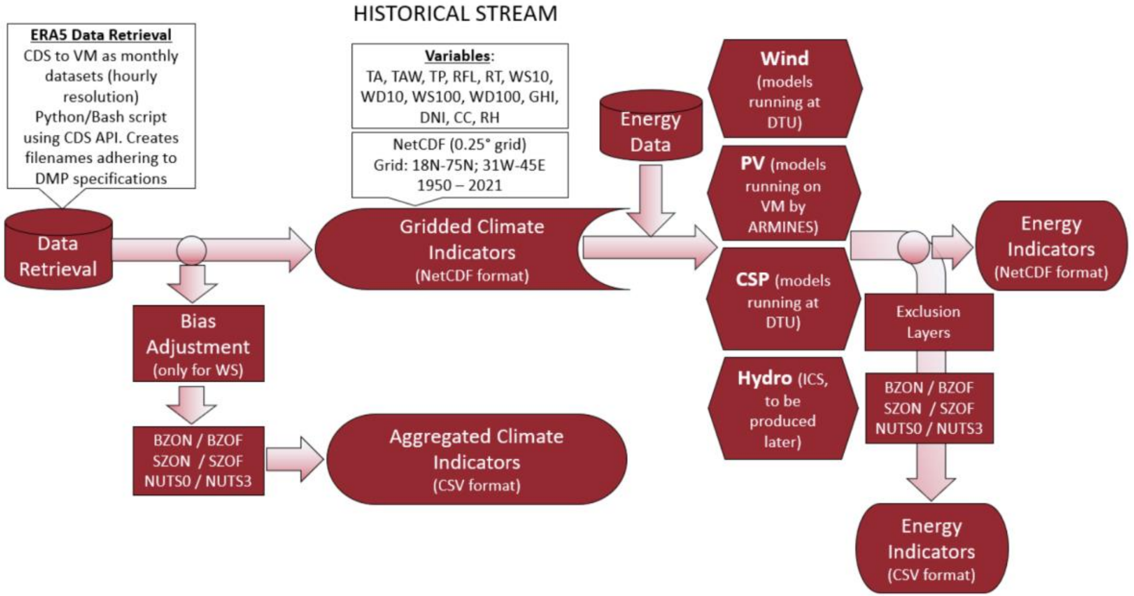
Climate Change

Information on:

- Key meteorological variables (wind speed, 2mT, total precipitation, srf solar radiation, sea level pressure)
- Energy related variables: electricity demand and energy production from solar, wind, hydropower

Timescale: Past period, Near Real Time, Possible future evolution scenarios & Seas Forecasts





C3S Operational Energy Service: a climate-energy reanalysis

The climate variables are based on the ERA5 reanalysis

A comprehensive set of measured energy *supply* and *demand* data from the European Network of Transmission System Operators (ENTSO-E) are collected

Climate variables are transformed into energy variable by using a combination of statistical models and physically based models

The *calibration* of the energy models was done over the *historical period*, for the longest period possible when energy data was available.

Energy indicators were extended to cover the entire period

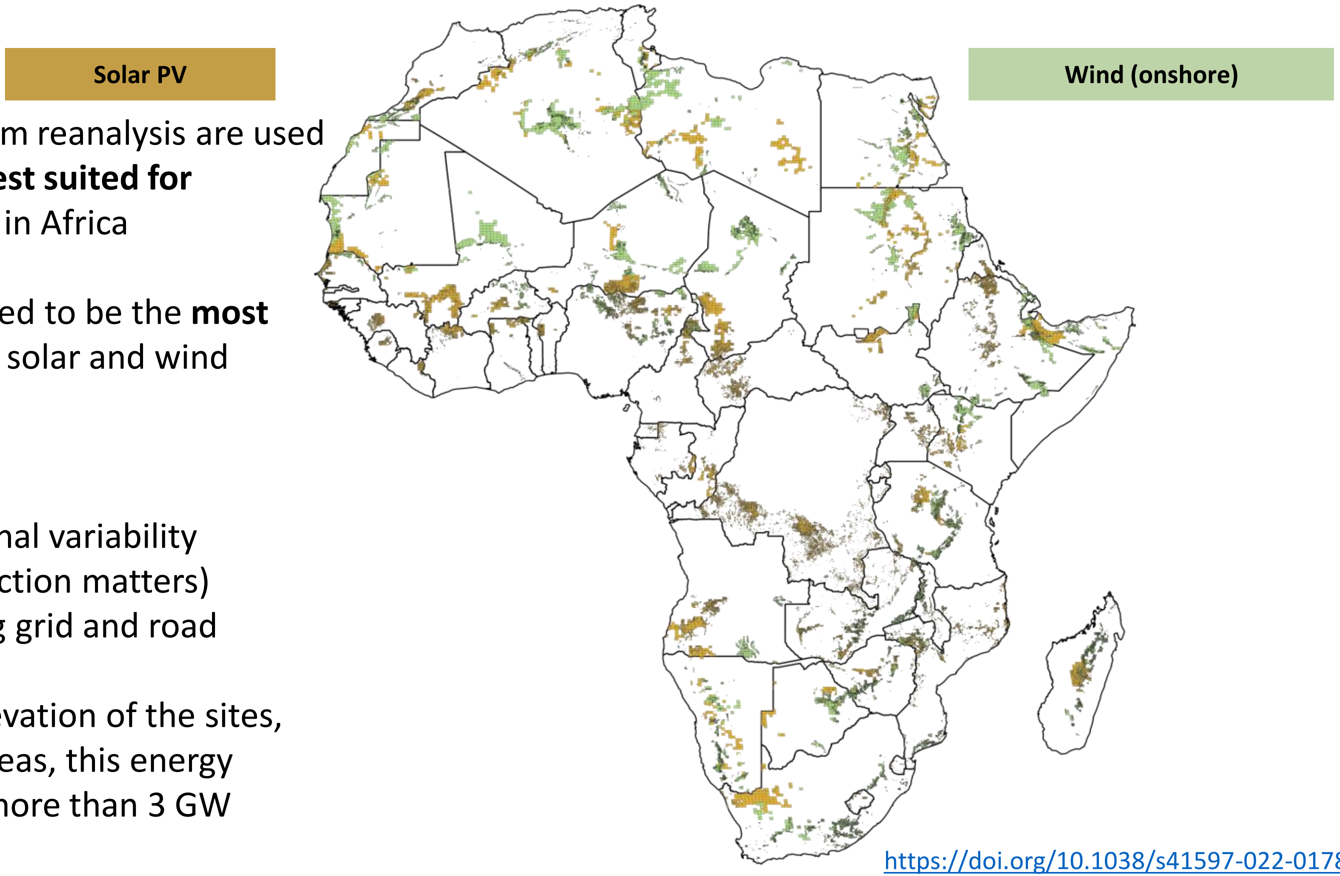
African Renewable Electricity Profiles open-access databases: solar and wind

Wind speed & solar radiation from reanalysis are used for **planning sites that are the best suited for investment** in new power plants in Africa

Map of locations of sites estimated to be the **most attractive for investment** in new solar and wind power plant

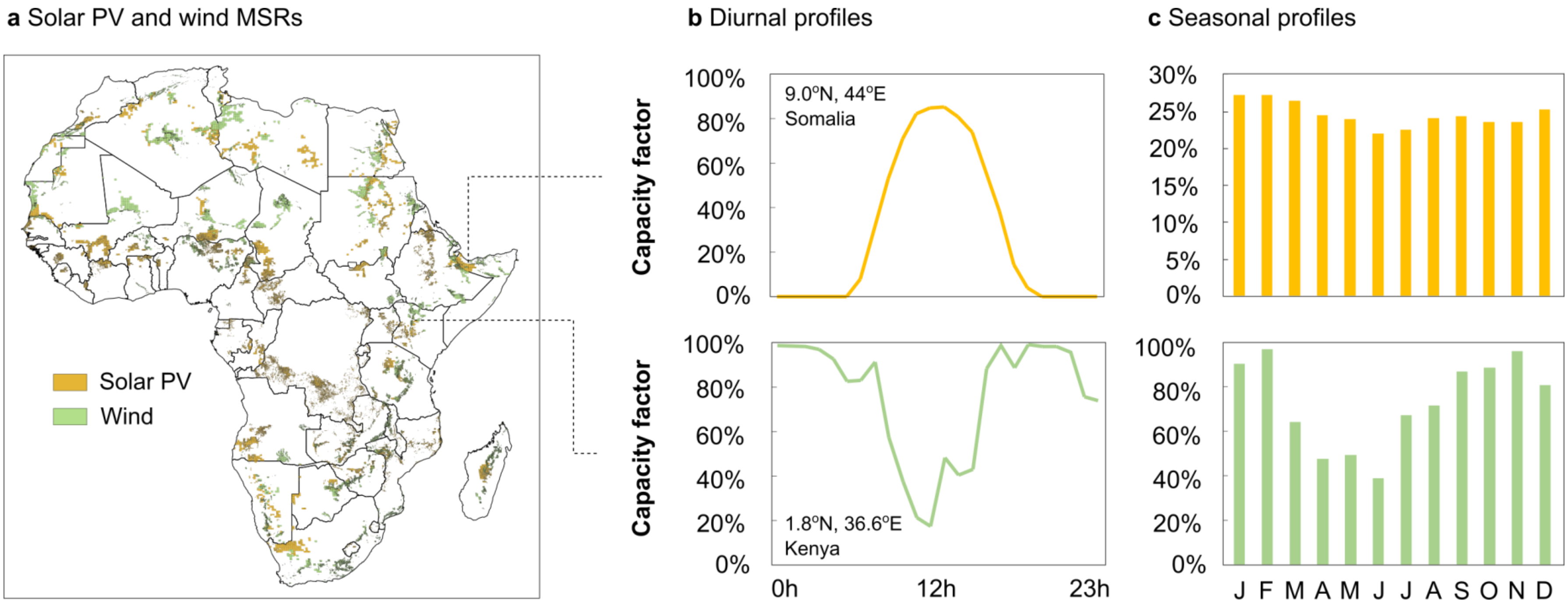
<u>It uses</u>:

- Wind and solar daily to seasonal variability (temporal variability of production matters)
- The distance from the existing grid and road infrastructures
- Other: population density, elevation of the sites, slopes, land use, protected areas, this energy supply area cannot produce more than 3 GW



https://doi.org/10.1038/s41597-022-01786-5

Analysing Africa’s solar and wind Model Supply Regions (MSRs) – up to 5% of country area



(12th of March of met year 2018)

(Met year 2018)

S. Sterl, B. Hussain, A. Miketa, Y. Li, B. Merven, M. Bassam Ben Ticha, M.A. Eltahir Elabbas, W. Thiery, and D. Russo. *An all-Africa dataset of energy model “supply regions” for solar PV and wind power*. Submitted to Scientific Data (2022).

Climate monitoring: a policy-driven example
NECD 5.2 : Directive on emission reduction commitments

Climate Change

*If in a given year a Member State, due to an **exceptionally cold winter** or an **exceptionally dry summer**, cannot comply with its emission reduction commitments, it may comply with those commitments by averaging its national annual emissions for the year in question, the year preceding that year and the year following it, provided that this average does not exceed the national annual emission level determined by the Member State's reduction commitment.'*

Reliable, quality, maintained near real time data

Robust, agreed and transparent methodology

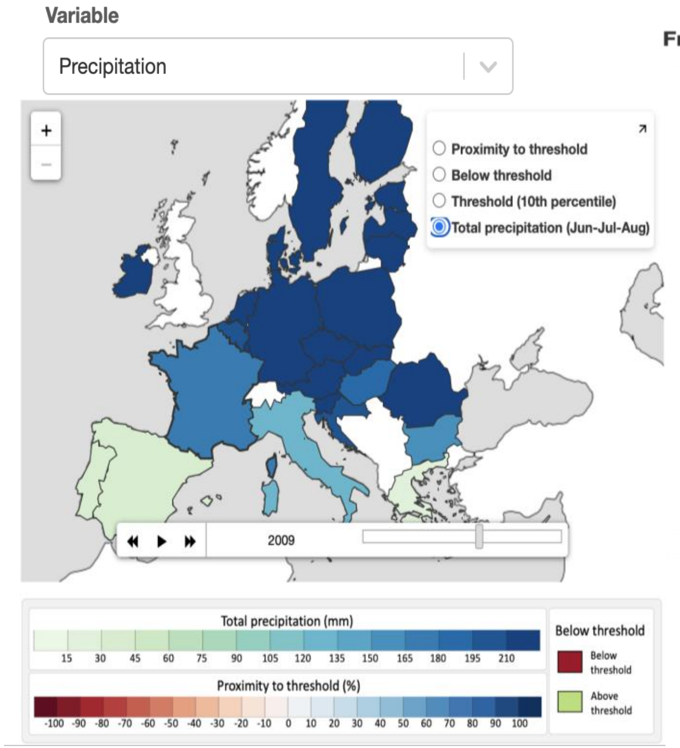
Fully documented & available tool

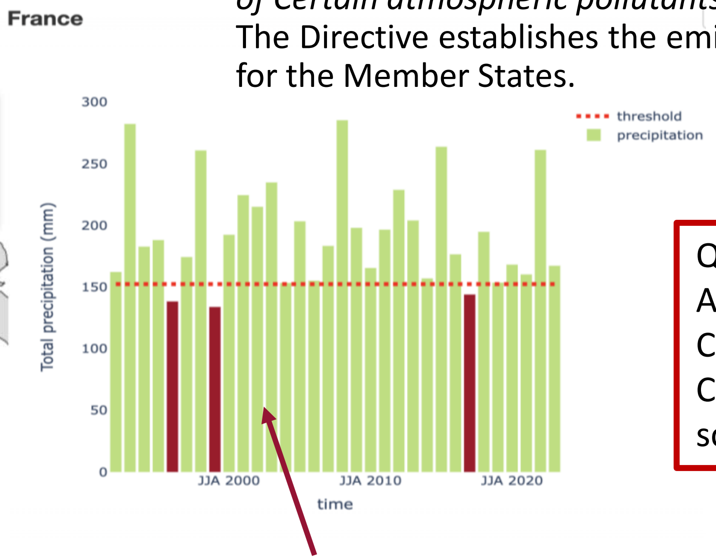
Data needs:

- Temperature at the Surface
- Total precipitation

Consistent across EU Member States
Homogeneous over time
Aggregated over countries
Very simple definitions

Climate monitoring: a policy-driven example





EU Directive 2016/2284 on the reduction of National Emissions of Certain atmospheric pollutants.
The Directive establishes the emission reduction commitments for the Member States.

Quality controlled
Authoritative
Continuity with policy cycles
Consistent across spatial scales

Red bars: Dry summer for the selected Member State

*ERA5 data are used to identify **exceptionally cold winter** and **exceptionally dry summers**, when flexibility article 5.2 of the Directive may be applied.*

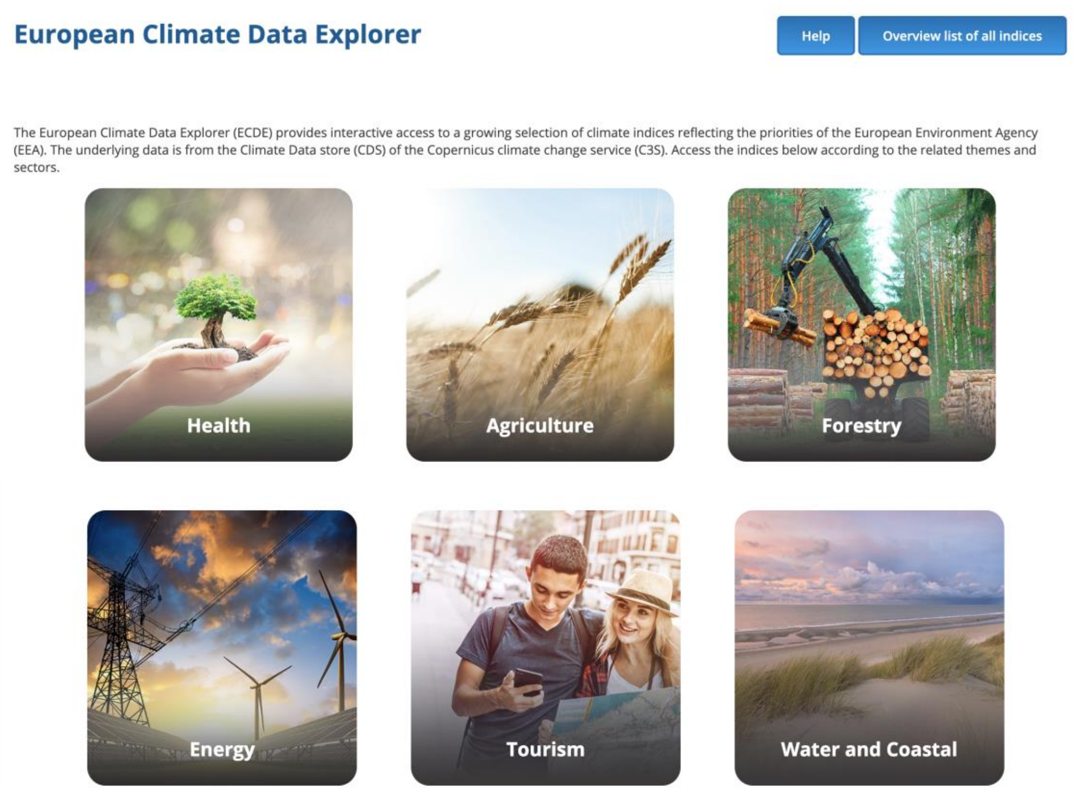
Climate monitoring in the Adaptation context

Climate Change

In collaboration with the **European Environment Agency (EEA):**
Supporting the EU Mission on Adaptation to Climate Change. It focuses on supporting EU regions, cities and local authorities in their efforts to build resilience against the impacts of climate change. The Mission's objective is to accompany at least 150 European regions and communities towards climate resilience by 2030

Key element: **connect climate change scenarios and current climate**

- Definition of reference periods
- Bias adjustment, indicator dependent
- Consistency across Administrative regions and transnational areas
- Monitor

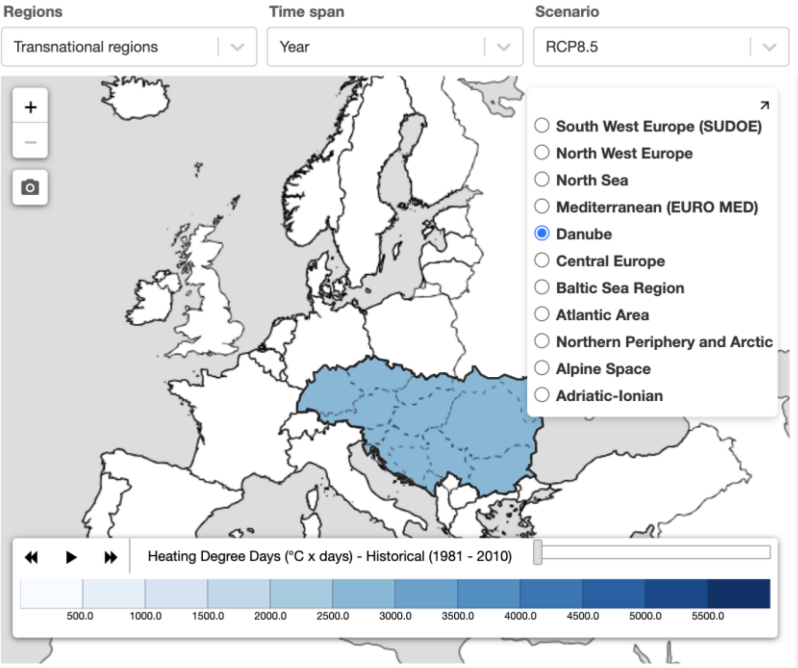


https://climate-adapt.eea.europa.eu/en/knowledge/european-climate-data-explorer

Climate ADAPT
SHARING ADAPTATION KNOWLEDGE FOR A CLIMATE-RESILIENT EUROPE

Climate Change

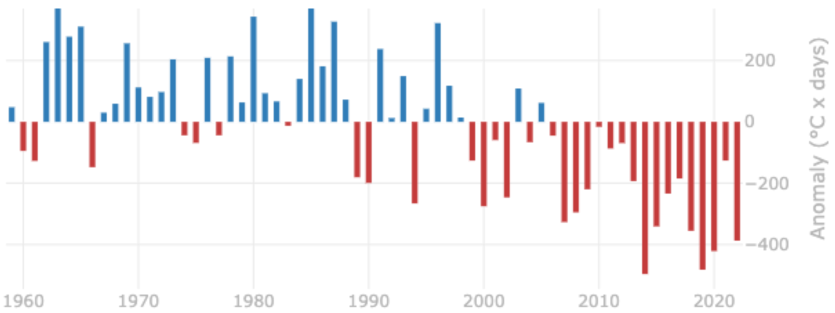
Climate monitoring in the Adaptation context



Interreg VI-B Danube

Historical variations of annual Heating Degree Days in Danube

Interactive plot showing the deviations of the historical annual Heating Degree Days from the 1981-2010 average (also called 'Anomaly') based on the ERA5 reanalysis.

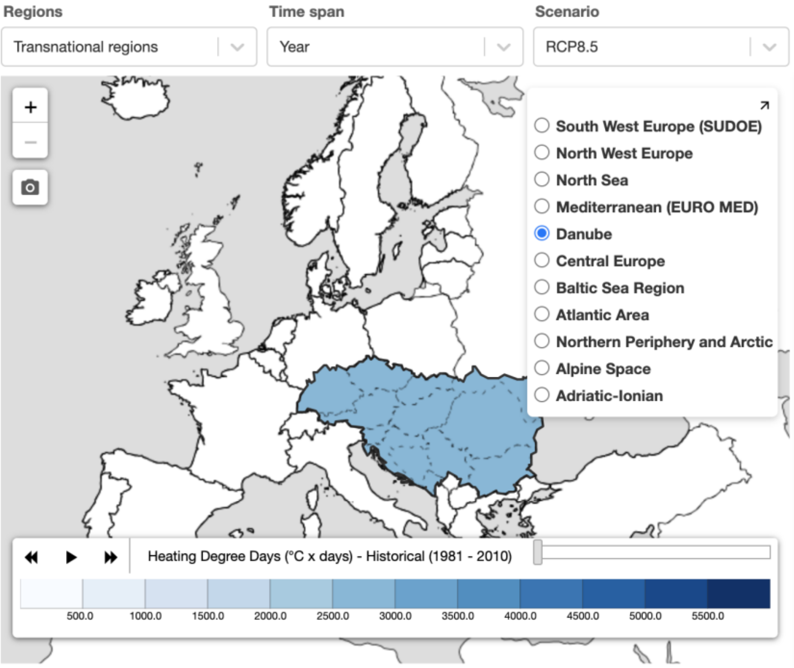


Connecting current climate mean and variability with climate change scenarios

$$\mathrm{HDD} = \sum_{1}^{182} \mathrm{HDD_i} \quad \text{with } \mathrm{HDD_i} = \begin{cases} T_{base} - T_{Avg} & \text{if } T_{base} \geq T_{Max} \\ \frac{T_{base} - T_{Min}}{2} - \frac{T_{Max} - T_{base}}{4} & T_{Avg} \leq T_{base} < T_{Max} \\ \frac{T_{base} - T_{Min}}{4} & T_{Min} \leq T_{base} < T_{Max} \\ 0 & T_{base} \leq T_{Min} \end{cases}$$

Climate monitoring in the Adaptation context

Climate Change

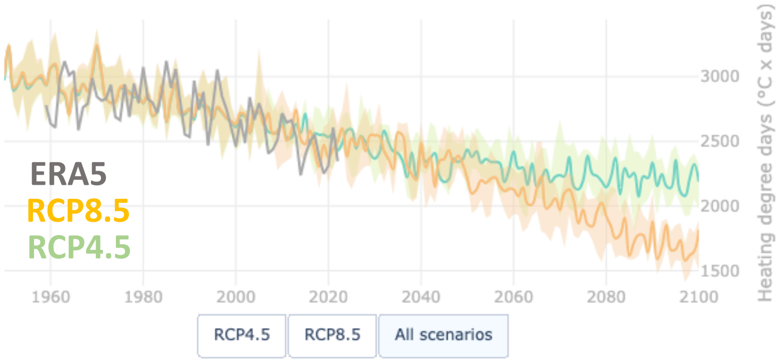


Connecting current climate mean and variability with climate change scenarios

Interreg VI-B Danube

Historical and projected evolution of annual Heating Degree Days in Danube

Interactive plot showing the observed annual Heating Degree Days along with the median and likely values (66% probability of occurrence) envelope from an ensemble of climate models.



$$\mathrm{HDD} = \sum_{1}^{182} \mathrm{HDD_i} \;\text{ with }\; \mathrm{HDD_i} = \begin{cases} T_{base} - T_{Avg} & \text{if } T_{base} \geq T_{Max} \\ \dfrac{T_{base} - T_{Min}}{2} - \dfrac{T_{Max} - T_{base}}{4} & \text{if } T_{Avg} \leq T_{base} < T_{Max} \\ \dfrac{T_{base} - T_{Min}}{4} & \text{if } T_{Min} \leq T_{base} < T_{Max} \\ 0 & \text{if } T_{base} \leq T_{Min} \end{cases}$$

ENTSO-E: European Network of Transmission System Operators

ENTSO-E is legally mandated to periodically deliver **pan-European outlooks** of the power system in the short-, mid-, and long-term.

→ THE TSO community CAN **coordinate actions in an integrated fashion** and provides technically-sound and consolidated information to policymakers and stakeholders that supports their decision-making.

Seasonal Outlook

Analysis of possible risks for the security of supply in Europe twice a year: for the summer and winter periods.

ERAA

A pan-European assessment of adequacy - the ability of a power system to cover demand in all conditions - up to 10 years ahead.

TYNDP

A study that investigates system needs (create max value for EU, ensure access to electricity & comply w/ climate agenda) in 2030/40.

Scenarios

A prerequisite for any study analysing the future of the EU energy system, describing possible EU energy futures up to 2050.

However, the variable nature of wind, solar renders the planning and operation of power systems an ever-more challenging task.

Courtesy of David Radu

entsoe

Climate Change

ENTSO-E: European Network of Transmission System Operators

The Pan-European Climate Database (PECD) used for SO, ERAA or TYNDP over the past years. Current version is based on reanalysis data

The current version (v3.1) of this database consists of climate timeseries

- at a spatial resolution defined by PECD zones
- covering a temporal horizon between 1982 and 2019
- originating from historical (reanalysis) data (i.e., wind speed, solar irradiance, temperature, etc.)
- where temperature data is corrected for climate change effects
- where 1 solar PV, 2 CSP, 3 offshore wind and 10 onshore wind technologies are available

Example of onshore PECD Zones. Source: ENTSO-E

PECD v4: a comprehensive meteorological database accounting for the impacts of climate change on demand and supply. Based on reanalysis and climate projections

- to produce an open, extensive dataset of RES timeseries replicating both historical and projected climate conditions (>10 climate models for the latter)
- to enhance the transfer functions for different RES technologies (e.g., more than one model for solar PV, improved hydro modelling)
- to improve the flexibility of data acquisition
- to provide an interface for prospective users that would facilitate the use of the dataset beyond current level

in partnership with entsoe

Use of ERA5 for impact studies: WFDE5

WFDE5: to support the impact assessments carried out in the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3b)

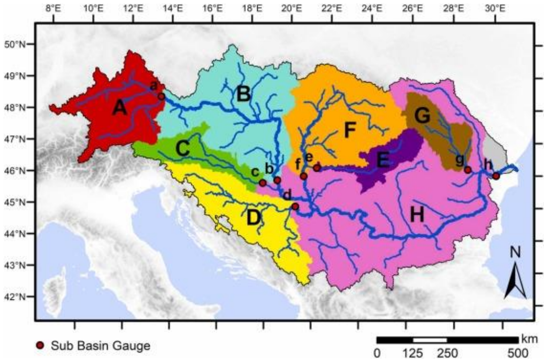
used to:

- directly drive historical impact simulations, which are needed for impact model validation
- as an observational reference dataset for the bias adjustment of climate projections, then used to drive future climate impact projections

It uses the WATCH Forcing Data methodology applied to ERA5

The CRU TS (Climatic Research Unit gridded Time Series)

GPCC Full Data Montlhy Product Version

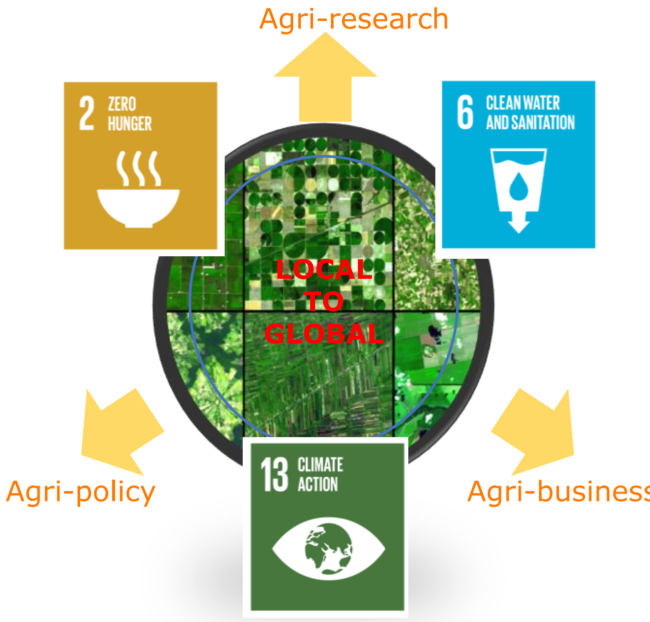


- Poor performance of the ERA5-driven across nearly all sub basins → bias correction is essential for hydrological modelling in the DRB
- Compared to ERA5, the WFDE5-driven simulation yielded much better results (especially in the mountainous Drava and Sava basins) → very suitable for hydrological modelling purposes

Probst & Mauser, 2022, J of Hydrology

Open data products: AgERA5

- Global product derived from ECMWF ERA5 reanalysis
- Bias-corrected towards operational ECMWF forecasts
- 0.1x0.1 degree (~10 km)
- Daily variables from 1979 up till realtime with a delay of ~1 week
- 22 variables relevant for agricultural applications:
  - Temperature (avg, min, max, etc.)
  - Precipitation and precipitation type
  - Global radiation
  - Daily avg vapour pressure and wind speed
  - Relative humidity at specific times of the day



Data portals using AgERA5
FAO: https://data.apps.fao.org
WorldCereal: https://ceos.org/gst/agriculture.html
openEO Hub: https://hub.openeo.org/

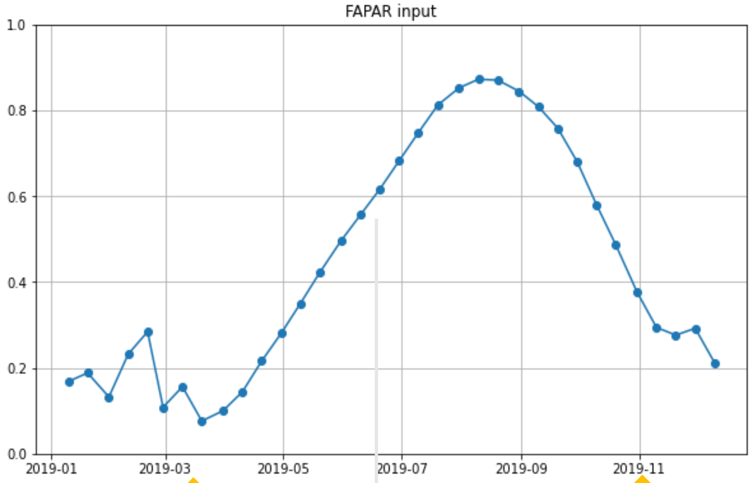
WAGENINGEN UNIVERSITY & RESEARCH

https://doi.org/10.24381/cds.6c68c9bb

Crop model - graphically

Outputs:

- Crop phenological stage;
- Total above-ground production (dry matter);
- Total weight storage organs (dry matter), e.g. grains or pods

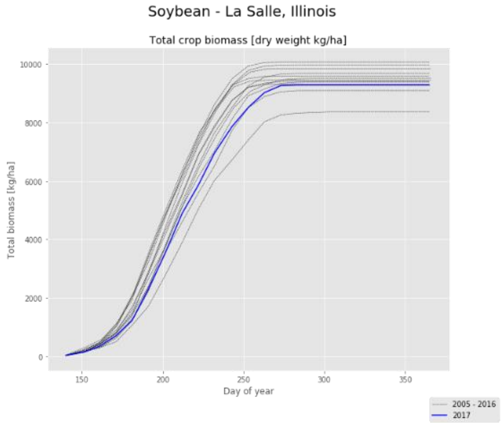


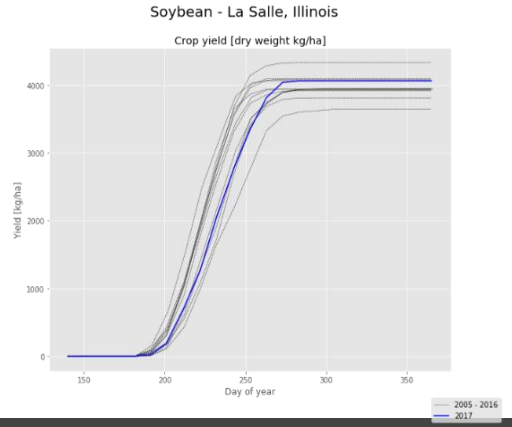
SAGE start

SAGE End

AgERA5 weather inputs

LUE crop model



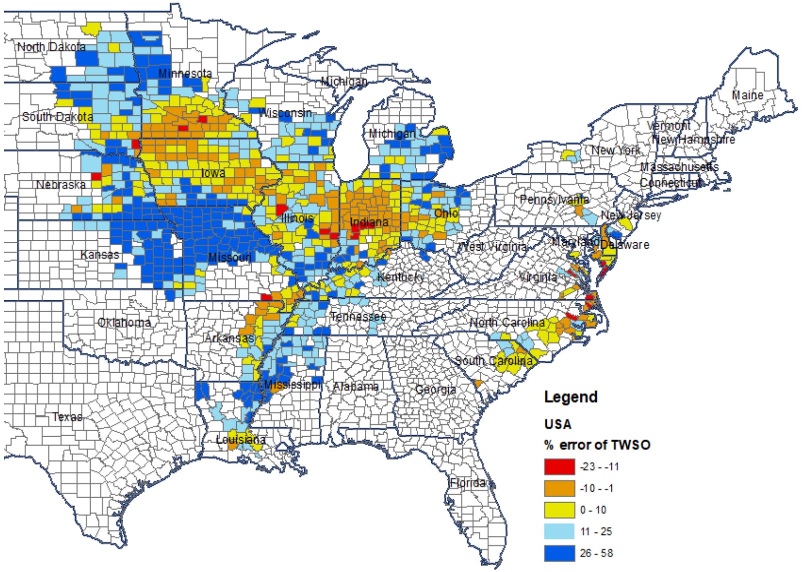


Courtesy of Allard de Wit

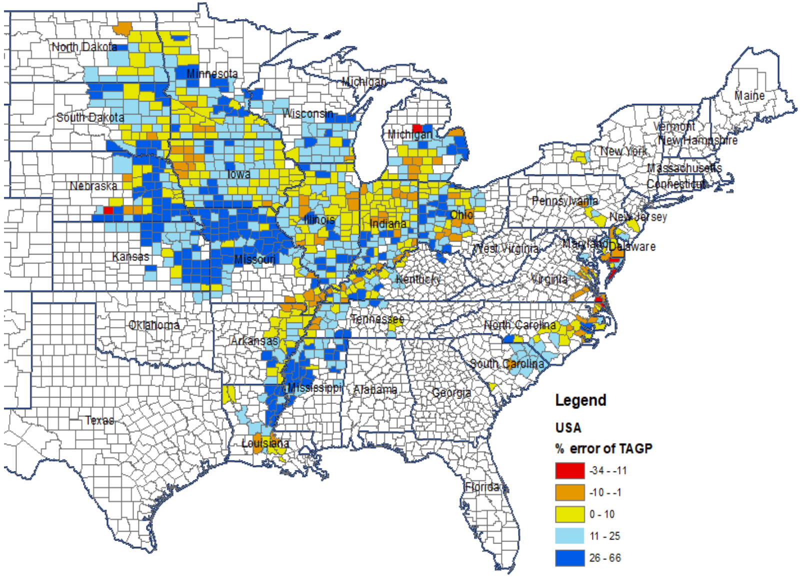
Climate Change

Validation – Soybean US

The total above-ground production TAGP (kg/ha)



The harvestable plant product TWSO (kg/ha)



WAGENINGEN UNIVERSITY & RESEARCH

Courtesy of Allard de Wit

Why Soybean ?

- Soybean used for food and feed
- Protein (high quality, warmer climates): food
- Oil (lower quality, colder climates): food & biofuels
- Meal: feed
- Grown all over the world

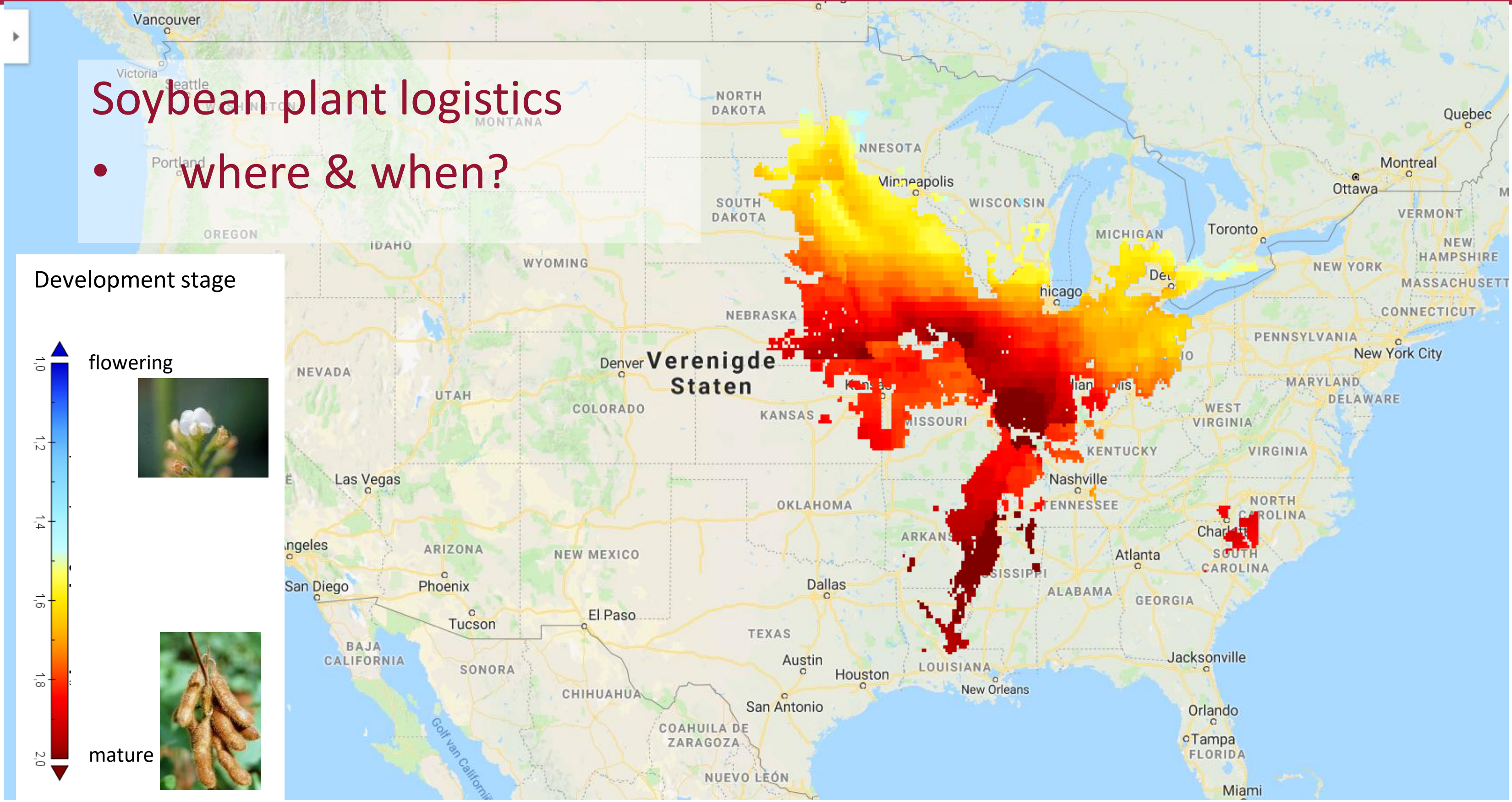
Courtesy of Allard de Wit

SHOW CASE : SOYBEAN USA

Climate Change

Soybean plant logistics

- where & when?



Development stage

1.0 flowering

1.2

1.4

1.6

1.8

2.0 mature

SHOW CASE : SOYBEAN USA

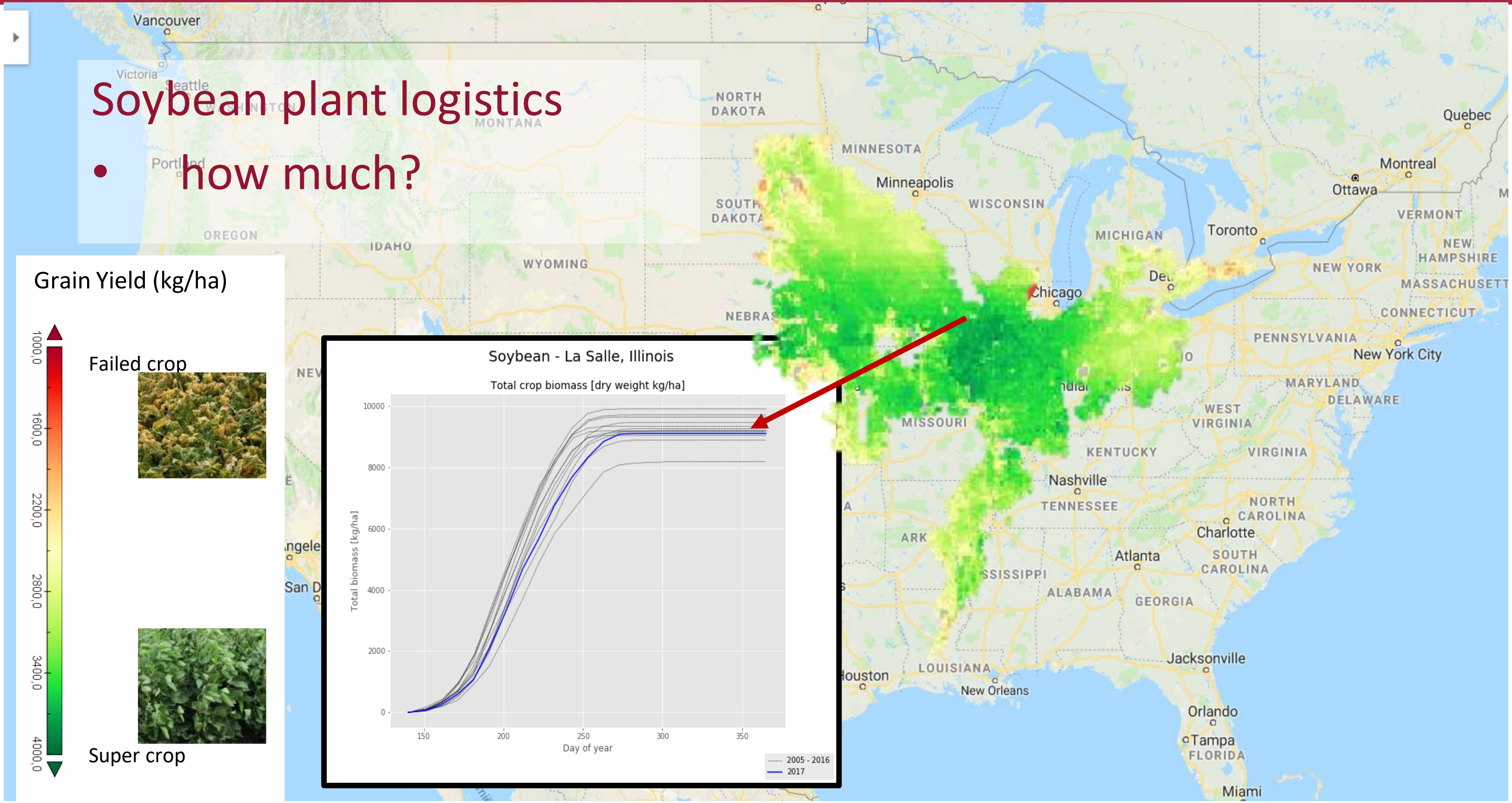
Soybean plant logistics

- how much?

Grain Yield (kg/ha)

Failed crop

Super crop



Climate Change

ERA5-based Fire Weather Index

- Forest fires are becoming more devastating and less predictable
- Need to characterise temporal trends and quantify impacts on population, ecosystems and infrastructures
- Current limitations in fire observations
- FWI : the meteorological conditions that would cause flames to spread out of control, conditional on an ignition occurring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Tragedy in Pedrógão Grande: 64 confirmed deaths and 254 injured

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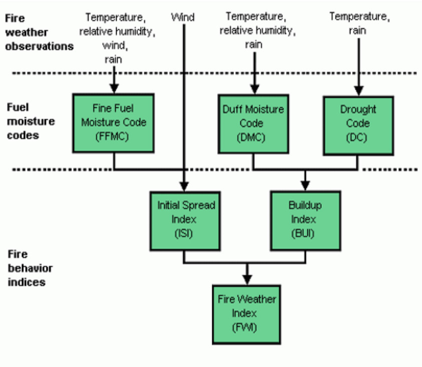
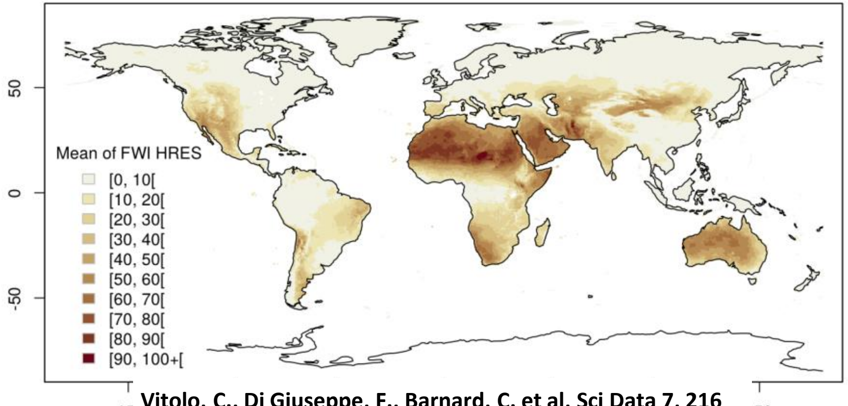
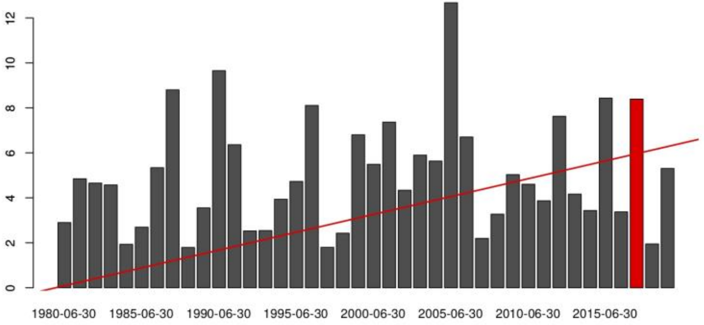
Driving through the killer inferno: Terrifying moment motorist escapes wildfires blamed on 'terrorist arsonists' that have claimed dozens of lives in Portugal and Spain





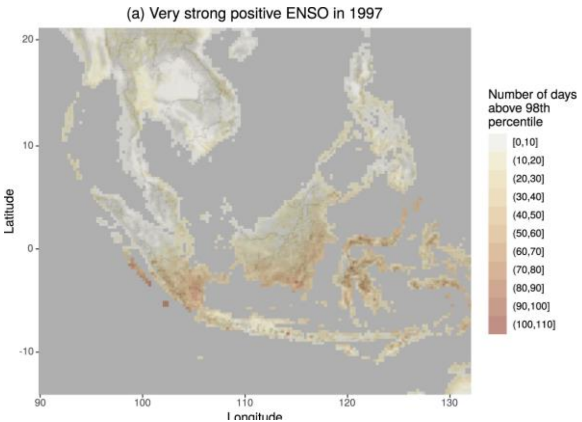
Vitolo, C., Di Giuseppe, F., Barnard, C. et al, Sci Data 7, 216 (2020). https://doi.org/10.1038/s41597-020-0554-z

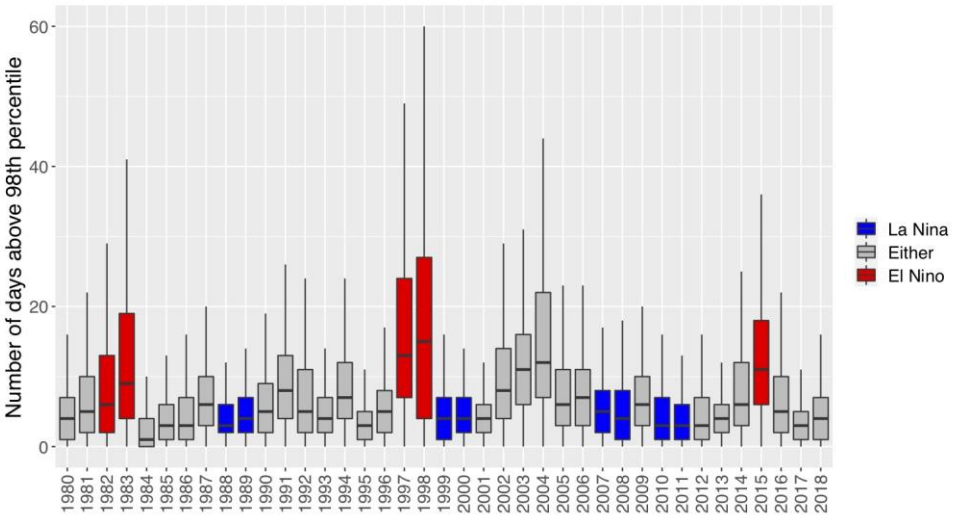
The monthly spread of the ensemble at Pedrógão Grande (Portugal)



FWI & ENSO: Health Sector

El Nino can establish favorable conditions for the triggering and sustainability of wildfires in several areas around the world
Reanalyses: FWI used to investigate the climatology of wildfire danger & links to ENSO





Users needs

What do you see are the most significant advances for the field of reanalysis in the next 5-10 years?

- Higher resolution reanalysis → More realism
- Reduce the bias → Handling of systematic errors
- Outputs tailored at energy modeling community→ New products
- Longer timeseries - back in time→ However, biases a problem

What observational datasets are required ?

- Gridded observation datasets or at least highly quality controlled data
- Direct wind speed measurements at 100m height
- More data for validation in certain parts of the world (esp. African continent)
- Reprocessed and rescued data

Are there significant barriers for quantifying uncertainty in your field?

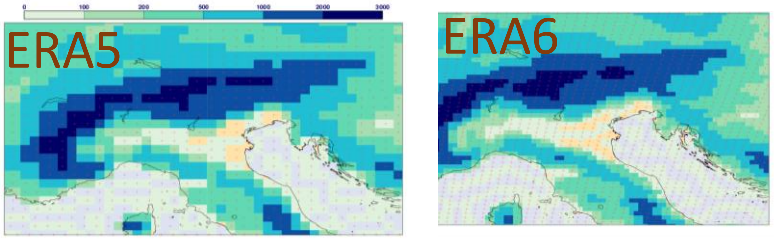
- Missing information on sub-grid scale
- Suggestion to add statistics (RMSE, bias) w.r.t. reference data, e.g. station observations

Climate Change

Evolution toward ERA6

In a nutshell: ERA6 will make use of:

- additional 8 years of ECMWF R&D plus dedicated reanalysis developments
- enhanced computer power and storage technologies
- more and better observations, reprocessed and rescued, satellite and in-situ from our C3S contractors
- invaluable feedback from the C3S reanalysis user community



Improved realism:

- Higher resolution (at least 18km), also for the ocean waves
    - Regional downscaling
    - ERA6-Land product (9km)
- Towards coupled Earth system:
    - Ocean coupling, either two-way or one-way from OCEAN6
- Improved forcing fields, potentially time-varying vegetation (outcomes from CONFESS)

- **Improve on systematic model bias**
    - better mean state and long-term trends
    - via better model
    - plus weak-constraint 4D-Var

Courtesy of Hans Hersbach

Enhanced uncertainty estimate:

- based on user feedback and user uptake
- improve the tuning of the 'error of the day'
- provide an estimate for the mean state

More tailored products:

- enhance output in the boundary layer, potentially adding height levels
- additional parameters, like relative humidity at 2m height
- limit the need to process/download large volumes, as overall dataset volumes increase considerably:
    - enhance monthly products, daily products, etc

See Hans and Bill's presentations

Users needs

How is uncertainty quantified for your application? Are there significant barriers for quantifying uncertainty in your field?

- need uncertainty estimation to interpret temporal variations
- need of longer timeseries back in time – time consistency

What modeling components are mature enough to enable reanalysis for your specific science question or application?

- interactive or changing Land Use and Land Cover

Beyond ERA6 → See Patricia's presentation

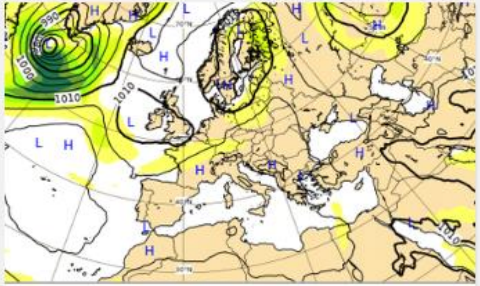
- To identify an optimal degree of coupling across the Earth system components for the benefit of seamless NWP and reanalysis
    - Enhance the quality of the reanalysis with a focus on land-atmosphere coupling (CERISE): Develop new and innovative ensemble-based coupled land-atmosphere data assimilation approaches and land surface initialisation techniques to pave the way for the next generations of the C3S reanalysis and seasonal prediction systems.

Machine Learning applications

Climate Change

An emerging new generation of ML models, developed using high-quality reanalysis datasets like ERA5 for training

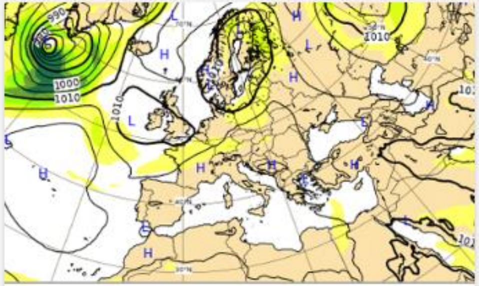
ERA5-based weather forecasting models on ECMWF open charts →



Latest forecast

(FourCastNet machine learning model: Experimental): Mean sea level pressure and 850 hPa wind speed

FourCastNet:a deep learning-based system developed by NVIDIA in collaboration with researchers at several US universities.It is initialised with ECMWF HRES analysis. FourCastNet operates at 0.25° resolution.



Latest forecast

(Pangu-Weather machine learning model: Experimental): Mean sea level pressure and 850 hPa wind speed

Pangu-Weather: a deep learning-based system developed by Huawei. It is initialised with ECMWF HRES analysis. Pangu-Weather operates at 0.25° resolution.

Different ways ERA5 empowers machine learning, particularly how ERA5 can be used to train accurate weather forecasting models

Matthew's presentation

Climate Change

The success of ERA5

- The feedbacks from users included in the evolution of the dataset
- Operational user support
- Reduced data latency
- Easy and fast access to data
- Extended documentation & peer reviewed articles
- No gaps in space & time + hourly resolution
- Back extension
- Consistency across domains (atmosphere, land, waves)

Climate Change

Thank you !

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