Energy Fluctuations & Extremes

ISIMIP winter workshop, January 11, 2021

Outline

- Part 1 (~15mins)
  - → Short overview of the The Inter-Sectoral Impact Model Intercomparison Project (www.ISIMIP.org)
- Part 2 (~45mins)
  - → Introduction of the Energy Fluctuations & Extremes track
  - → Presentations of the different modeling approaches
- Part 3 (~30mins)
  - → Discussion on input data needs and first steps towards an ISIMIP3 protocol for this track

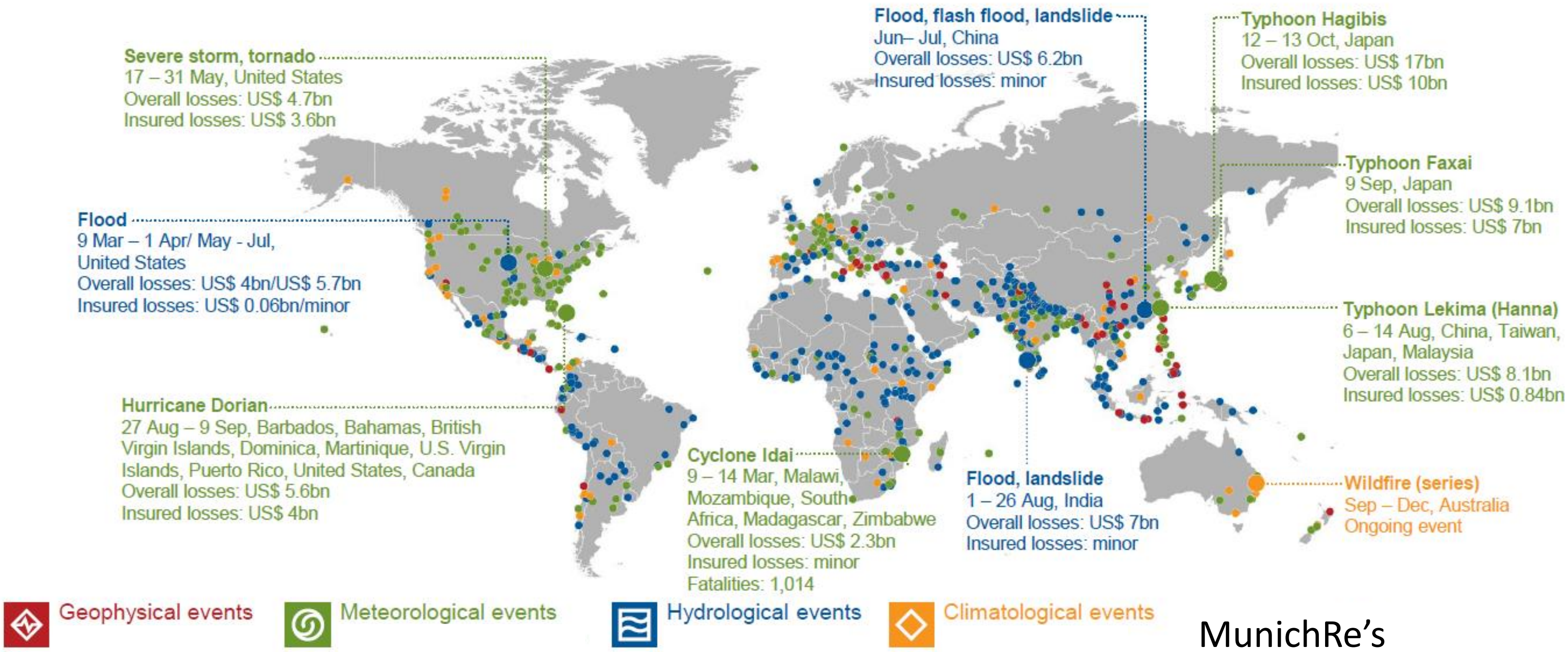
ISIMIP – Main research questions

How does climate change affect natural and human systems already today?

How will it do so in the future?

P I K

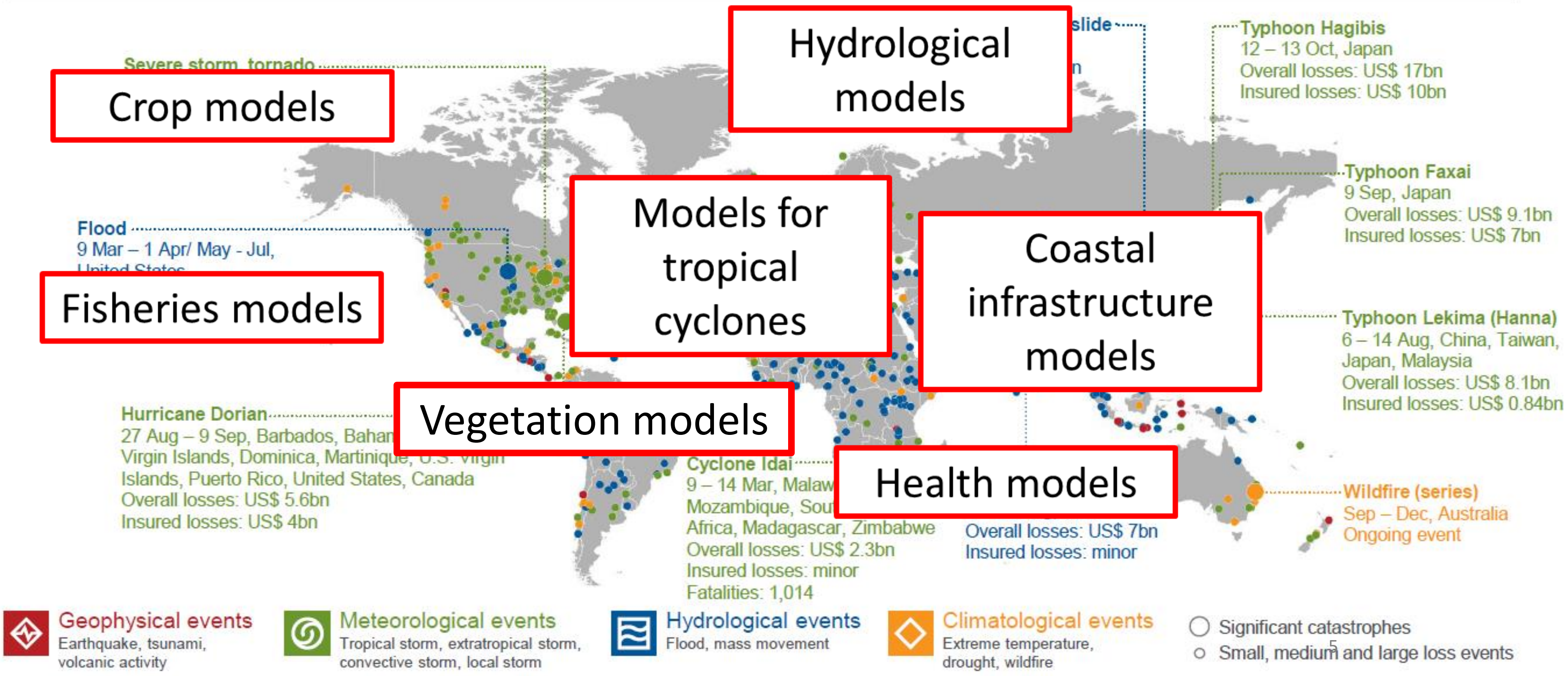
Economic losses induced by weather extremes in 2019



7% 38% 45% 10%

MunichRe's NatCatService

Future projections need a range of different impact models



Source: Munich Re, NatCatSERVICE, 2019

Pre-ISIMIP era

Common future Emission pathways (RCPs)

RCP2.6

RCP4.5

RCP6.0

RCP8.5

Harmonized climate model runs (CMIP)

Climate model 1

Climate model 30

Impact models

Hydrological model

Hurricane model

Ice Sheet model

Health model

Crop model

Coastal infrastructure model

Fisheries model

Wild fire model

Energy model

Aim of ISIMIP project

Common future Emission pathways (RCPs)

RCP2.6

RCP4.5

RCP6.0

RCP8.5

Harmonized climate model runs (CMIP)

Climate model 1

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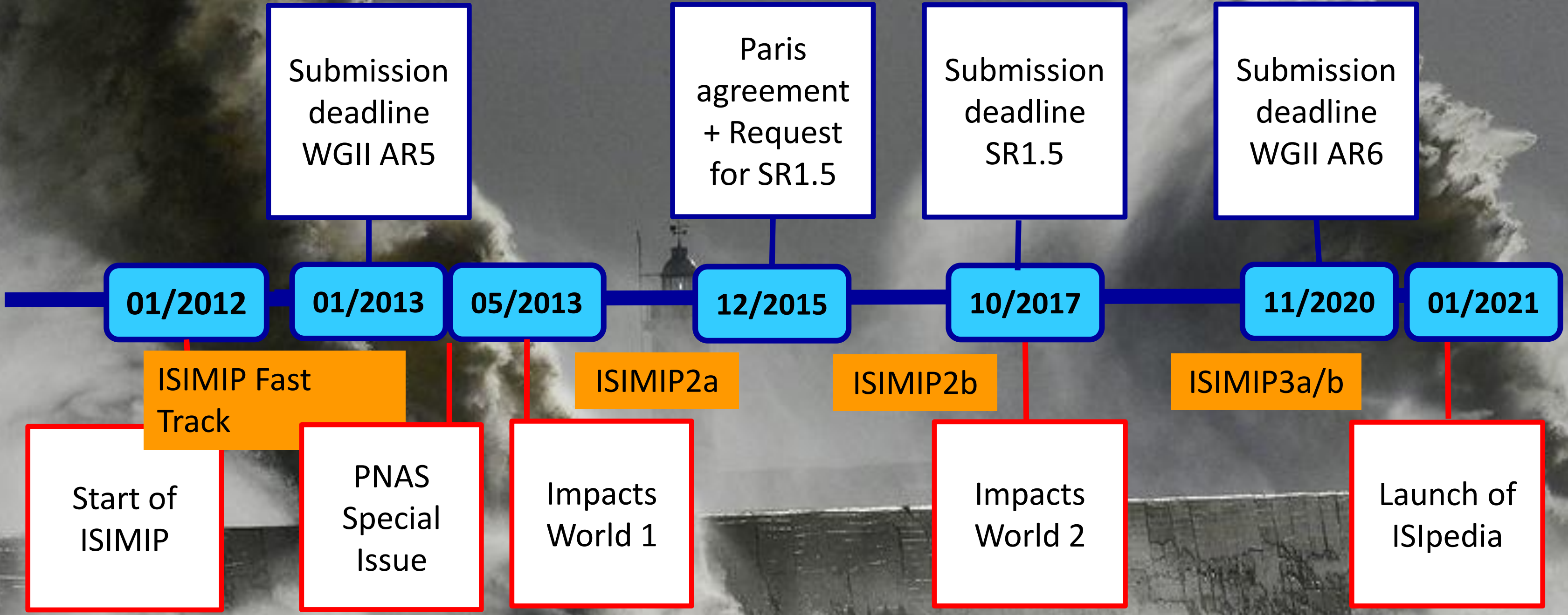
Climate Impact Science
ISIMIP
Inter-Sectoral Impact Model Intercomparison Project
www.ISIMIP.org
CMIP
The World Climate Research Programme's Coupled Model Intercomparison Project
Climate Science

External forcing: IPCC deadlines



ISIMIP timeline

How ISIMIP works

Provided by ISIMIP coordination team

Climate data
(daily, 0.5° x 0.5°)
Historical observations
+
Projections
CMIP 6 (bias corrected)

Socio-economic input
(population, land-use, GDP, agricultural + water management)

Historical observations
+
Future Projections (SSP)

Contributed by sectoral modelers

Impact Models (global + regional)

- Water
- Agriculture
- Coastal infrastructure
- Biomes
- Health
- Permafrost
- Energy
- Biodiversity
- Marine Ecosystems

Joint outcome

Main objectives

- Cross sectorally consistent, temporally and spatially explicit impact analyses
- Model validation
- Impact attribution
- Assessements of future climate risks

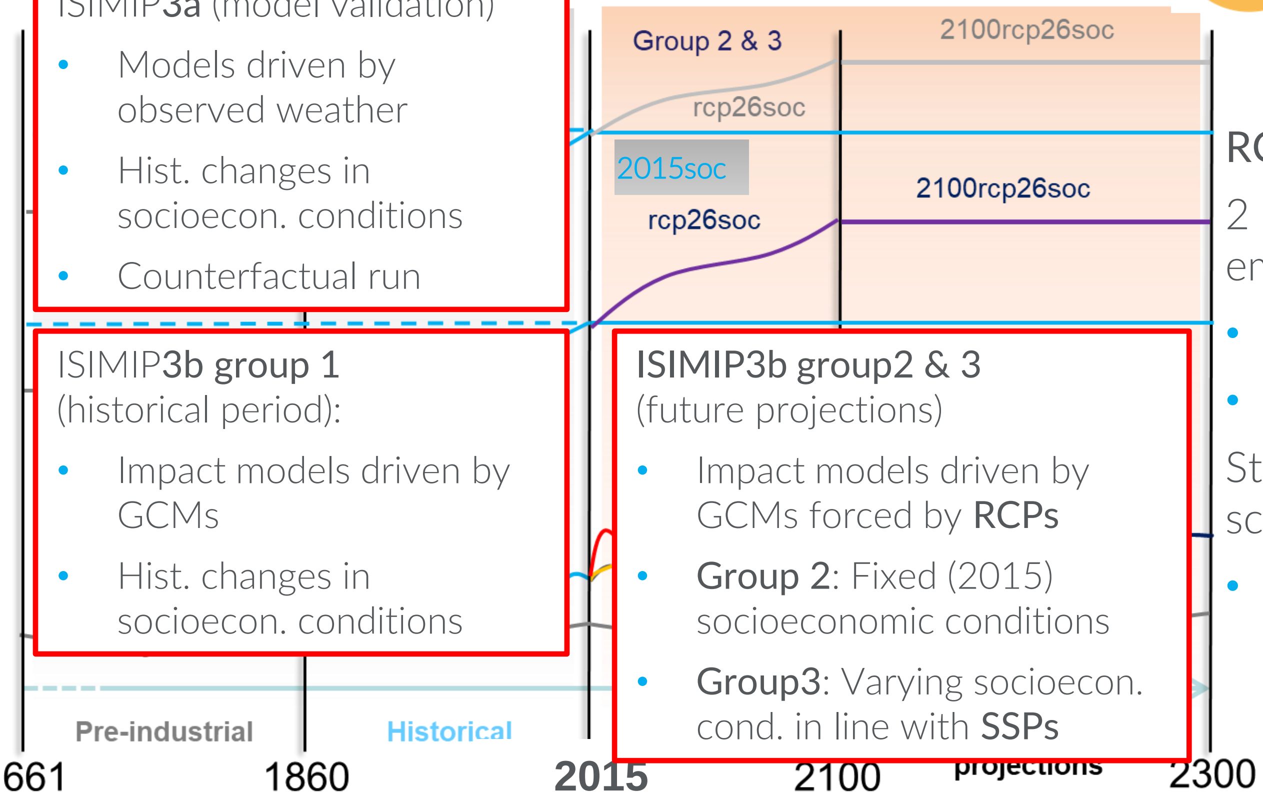
ISIMIP – The modeling protocol

ISIMIP
Inter-Sectoral Impact Model Intercomparison Project

Population, GDP, etc.

Landuse

Climate



ISIMIP3a (model validation)

- Models driven by observed weather
- Hist. changes in socioecon. conditions
- Counterfactual run

ISIMIP3b group 1 (historical period):

- Impact models driven by GCMs
- Hist. changes in socioecon. conditions

ISIMIP3b group2 & 3 (future projections)

- Impact models driven by GCMs forced by **RCPs**
- **Group 2**: Fixed (2015) socioeconomic conditions
- **Group3**: Varying socioecon. cond. in line with **SSPs**

RCPs and SSPs

2 high GHG emission scenarios

- SSP5 – RCP8.5
- SSP3 – RCP7.0

Strong mitigation scenario

- SSP1 – RCP2.6

- Process based simulations permit separation of climate and socio-economic drivers

Overview of input data (relevant for Energy Sector)

Atmospheric variables (reanalysis datasets 1901-2016 and CMIP6 (bias corrected) 1901-2016 & 2015-2100), daily time step, 0.5°:

→ Near-surface air temperature, surface down-welling radiation (longwave, shortwave), near-surface wind speed, precipitation, evapotranspiration, soil moisture, near surface air pressure

Biophysical variables:

→ From water models:

- River runoff/discharge
- Flood affected areas accounting for present day protection levels (18 arcsec)

→ From tropical cyclone models:

- Storm tracks and wind fields

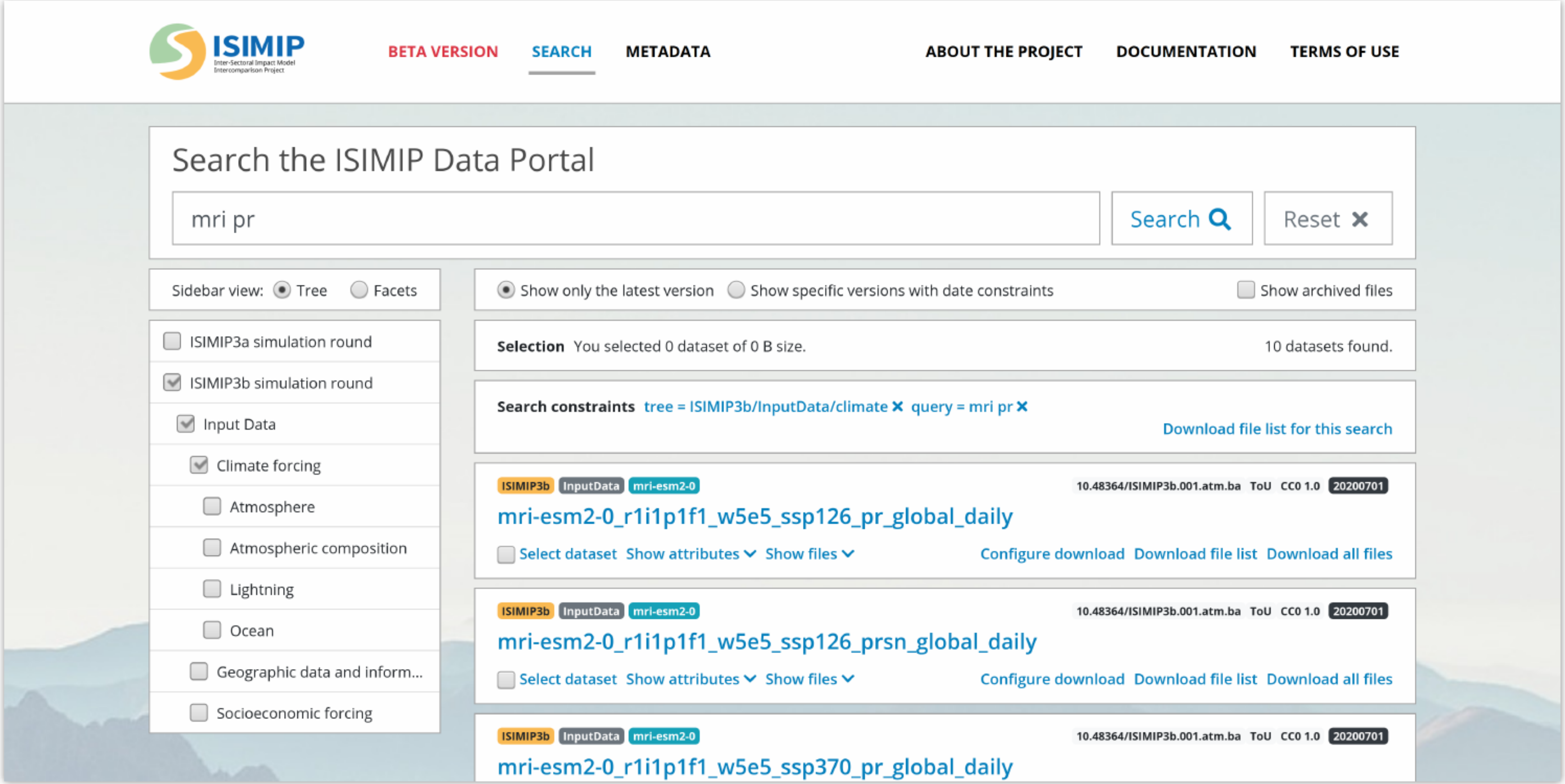
Socioeconomic data

→ Gridded population, GDP, land-use patterns, dam locations, …

Plans to downscale to 1km x 1km and 3 hourly resolution

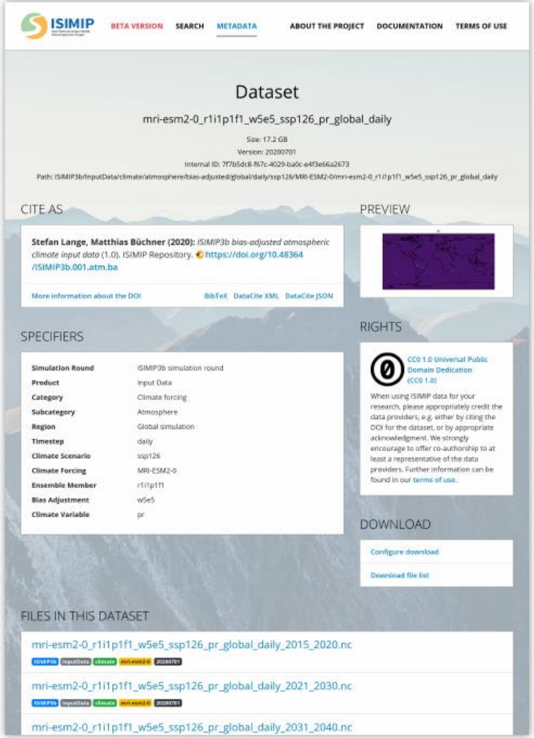
→ Session on Climate Forcing Data, **today 4.15pm**

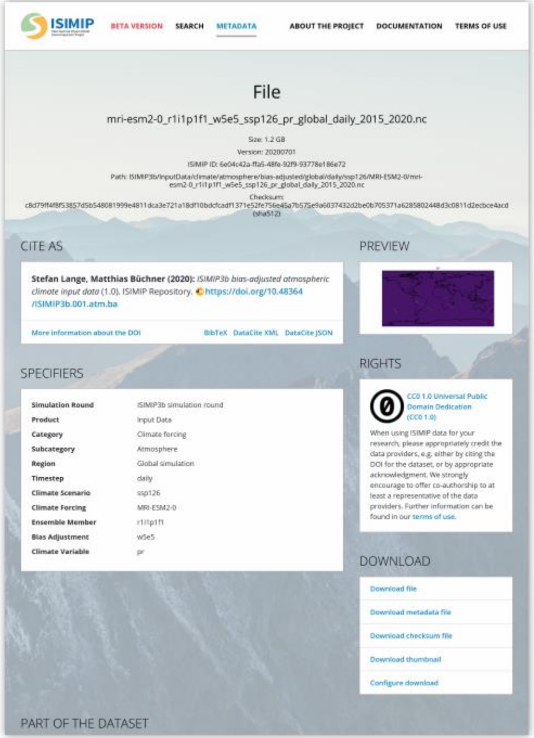
Archive for ISIMIP3 data

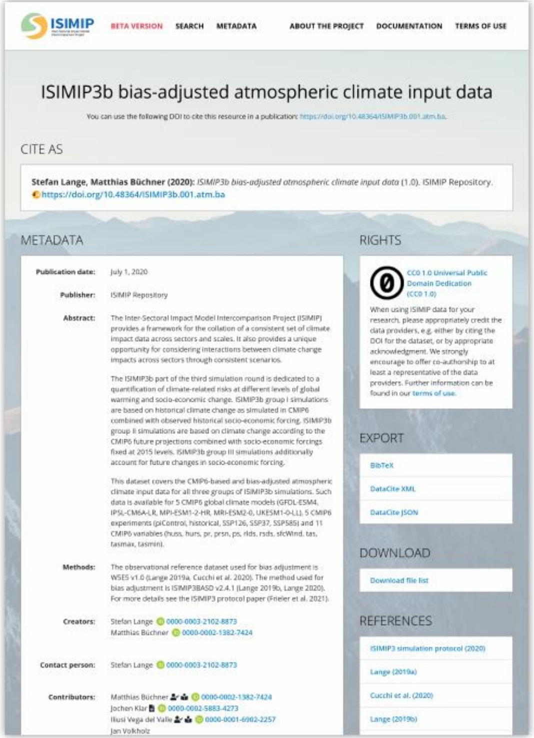


www.data.isimip.org

Datasets, Files, DOIs

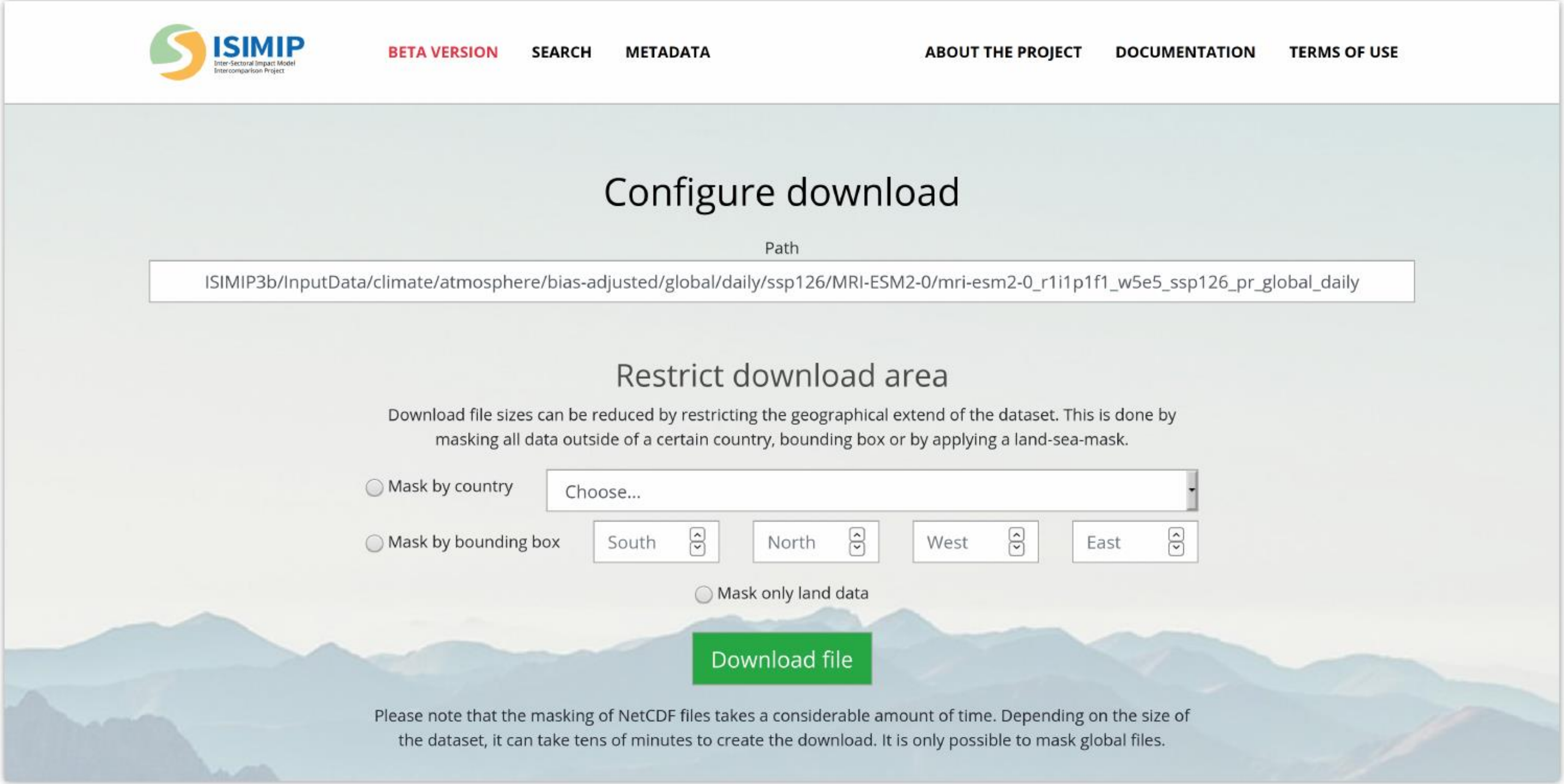






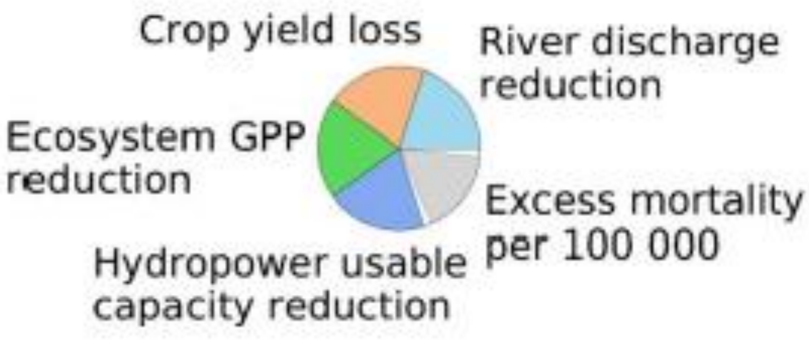
e.g. https://data.isimip.org/datasets/7f7b5dc8-f67c-4029-ba0c-e4f3e66a2673/

Tailored downloads



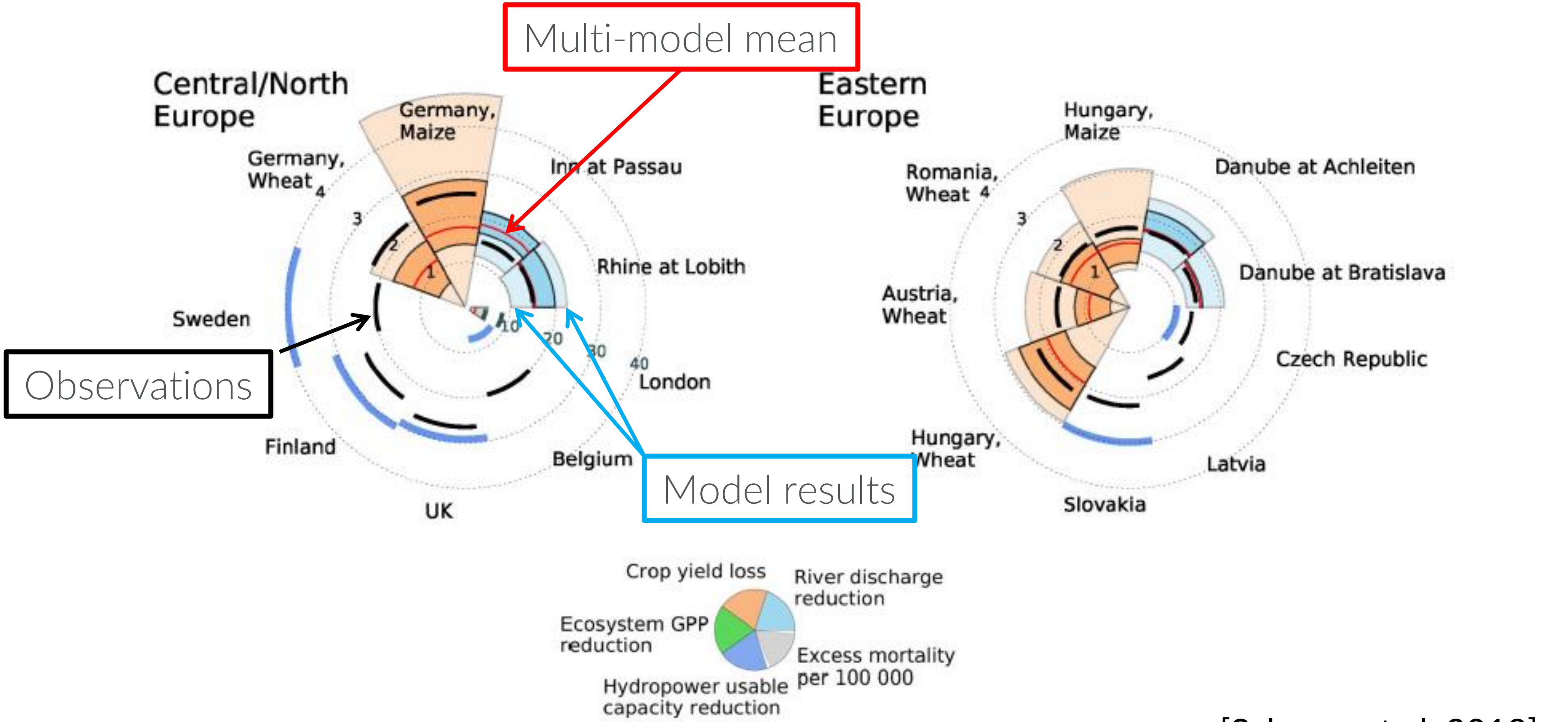
- Bulk downloads via wget
- ISIMIP-API

Example - Multi-sector impact analysis of 2003 European heatwave



[Schewe et al. 2019]

Example - Multi-sector impact analysis of 2003 European heatwave



[Schewe et al. 2019]

What are the benefits in participating?

- … aside from being a part of a thriving community of impact modelers at the forefront of science …
- Influence on focus topics / protocol / ISIMIP input data (e.g., downscaled and harmonized data)
- Access to all ISIMIP output data – embargo period for exclusive use within ISIMIP community
- Lots of exciting (cross-sectoral) studies (papers written in embargo period should offer co-authorship to all modeling teams whose data are used in the paper)

  → Paper writing workshops
- Synergies with existing modeling efforts (e.g., sector specific MIPs)

Requirements:

- Output data submitted to ISIMIP have to adhere to certain standards/formats specified in the protocol
- Publication of data on ESGF for public use

Energy Fluctuations & Extremes

PIK

Potsdam Institute for Climate Impact Research

Main research questions

- How will **changes in weather variability and extremes**
- … impact on biophysical potentials, potential **supply**, and usable capacity?
    - E.g., how does usable capacities of thermal and hydro power plants change due to water shortages and high water temperatures under global warming?
- …. **change demand**
    - How does frequency of high cooling/heating episodes changes under global warming?
    - Can this induce short-term supply-demand mismatches (in the present day power system infrastructure)?
- How will **damages** of extreme weather events **to the energy infrastructure** affect power supply?
    - Cascading failures induced by tropical cyclones

Long-run Climate Change Induced Impacts on Energy Systems

	Gradual climate change	Fluctuations & Extremes	Damages induced by weather extremes
Energy supply	• Renewable potential (wind, solar, biomass, hydro) IAMs, Energy models	• Renewable reliability (wind, solar, biomass, hydro) System regulators, Electricity models	• Tropical cyclones breaching power poles • Fluvial floods interrupting power plant operation Power grid models, Energy system models
Energy demand	• Long term changes in cooling and heating demand IAMs, Energy models	• Changes in frequency of episodes with high cooling/heating demands	
Validation		• Historical episodes with low renewable supply and high energy demand	• Historical power outages and reconstruction periods

Impacts of Changes in Fluctuations and Extremes on Energy Systems

	Gradual climate change	Fluctuations & Extremes	Damages induced by weather extremes
Energy supply	• Renewable potential (wind, solar, biomass, hydro) IAMs, Energy models	• Renewable reliability (wind, solar, biomass, hydro) Electricity models, Energy system models	• Tropical cyclones breaching power poles • Fluvial floods interrupting power plant operation Power grid models, Energy system models
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Short introduction of modeling approaches

1. *Global hydropower and thermoelectric power vulnerability to climate and water resources changes and variability*, **Michelle van Vliet**, Univ. of Utrecht, Netherlands
2. *Water Risk for the Bulk Power System: Asset to Grid Impacts*, **Ariel Miara**, National Renewable Energy Laboratory, USA
3. *Meteorological conditions leading to extreme low variable renewable energy production and extreme high energy shortfall*, **Karin van der Wiel**, Royal Netherlands Meteorological Institute
4. *Wind and solar power modeling*, **Robert Vautard,** Institut Pierre-Simon Laplace, France
5. *Methods to explore Climate impacts on zero carbon energy system mitigation pathways in TIMES-GEO*, **James Glynn**, MaREI-UCC, Ireland
6. *Clim2power - impacts of climate variability for a carbon-neutral EU power sector*, **Sofia Simões**, National Laboratory of Energy and Geology, Portugal
7. *Investigating the Risk of Hurricane-Induced Cascading Failures in Power Systems of the U.S. East Coast*, **Julian Stürmer**, Potsdam Institute of Climate Impact Research, Germany

Protocol

POTSDAM INSTITUTE FOR
CLIMATE IMPACT RESEARCH

The ISIMIP3 protocol

ISIMIP3a: Model validation for extended historical period (varSoc)

- Climatic forcing according to observed weather
- Observed changes in socioeconomic drivers

Requires:

  - Database capturing historical changes in **energy infrastructure**
    - e.g., Global Power Plant Database, WRI
  - Historical **data on power grids**
- **Datasets for model validation**
  - Historical **data on energy supply and demand**
  - Historical impacts of extremes on power supply

Start community data-collection effort in ISIMIP?

- Focus regions or global?
  - For which regions beyond the US are good data available?

The ISIMIP3 protocol

ISIMIP3a: Model validation for extended historical period (varSoc)

- Climatic forcing according to observed weather
- Observed changes in socioeconomic drivers:

ISIMIP3b: Climatic forcing provided by (bias corrected) GCMs

- **Group1**: historical period, varSoc
- **Group2**: future period, 2015soc
  - Climatic forcing changes according to RCP scenarios
- **Group3**: future period, varSoc
  - Socioeconomic conditions (e.g., energy infrastructure) varies according to SSPs

Overview of input data (relevant for Energy Sector)

Atmospheric variables (reanalysis datasets 1901-2016 and CMIP6 (bias corrected) 1901-2016 & 2015-2100), daily time step, 0.5°:

→ Near-surface air temperature, surface down-welling radiation (longwave, shortwave), near-surface wind speed, precipitation, evapotranspiration, soil moisture, near surface air pressure

Plans to downscale to 1km x 1km and 3 hourly resolution

Biophysical variables:

→ From water models:

- River runoff/discharge
- Flood affected areas accounting for present day protection levels (18 arcsec)

→ From tropical cyclone models:

- Storm tracks and wind fields

Further needs on atmospheric data and biophysical impact data?

Next steps

- Let us know whether you would like to participate
- Link to ISIMIP3 protocol paper (in preparation)
- Review paper?
- Follow-up meetings to discuss input data needs and protocol development

Impacts of Changes in Fluctuations and Extremes

	Gradual climate change	Fluctuations & Extremes	Damages induced by weather extremes
Energy supply	• Renewable potential (wind, solar, biomass, hydro) IAMs, Energy models	• Renewable reliability (wind, solar, biomass, hydro) System regulators, Electricity models	• Tropical cyclones breaching power poles • Fluvial floods interrupting power plant operation Power grid models, Energy system models
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Utrecht University

Global hydropower and thermoelectric power vulnerability to climate and water resources changes and variability



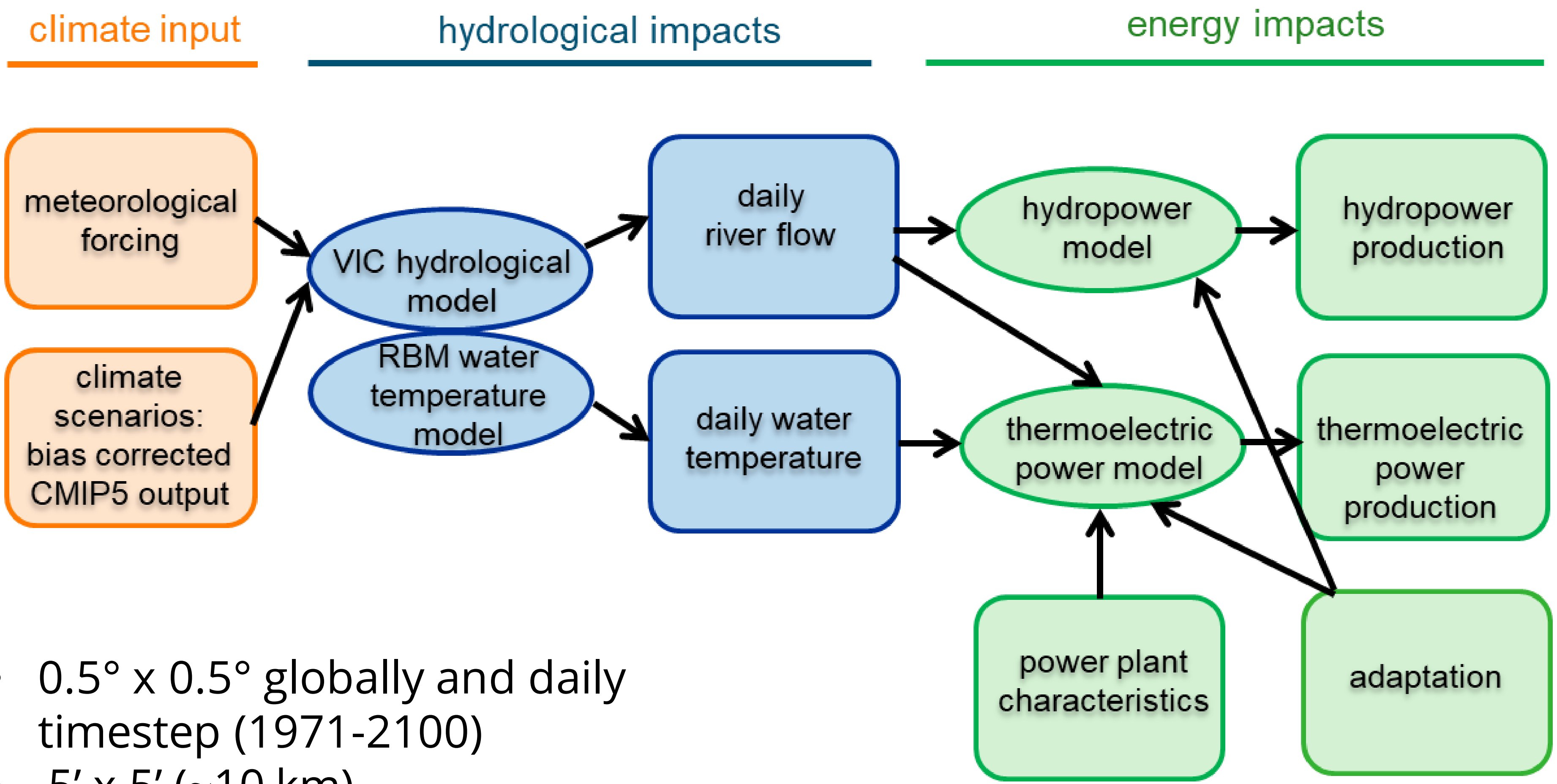

Dr. Michelle van Vliet

Assistant Professor, Department of Physical Geography, Utrecht University, The Netherlands

ISIMIP workshop session energy fluctuations and extremes, 11 January 2020

Global model framework

To study hydropower and thermoelectric power plant vulnerability to climate change and variability



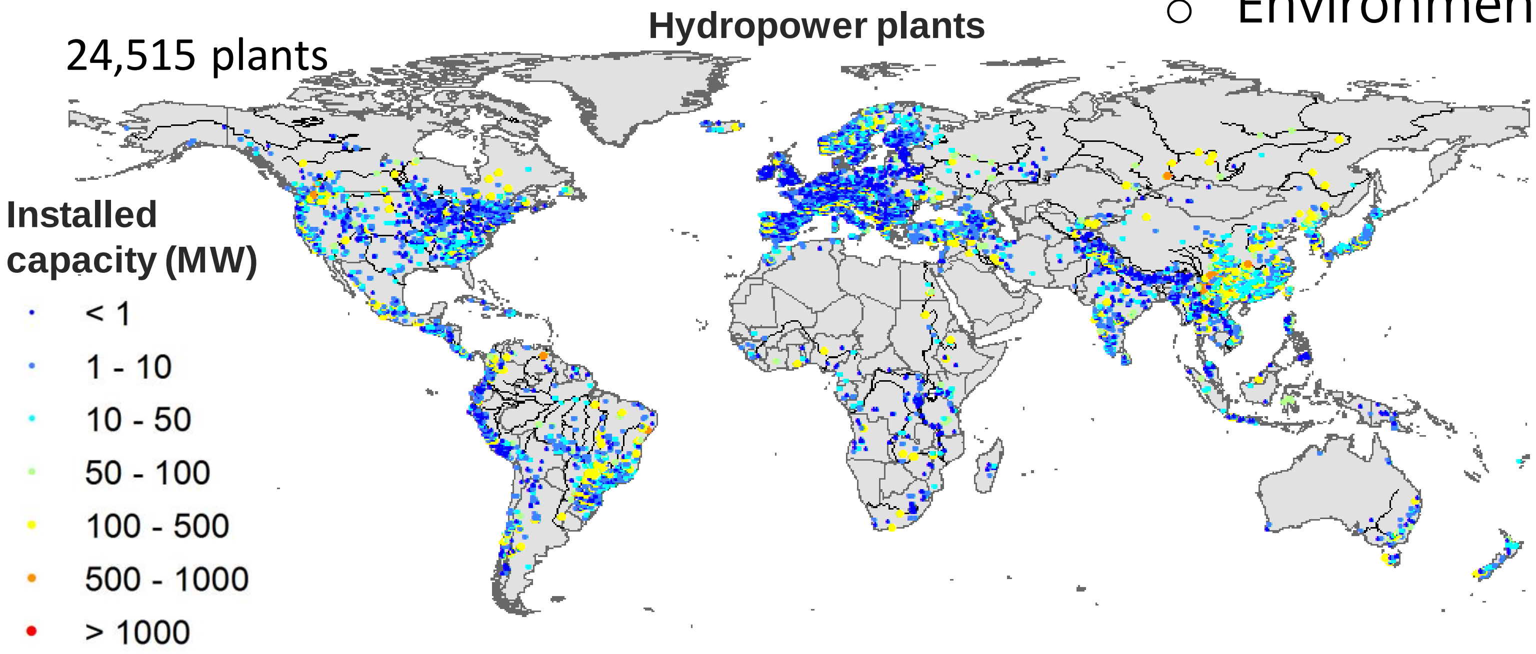
- 0.5° x 0.5° globally and daily timestep (1971-2100)
- 5′ x 5′ (~10 km)

Input data

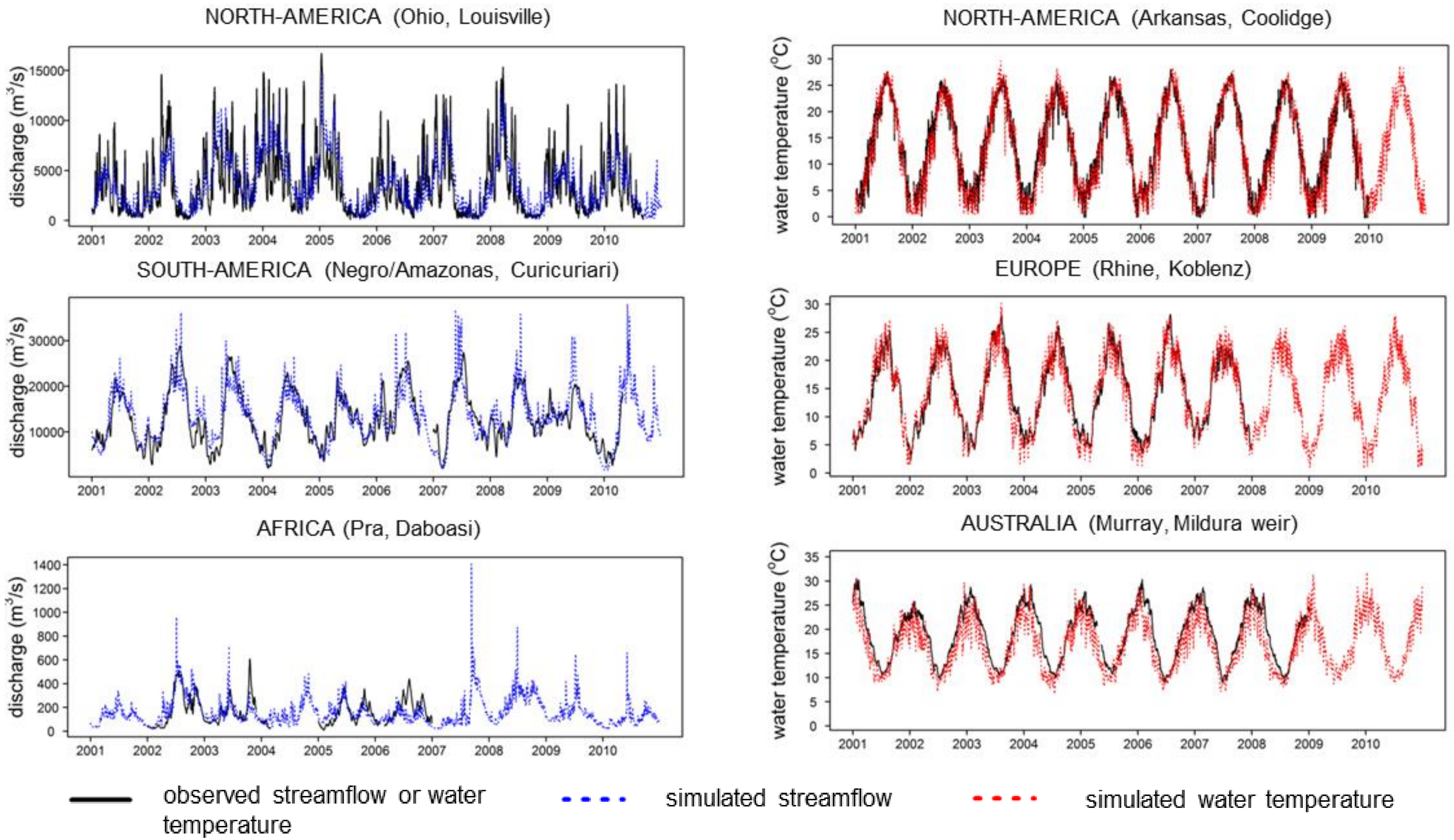
- World Electric Power Plant Database (WEPPD)

- **Hydropower**:
  - Simulated discharge
  - Hydraulic head
  - Efficiency
  - Installed capacity

- **Thermoelectric power:**
  - Daily discharge and water temperature
  - Efficiency
  - Installed capacity
  - Cooling system type
  - Environmental limitations

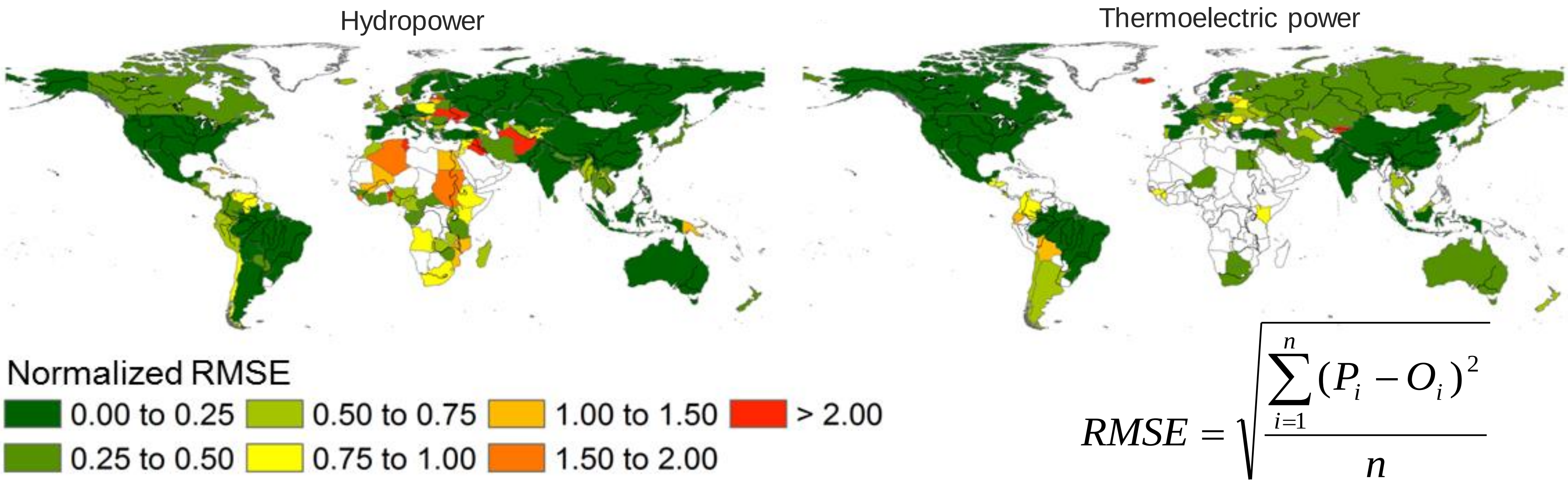


Model validation discharge and water temperature

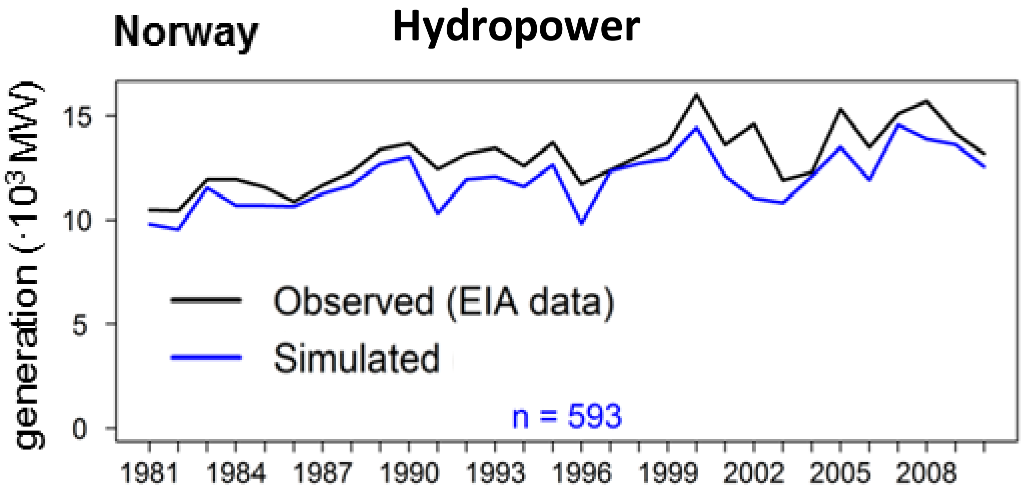


van Vliet et al (2016) Env. Res. Lett.

Model validation

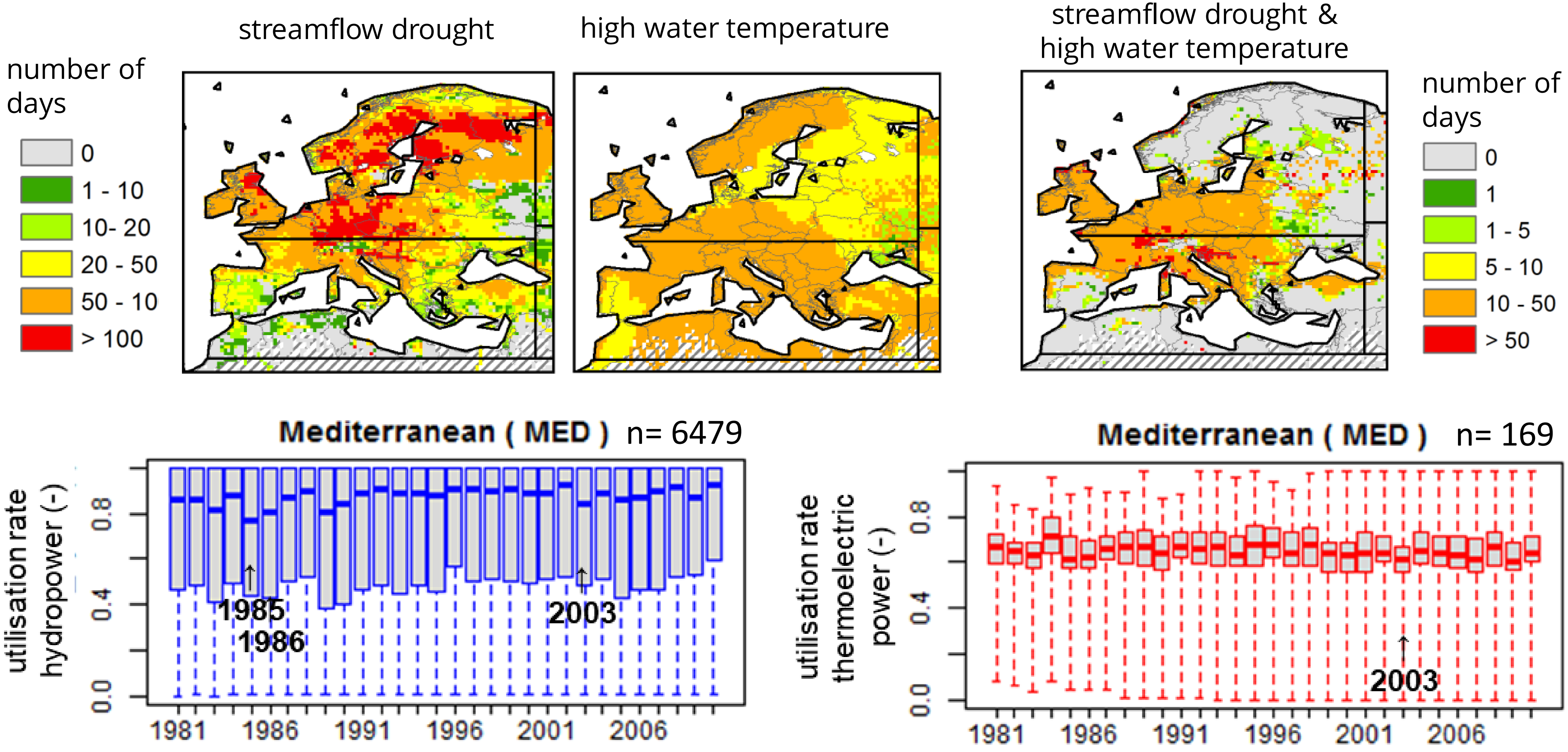


$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}}$$



- Aggregate simulations from plants to country level (annual timestep) to compare with reported values of EIA

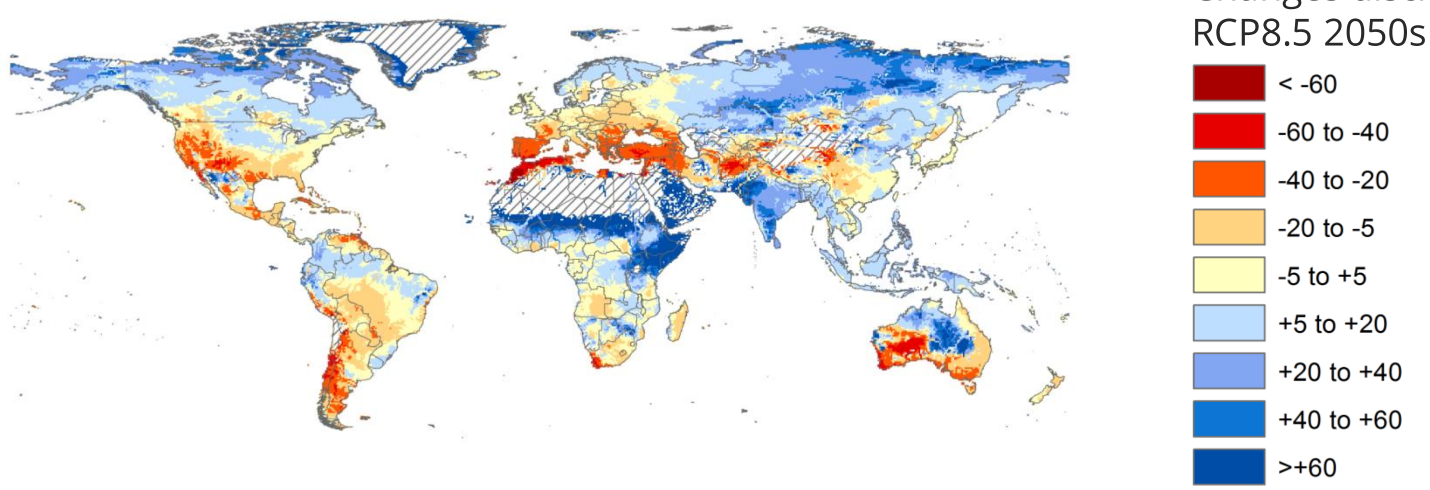
Impacts of European 2003 drought

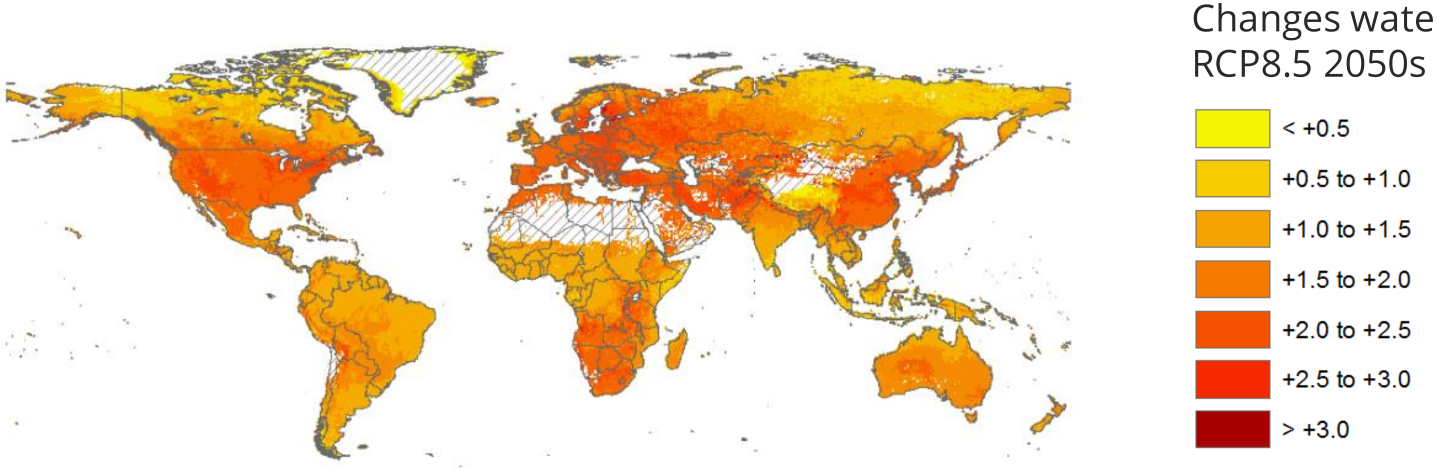


2003 European drought: reductions of 6.6% in hydropower and 4.7% in thermoelectric power compared to long-term average for 1981-2010

van Vliet et al (2016) Env. Res. Lett.

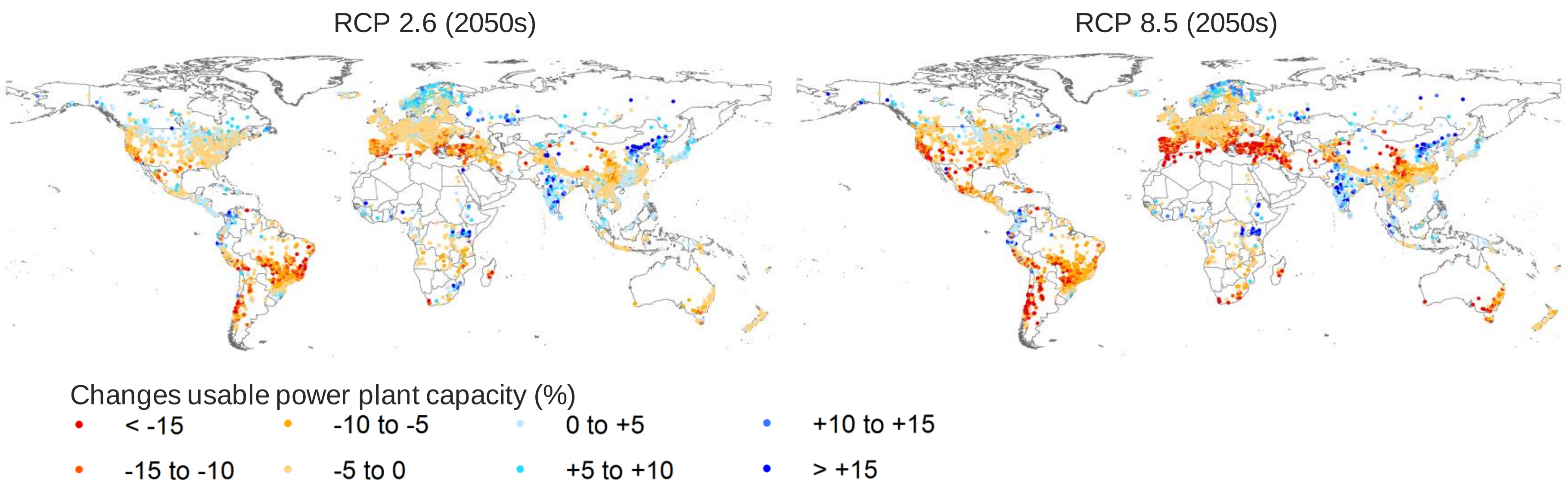
Climate change impacts on discharge and temperature



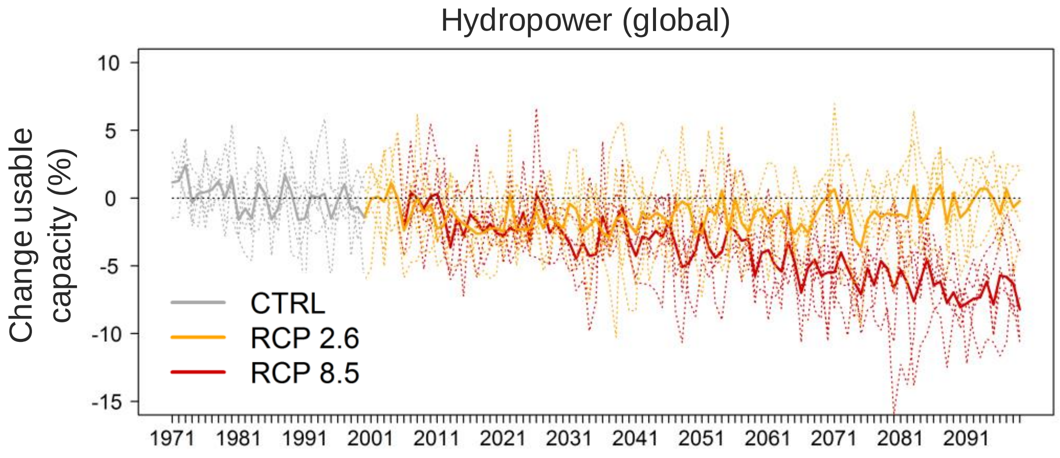


van Vliet et al (2016) Global Environmental Change

Climate change impacts on hydropower



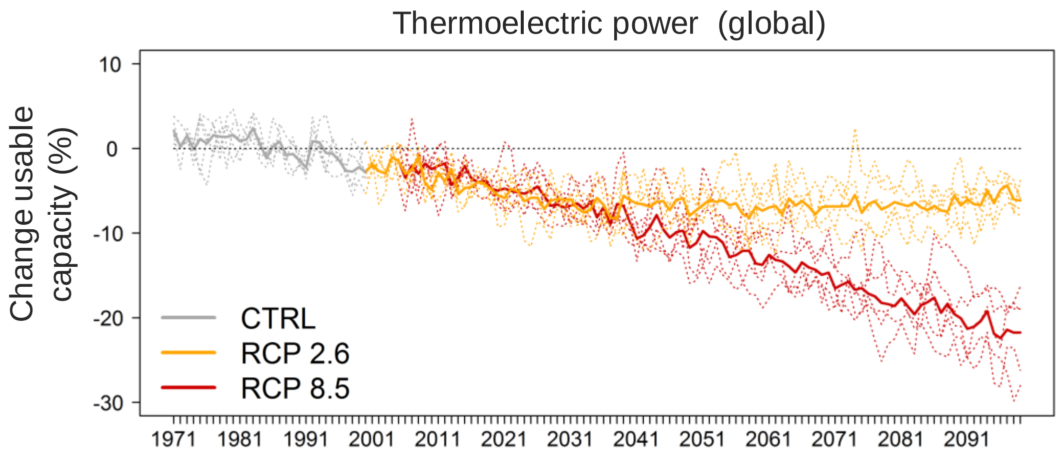
- Declines projected for **61 - 74%** of the hydropower plants
- Global reductions of **1.2 – 3.6%** for RCP2.6 - RCP8.5 (2050s)



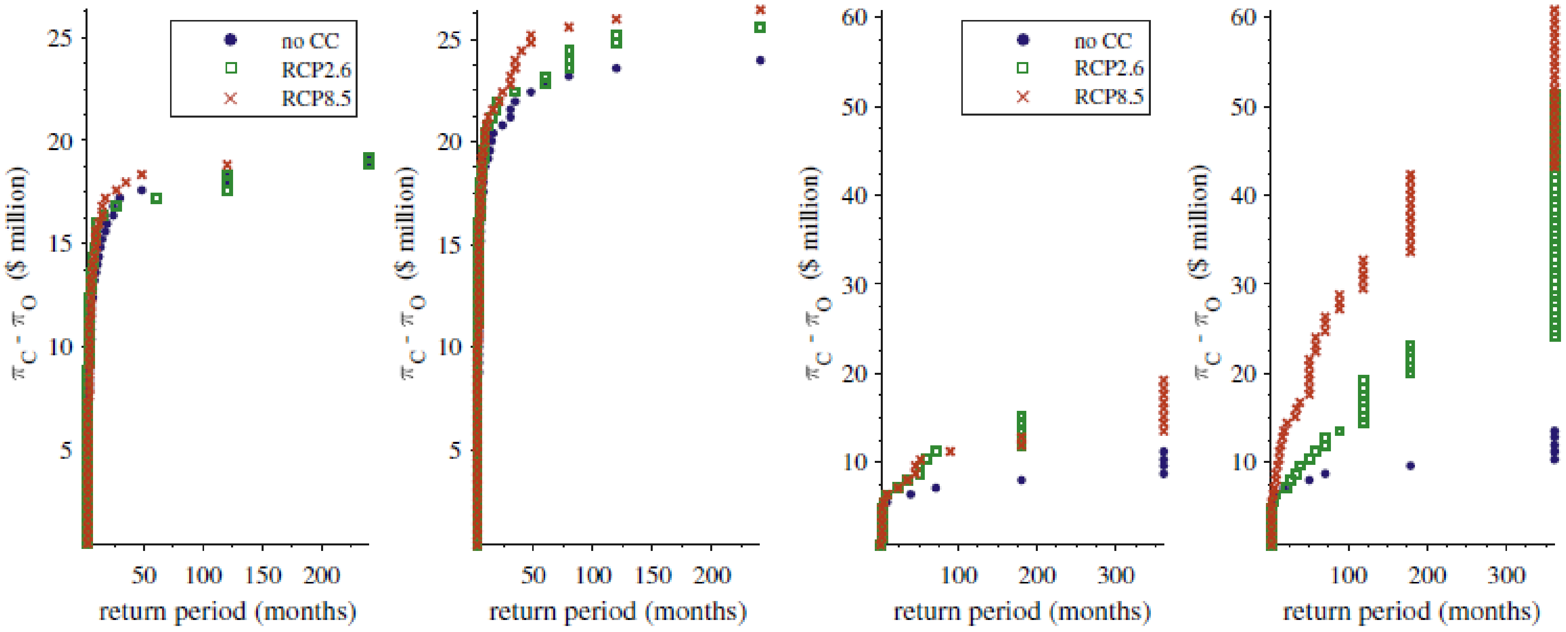
van Vliet et al (2016), Nature Climate Change

Climate change impacts on thermoelectric power

- Declines projected for **81 - 86%** of the thermoelectric plants
- Global reductions of **7 – 12%** for RCP2.6 - RCP8.5 (2050s)



Lost power plant profits due to decreased thermoelectric power plant usable capacities



Bogmans et al (2018) Energy Economics

Thank you very much!

Contact:

Dr. Michelle van Vliet
m.t.h.vanvliet@uu.nl

Utrecht University

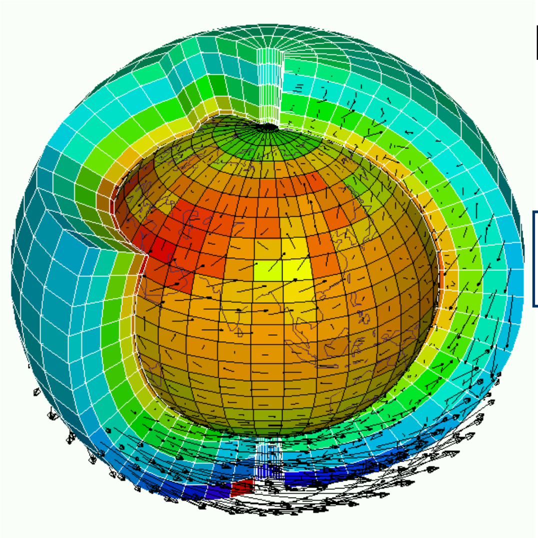
Wind & solar modeling for climate impacts

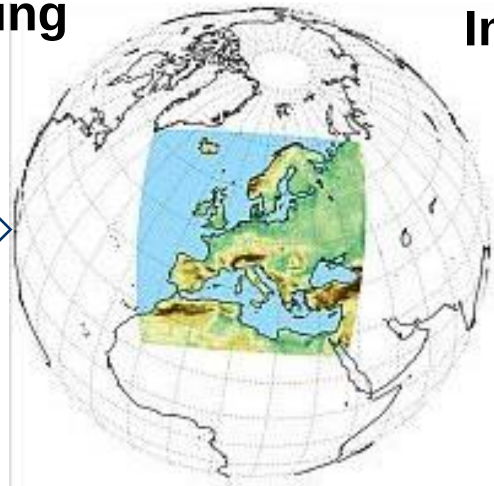
Robert Vautard Institut Pierre-Simon Laplace

Regional impact studies

Model assessment
Bias correction
Impacts modeling

Downscaling





Global climate model (100-300 km)

Regional climate model (10-50 km)

Impact model

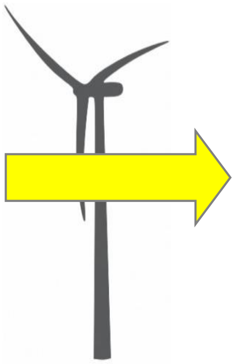
→ MED-CORDEX: new coupled simulations, processes

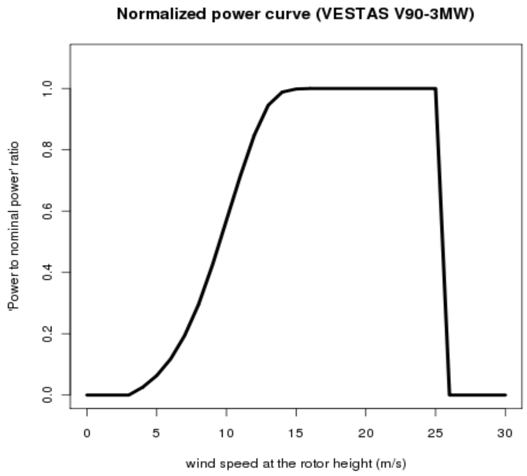
→ EURO-CORDEX : now~65 GCM-RCM projections (12 km)

→ To come: Convection permitting simulations

Wind / solar power load factor

100m wind





Load factor

In models: requires hourly 100 m (or 80 or 150) winds

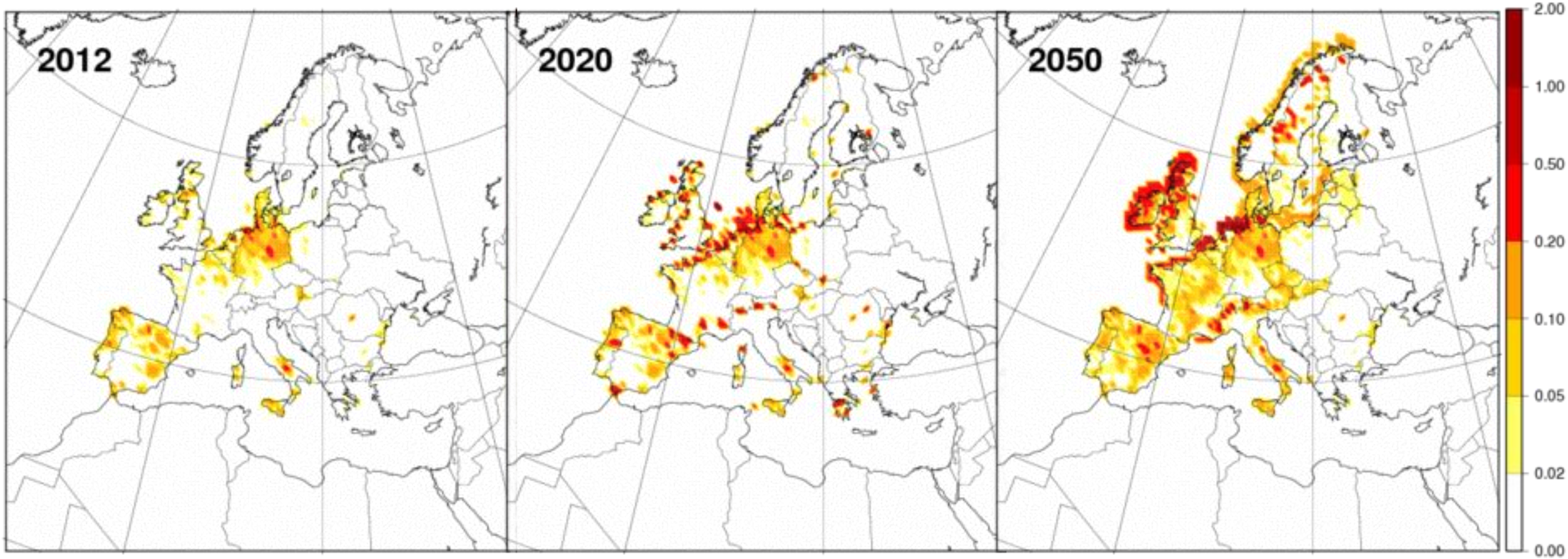
- → Usually 10m winds available (very different diurnal profile)
- → Usually daily data available only
- → Now consider several technologies

Solar power (PV): requires radiation, cloudiness, wind, temperature

- → Usually oversimplified formulae using global radiation
- → Recent progresses to include:
  - → Direct/diffuse radiation decomposition
  - → Separate rooftop, central with/without dual trackers

Development scenarios

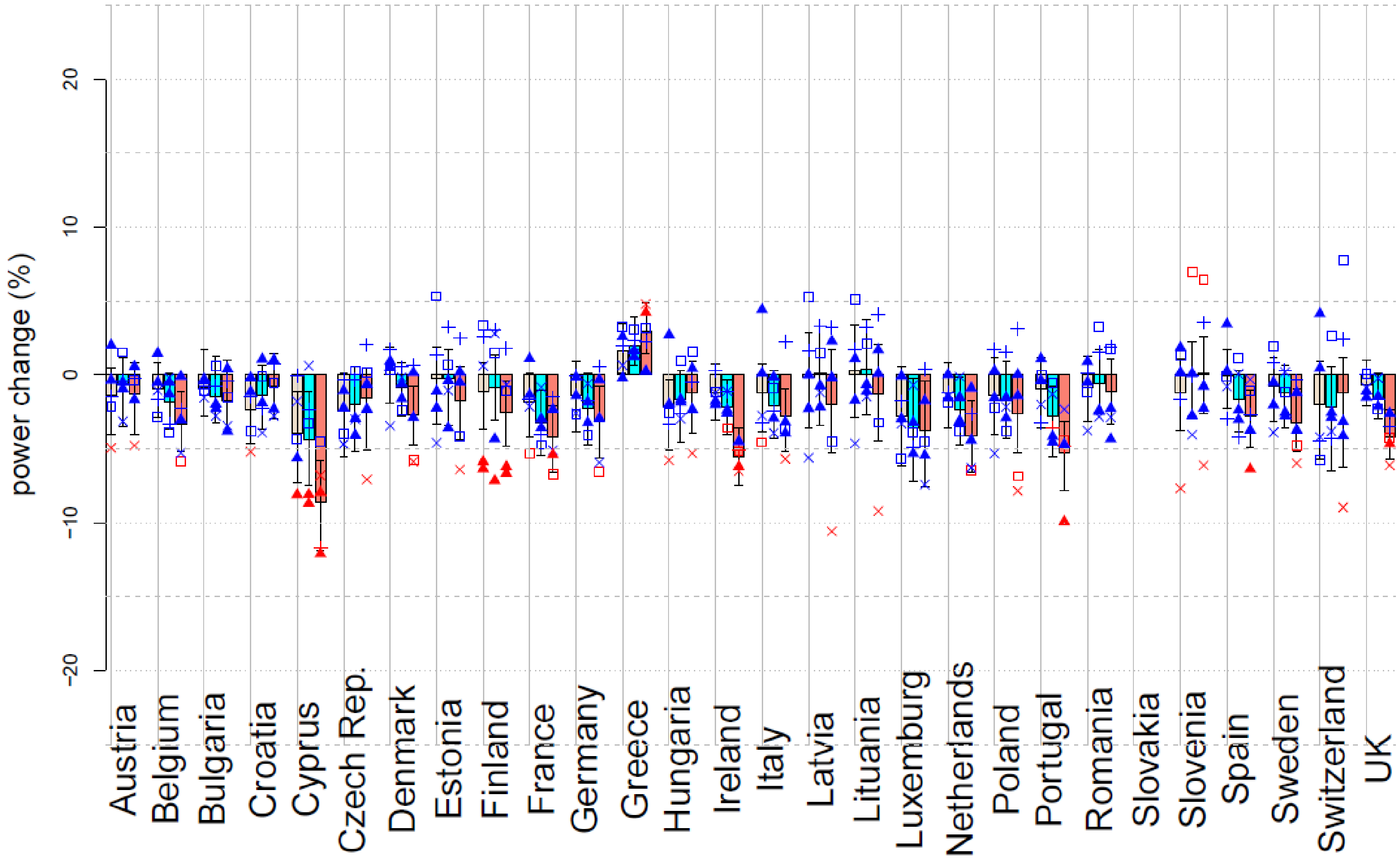
Tobin et al., 2018



Installed wind power according to 60% or 80% REs in 2050 (here 80%), 450 GWatts

Wind Power Changes for a 1.5°C, 2°C and 3°C global warming level

5 Euro-Cordex models used (Tobin et al., 2018, ERL)



Several projects and applications

- IMPACT2C (H2020) : estimating impacts for energy systems for 1.5°C and 2°C warming
- C3S Energy: CLIM4ENERGY demonstrator, then operational services
- EUCP (H2020) : case study on impacts for wind droughts estimation for producers or countries (see below)
- Several industry-led climate services projects (scenarios 2050, risk analysis)

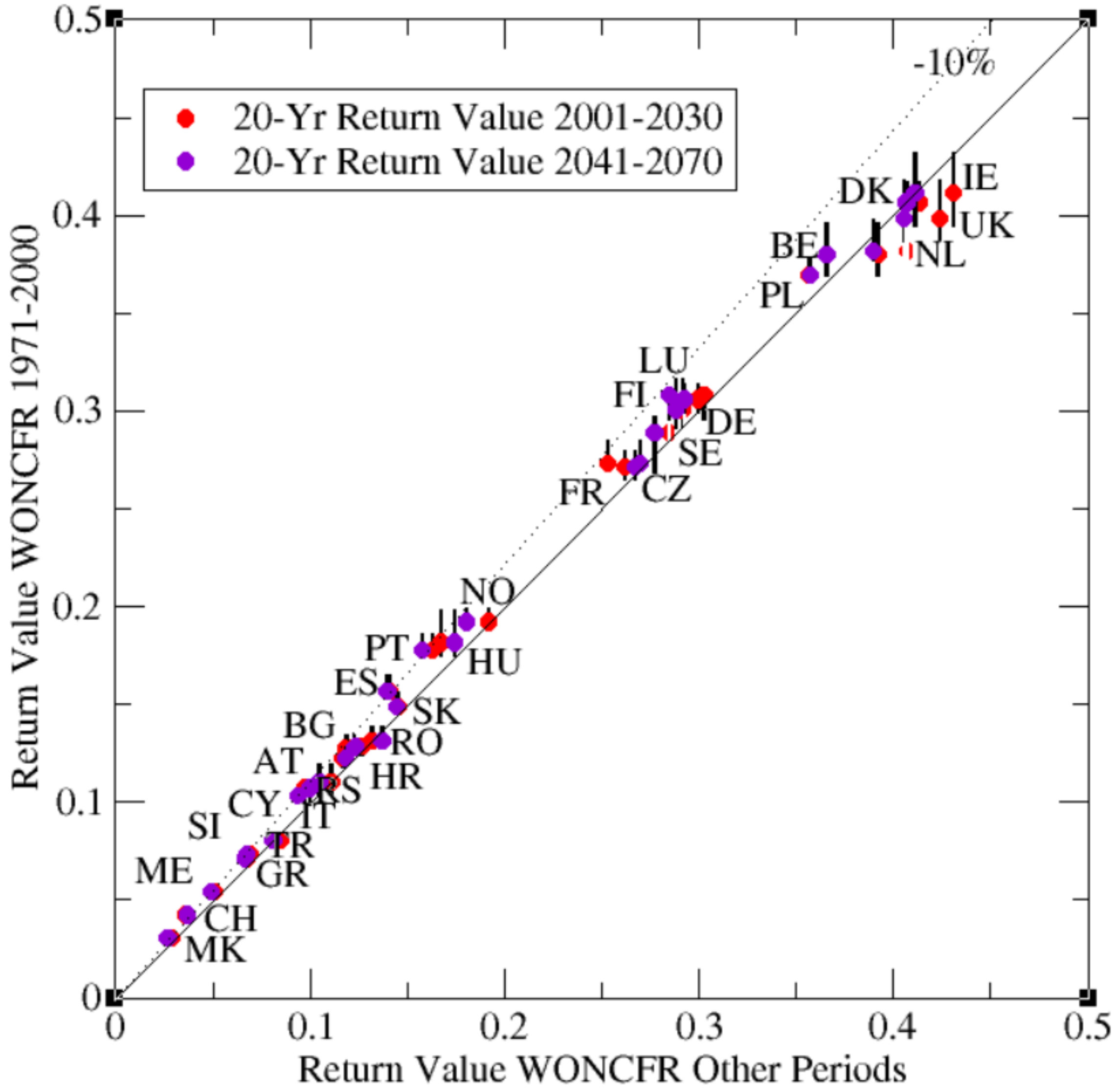
WIND POWER DROUGHTS: Change in intensity of 20-year return events of low-seasonal events

Using the C3S Energy projections (bias corrected) of the wind power load factor

Averaging over countries the load factor and over the winter season

Pooling models

Calculating extreme statistics (nonparametric method) over 2 time periods



H2020 EUCP Project

EXTREMES

Types of extremes for Res / Transmission network:
- Wind « droughts »
- Wind storms
- Low radiation extremes
- Heat waves (risks for power lines)
- Unbalanced loads

Attribution of extremes/events:
- How does the current extreme relate to climate change
- Can be applied to Res but also most types relating to energy sector (eg heat wave, cold spell, hydro drought, storms, wind/solar power bad seasons, …)

Thanks for your attention!

Robert Vautard Institut Pierre-Simon Laplace

Model eTIMES-EU

Clim2power - impacts of climate variability for a carbon-neutral EU power sector

Cross-sectoral ISIMIP and PROCLIAS online workshop 2021

ISIMIP Sector meeting: Energy (Fluctuations and extremes)

Sofia G. Simões[1], Edi Assoumou[2], Gildas Siggini[2], V. Sessa[2], Y-M., St. Drenan[3], S. Carvalho[4], P. Fortes[5], et al.

[1]LNEG, [2]ARMINES CMA - Sophia Antipolis, [3]ARMINES OIE, [4]FCUL Lisbon University, [5] CENSE–FCT NOVA University Lisbon

Key information

modeling approach

Energy (power) systems optimization model: *eTIMES-EU*

Unit commitment model - *DispaSET*

spatial and temporal scales of the model

National level (but NUT2 capacity factors)

eTIMES-EU: 3hr, week and weekend days for each season, 2016-2060

DispaSET: hourly, 2020

focus regions

each EU country + UK, NO, CH, IS

covered technologies

whole power sector

Solar PV

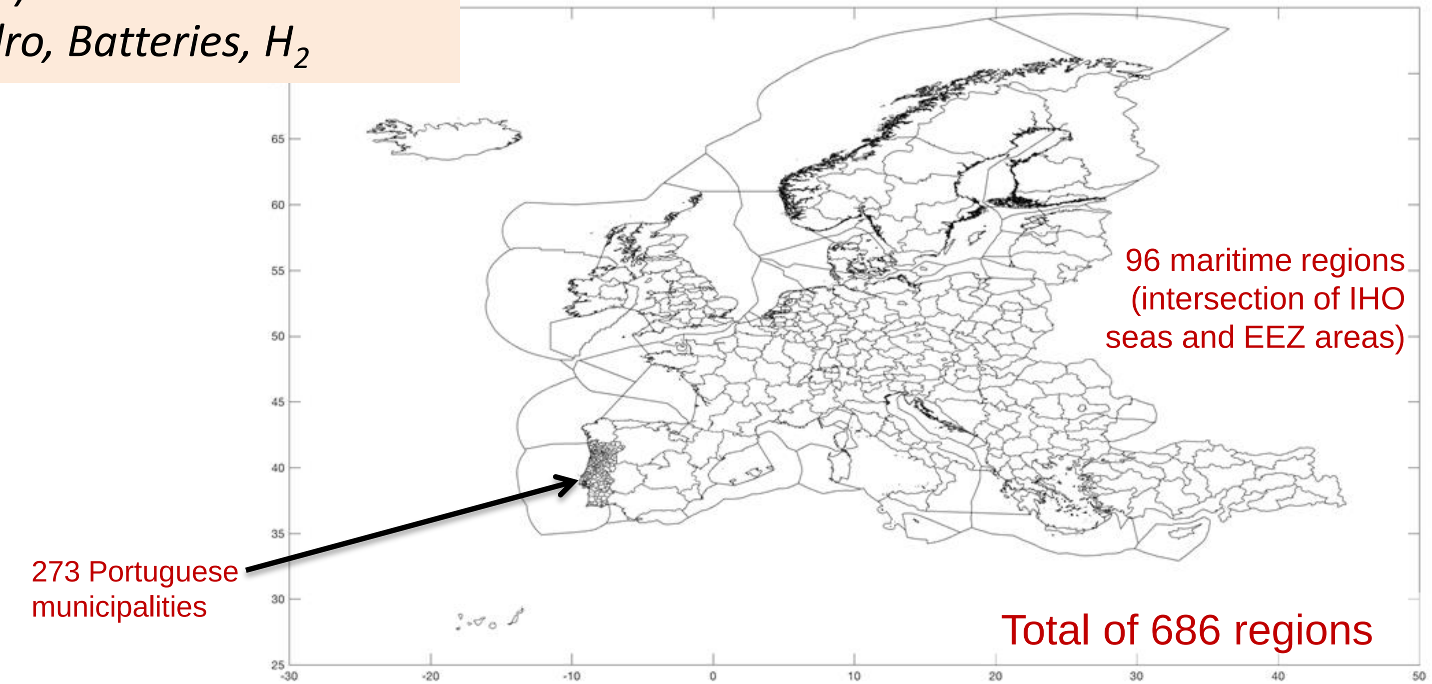
Onshore and offshore wind

Hydropower

Gas, coal, nuclear, geothermal, bioenergy (…)

Pumped hydro, Batteries, H_2

Capacity factors for solar and wind for 263 NUTS2 regions for Europe



IHO: international hydrographic association, EEZ: exclusive economic zone, NUTS: Nomenclature des unités territoriales statistiques

Clim2Power Pipeline – from climate data to energy/power indicators

Climate Data

- Reanalysis
  COSMO REA6, 1995-2015, 1hr (daily), 6km
- Seasonal Forecasts
  MPI-ESM-HR/GCFS2.0
  10+ runs, 6 months ahead, daily, 6km, monthly updates
- Climate Projections
  EUROCORDEX, 11 climate models, RCP4.5 & 8.5, 1976-2065, daily, 12.5km

Machine Learning non-Douro + Hydrological models (Danube, Lule älv, Douro)

PV and wind statistical simulation tools

Electricity, space heating demand (machine learning)

TIMES (long-term) Dispa-SET (seasonal) models

Co-Development with User Board(s)

with end-users

Web Service Application

interactive, user-friendly layout

Input Indicators

- Hydro capacity factors (national)
- Wind & Solar capacity factors (NUT4)
- Variation in demand for space heating in buildings (national)

Output Indicators (national,

- % of electricity generated from RES
- g CO_2/kWh
- GWh and % power generated from wind, solar, hydro and total
- % usage of existing electric grid interconnection capacity
- electricity stored in batteries and hydro pumped storage (GWh)

(...)

Long-term
2030, 2050
(22

- RCP4.5 Carbon-neutral power system in 2050
- RCP8.5 Carbon-neutral power system in 2050

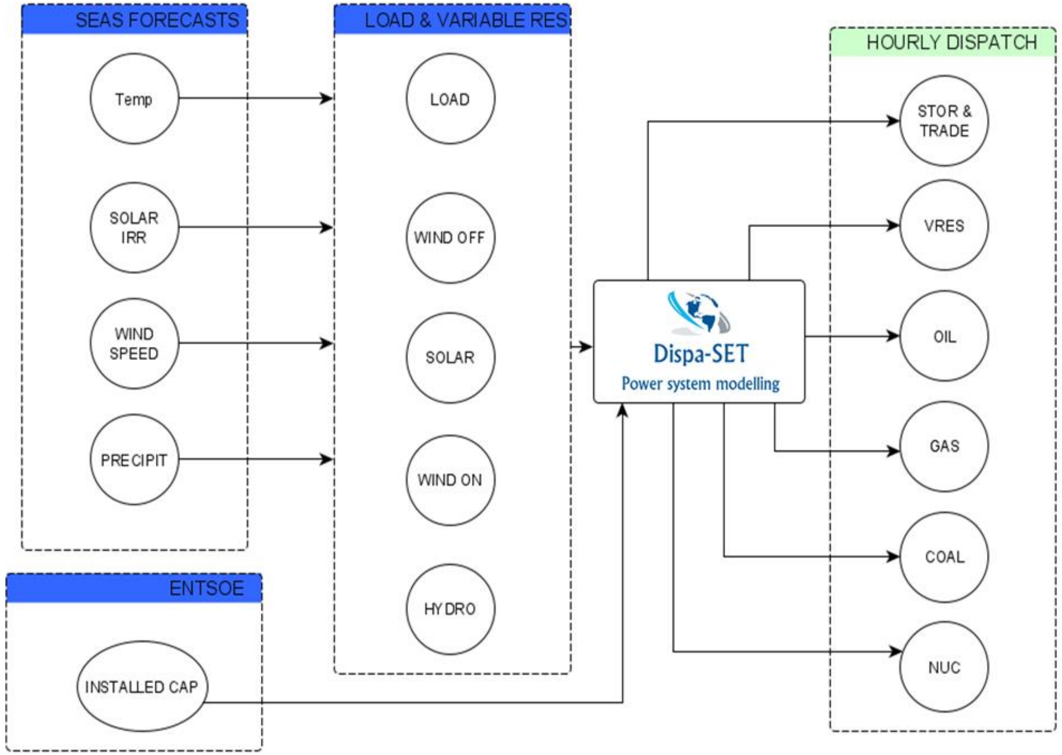
Seasonal
(50 members)

1. Fall 2019 [SON]
2. Winter 2019/2020 [DJF]
3. Spring 2020 [MAM]
4. Summer 2020 [JJA]

Models for interconnected power system in Europe

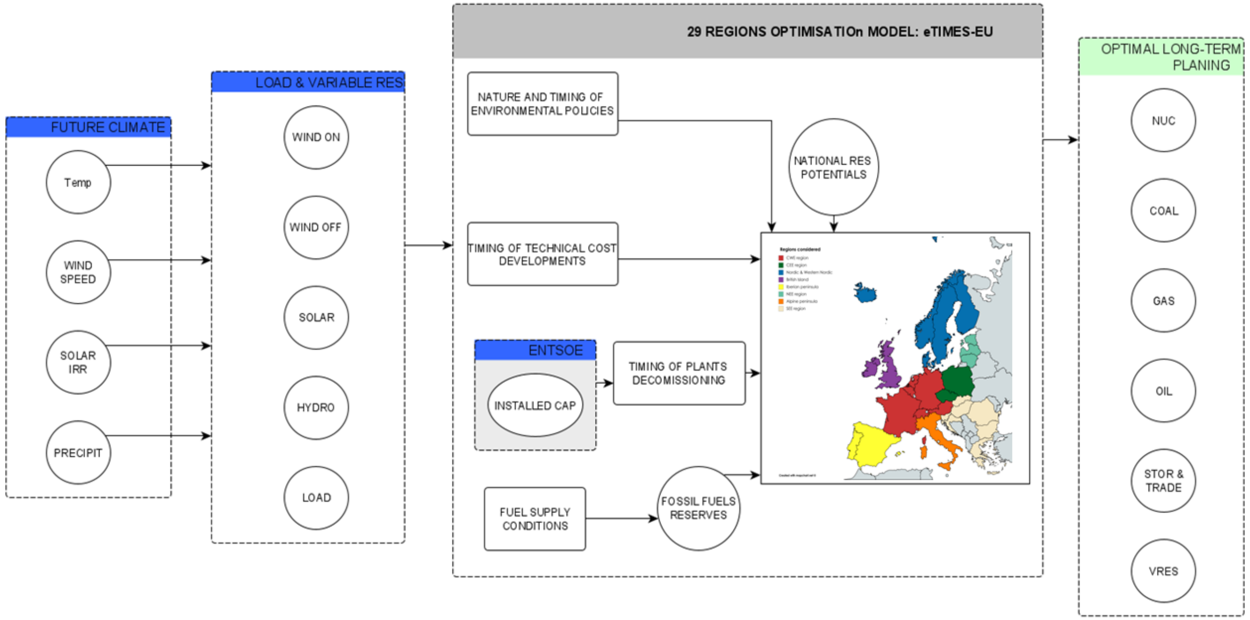
(each country is disaggregated)

Seasonal Forecasts: Dispa-SET unit commitment model (hourly balancing)



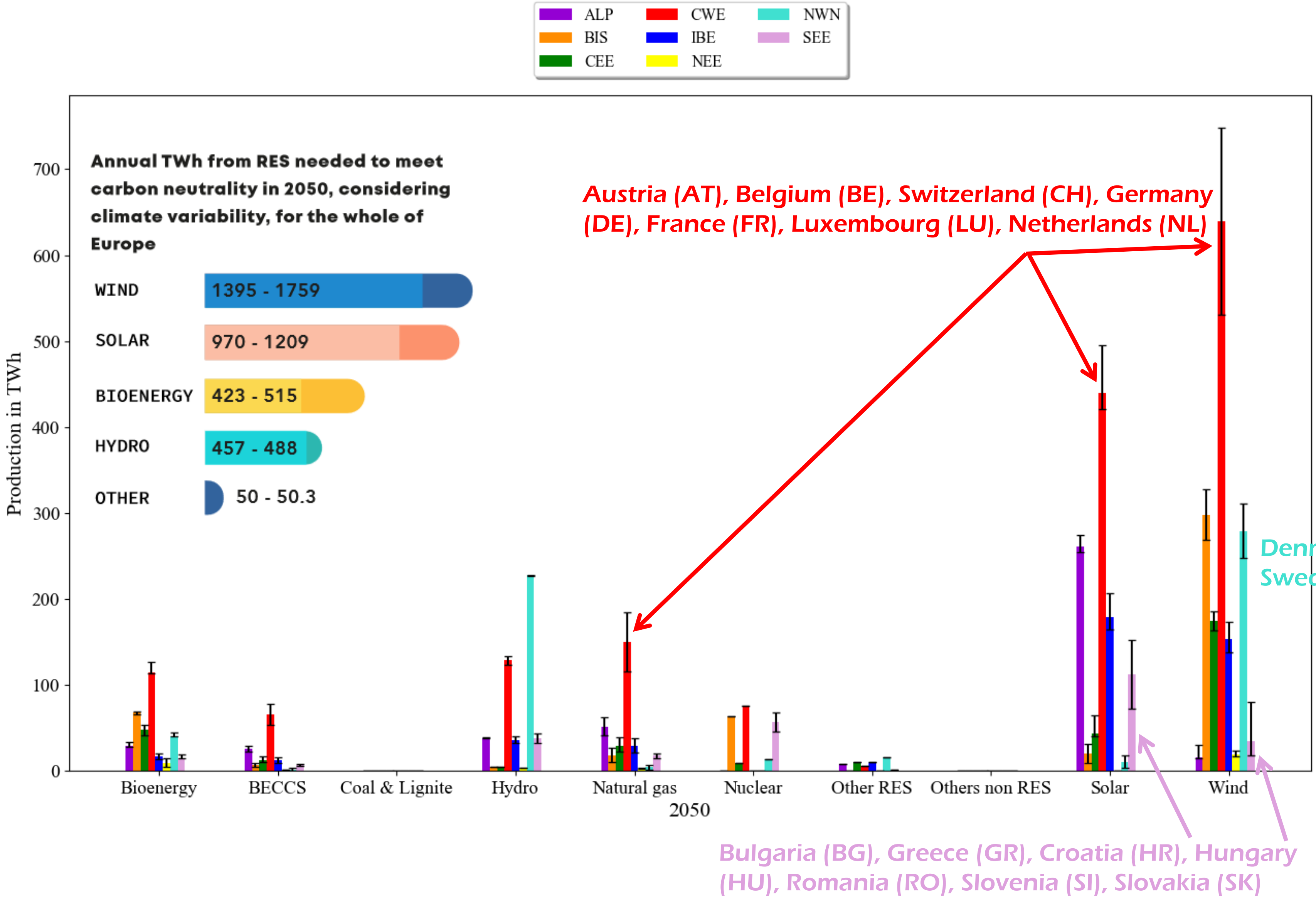
Run for all ensemble members in each forecast

Long-term Projections: eTIMES-EU cost minimisation model (3hr, week and weekend days for each season)



Run for 22 climate projections, 2016-2050, carbon neutral by 2050

Long-term→ Generated power in 2050 (TWh)



By considering climate projections when having a carbon neutral EU+ by 2050:

- variations TWh from wind and solar (CWE, NWN, SEE)
- affect natural gas (CWE) and nuclear (SEE)

Alpine Peninsula	ALP	Italy (IT)
British Islands	BIS	Ireland (IE), United Kingdom (UK)
Iberian Peninsula	IBE	Spain (ES, Portugal (PT)
Central West Europe	CWE	Austria (AT), Belgium (BE), Switzerland (CH), Germany (DE), France (FR), Luxembourg (LU), Netherlands (NL)
Central East Europe	CEE	Czech Republic (CZ), Poland (PL)
Nordic & Western Nordic	NWN	Denmark (DK), Finland(FI), Norway (NO), Sweden (SE), Iceland (IS)
Nordic & Eastern Nordic	NEE	Estonia (EE), Lithuania (LT), Latvia (LV)
South Eastern Europe	SEE	Bulgaria (BG), Greece (GR), Croatia (HR), Hungary (HU), Romania (RO), Slovenia (SI), Slovakia (SK)

Clim2power webservice

http://viewer.webservice-energy.org/clim2power/

2-4 pages report (pfd) with most relevant output indicators per country

Interactive maps for outputs and indicators per country, region or whole of Europe

Raw data (output indicators) to be downloaded)

3 infographics for selected output indicators

Thanks everyone!

More on CLIM2POWER:

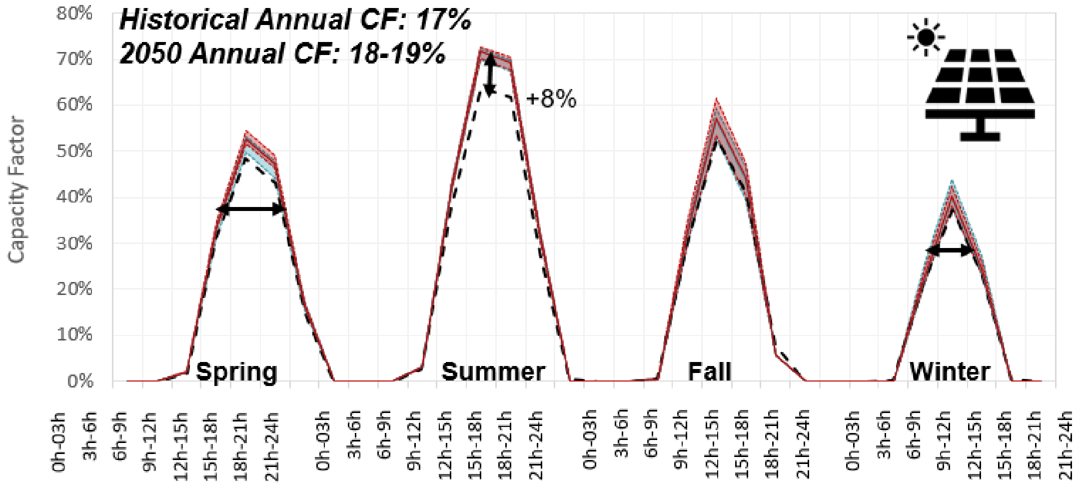
https://clim2power.com/

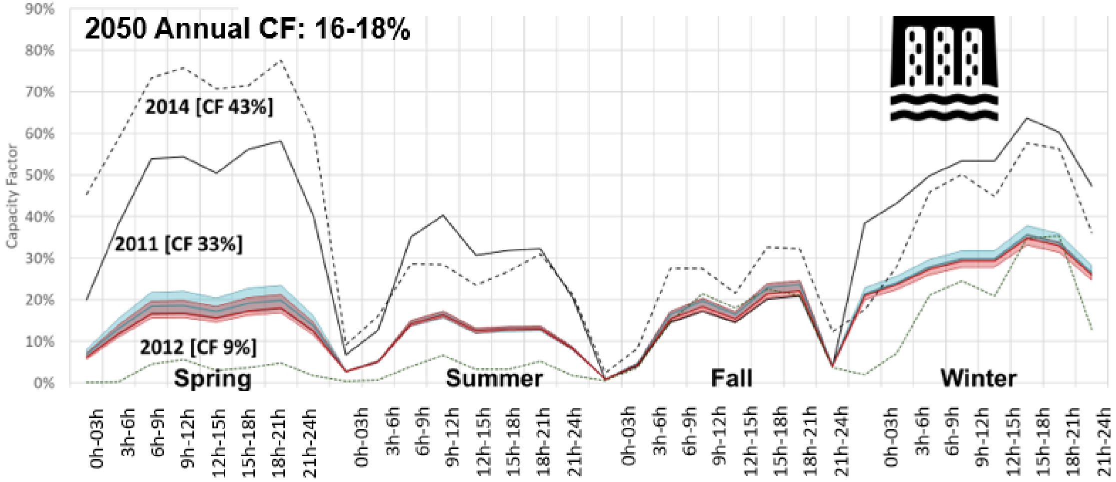
sofia.simoes@lneg.pt

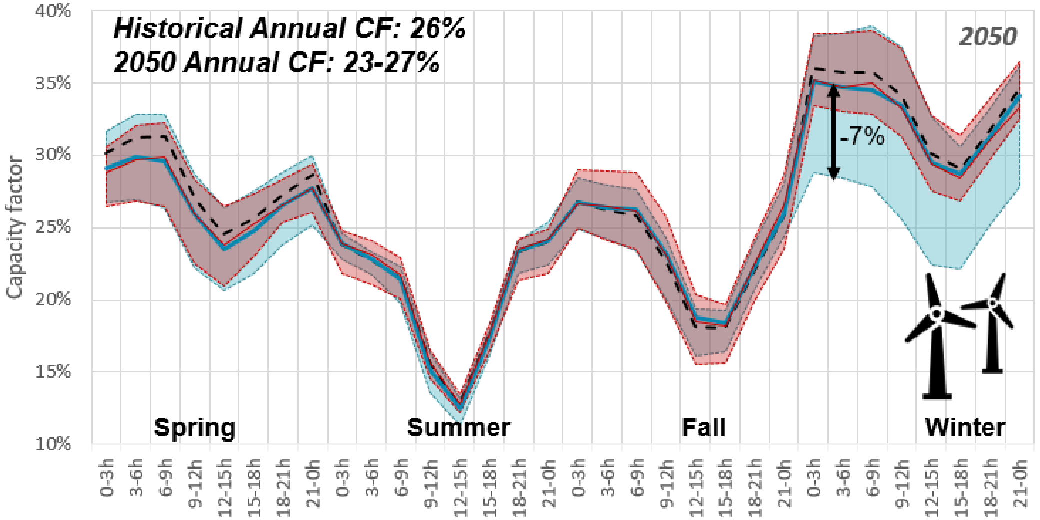
Project CLIM2POWER is part of ERA4CS, an ERA-NET initiated by JPI Climate, and funded by FORMAS (SE), DLR (DE), BMWFW (AT), FCT (PT), EPA (IE), ANR (FR) with co-funding by the European Union (Grant 690462).

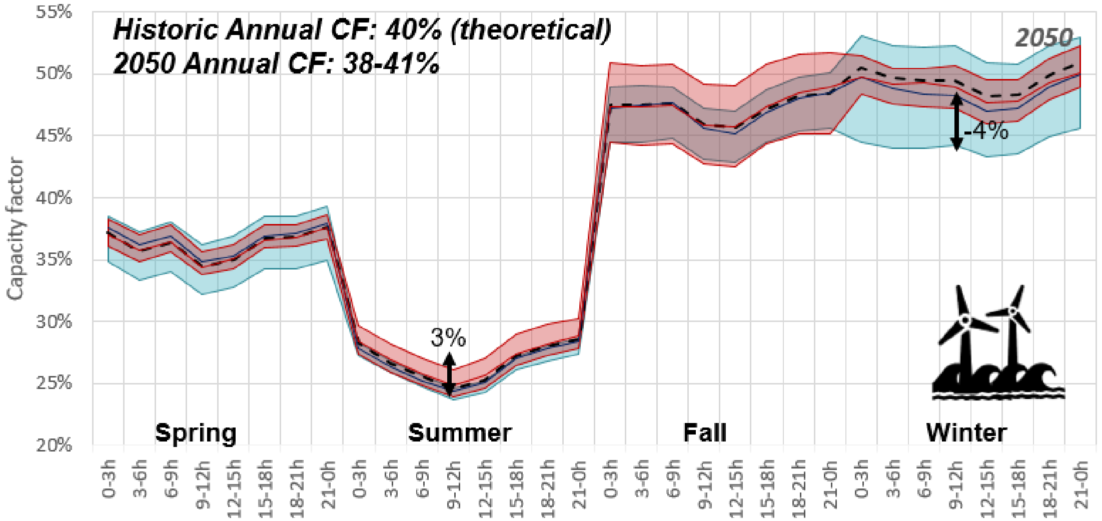
How capacity factors could look like in 2050

RCP4.5 RCP8.5 - - - - Historic climate trends (no climate change)









Potsdam Institute for Climate Impact Research

Investigating the Risk of Hurricane-Induced Cascading Failures in Power Systems of the U.S. East Coast

Julian Stürmer

Julian.Stuermer@pik-potsdam.de

11.01.2021

Leibniz-Gemeinschaft

Motivation

Collaboration:

Mehrnaz Anvari[1], Anton Plietzsch[1], Frank Hellmann[1],
Christian Otto[2], Thomas Vogt[2]

[1] Research Department 4: *Complexity Science* (PIK)

[2] Research Department 3: *Transformation Pathways* (PIK)

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Idea: Study the impact of hurricanes on power grids

→ Combine two research topics:

1. Storm impact modeling
   (focus on power grids)
2. Power grid modeling
   (focus on cascading failures)

Hurricane Laura, Sulphur, LA (August 30, 2020)

Image courtesy of Entergy Louisiana

Model Overview

First step: Choose a geographical region of interest (e.g. Texas)

Storm impact modeling **Power grid modeling**

Input Data

Algorithms

Results

Model Overview

First step: Choose a geographical region of interest (e.g. Texas)

	Storm impact modeling		Power grid modeling
Input Data	Wind data (discrete)	Historical damage data	Power grid data (topology etc.)
Algorithms			
Results			

Model Overview

First step: Choose a geographical region of interest (e.g. Texas)

Storm impact modeling

Power grid modeling

Input Data

Wind data (discrete)

Historical damage data

Power grid data (topology etc.)

Algorithms

Probabilistic component fragility model

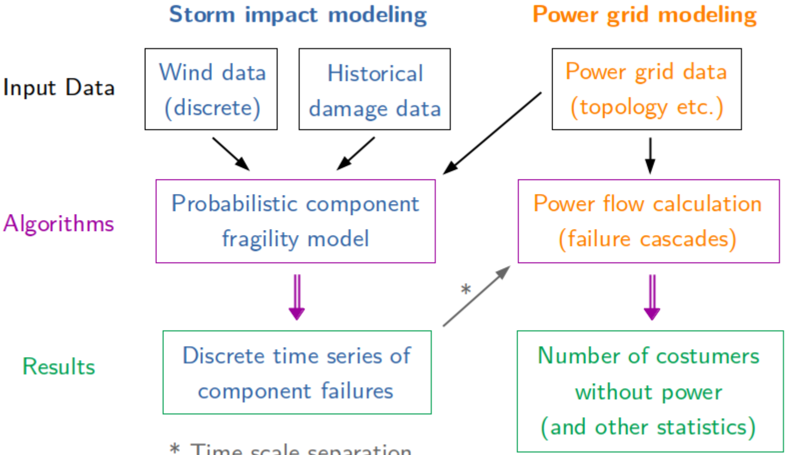
Results

Discrete time series of component failures

Julian.Stuermer@pik-potsdam.de

Model Overview

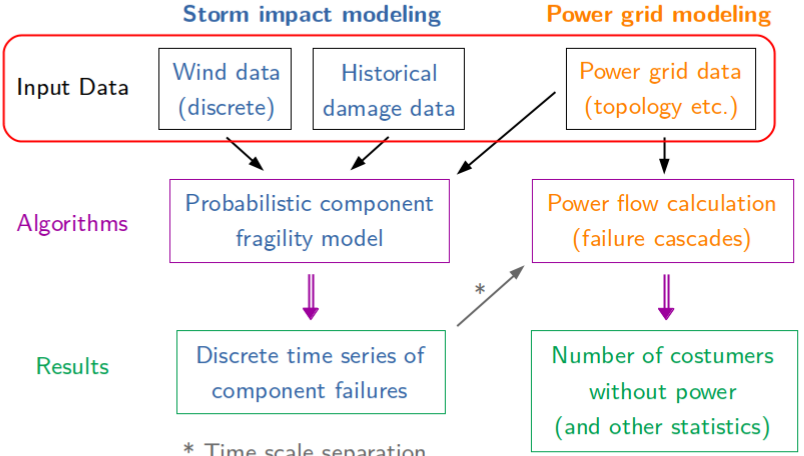
First step: Choose a geographical region of interest (e.g. Texas)



* Time scale separation

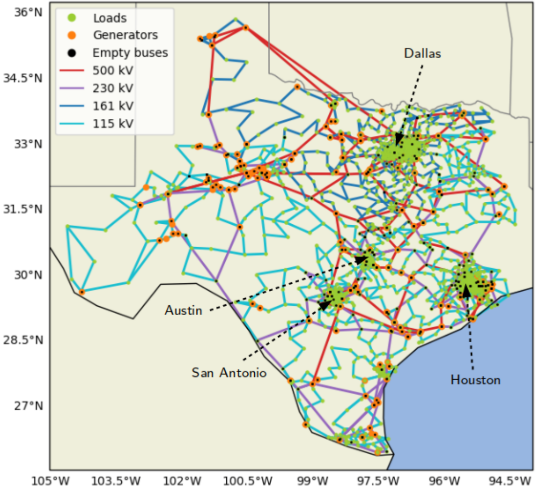
Model Overview

First step: Choose a geographical region of interest (e.g. Texas)



* Time scale separation

Synthetic Grid for Texas



Test case data with:

- 2000 buses
- 1125 load buses with $\sim 70\,\mathrm{MVA}$ total load
- 432 generator buses

... in 1250 substations

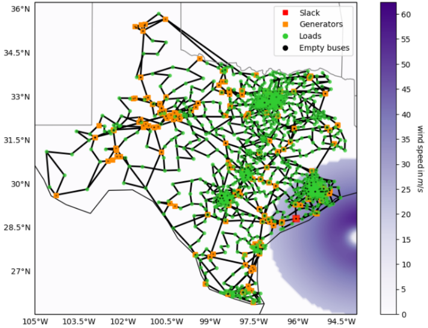
- 861 transformers
- 2345 transmission lines
- 4 high voltage levels

Grid data available at https://electricgrids.engr.tamu.edu/electric-grid-test-cases/

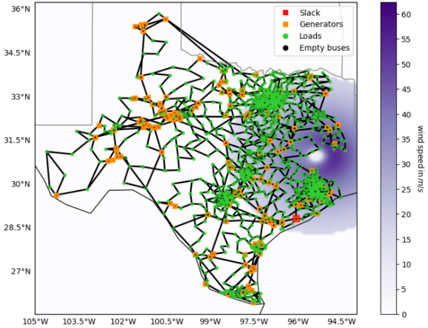
constructed by the group of T. J. Overbye at Texas A&M University

Wind Data

- Wind fields calculated by Thomas Vogt using **CLIMADA** (Python) and historical storm tracks from **IBTrACS**
- For now: $0.1° \times 0.1°$ spatial resolution and $1\,\mathrm{h}$ time resolution



Hurricane Ike 2008-09-13 00:00:00 UTC



Hurricane Ike 2008-09-13 12:00:00 UTC

Transmission Line Fragility

Standard wind force design equation:

$$F_{\text{wind}}(v, L) = Q k_z I_{\text{FW}} G_{\text{WRF}}(L)\, C_{\text{f}} A_{\text{C}} v^2 \quad (1)$$

Q - air density,
k_z - terrain correction,
I_{FW} - importance factor,

G_{WRF} - wire gust response factor,
C_{f} - force coefficient,
v - wind speed in m/s,
L - line length in m

Eq. (1) taken from ASCE Report 113, *Substation Structure Design Guide* (2007)

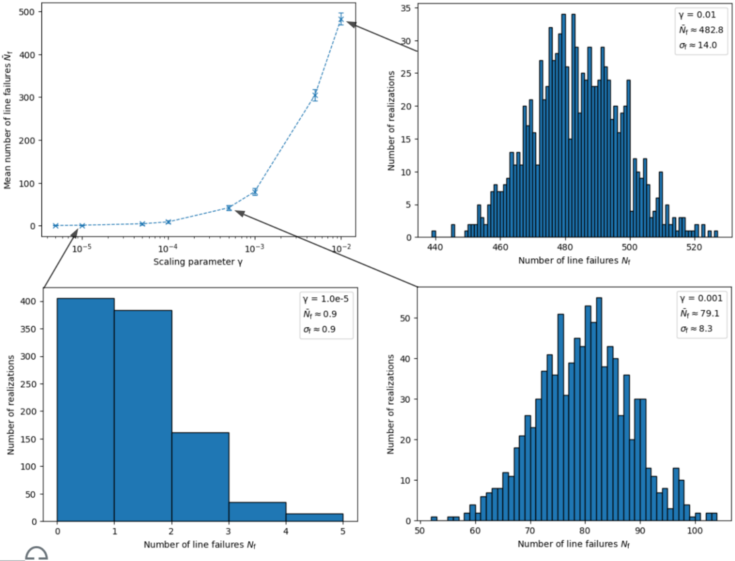
→ Damage probability for line l:

$$p_{\text{f,wind},l} = \min\left(\gamma \frac{F_{\text{wind},l}}{F_{\text{brk},l}}, 1.0\right), \quad (2)$$

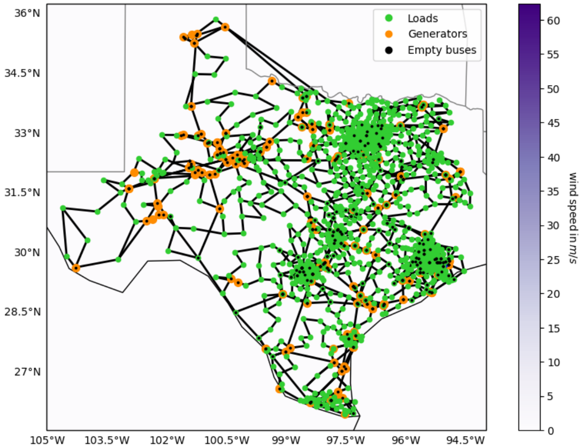
with scaling factor γ and breaking load $F_{\text{brk},l}$

Eq. (2) taken from J. Winkler et al., Reliability Engineering and System Safety 95 (2010) 323–336

Transmission Line Fragility Results

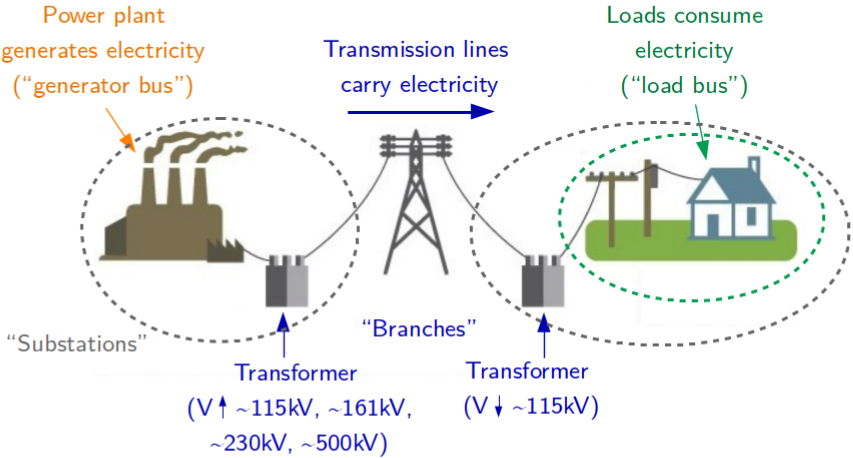


Transmission Line Fragility Results



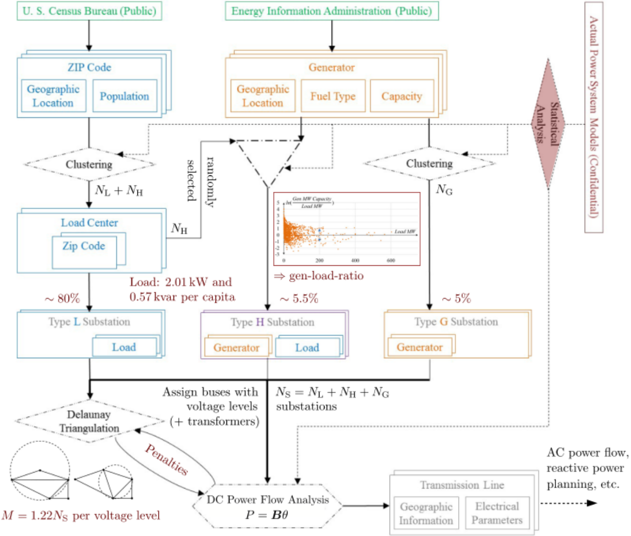
Hurricane Ike (2008) passing over Texas ($\gamma = 0.055$)

Power Grid Components



Source: Adapted from National Energy Education Development Project (public domain)

Transmission Grid Synthesis



T. Xu et al., Proc. 50th Hawaii Int. Conf. Syst., 3123-3129 (2017)
A. B. Birchfield et al., IEEE Trans. Power Syst. Vol. 32, 3258-3265 (2017)

AC Power Flow Equations

Apparent power $S_i = P_i + \mathrm{i}Q_i = V_i I_i^*$, voltage $V_i = |V_i| e^{\mathrm{i}\theta_i}$,

current $I_i = \sum_{j=1}^{N} Y_{ij} V_j$, admittance $Y_{ij} = G_{ij} + \mathrm{i}B_{ij}$,

$$\Rightarrow P_i = \sum_{j=1}^{N} |V_i||V_j|(G_{ij}\cos(\theta_i - \theta_j) + B_{ij}\sin(\theta_i - \theta_j)), \tag{3}$$

$$\Rightarrow Q_i = \sum_{j=1}^{N} |V_i||V_j|(G_{ij}\sin(\theta_i - \theta_j) - B_{ij}\cos(\theta_i - \theta_j)), \tag{4}$$

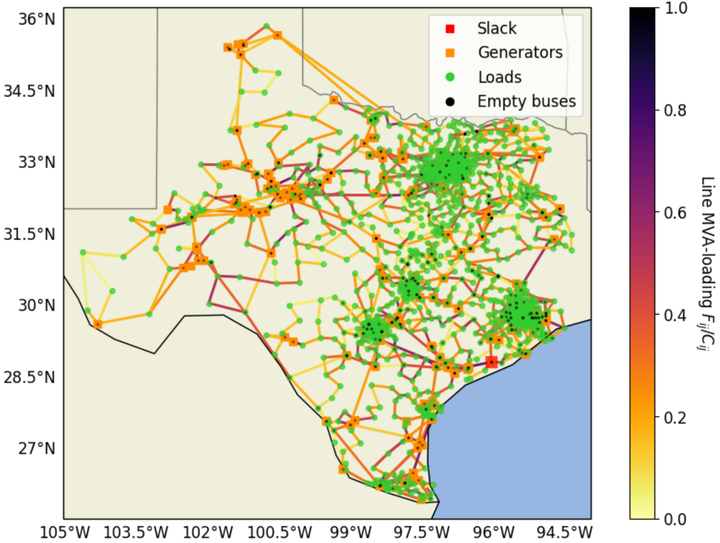
Loads: PQ-buses with $P, Q < 0$ ($|V|$, θ unknown)

Generators: PV-buses with $P, |V| = \text{const}$ (θ unknown)

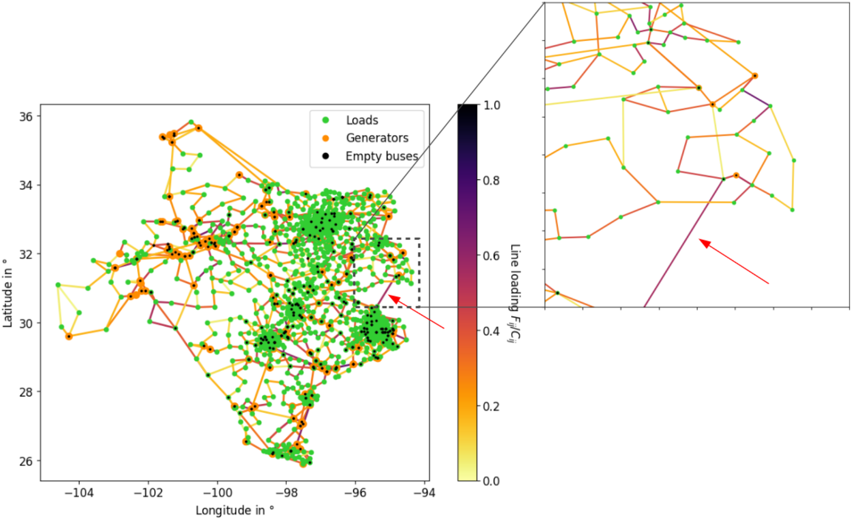
Slack bus: $|V|, \theta$ fixed and P compensates losses

https://github.com/lanl-ansi/PowerModels.jl

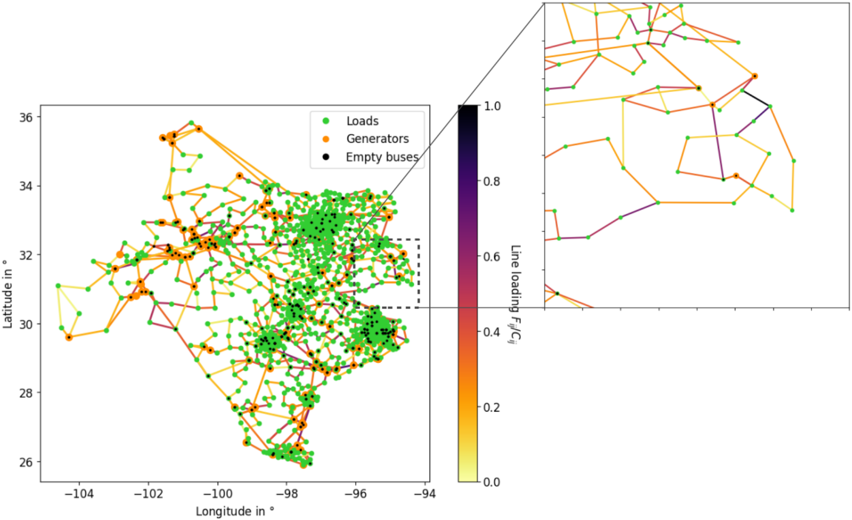
Texas AC Power Flow



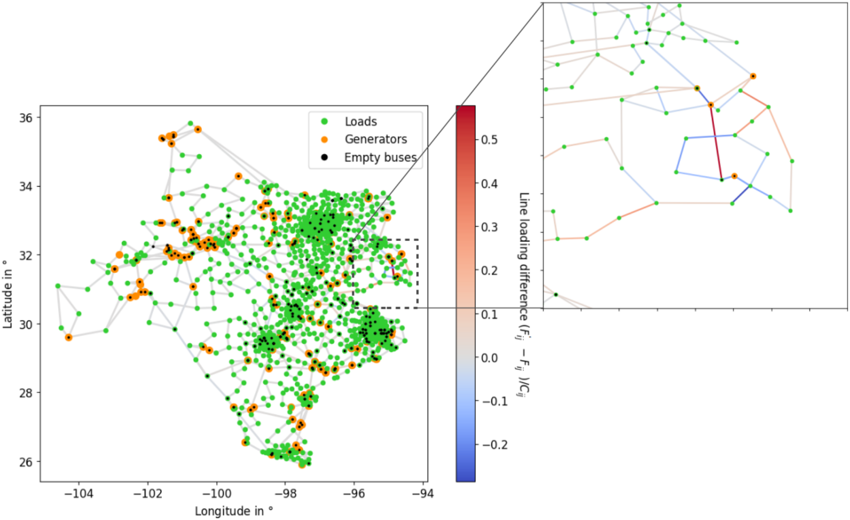
Outlook - Exemplary Line Failure



Outlook - Exemplary Line Failure



Outlook - Exemplary Line Failure



Outlook - Exemplary Line Failure