

ENERGY FORECASTING SYSTEMS FOR RENEWABLE ENERGY

AN APPROACH TO THE INDIAN POWER MARKET

BY: DHANAJI PATIL & OMAR HALASA
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Our Story



Founding Partners

Sirocco Energy is a spin-off company from Vortex FDC and Meteored, two industry giants in wind modeling and weather forecasting with **more than 20 years of experience.**

Sirocco Energy

We offer accurate **short-term forecasting** solutions for power generation and weather variables for **wind and solar farms in the renewable energy industry.**

Our Experience

350

GW of forecasted
power

10

TB of analyzed data

15

minutes provided
for nowcasting

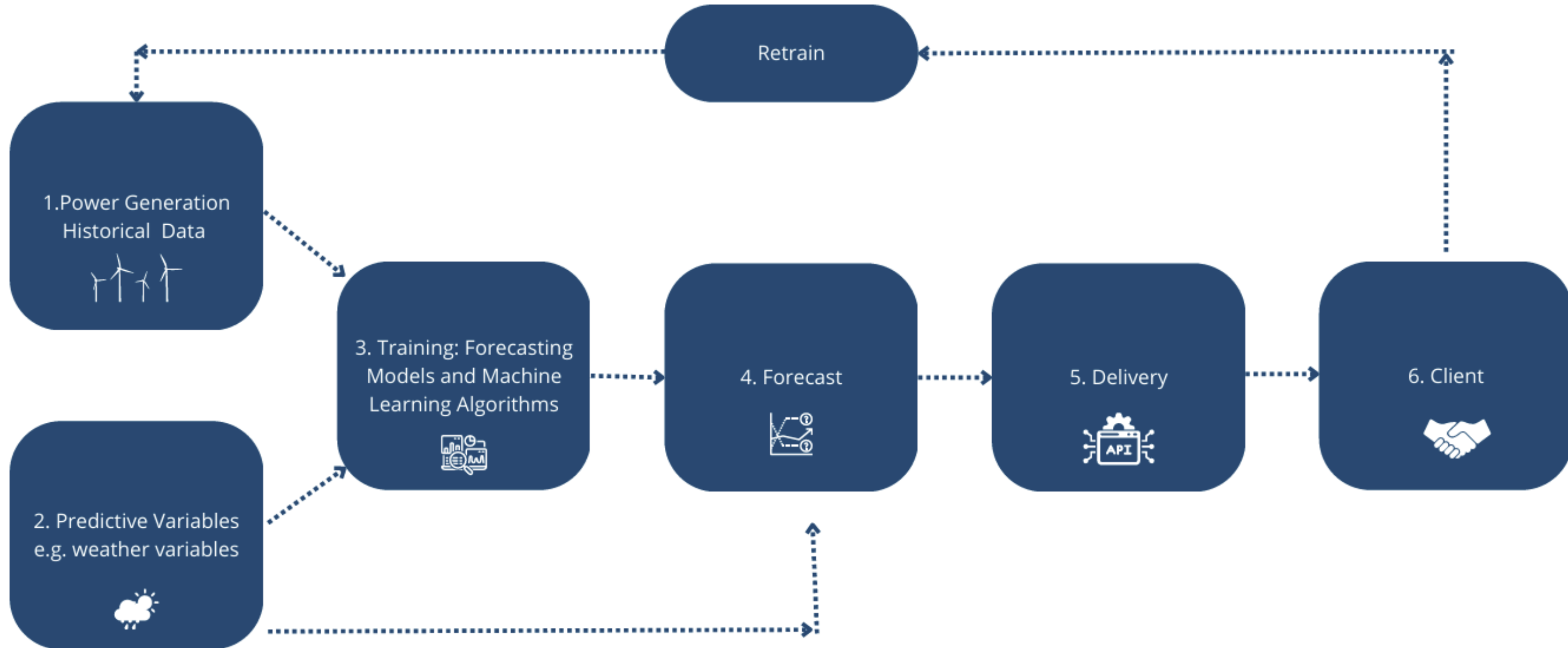
35

countries trust
our services

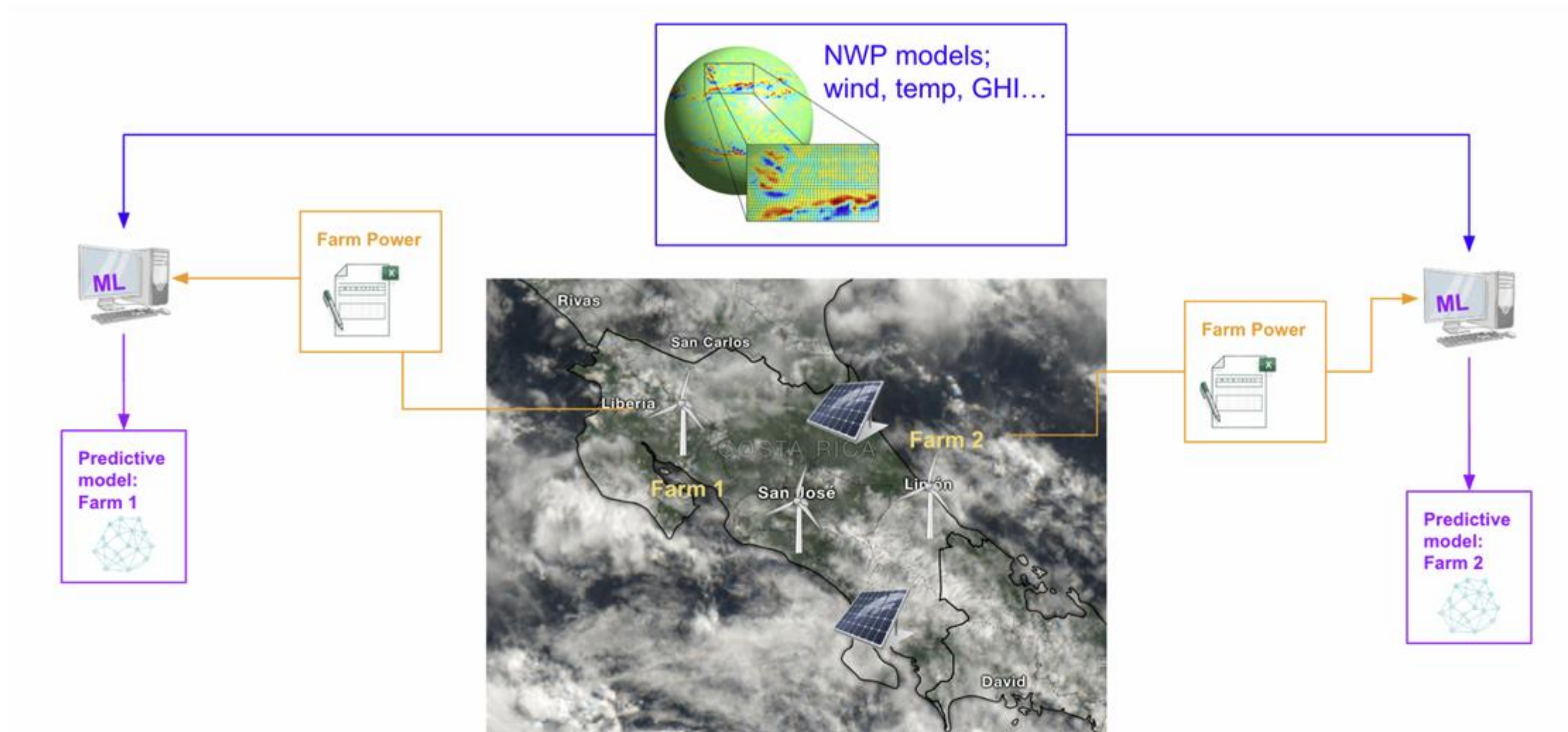
Our Products

- **Day-Ahead Forecasts:** We provide accurate short-term power production forecasts for wind and solar assets, up to 4 updates per day.
- **Intraday Forecasts and Nowcasting:** Hourly resolutions to help imbalance form the electric market. Up to 5 minutes with interpolation.
- **Weather Variable Forecasts:** Wind speed, wind direction, Irradiance, and temperature.
- **Backtest and Hindcast Models:** Our backtesting solutions simulate past forecast scenarios.

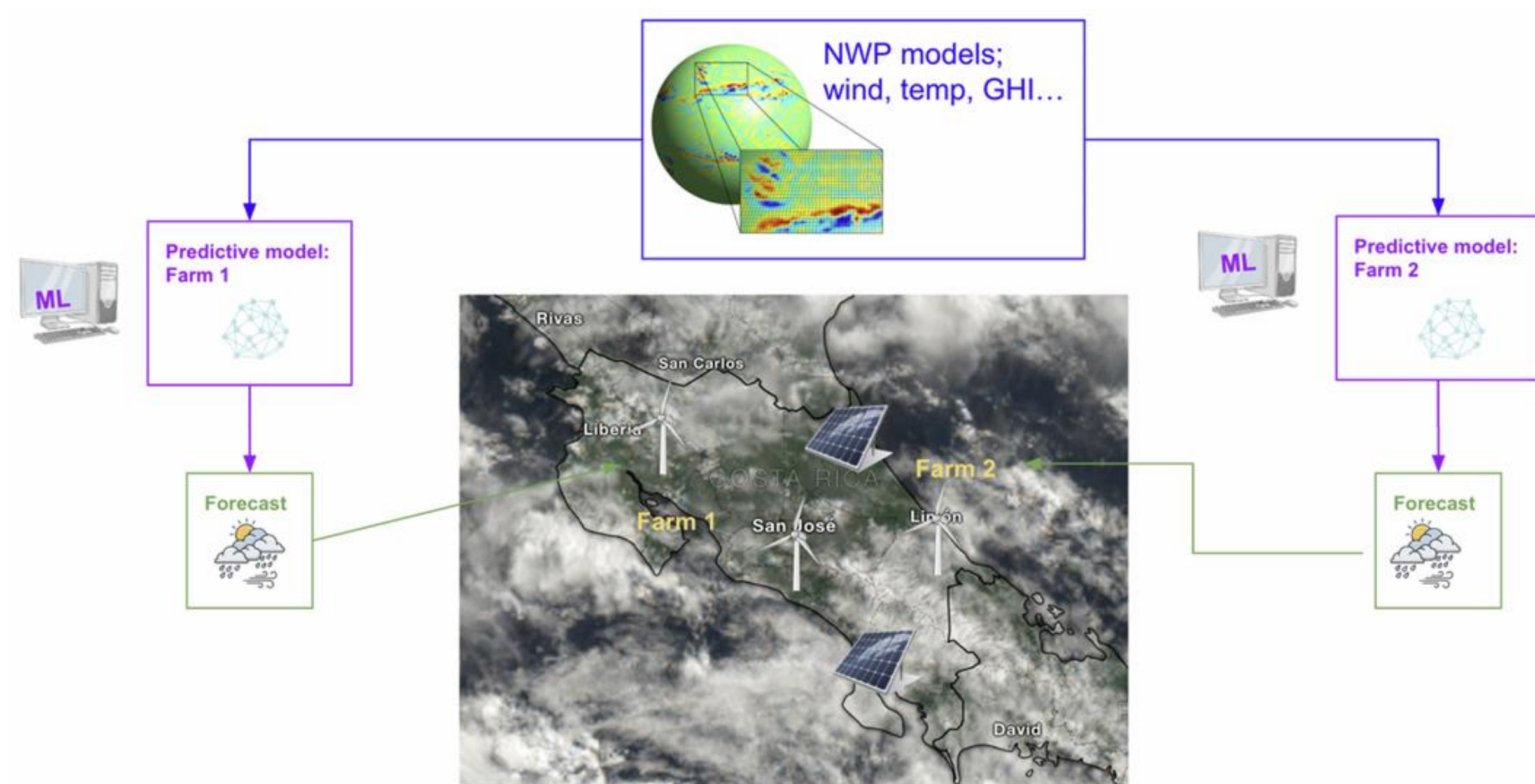
Forecasting Technical Model



The Methodology

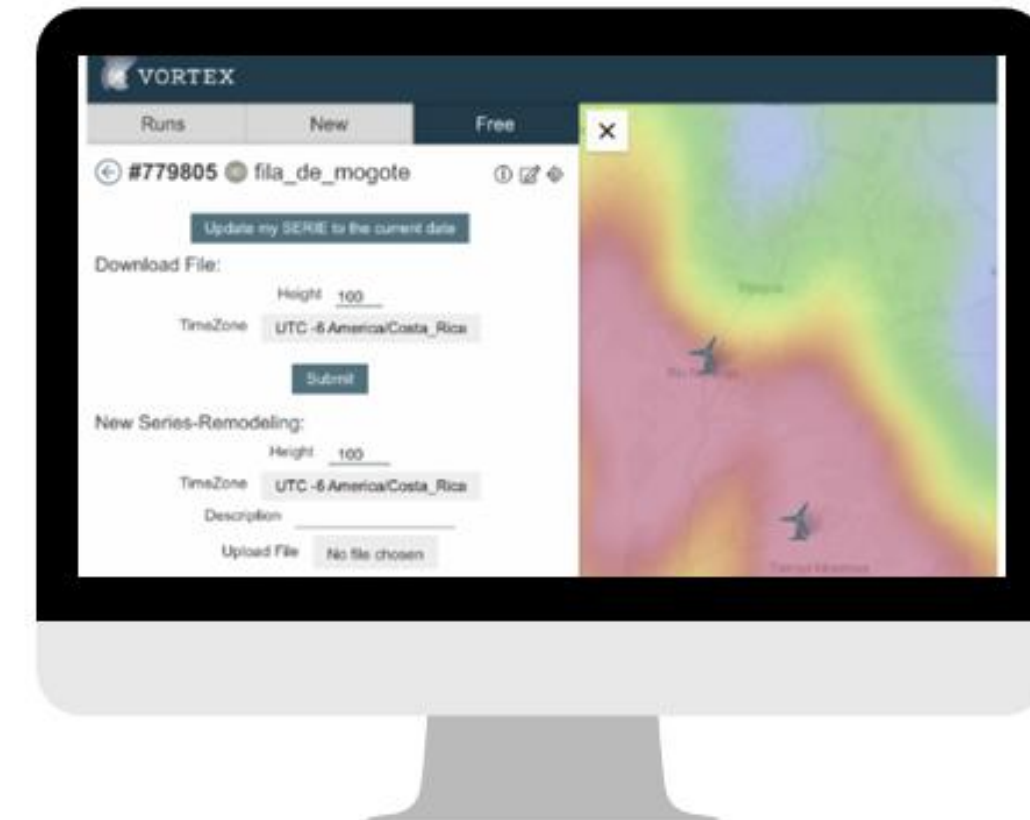
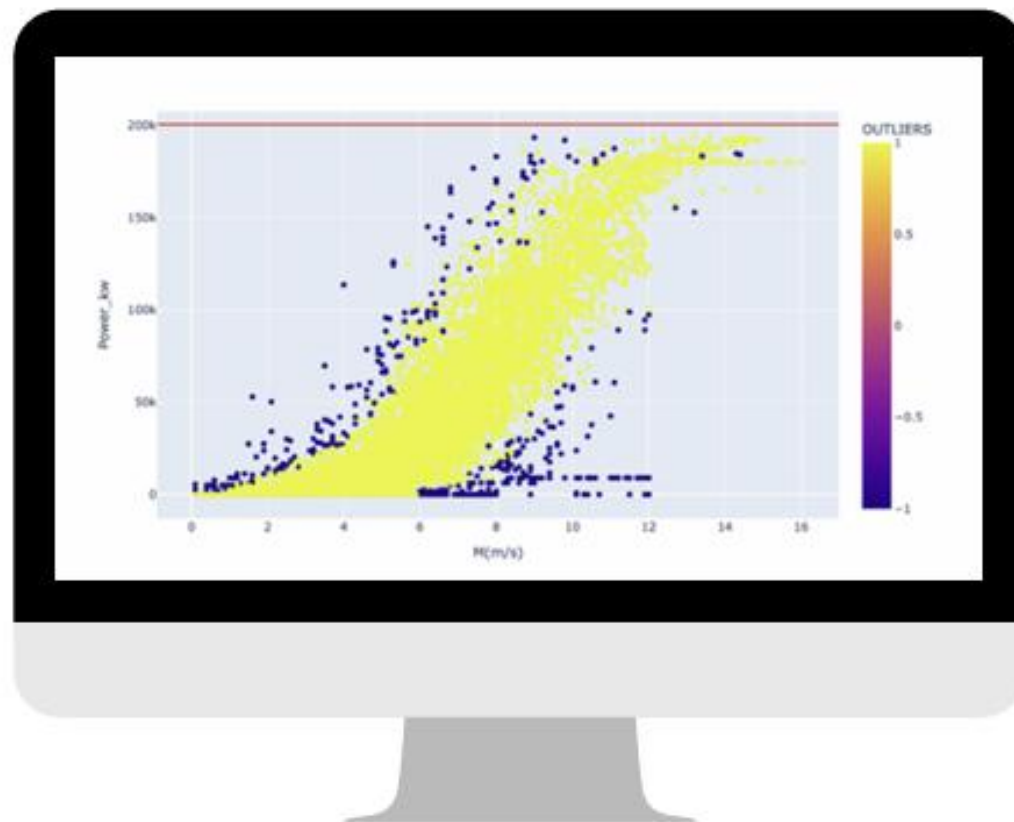


The Methodology



Historical Data

We use the client's historical generation data and apply data cleaning techniques to improve forecast performance.



For new construction sites without historical data, we generate synthetic datasets based on Vortex data.

Data Cleansing (Wind & Solar)



Outlier Identification



Detection of interruptions and availability variations



NWP Models

Several agencies provide meteorological forecasts based on the numerical solutions of the physical-mathematical models that describe atmospheric behavior.



Key Variables to Consider

Solar

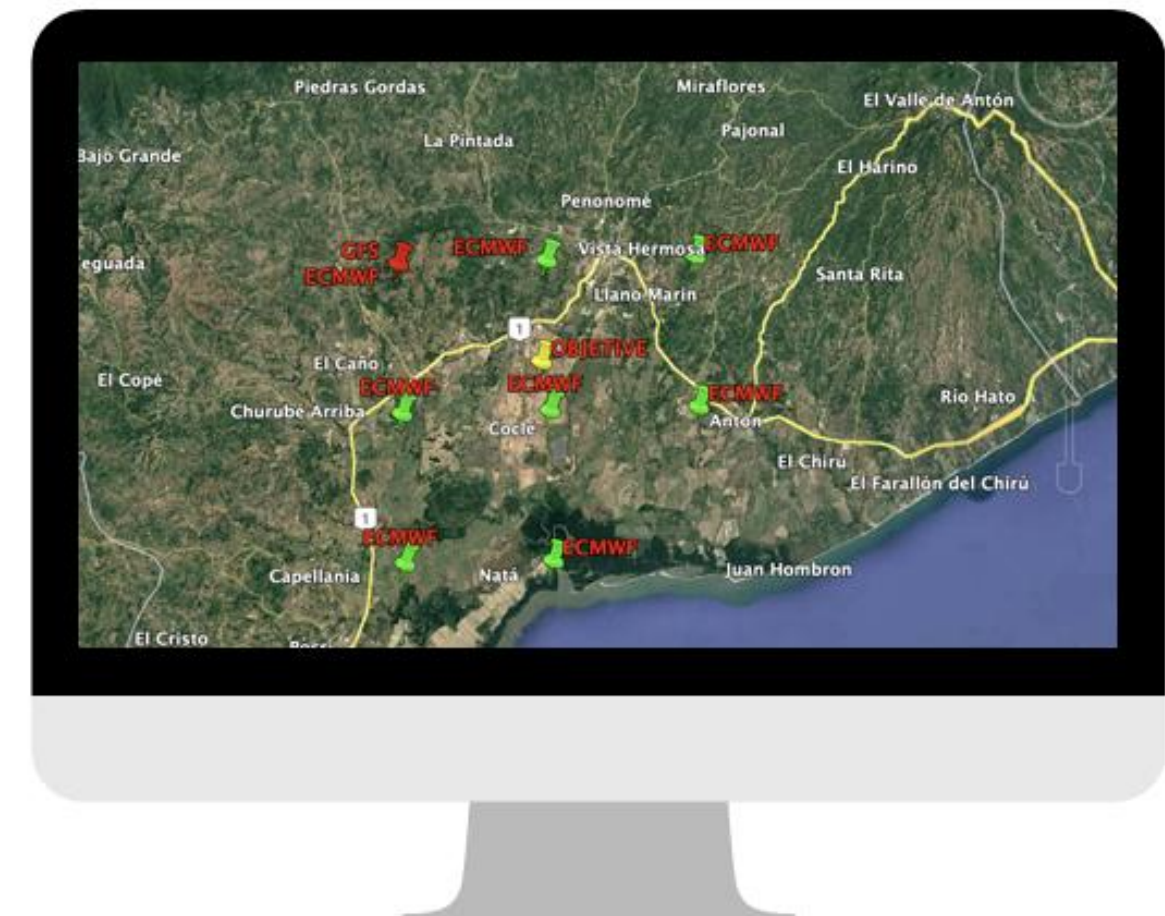
- Global Horizontal Irradiance (GHI)
- Direct Normal Irradiance (DNI)
- Temperature
- Pressure

Wind

- Wind Speed
- Wind Direction
- Temperature
- Pressure

Machine Learning Model Training

- Machine learning downscaling to capture the plant's local characteristics.
- Identifies relationships between meteorological variables and the target variable.
- Uses past data to recognize similar future scenarios through mathematical modeling.



Our Services

VARIABLES

Power Production Forecast - Wind Speed & Direction -
Temperature & Irradiation - Pressure & Density

HORIZON

Up to 15 days ahead on an hourly resolution - Monthly on a daily
resolution - Yearly on a daily resolution

GRANULARITY

15 minutes or hourly

DAILY UPDATES

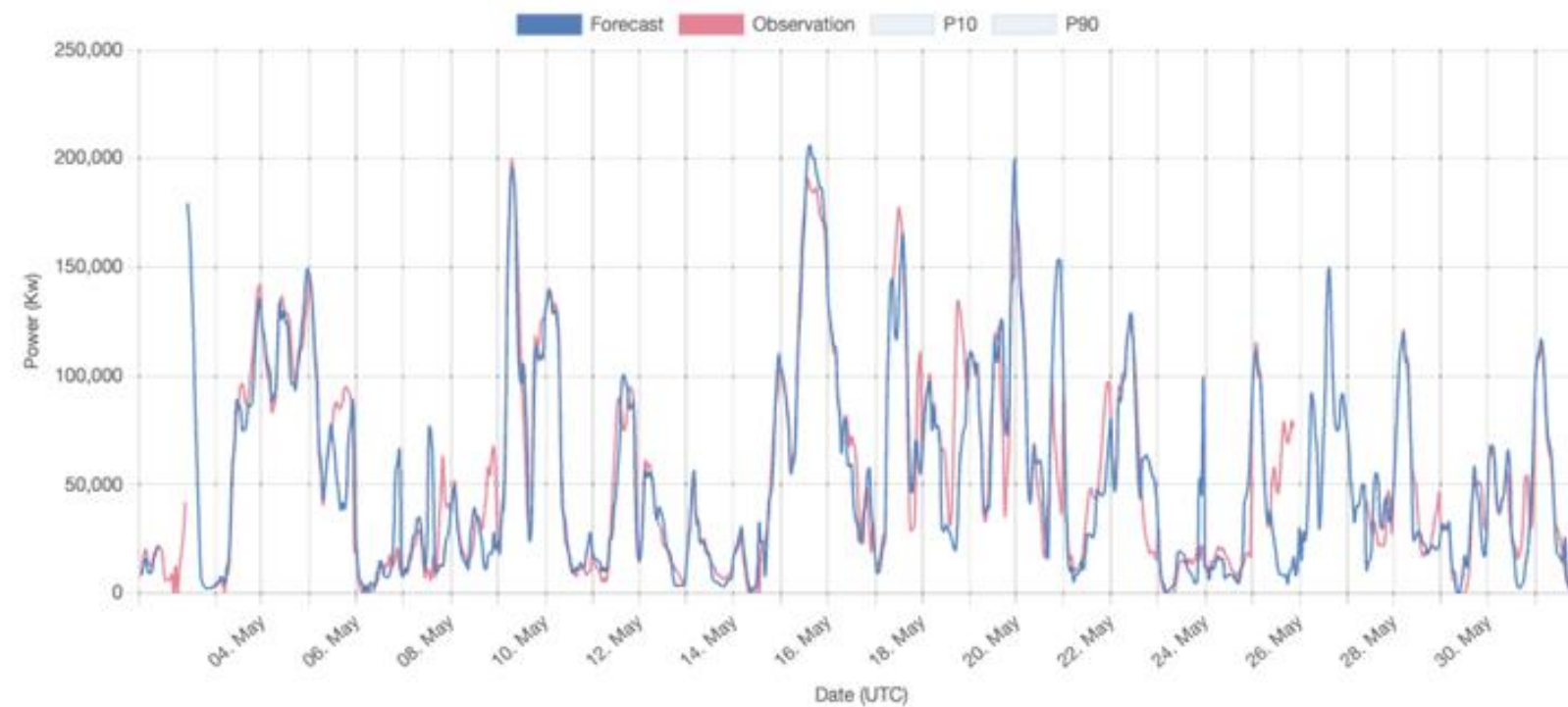
Upon Client's Request from:
Every 15 minutes (96 updates if need be), by default 1 every 6 hours

DATA & FORMAT DELIVERY

Upon Client's Request:
API , (S)FTP, Web Interface
Files: CSV, TXT, XLS. XML

Sirocco's Metrics

At Sirocco Energy, we evaluate our forecasts using real-time connection to measure several metrics, as each one provides a different perspective to help us make informed decisions for our power plants.



Relative to nominal ⓘ		
MAE	RMSE	ME
3.64 %	4.43 %	2.72 %

Relative to observation ⓘ		
MAE	RMSE	ME
80.51 %	97.98 %	60.25 %

Absolute ⓘ		
MAE	RMSE	ME
8366.23 Kw	10181.10 Kw	6260.31 Kw

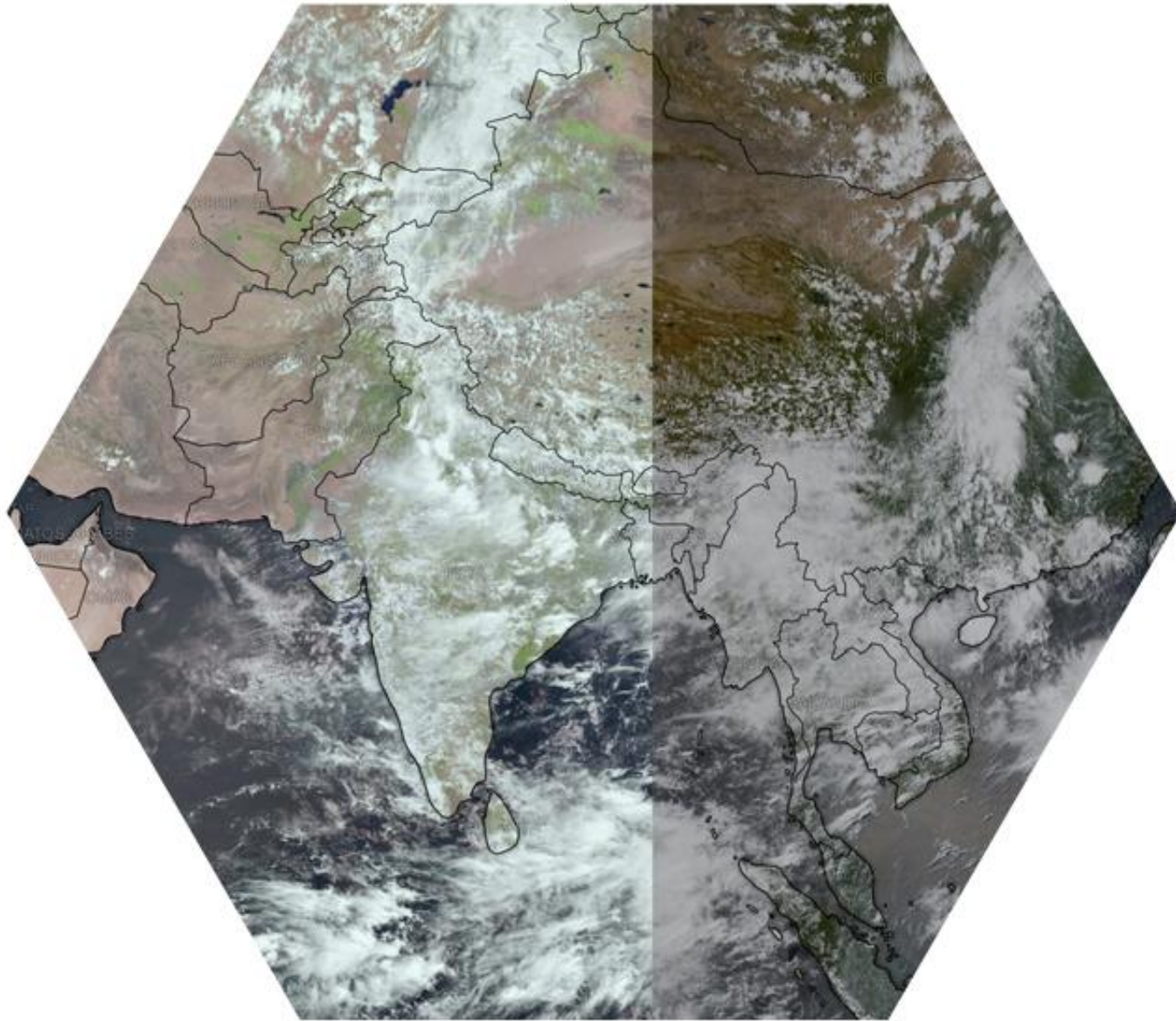


Data Delivery Channels

Information is delivered via API, FTP, or SFTP in the format requested by the client or operator. Regardless of the delivery method, users have access to the Dashboard to visualize production graphically or download the data.



Forecast Requirements

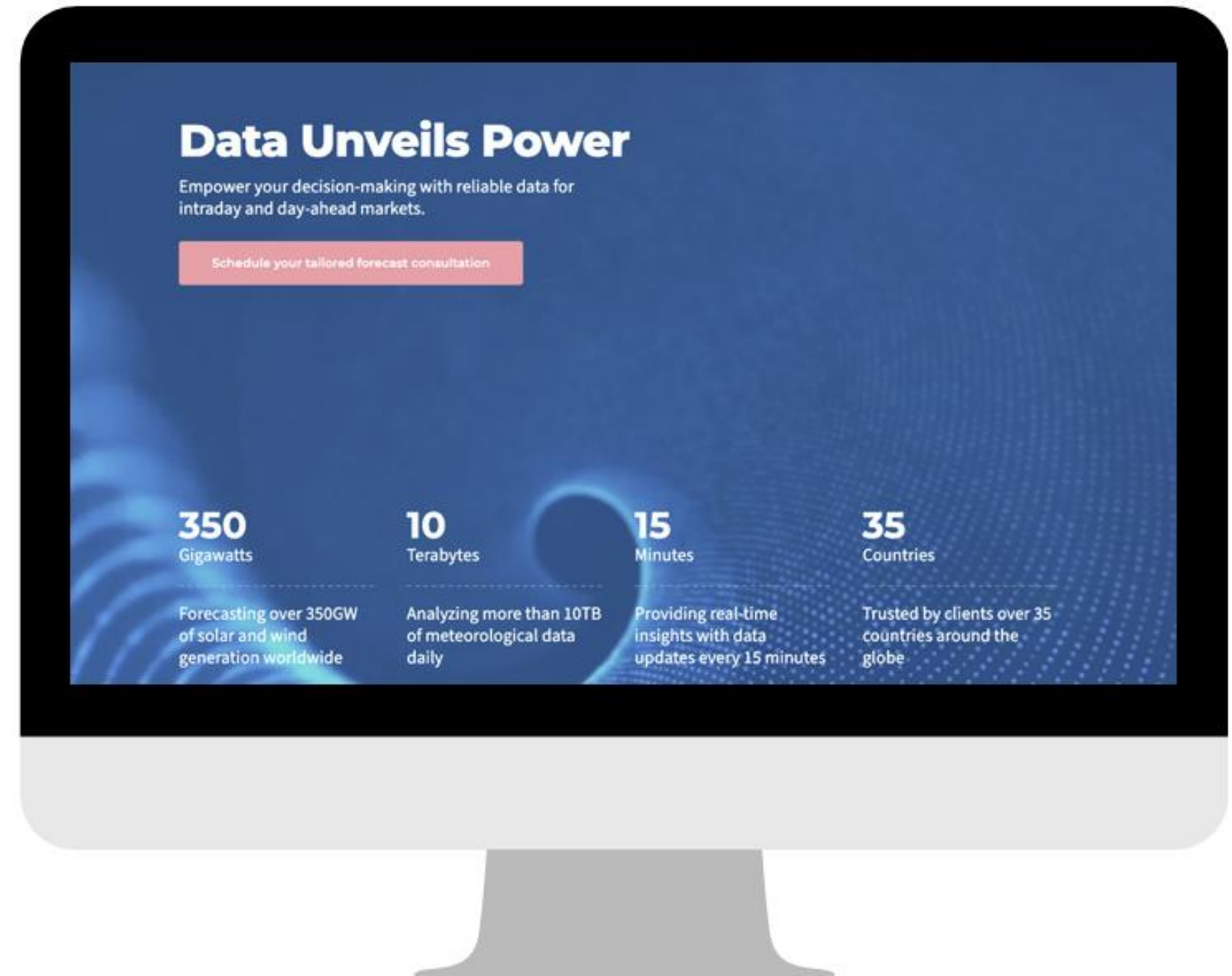


- Geographical coordinates
- Installed capacity
- Historical production and weather data (synthetic data generated if not available)



Thank You

If any doubts please contact us:
contact@sirocco.energy



nebb



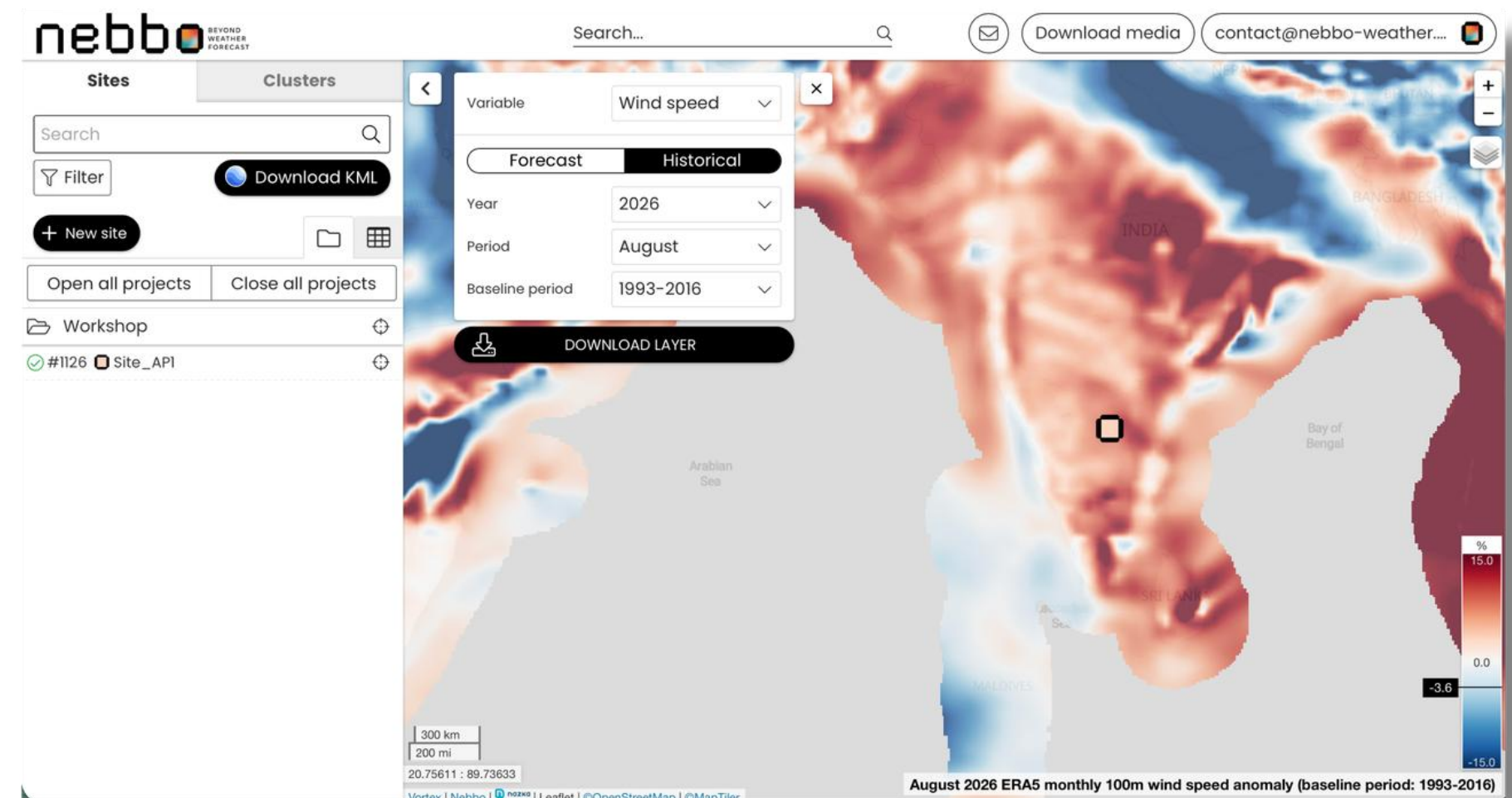
BEYOND
WEATHER
FORECAST

Introduction to Nebbo

Nebbo provides **meteorological services** for the **energy** sector. As a **Vortex spin-off**, we leverage high-resolution data and the latest AI technology to downscale and calibrate models.

Our **AI-powered forecasting** solution is **purpose-built for...**

- **Energy markets** & portfolios
- **Long-horizon** risks requiring mitigation.
- **Operative solutions** for daily execution.



Nebbo's complete prediction spectrum

FORECAST HORIZON	RANGE	GRANULARITY	UPDATE	VARIABLE
SUBSEASONAL	day 15 to 45	daily / weekly	daily	Wind energy related (wind speed & wind production) Many others (solar irradiance, precipitation, temperature...)
SEASONAL	month 1 to 6	weekly / monthly	monthly	
YEARLY+	month 7 to 18	monthly / semesterly	monthly	
CUSTOM	Ad-hoc / co-development of custom services			Tailored Climate Indices, Predictability Studies, and Dedicated API Integration



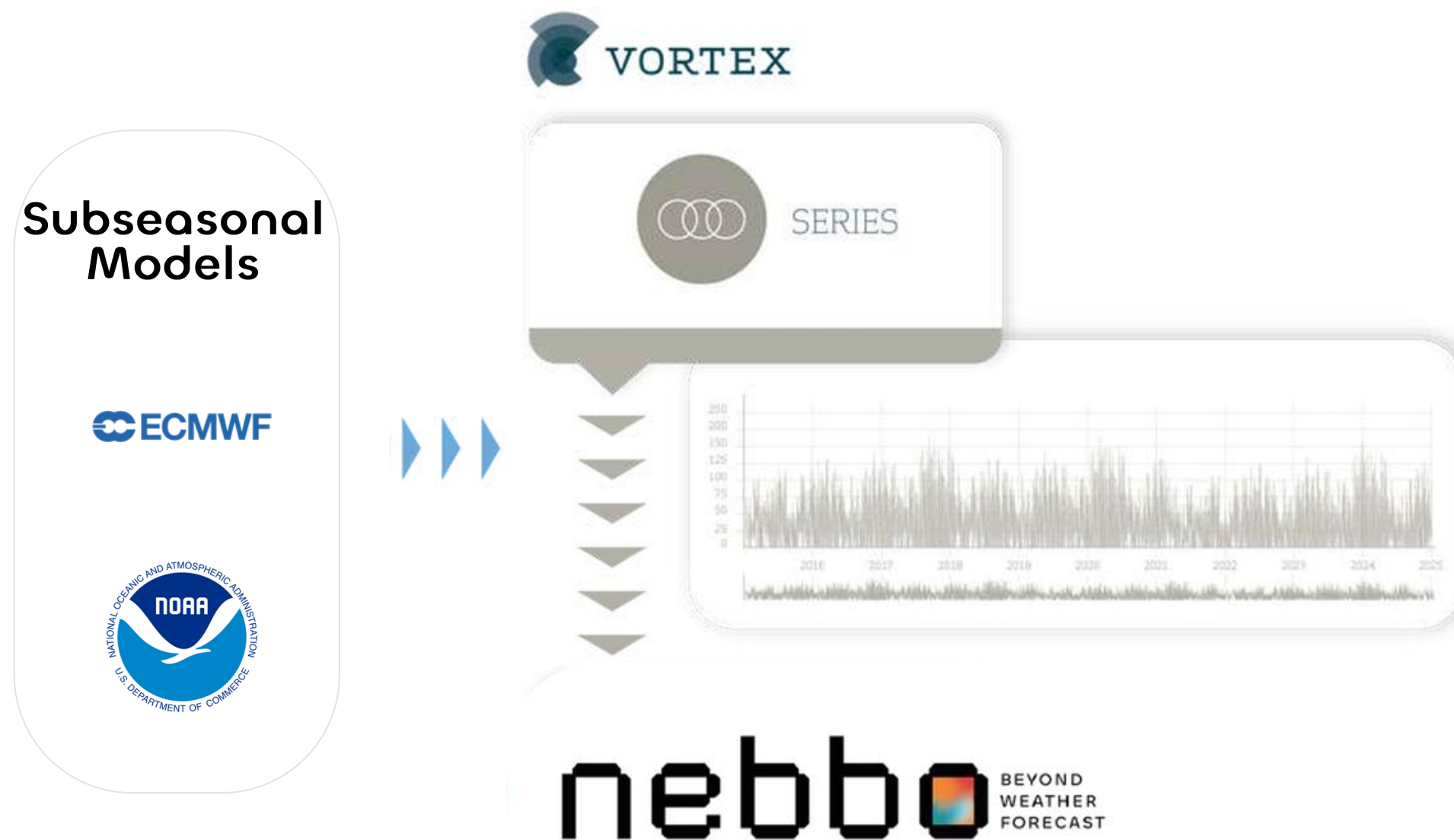
01 / FORECAST HORIZON

Subseasonal

Day 15 to 45 | Daily & Weekly Updates

Subseasonal, from day 15 to 46:

To anticipate market Imbalances & optimize operational windows



State-of-the-art Tech Stack

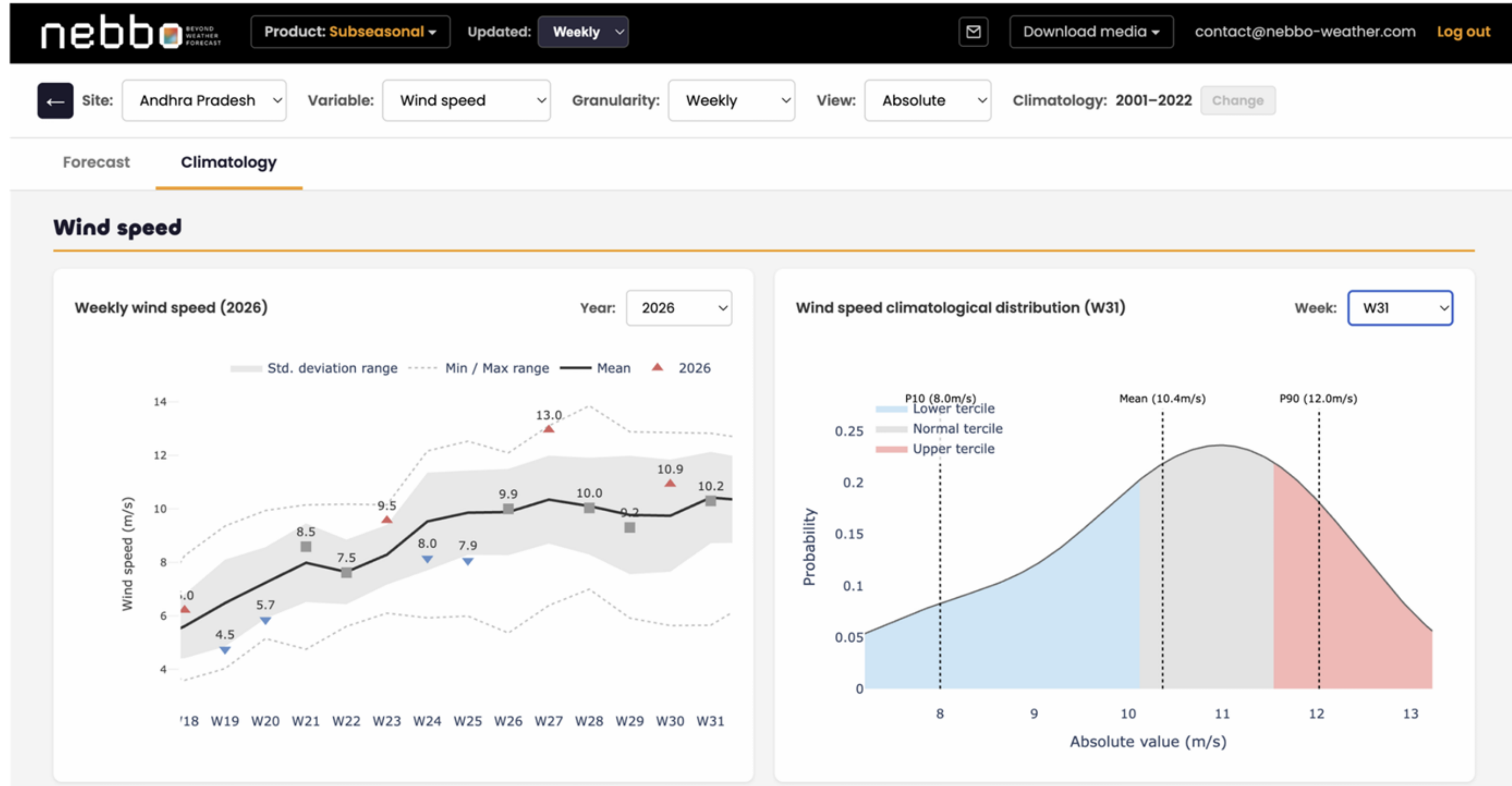
- **Hybrid-modeling**
 - Combining subseasonal physical weather models with regional AI/DL calibration
- **>30 years of high-resolution data**
 - Exclusive access to VORTEX's high-resolution weather data (3km)
- **Updated every week or every day**
 - Providing weekly/daily aggregations insights

Subseasonal, from day 15 to 46:

To track historical wind droughts and properly characterize site's climatology

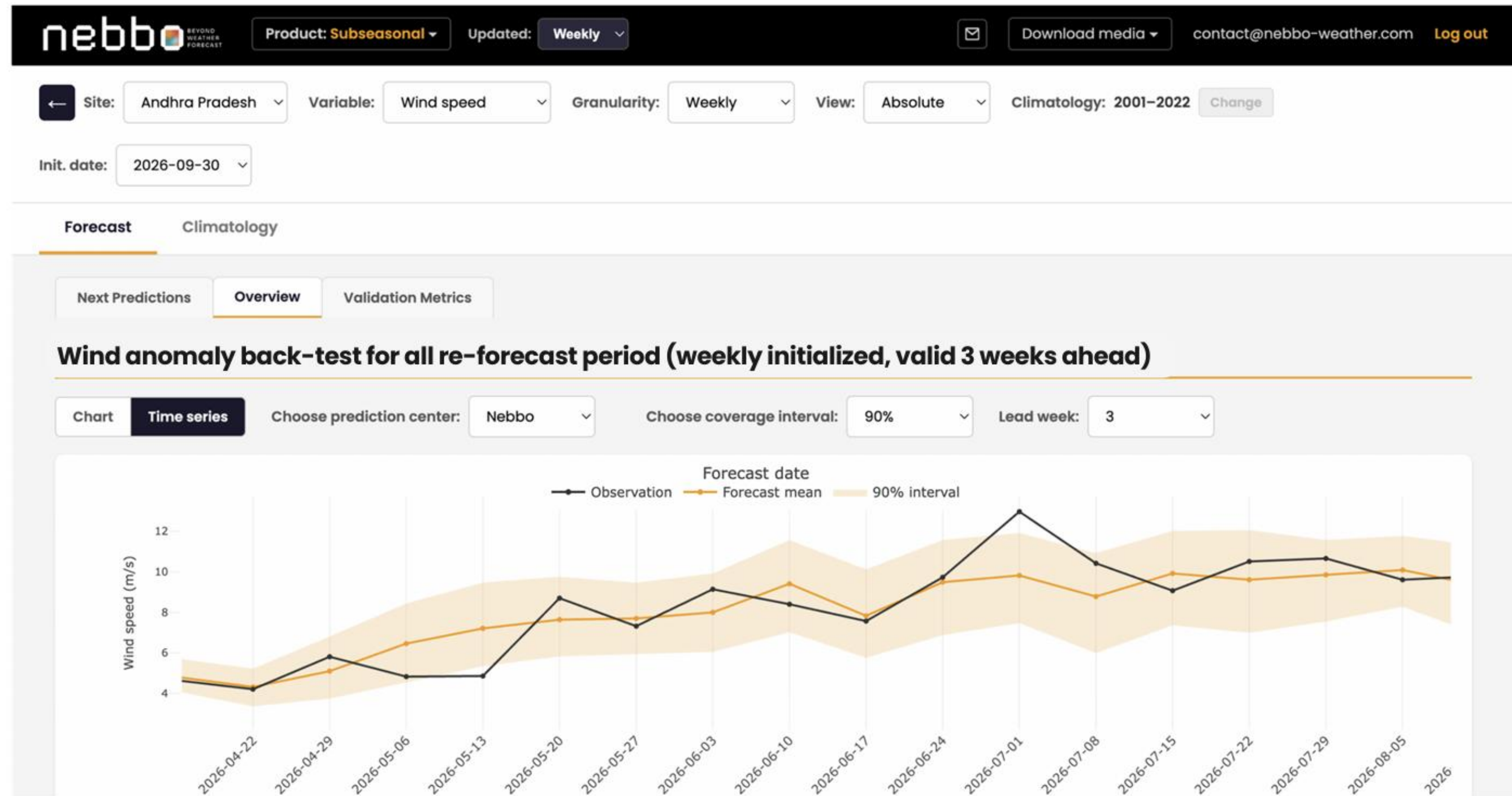


BEYOND
WEATHER
FORECAST



Sub-seasonal, from day 15 to 46:

Anticipate market imbalances (e.g. Monsoon onset) & optimize operational windows

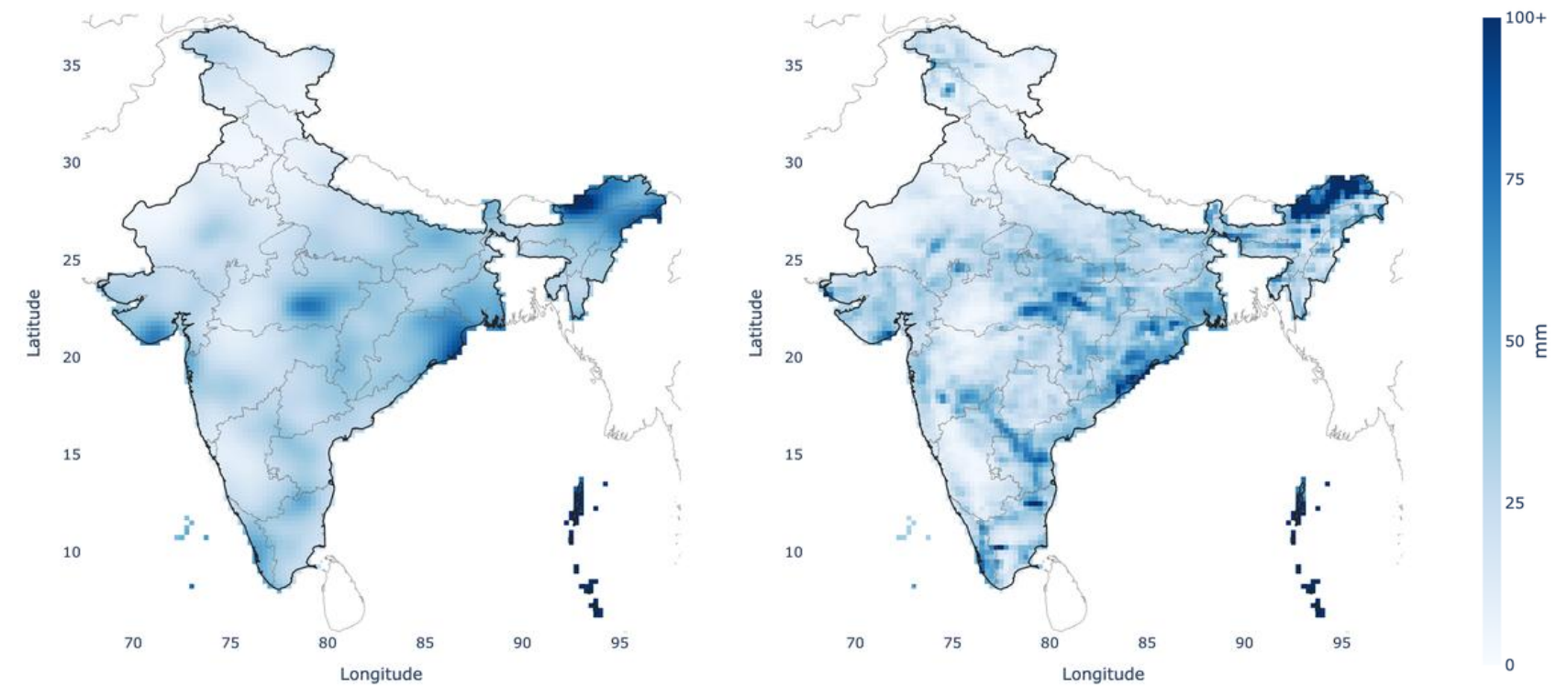


Regional Approach & Multi-Variable Scopes

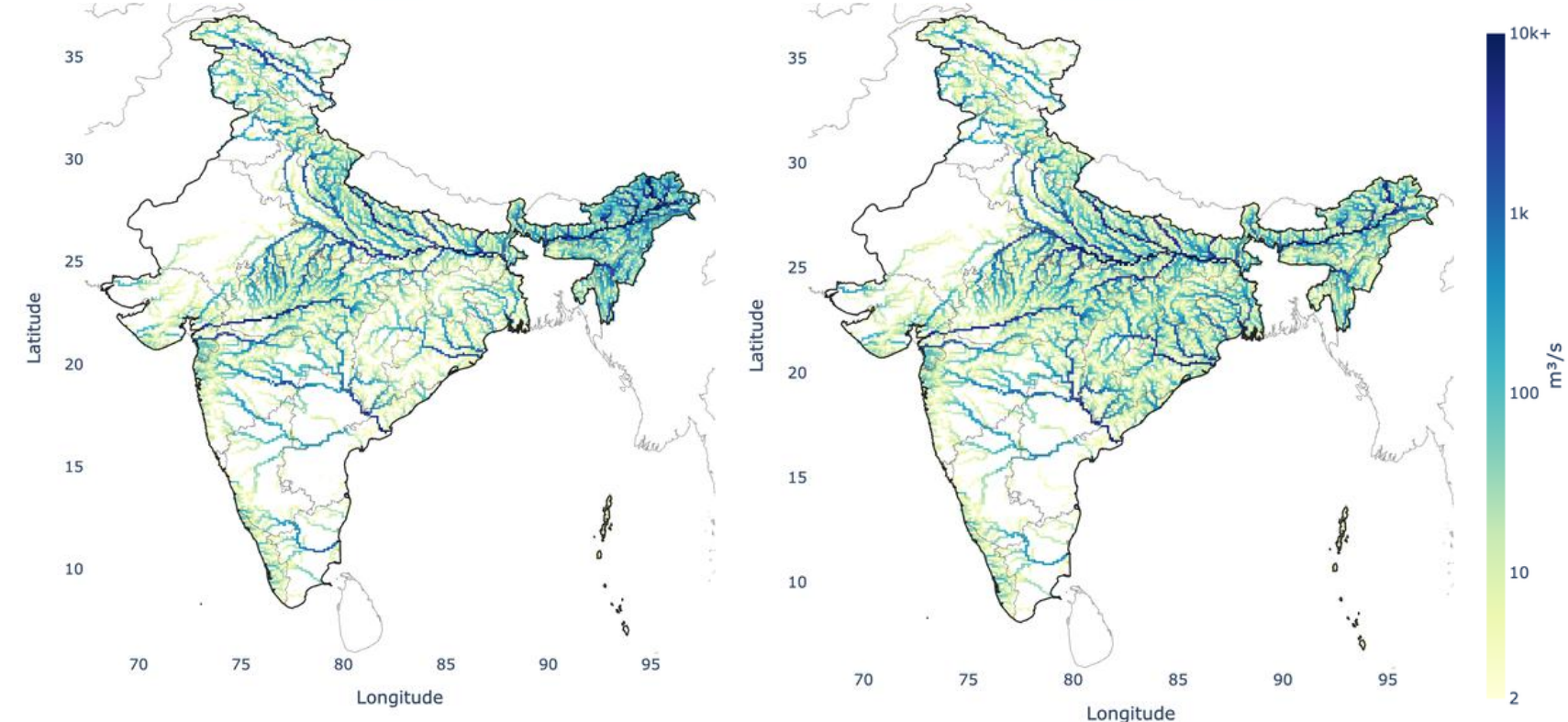
Anticipating river inflow and extreme weather events weeks in advance.

- **Beyond wind**
 - We cover other variables such as total precipitation, river discharge, and more.
- **Regional Scale**
 - Full regional or country-wide mapping.
- **Examples in the right**
 - Weekly Mean Forecasts. Initialized Sep 1, valid 3 weeks ahead (15 Sep – 21 Sep 2026)

**Total
Precipitation**



**River
Discharge**



What was predicted

What was observed



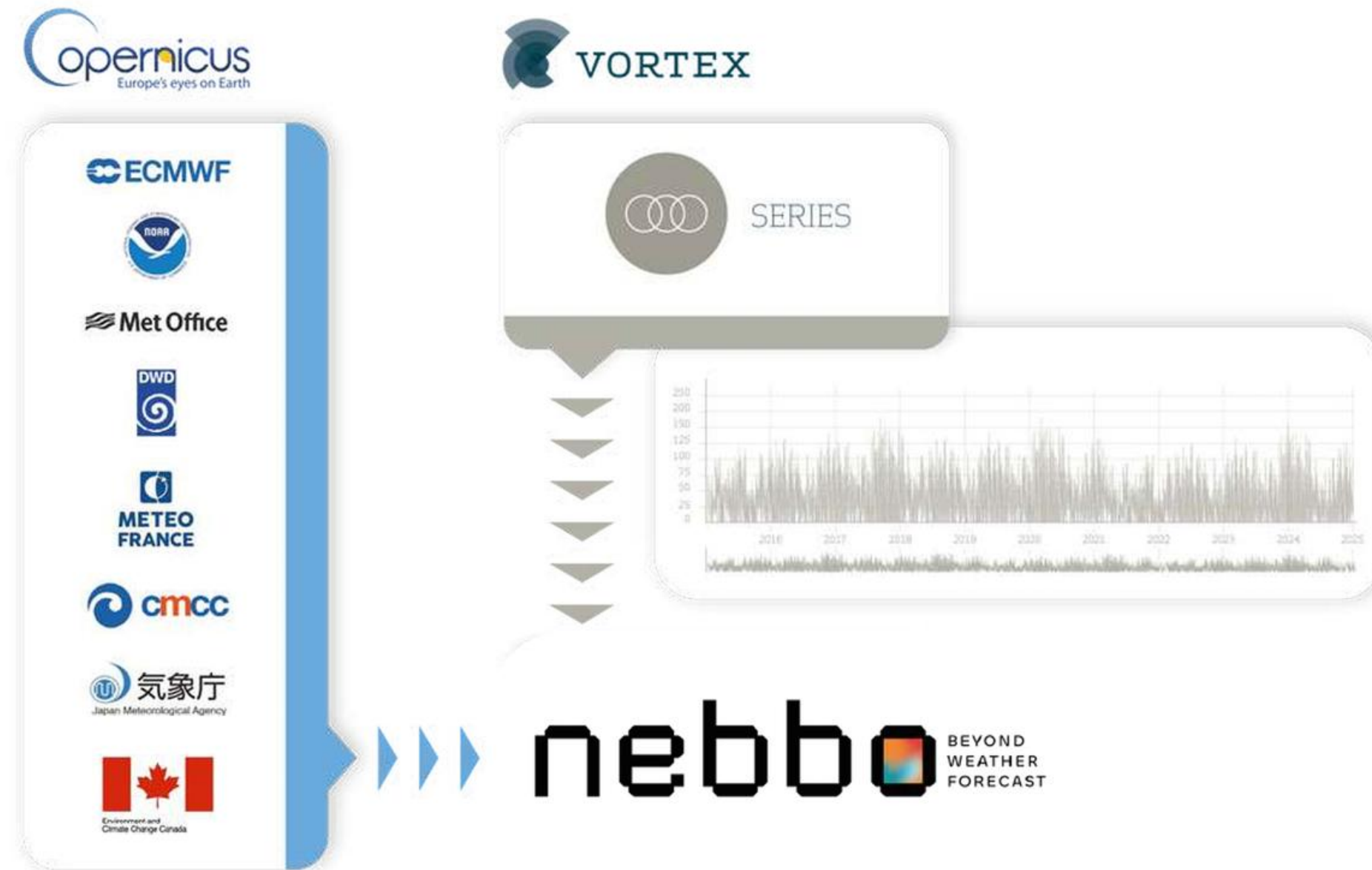
02 / FORECAST HORIZON

Seasonal

Month 1 to 6 / Weekly & Monthly Updates

Seasonal, from month 1 to 6:

To Mitigate Volum Risk and Anticipate Low-Yield Periods

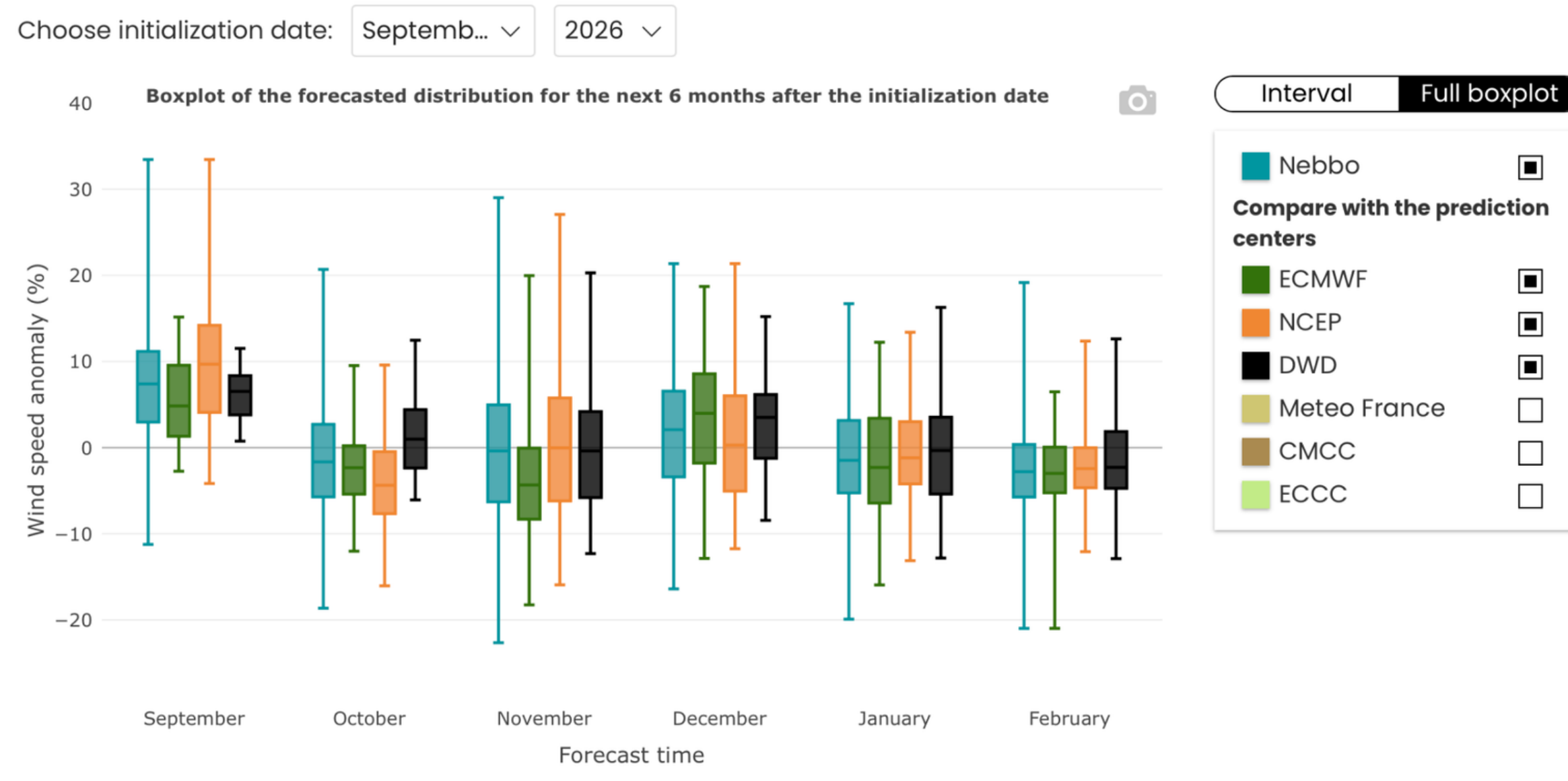


State-of-the-art Tech Stack

- **Multi-model**
 - 9 physical models from C3S + AI with hyper-local downscaling using Vortex SERIES
- **Updated every month**
 - Providing monthly average data
- **India Track Record:**
 - Demonstrable accuracy in key wind regions, especially throughout the Monsoon

Seasonal, from month 1 to 6:

To Mitigate Volum Risk and Anticipate Low-Yield Periods

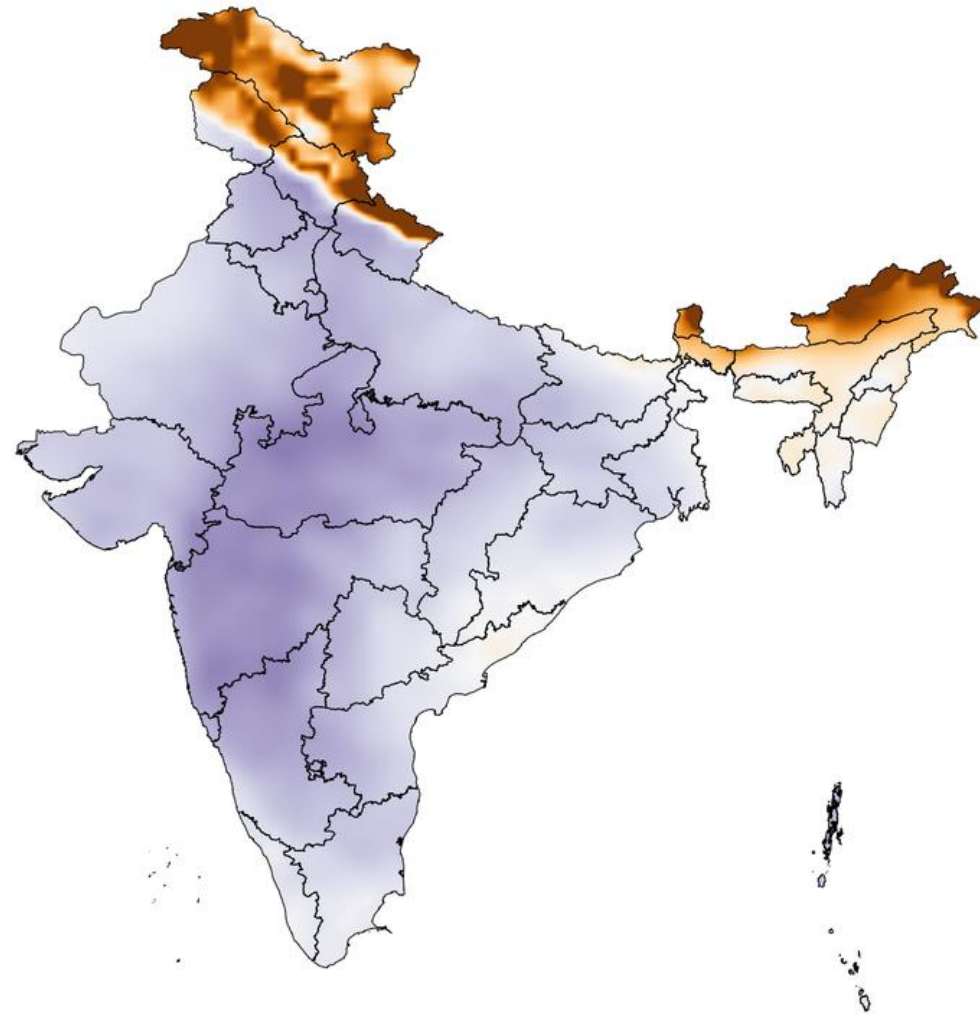


State-of-the-art Tech Stack

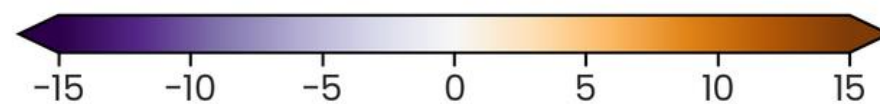
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Useful for tracking historical resource

What happened across India last financial year and past quarter?

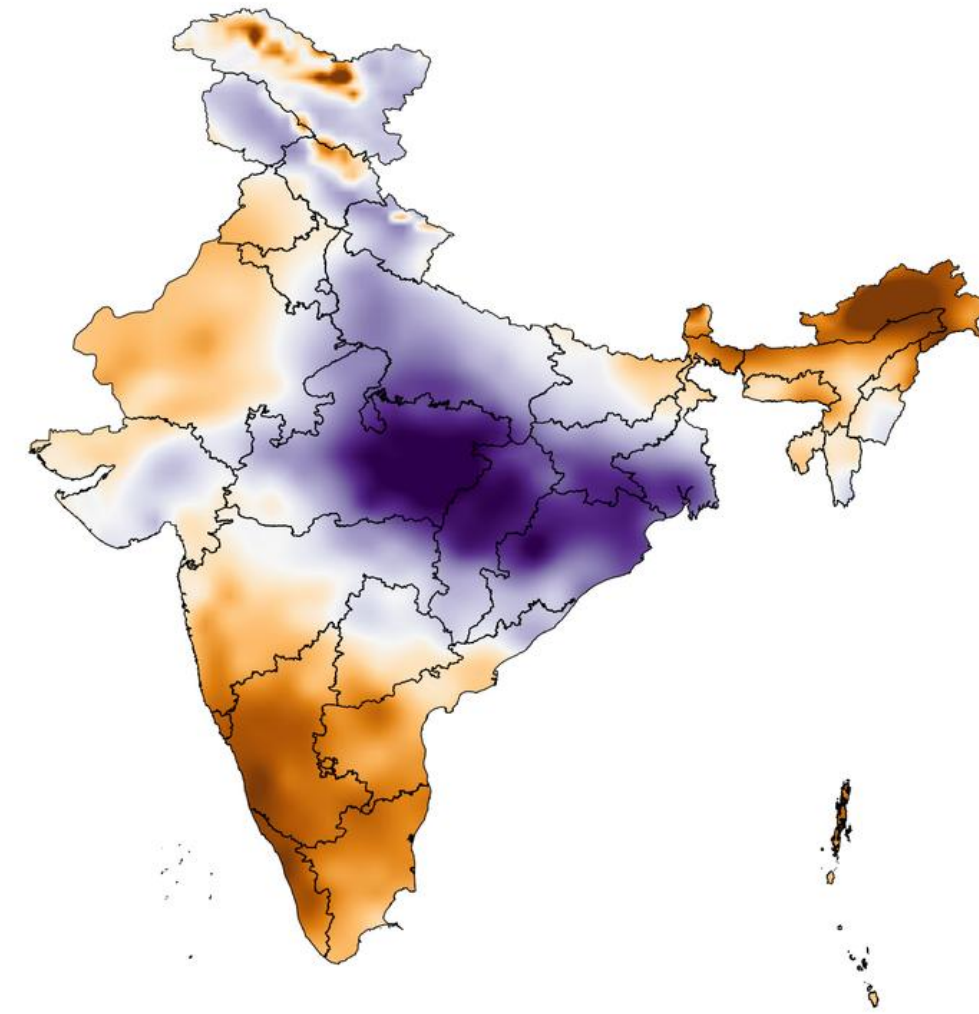


Reference period 2001 - 2020 | Resolution 0.25° x 0.25° | Mean of monthly anomalies

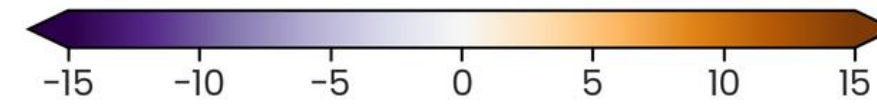


Solar radiation anomaly (%)

Apr 25 - Mar 26 financial year



Reference period 2001 - 2020 | Resolution 0.25° x 0.25° | Mean of monthly anomalies



Solar radiation anomaly (%)

JAS 2026 months

And also to foresee nexts months

Regional Overview & Validation: a Gujarat case study

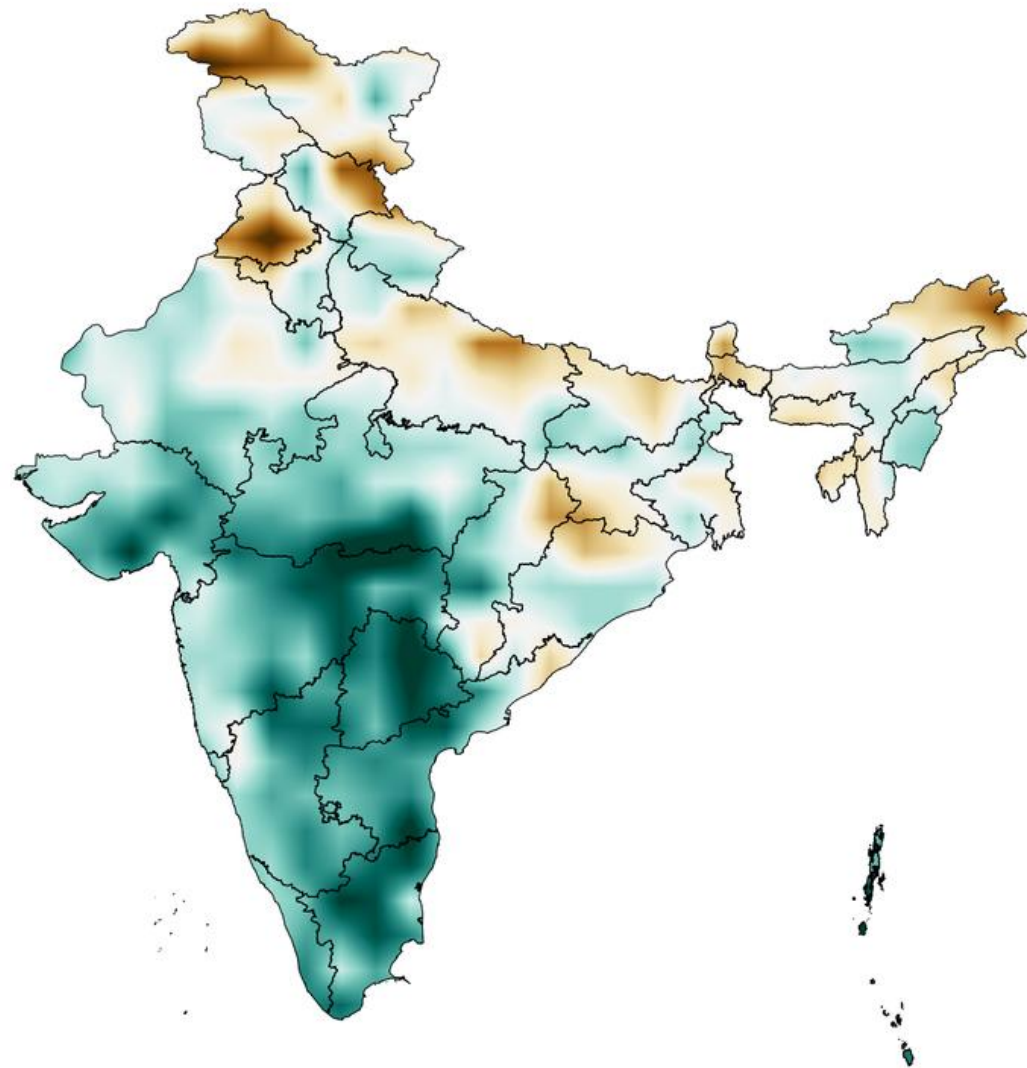
Monthly wind speed anomalies and six-months-ahead Nebbo seasonal predictions %

Forecast date	Ground truth	1 month	2 month	3 month	4 month	5 month	6 month
2027 February							-2.52
2027 January						-1.31	-0.67
2026 December					1.77	2.43	2.80
2026 November				-0.24	0.74	2.34	1.34
2026 October			-1.32	-1.25	0.26	0.03	0.82
2026 September		7.45	3.20	5.30	5.66	5.51	4.42
2026 August	8.87	9.29	8.68	7.87	8.30	5.15	4.17
2026 July	7.22	11.01	7.29	6.60	4.85	4.99	3.32
2026 June	5.71	6.46	3.87	3.35	4.84	3.88	2.42
2026 May	-1.02	-1.32	-4.54	-1.21	-0.77	-0.71	-0.57
2026 April	0.91	-1.87	-1.00	-2.33	-0.97	-1.71	-2.28
2026 March	-4.05	-3.45	-3.53	-2.53	-2.49	-2.21	-2.08

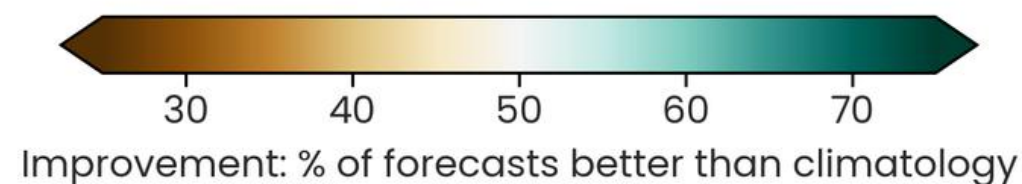
- **Robust Regional Signal**
 - Aggregated performance based on the mean of strategically selected wind assets across the Gujarat region.

Was this a lucky guess?

India Wind Predictability for JJA in Review



Validation 1993–2025 vs ERA5 | Mean of lead months 2–4 | 50 = no better than climatology



Seasonal **predictability** is **great** in India

- **What we mean by predictability**

- The ability to reliably capture the monthly mean distribution months in advance

- **Why it works so well**

- Monsoon wind follows the large-scale circulation, predictable months ahead.

- **Quantifying predictability through a metric**

- While a probabilistic prediction is needed for reliable decisions, one can summarize it into a single value averaging ensembles (*ensmean*).
- Left plot: the **% of times** our ***ensmean*** forecast was **better** (less error) **than climatology** guess ¹
- Validated with the forecasts initialized in May and valid for the quarter from **June to August** (i.e. during **Monsoon peak**), from 1993 to 2025.

¹ *Climatology guess* = always forecasting 0% anomaly, i.e. “next month will be equal to the last 30 years’ month”



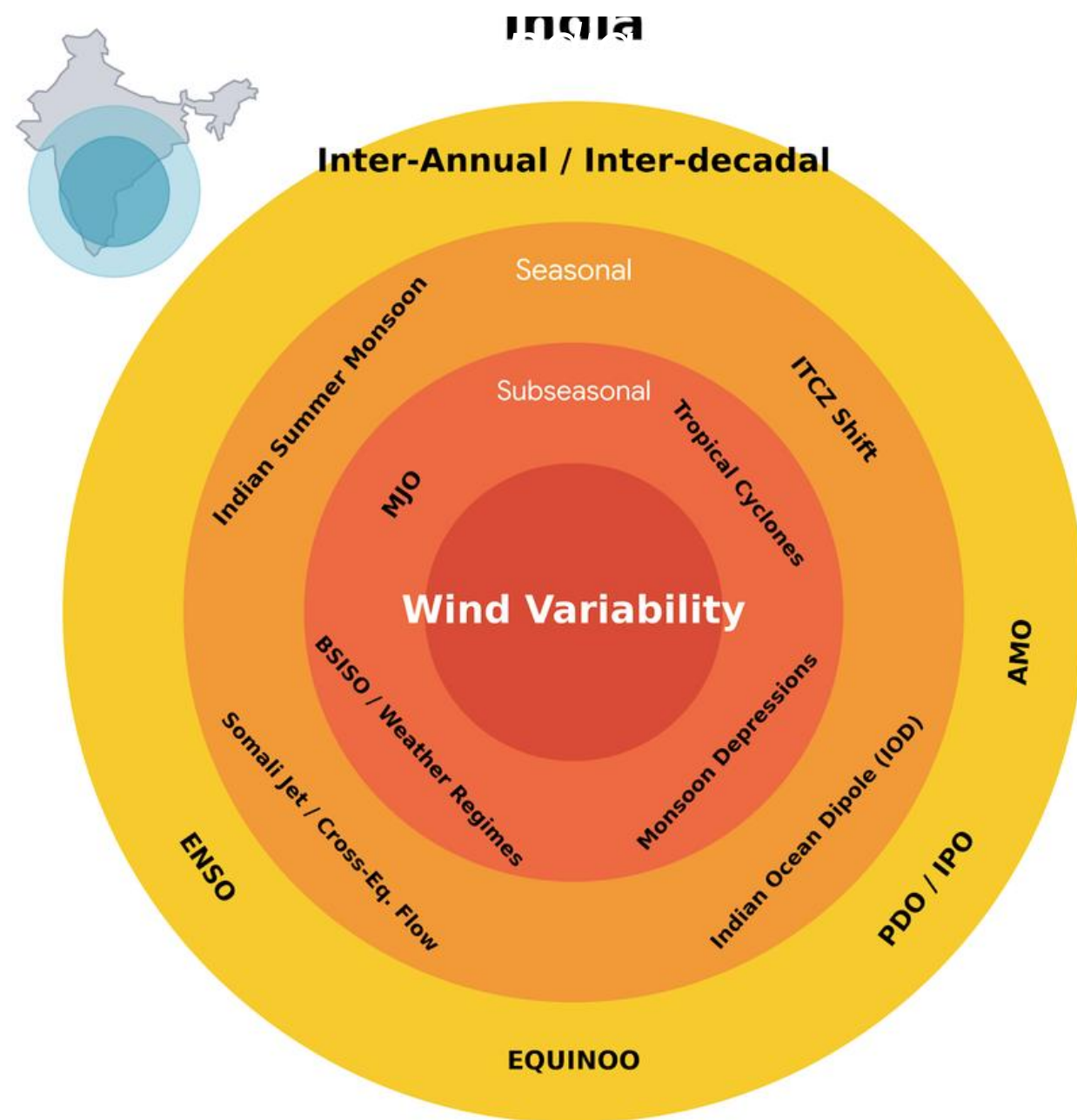
03 / FORECAST HORIZON

Yearly

Month 7 to 18 | Monthly & Semesterly Updates

How it works

Exploiting large-scale predictability drivers



Designed to assist in yearly **budgeting exercises**

- **Key Objective**

- Verify budget alignment with climatology and anticipate anomalous events.

- **Data & Verification**

- Production MCP with 30y Vortex SERIES & we derive all climatological statistics for realistic budgets.

- **Methodology**

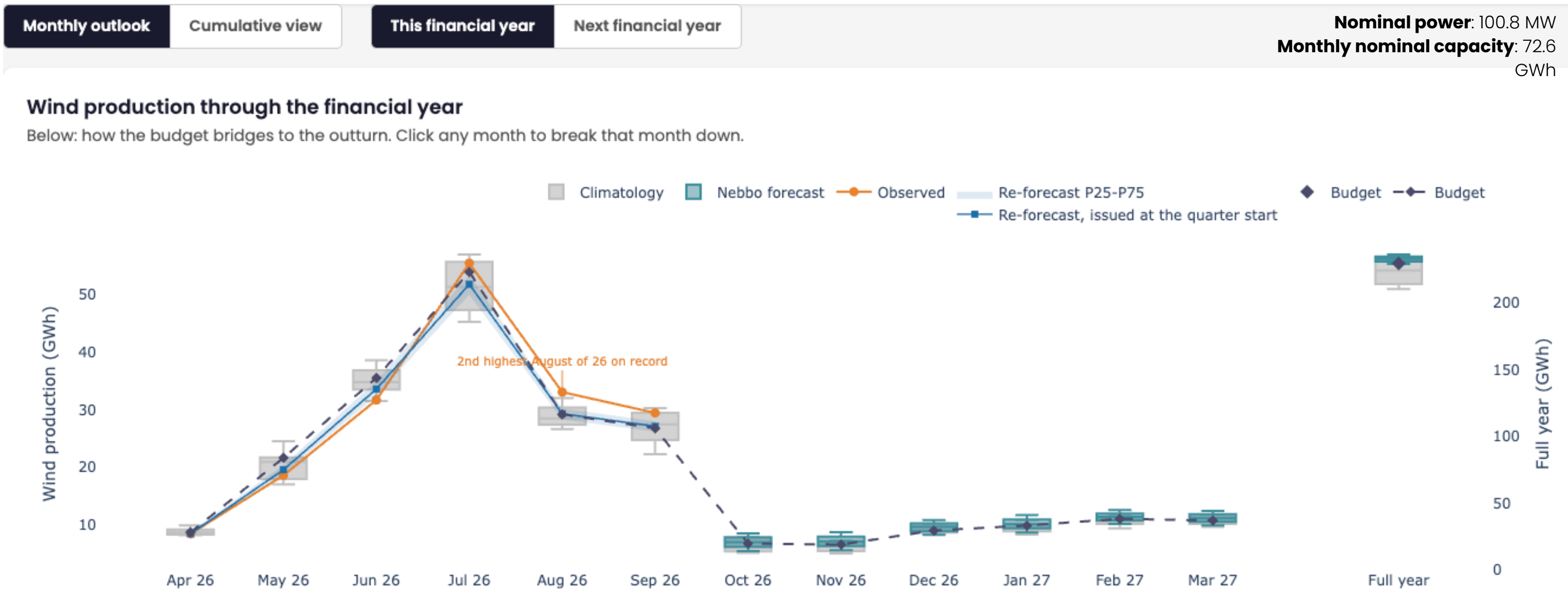
- 1. Driver Analysis → Identifying large-scale climate drivers.
- 2. Pattern Matching → Defining similarity criteria across historical data.
- 3. Probabilistic Forecast → Leveraging analogous years to project future scenarios.

Yearly, month 7 to 18

Budgeting exercises for next financial year, validating budget with climatology & mitigating low-yield years

Andhra Pradesh case-study:

- Bottom plot: predictions were initialized in **Jan 26** valid for **Apr 26 – Mar 27** (FY27)
- **Objective:** to budget FY27 in early 2026





04 / FORECAST HORIZON

Custom

Tailored Services / Ad-hoc Co-development

Custom

We build custom products tailored to your specific assets and regions.

4. Model Maintenance

Available as the portfolio evolves

1. Operational Pain

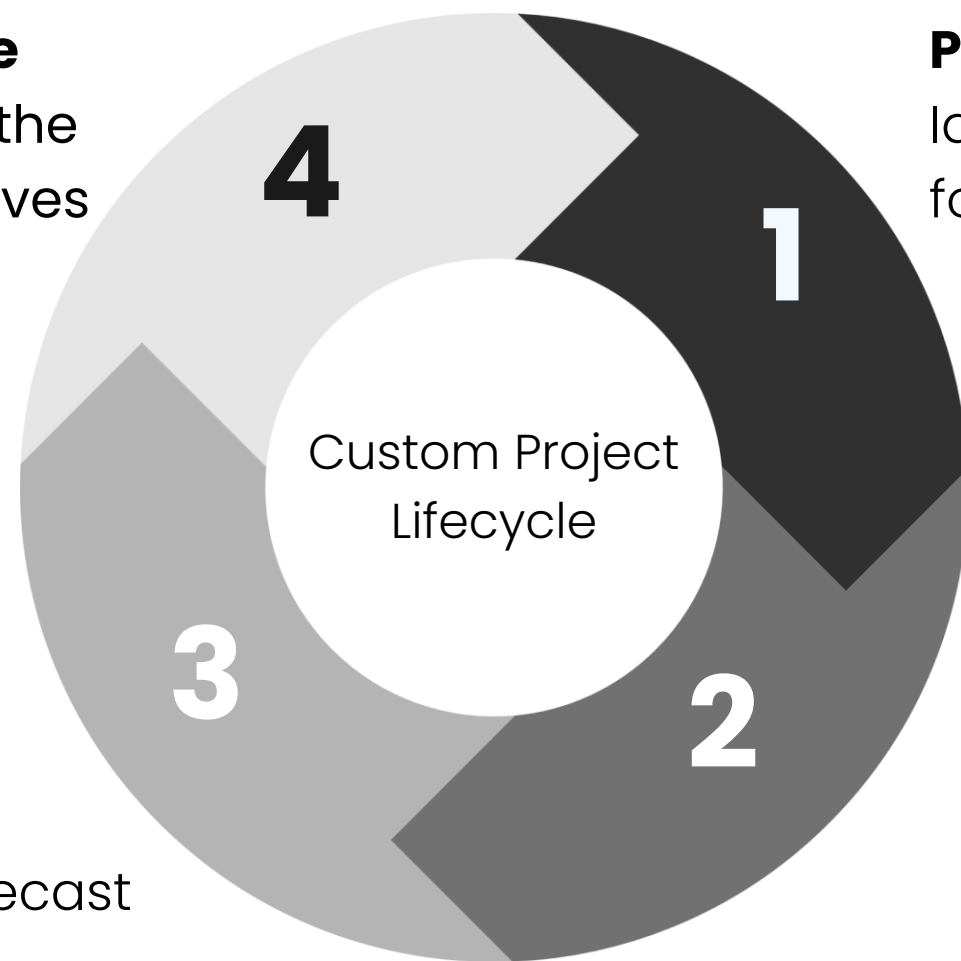
Identifying client's forecasting gap

3. Custom Pipeline

Tailored forecast delivery

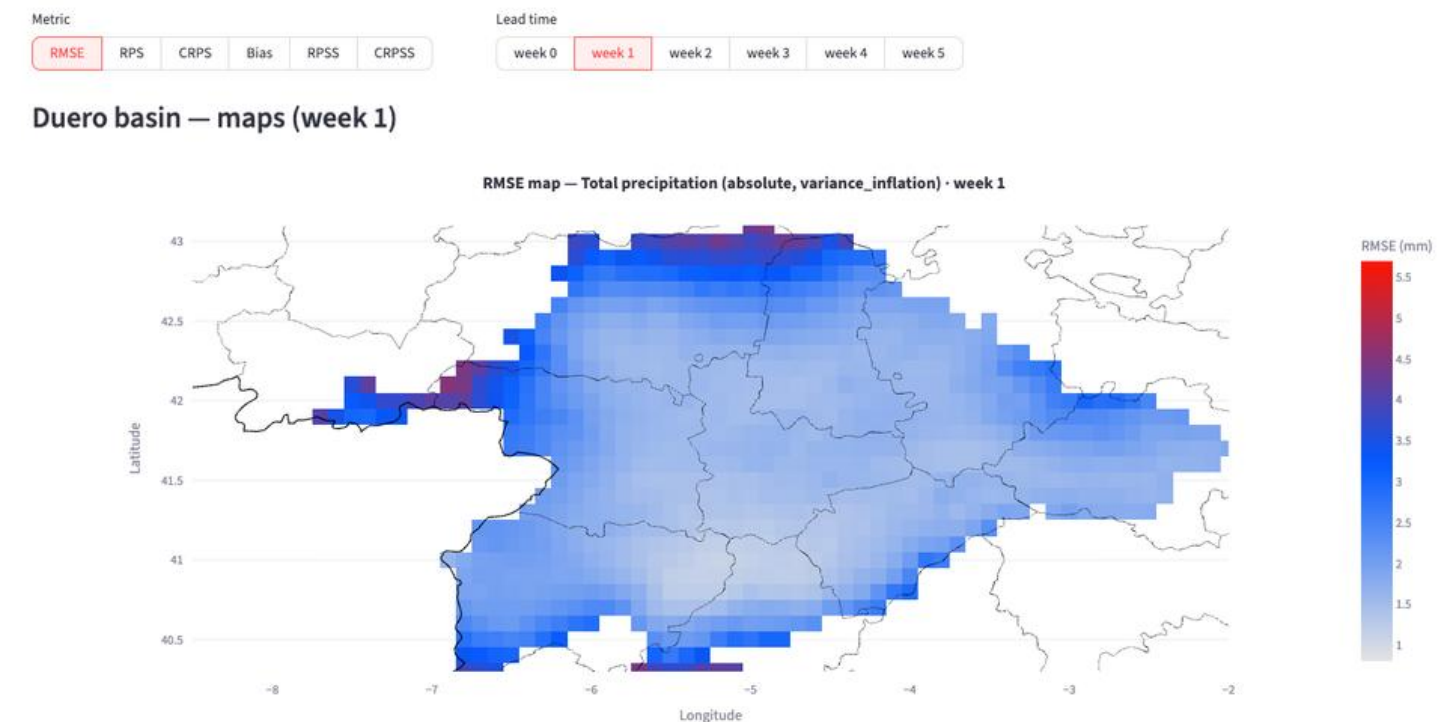
2. Joint Assessment

Mapping assets & local physics



Examples of use-cases

- **Identifying maintenance windows**
 - Targeting low-wind (<10 m/s) & rain-free operational windows weeks ahead.
- **Quantifying predictability for hydro decisions**
 - Validating the error of precipitation forecasts for hydro in a Spanish river basin.



SEE FURTHER,
PLAN BETTER.

CLIMATE SCALE

Climate Scale

6-8 October, 2026

powered by
VORTEX 

explore.climatescale.com

Outline

Understanding the past

Wind resource over the last ~ 40 years

Projecting the future

Climate Scenarios and climate Projections

Climate Scale approach and products

Examples of use

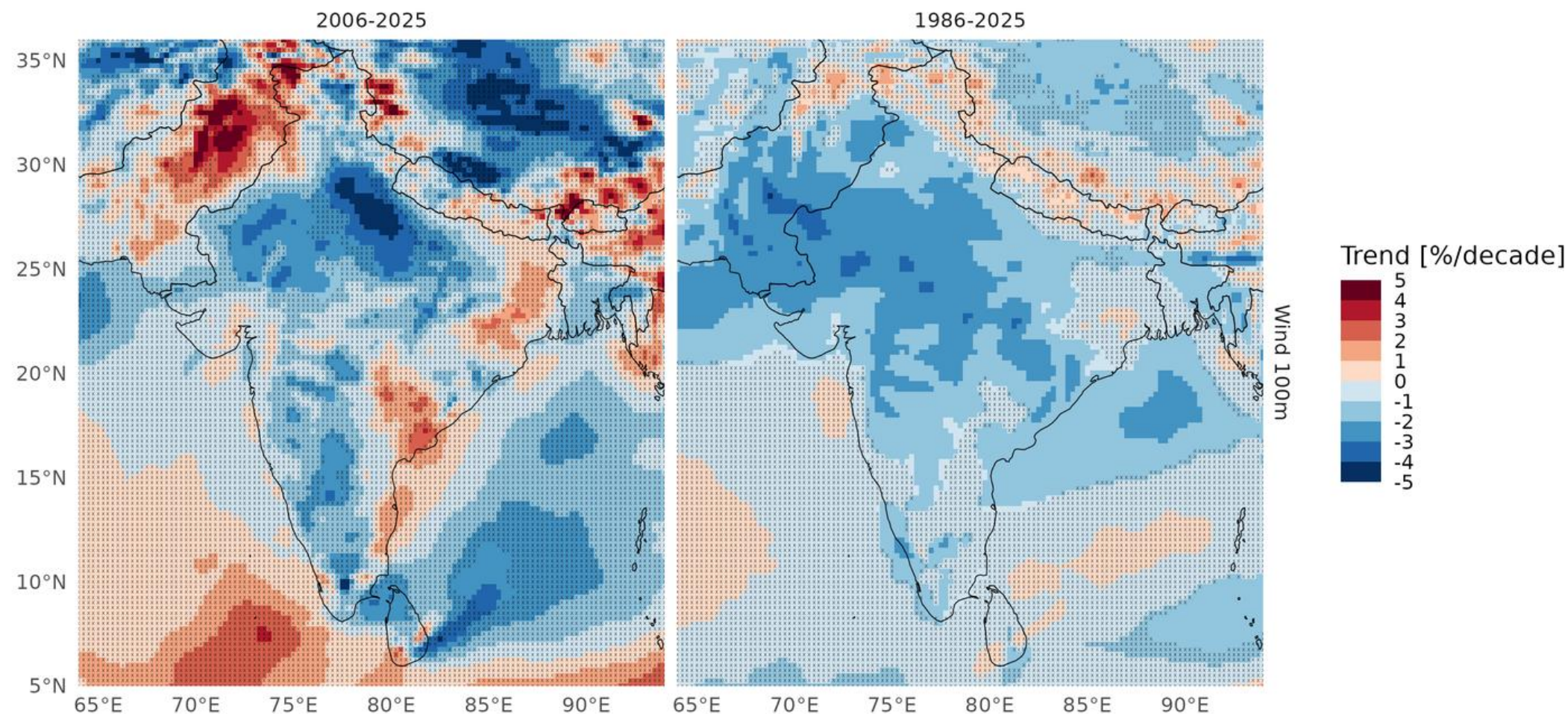
Will the trends continue?

Energy +

Wind resource over the last ~ 40 years

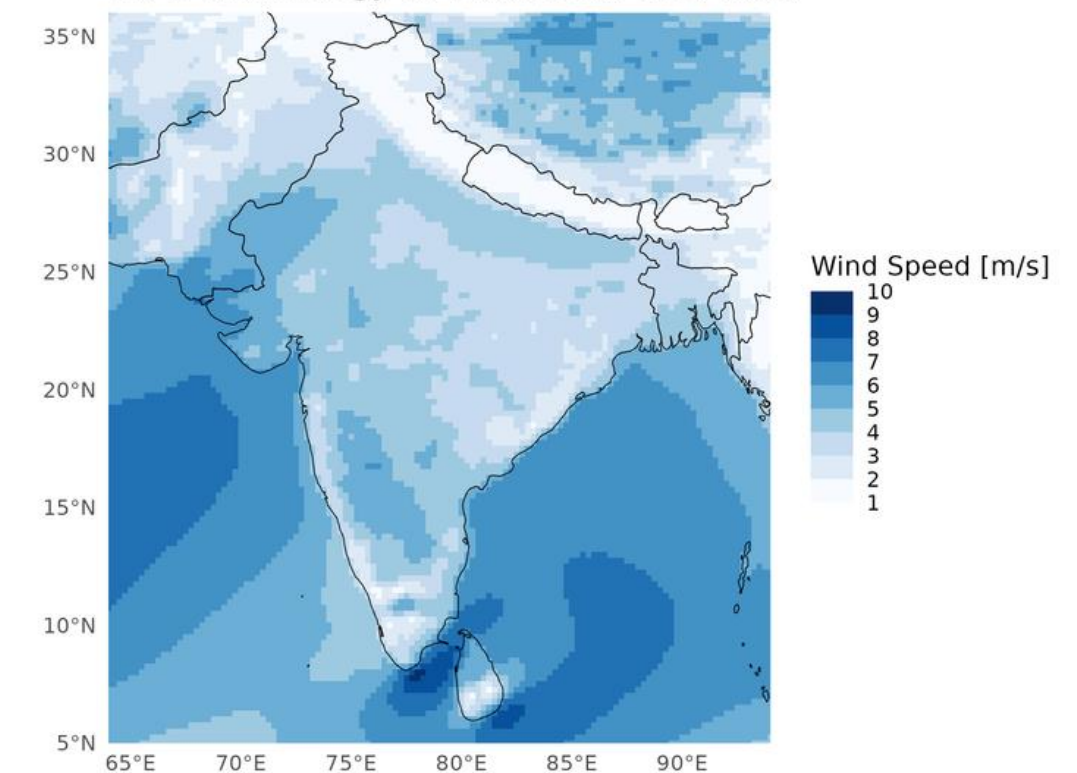
Wind speeds @100m show significant negative trends over the last 40 years in most wind development regions

ERA5 trends in Wind 100m over India



- Trends are expressed as % of the climatology, shown below.
- Stippling denotes not significant trends

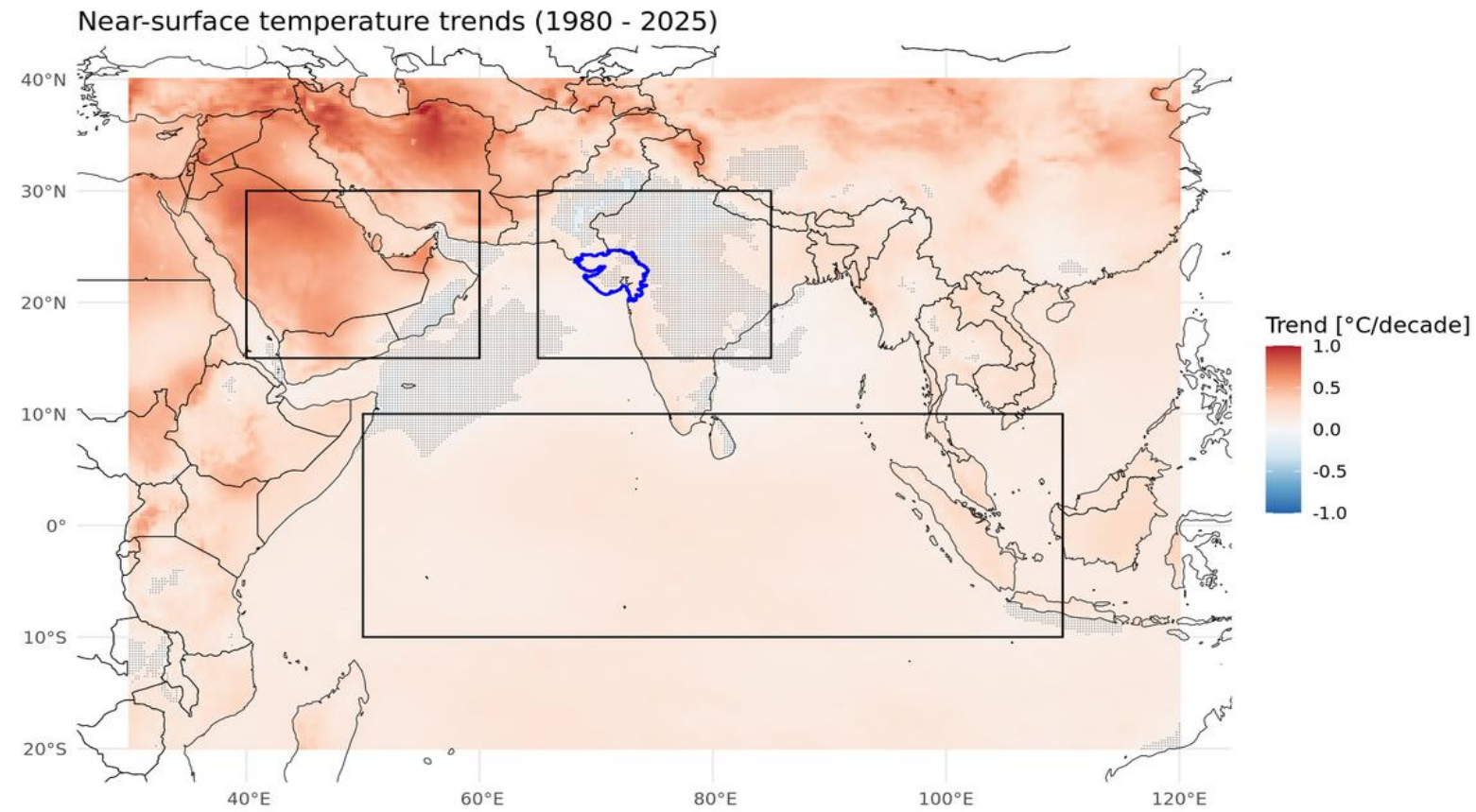
ERA5 climatology of Wind 100m over India



Note: here the focus is on long term trends to identify changes in 'climate' time scales. Trends reflect long term changes, not the year on year variability.

Wind resource over the last ~ 40 years

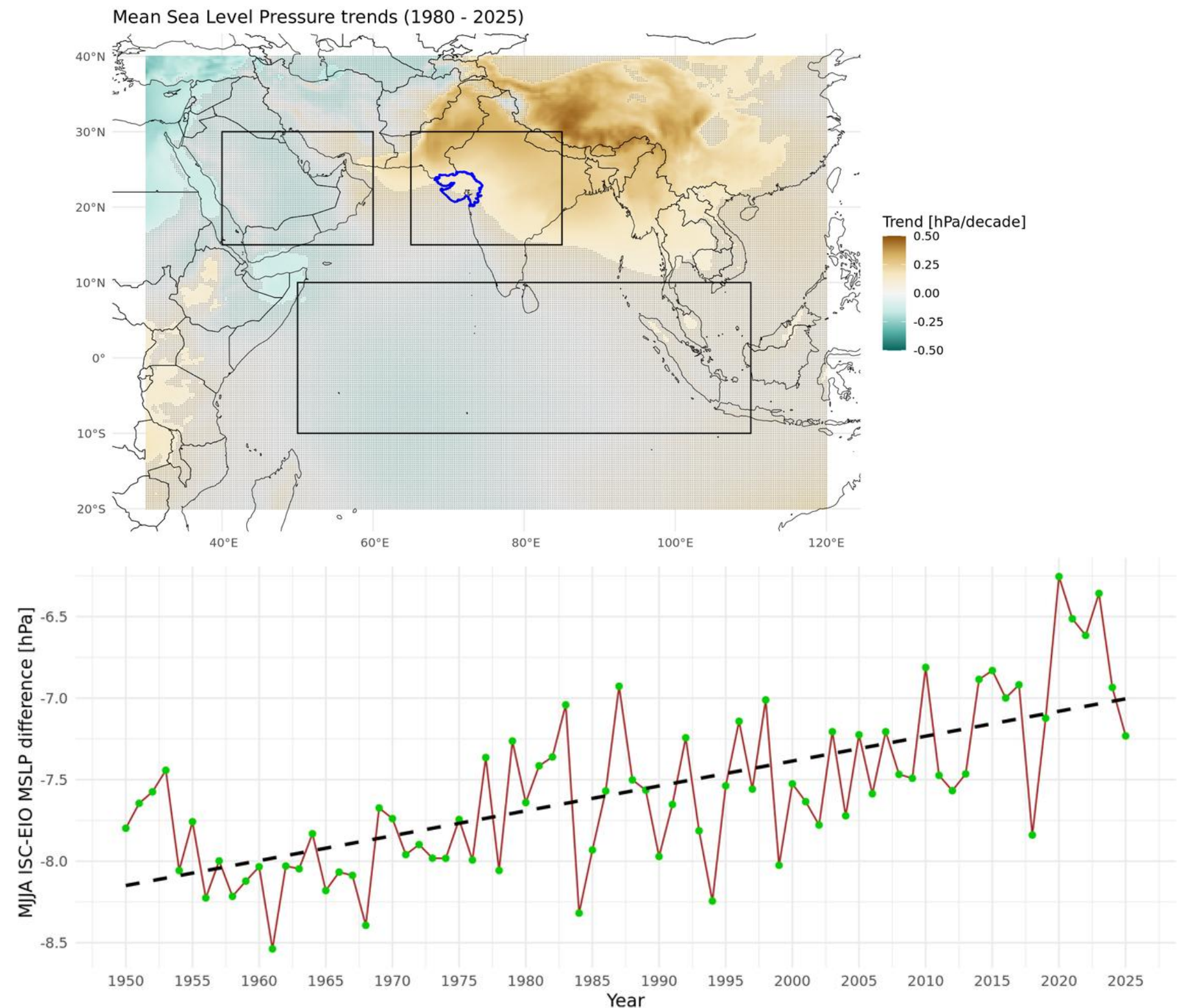
Aerosols over ISC



Arabian Peninsula warming
because of greenhouse gases

Sea level pressure gradient between the
EIO and the subcontinent (ISC) decreases
by 0.15 hPa per decade.

Decreasing pressure gradient (EIO & ISC)



Climatology and trends calculated over the Indian Summer Monsoon months (June–September) over 41 years (1980–2020).

Source: Upadhyaya et al, 2024, <https://doi.org/10.1038/s41612-024-00777-0>

source:
ERA5 data

explore.climatescale.com

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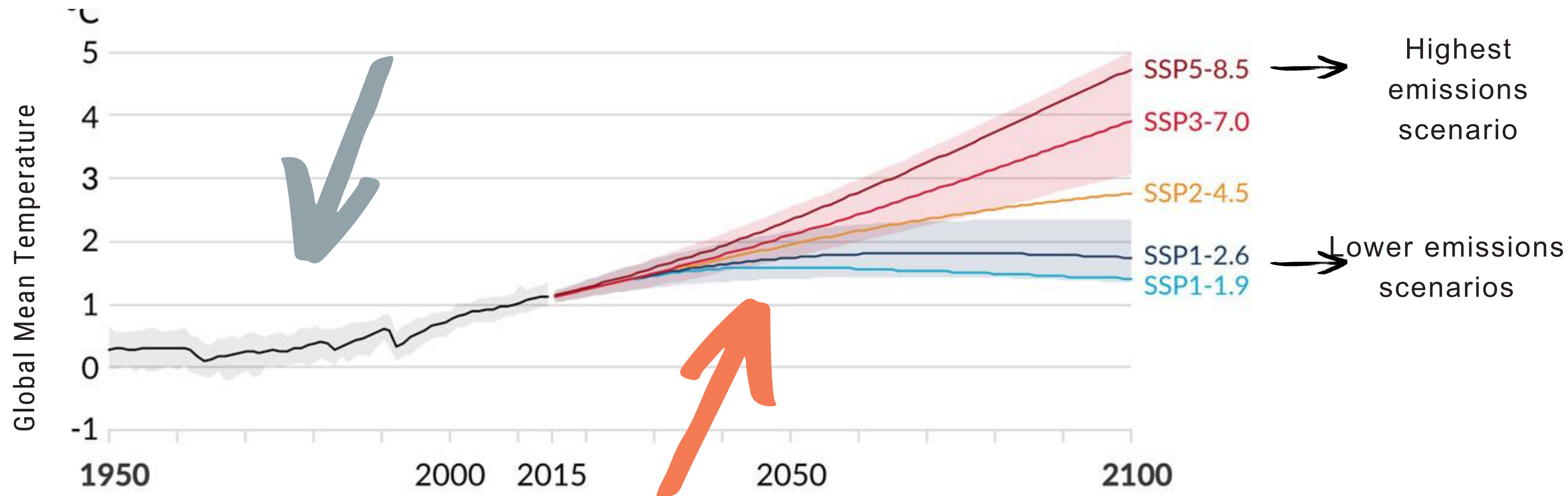
Examples of use

Will the trends continue?

Energy +

Climate models simulate

Past climate using historical values of greenhouse gases and natural forcings



plausible futures (what might happen in the future) conditioned on

- concentrations of greenhouse gases and land use changes and
- other modelling assumptions/choices.

CLIMATE

SCALE

SSP1-2.6

SSP2-4.5

SSP3-7.0

SSP5-8.5

Green house gases
(CO₂ Gt/year)
Methane CH₄, Nitrous Oxide N₂O
Fluorinated gases

22-48

65-85

76-86

104-126

Aerosols (SO₂ sulphates)

2020-2050
Deep/rapid
reductions

2020
slow steady
decline

2050 Peak

2020
strong decrease

Assumption

Balanced
Human development &
Environmental action

Slow progress
Middle of the road

Regional rivalry
Pessimistic about future
economic and social development

Human development
Cost of environment

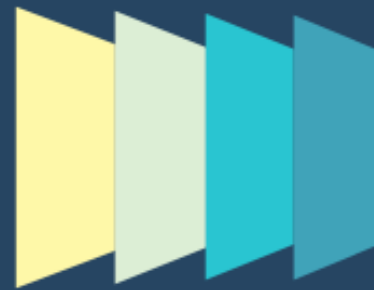
Economic growth, technological development, population growth, energy equality, global trade, resource exploitation etc.



REPORTS



SERIES



MAPS



ENERGY +



CONSULT



6h time series

Wind speed and direction at 100, 150, 200m hub-height



CMIP6 Models

Based on native model level data from GCMs (CMIP6)



Emission scenarios

Historical data and 4 future SSP scenarios



Wind & Site

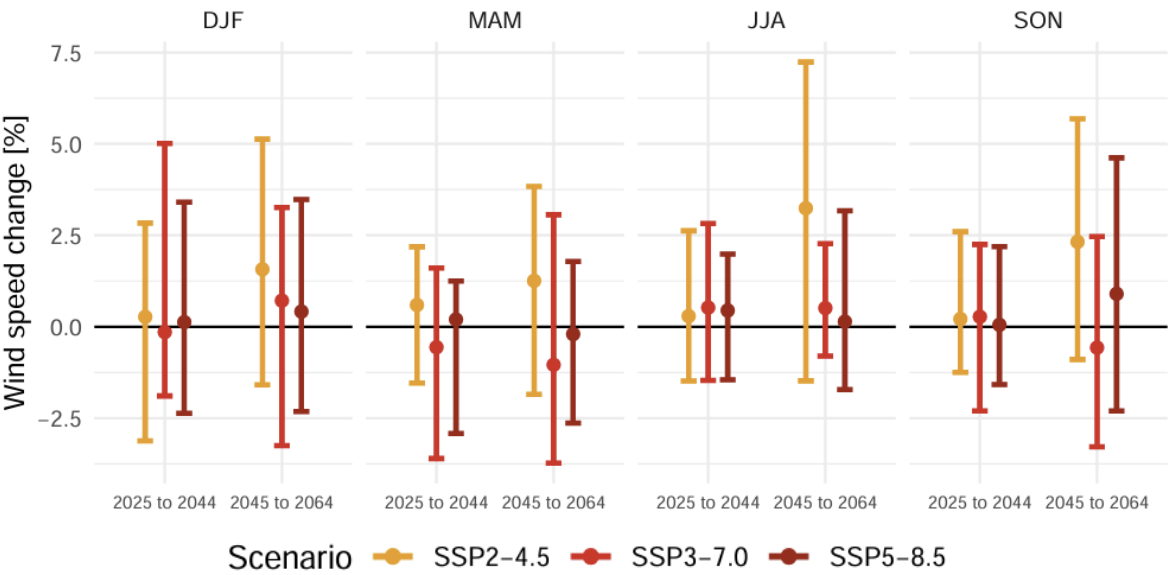
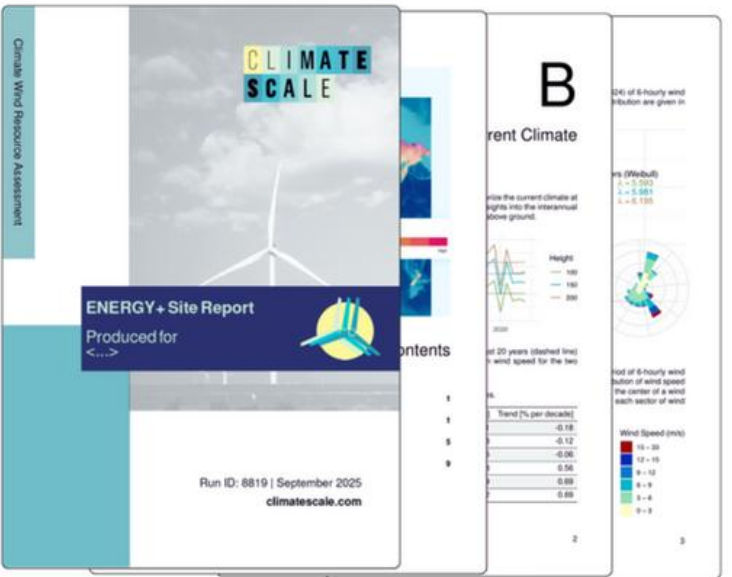
From 1984 to 2060, with up to 24 climate models



VORTEX

Powered by Vortex

Calibrated with high-resolution Vortex data

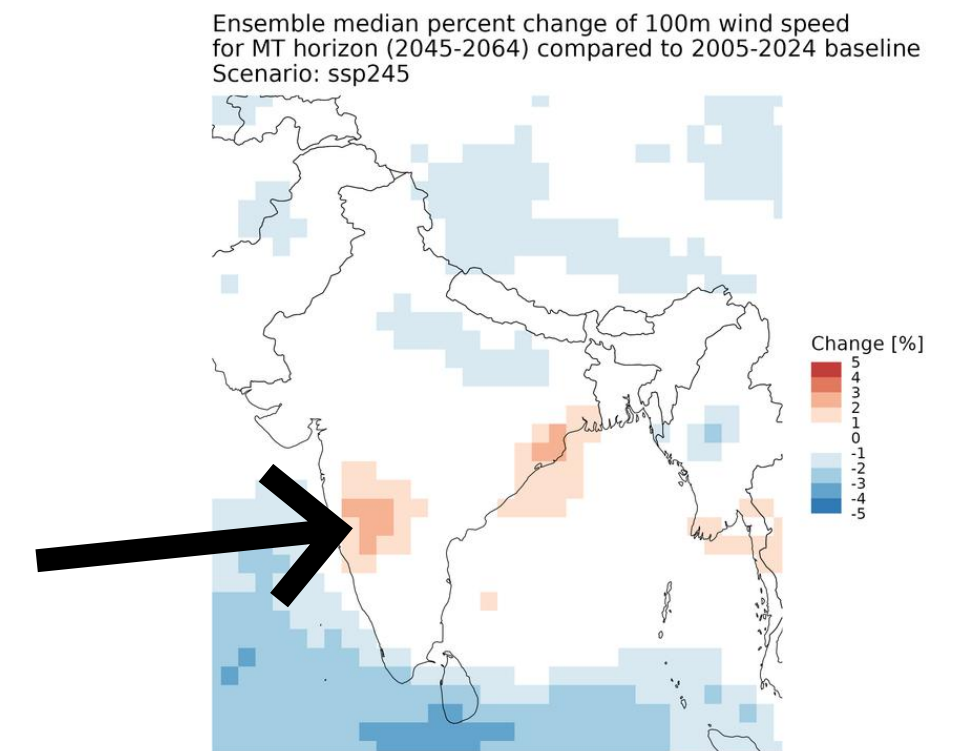
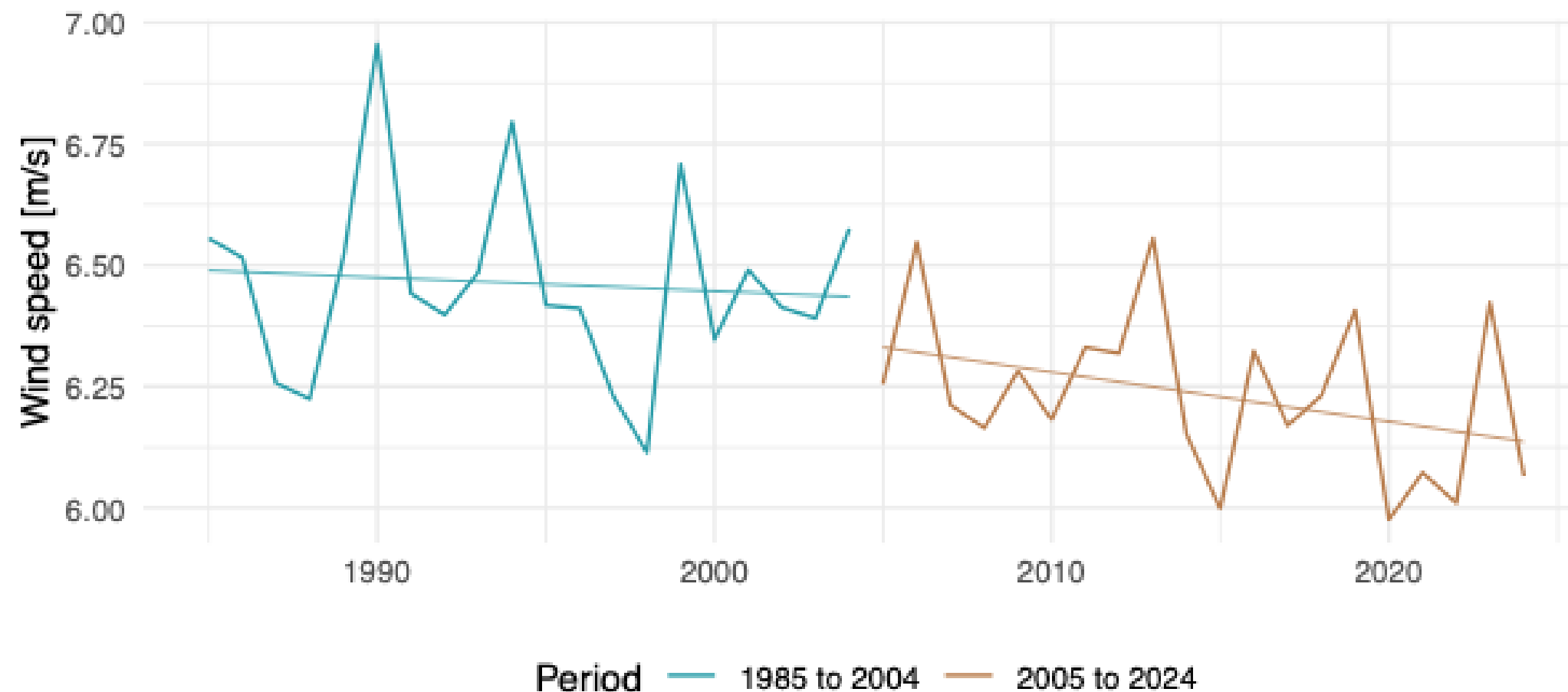


How do projected changes look like when we focusing on a particular location?

Current climate shows declining (non significant) trends

Period	Average	IAV	Trend
1985 to 2004	6.5 m/s	3.1 %	-0.4 %/decade
2005 to 2024	6.2 m/s	2.7 %	-1.6 %/decade

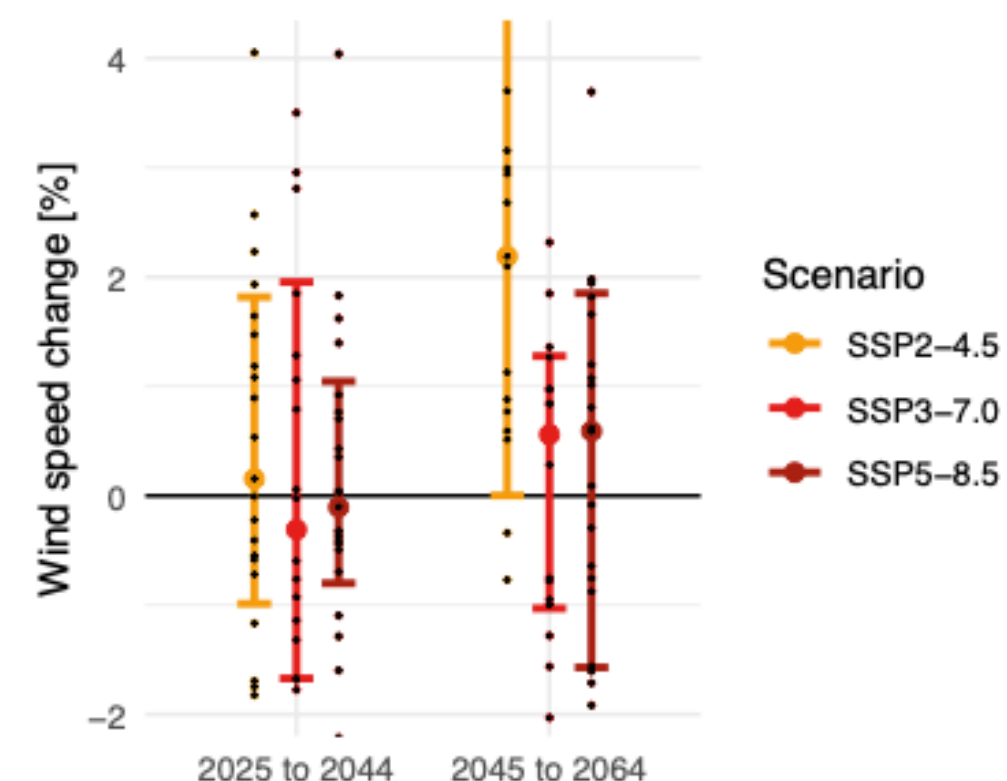
Long-term trends of wind speed



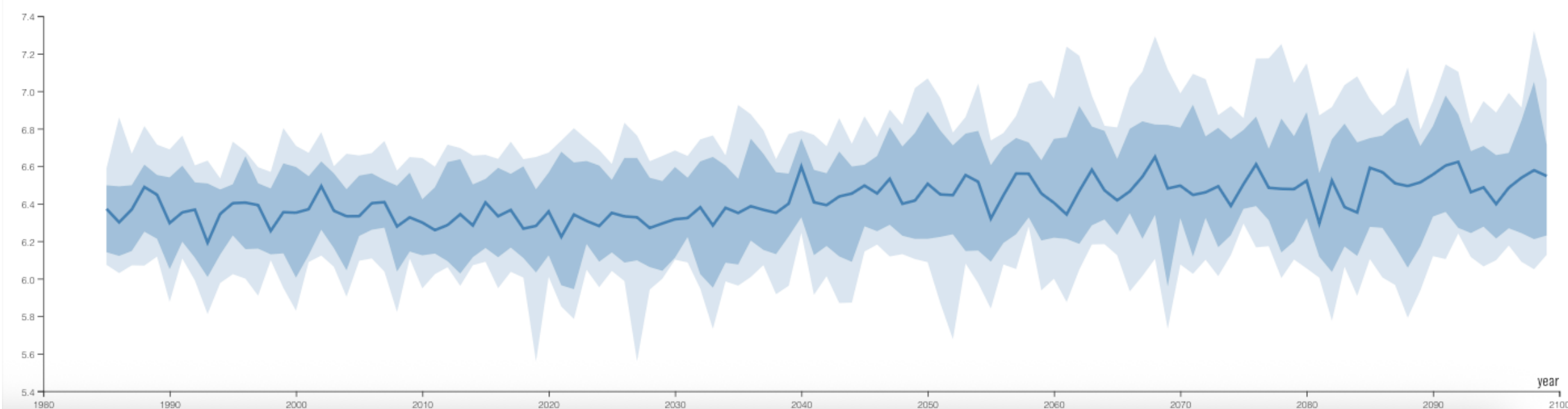
How do projected changes look like when we focusing on a particular location?

Projected changes over the next 40 years are

- mostly positive for SSP2-4.5
- not clear signal, either positive or negative, for SSP3-7.0 and SSP5-8.5

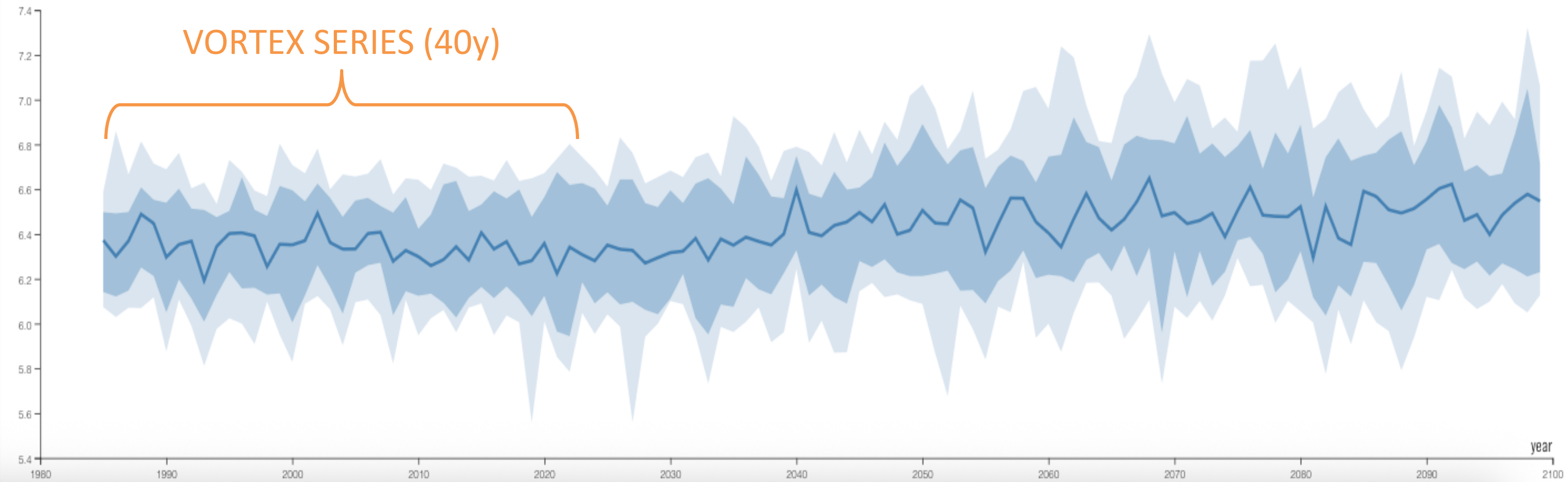


CMIP6 Statistical Downscaled Stream for Scenario SSP2-4.5
Wind Speed at hub height [m/s], 150m above ground





CMIP6 Statistical Downscaled Stream for Scenario SSP2-4.5
Wind Speed at hub height [m/s], 150m above ground



5-95%
17-83%
Ensemble Median

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Examples of use

Will the trends continue?

Energy +

C	L	I	M	A	T	E
S	C	A	L	E		

How we derive the data

Histori



cal
VORTEX

Wind



ERA5

Climate
Change Service

climate.copernicus.eu



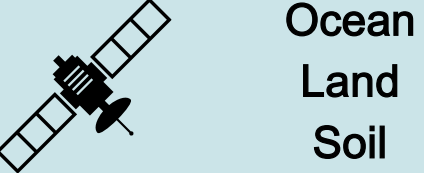
Ocean
Land
Soil

25-3 km
resolution

CLIMATE SCALE

How we derive the data

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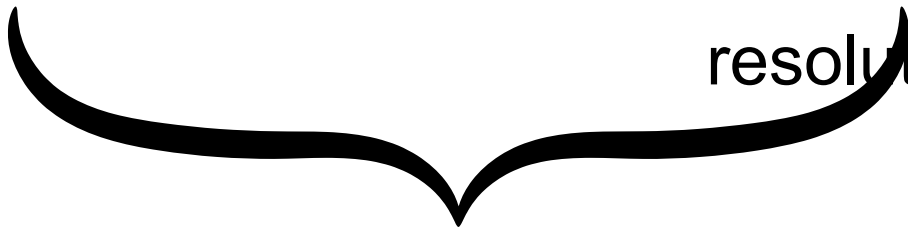
25-3 km
resolution

Climate Change
projections



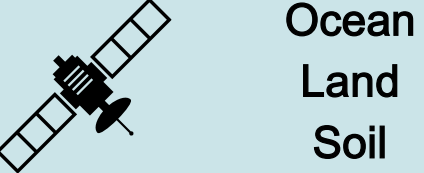
- More than 100TB of Data
- 20+ Climate Models
- 4 Climate Scenarios
- 1980-2100
- 7 Essential Climate Variables

100-200 km
resolution



+ External
sources

Historical



25-3 km
resolution

Climate Change
projections

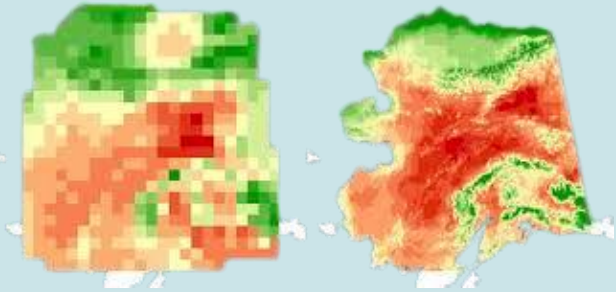


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100-200 km
resolution

Climate Change
projections

Statistical Downscaling
applied to CMIP6



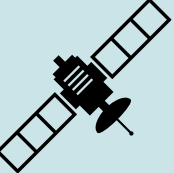
25-3 km
resolution

All variables: interpolation + Bias Correction (MBCn)
But for Precipitation: Rainfarm + Bias correction (MBCn)

Historical

 cal VORTEX Wind

 ERA5
Climate Change Service
climate.copernicus.eu

 Ocean
Land
Soil

25-3 km
resolution

Climate Change
projections

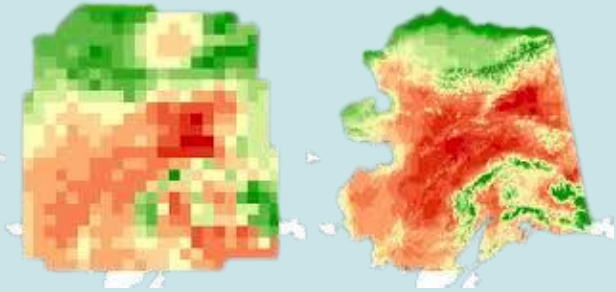
 WCRP CMIP6
World Climate Research Programme

- More than 100TB of Data
- 20+ Climate Models
- 4 Climate Scenarios
- 1980-2100
- 7 Essential Climate Variables

100-200 km
resolution

Climate Change
projections

Statistical Downscaling
applied to CMIP6



25-3 km
resolution

Climate Metrics
Climate related Risks

 REPORTS

 SERIES

 MAPS

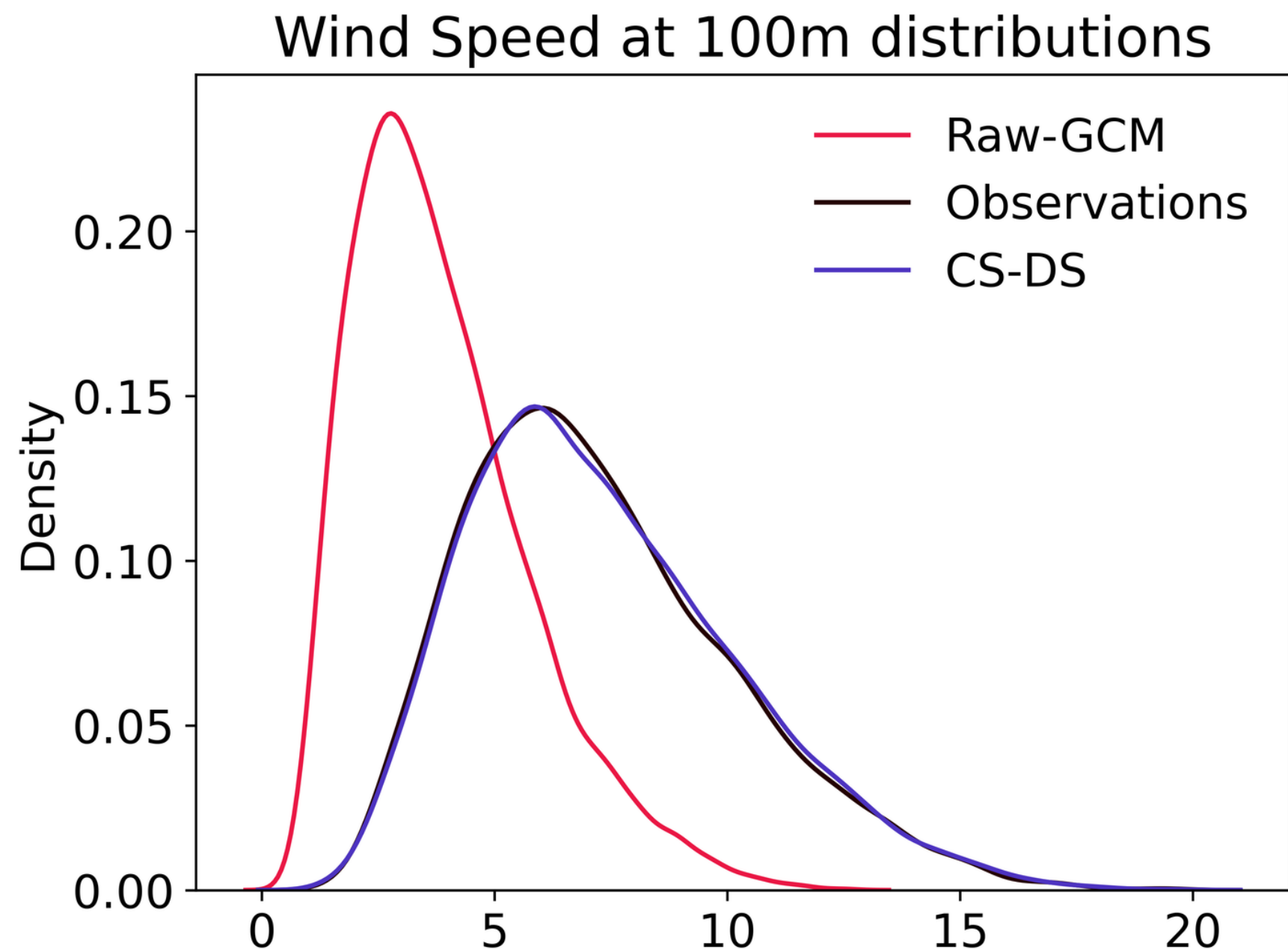
 ENERGY+

Climate Scale statistical downscaling and bias correction methodology combines

- bilinear interpolation of GCMs to ERA5 resolution, plus
- a bias correction algorithm based on Multivariate Bias Correction (MBCn) approach developed by [Cannon \(2018\)](#)

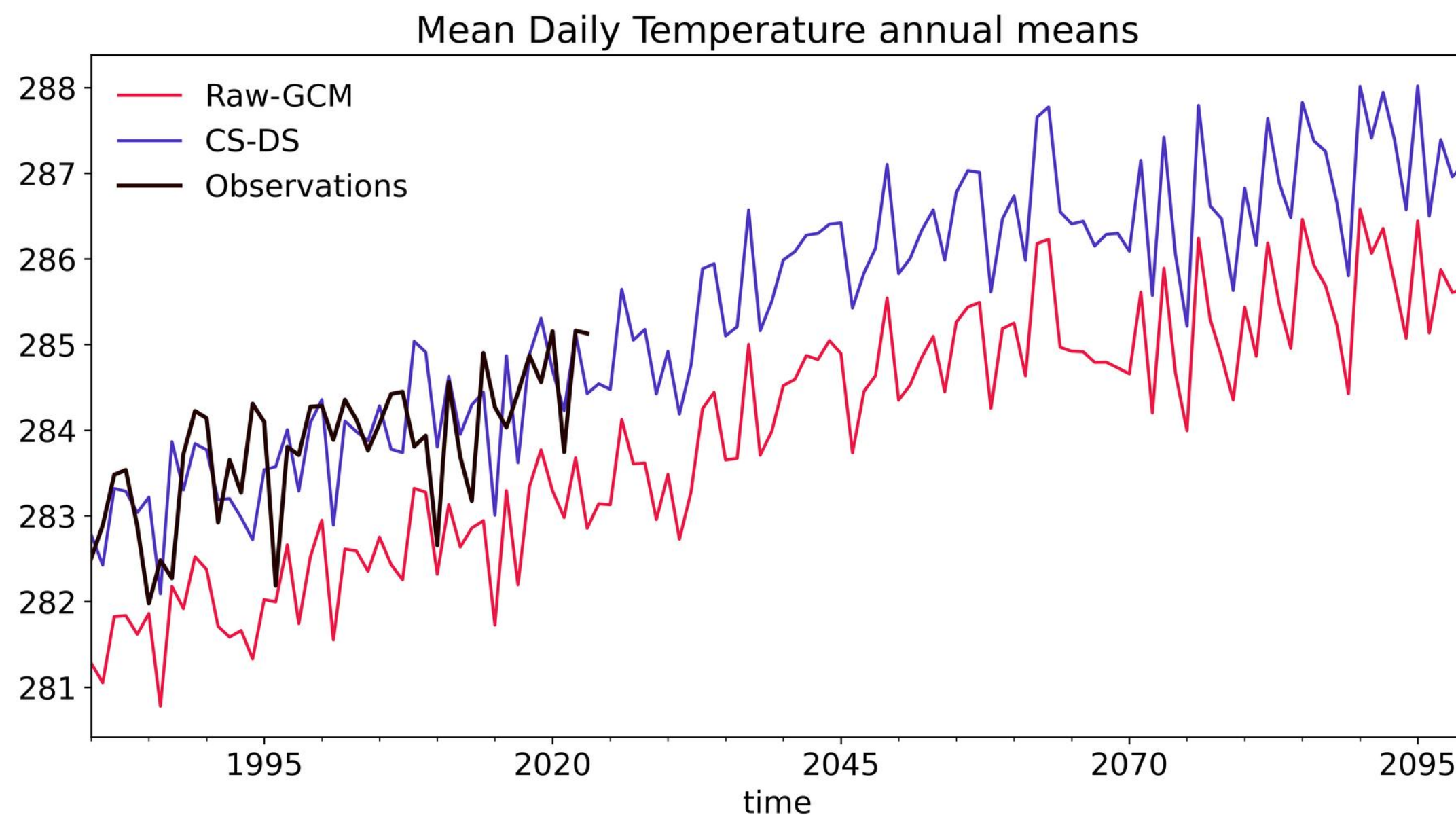
MBCn

- Preserves spatial and inter-variable correlations
- Preserves projected climate change signals
- It is interpretable: quantile mapping plus delta change



Applying MBCn calibrates the distribution of the climate model output during the observational period to that of the observational data set

- reducing the bias and adjusting the standard deviation (see period 1980-2023)
- and keeping the climate change signal (see period 2024-2100)





- More than 30 climate hazards
- Risk indicators
- Ensemble statistics and indicator of confidence

		Baseline Observed Climate				Climate Projections CMIP6						
						Display: Changes						
Hazard Metric	Type	Reference	Units	IAV	Units	Future Horizon	Emissions Scenario	Ensemble Median	Likely Low	Likely High	Units	Confidence
Mean Daily Temperature	Chronic	14	degC	0.5	degC	2020-2039	SSP5-8.5	0.8	0.5	1	degC	High
Min Daily Temperature	Chronic	8.8	degC	0.4	degC	2020-2039	SSP5-8.5	0.7	0.4	0.9	degC	High
Max Daily Temperature	Chronic	19.5	degC	0.7	degC	2020-2039	SSP5-8.5	0.9	0.6	1.2	degC	High
Heat Wave Index	Acute	18	days/year	13	days/year	2020-2039	SSP5-8.5	11	6	16	days/year	High
Cold Wave Index	Acute	20	days/year	15	days/year	2020-2039	SSP5-8.5	-3	-7	1	days/year	Medium
Cold Days Index	Chronic	26	days/year	12	days/year	2020-2039	SSP5-8.5	-5	-10	-1	days/year	High
Icing Days Index	Chronic	0	days/year	0	days/year	2020-2039	SSP5-8.5	0	0	0	days/year	Medium
Wet Bulb Globe Temperature Acute	Acute	0	days/year	0	days/year	2020-2039	SSP5-8.5	0	0	0	days/year	High
Wet Bulb Globe Temperature Chronic	Chronic	19.1	degC	0.7	degC	2020-2039	SSP5-8.5	0.7	0.6	1	degC	High
Mean Daily Precipitation	Chronic	2	mm/day	19	%	2020-2039	SSP5-8.5	-2	-10	5	%	Low
Extreme Precipitation	Acute	64	mm/day	-	%	2020-2039	SSP5-8.5	7.8	-0.7	18	%	Medium
Consecutive Wet Days	Chronic	8	days/year	2	days/year	2020-2039	SSP5-8.5	0	-1	1	days/year	Medium
Consecutive Dry Days	Chronic	29	days/year	9	days/year	2020-2039	SSP5-8.5	2	-1	4	days/year	Medium
Hydrological Drought Mean Duration	Acute	14	month	-	month	2020-2039	SSP5-8.5	12	-1	21	month	Medium
Hydrological Drought Events	Acute	4	events	-	events	2020-2039	SSP5-8.5	1	0	3	events	High
Agricultural Drought Mean Duration	Acute	5	month	-	month	2020-2039	SSP5-8.5	1	0	3	month	Medium
Agricultural Drought Events	Acute	6	events	-	events	2020-2039	SSP5-8.5	3	1	7	events	High
Mean Daily Wind Speed @10	Chronic	4	m/s	3.3	%	2020-2039	SSP5-8.5	-0.1	-2.1	1.8	%	Low
Mean Daily Wind Speed @100	Chronic	6.9	m/s	3.3	%	2020-2039	SSP5-8.5	-0.1	-2	1.8	%	Low
Max Daily Wind Speed @100	Chronic	10.7	m/s	2.8	%	2020-2039	SSP5-8.5	-0.2	-1.5	1.4	%	Medium
Extreme Wind Speed @100m (Vref)	Acute	33.3	m/s	-	%	2020-2039	SSP5-8.5	1	-4.3	2.7	%	Medium
Air Density	Chronic	1.163	kg/m3	0.2	%	2020-2039	SSP5-8.5	-0.3	-0.3	-0.2	%	High
Fire Weather Index Acute	Acute	33.8	-	-	% of days	2020-2039	SSP5-8.5	7.9	5.4	11.2	% of days	High
Fire Weather Index Chronic	Chronic	23.7	-	2.4	-	2020-2039	SSP5-8.5	1.7	0.2	4.3	-	High

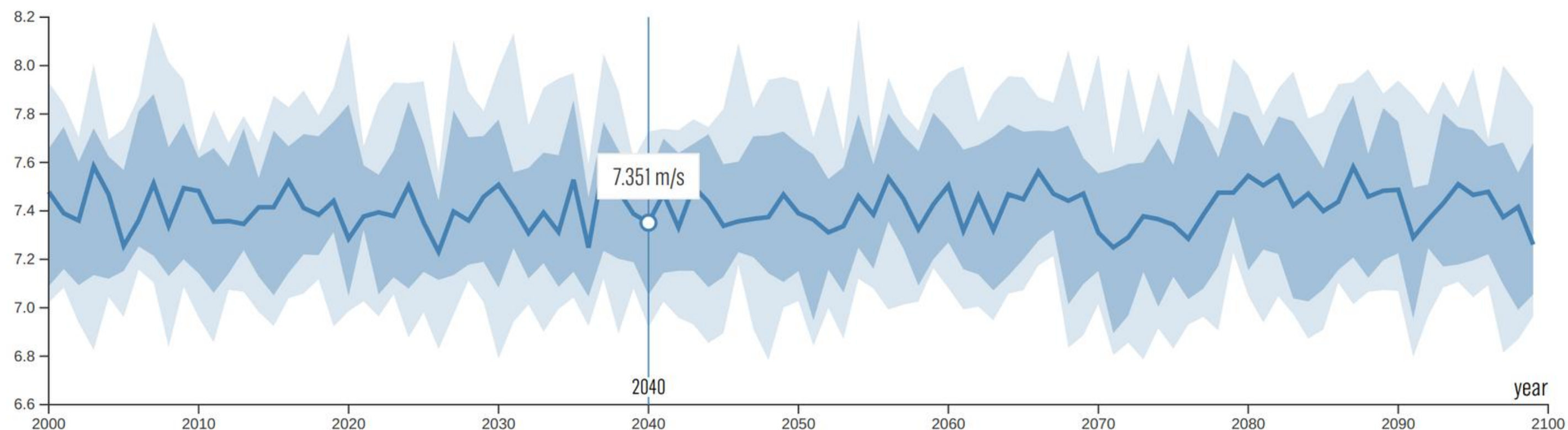
Products





CMIP6 Statistical Downscaled Stream for Scenario SSP2-4.5

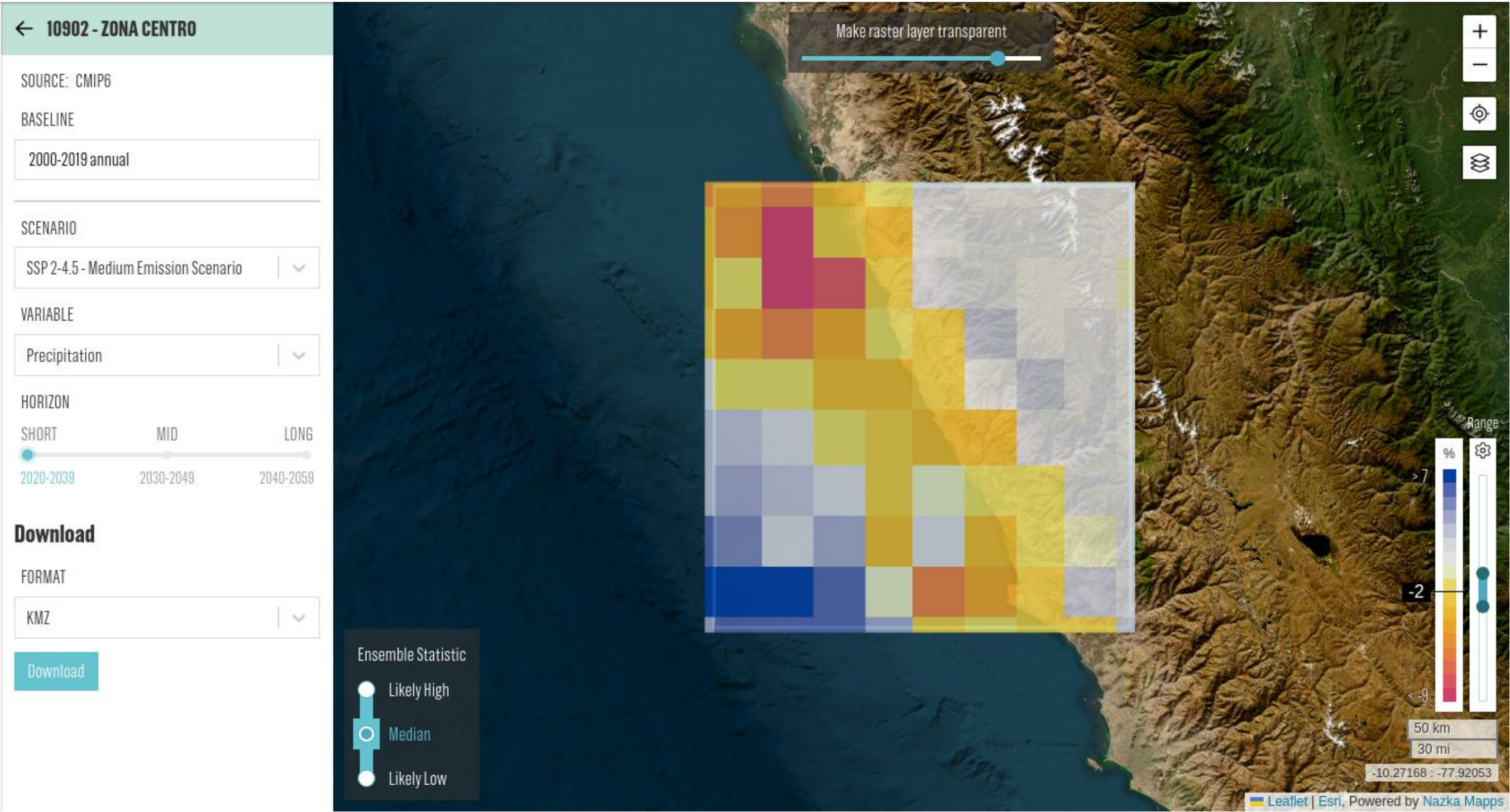
Mean Daily Wind Speed @100 [m/s]



- Downscaled time series for specific locations
- 1980-2100
- Essential climate variables and derived hazards
- Time series for each variable, Global Climate Model, and scenario

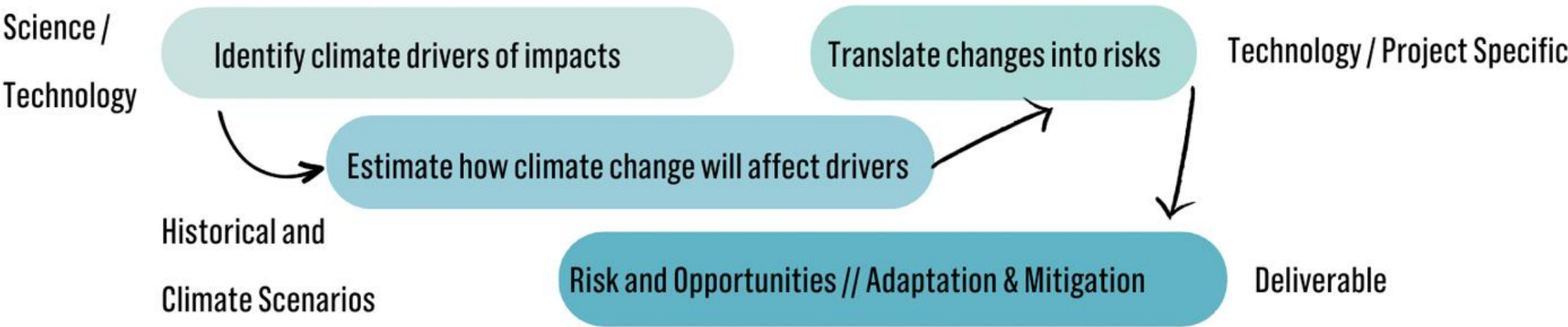


- Downscaled maps
- Different horizons
- 300x300 km²
- 25km resolution
- GeoTiff, kmz





- Climate Physical Risks assessments for EYA and due diligence, wind and solar.
- Development of climate risk indices, including economic impacts, from local to regional scales.
- Data provision and analysis to support National Adaptation Plans.
- Capacity building: understanding and working with climate projections, and using information for decision support.





Specifically for wind:

- understanding large scale drivers of regional/local wind variability, e.g phases of NAO/AMO, El Niño, Jet stream variability.
- changes in surface or boundary layer processes, e.g land use changes.
- changes in regional or local processes , e.g blocking.

and how the above affects the wind resource, and wind farm OPEX/CAPEX at a specific site.

Outline

Understanding the past

Wind resource over the las ~ 40 years

Projecting the future

Climate Scenarios and climate Projections

Climate Scale approach and products

Examples of use

Will the trends continue?

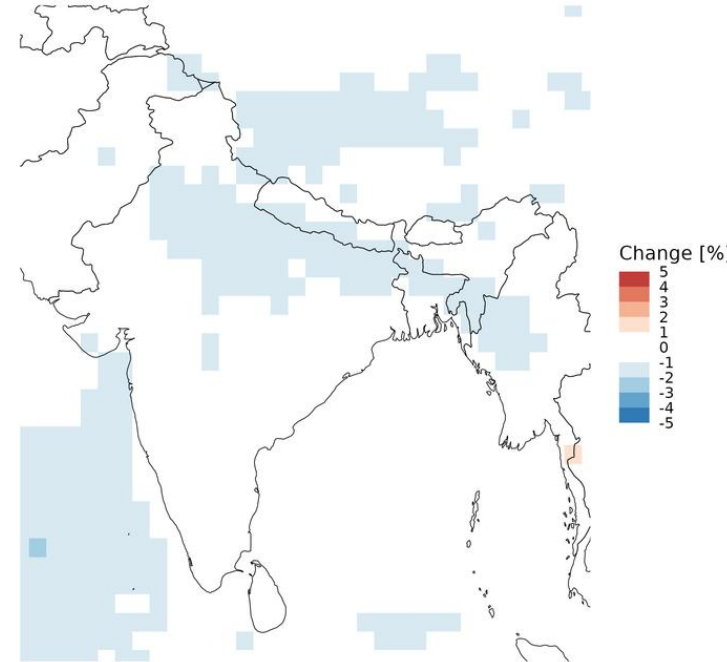
Energy +

Projected wind speed
changes

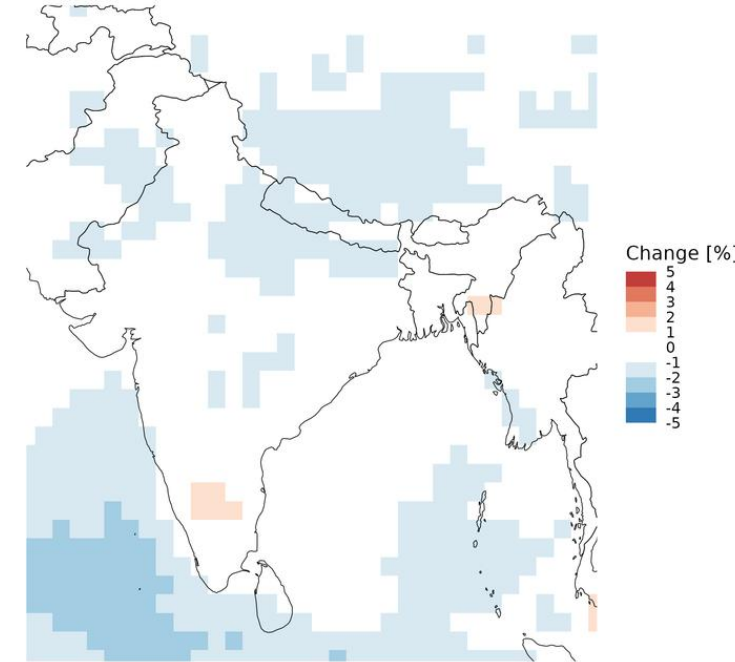
Observed declining trends are not projected to continue over the next 40 years

2025-2044
changes w.r.t. 2005-2024

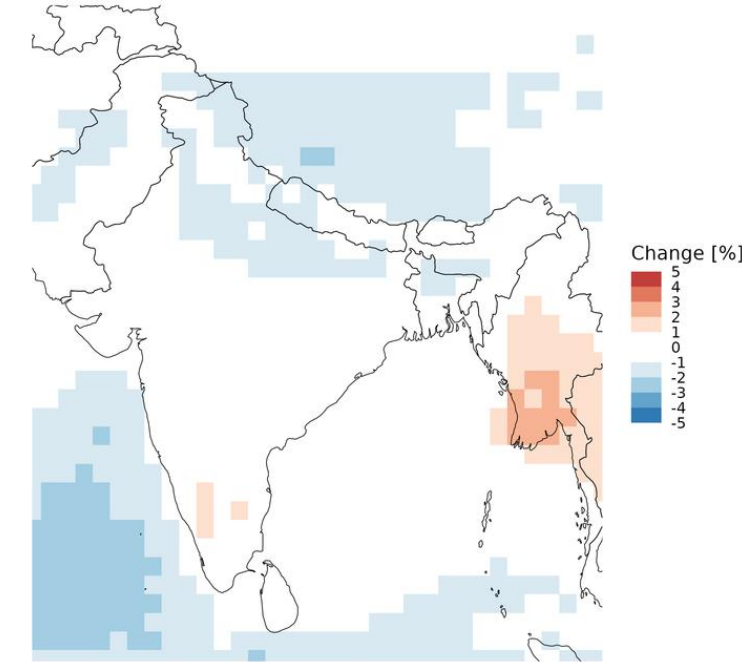
Ensemble median percent change of 100m wind speed
for ST horizon (2025-2044) compared to 2005-2024 baseline
Scenario: ssp245



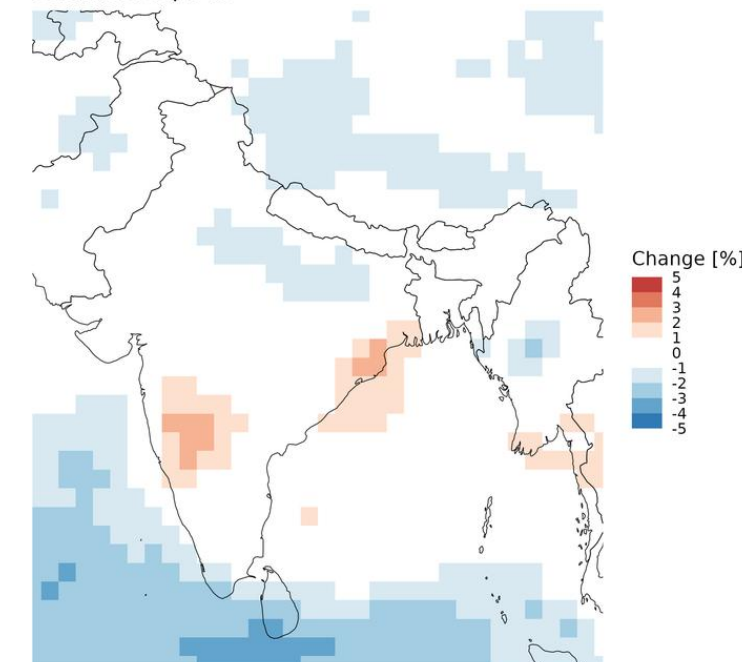
Ensemble median percent change of 100m wind speed
for ST horizon (2025-2044) compared to 2005-2024 baseline
Scenario: ssp370



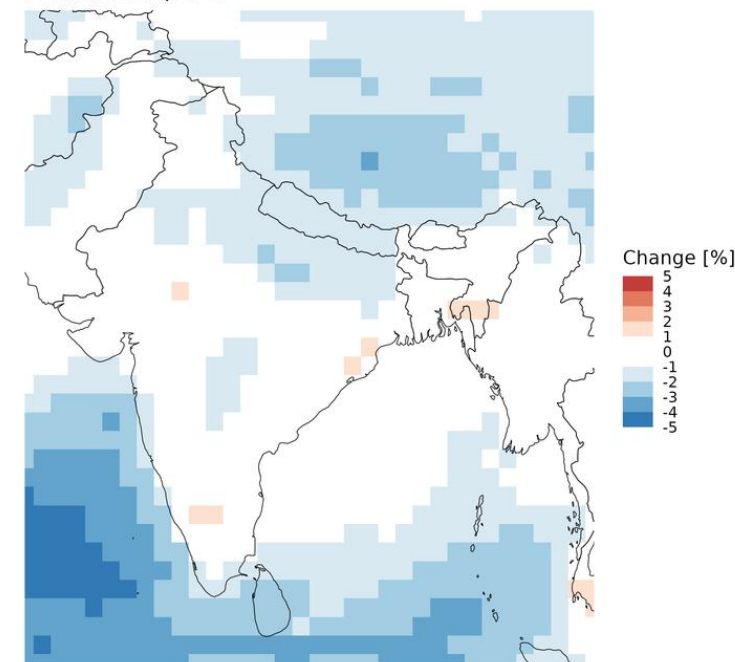
Ensemble median percent change of 100m wind speed
for ST horizon (2025-2044) compared to 2005-2024 baseline
Scenario: ssp585

2045-2064
changes w.r.t. 2005-2024

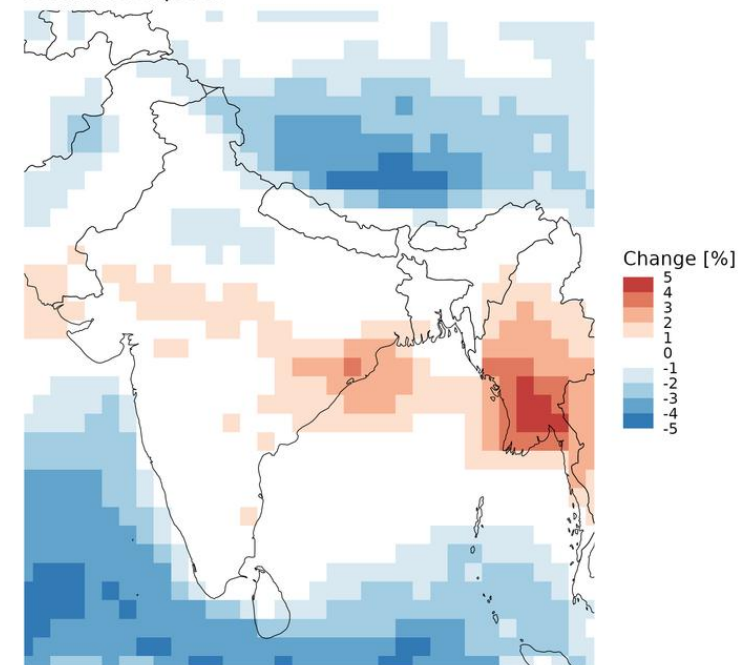
Ensemble median percent change of 100m wind speed
for MT horizon (2045-2064) compared to 2005-2024 baseline
Scenario: ssp245



Ensemble median percent change of 100m wind speed
for MT horizon (2045-2064) compared to 2005-2024 baseline
Scenario: ssp370



Ensemble median percent change of 100m wind speed
for MT horizon (2045-2064) compared to 2005-2024 baseline
Scenario: ssp585



- ensemble median of models' changes across CMIP6 ensemble
- Coarse resolution- no downscaling performed
- decreases or increases small than 1% are considered too small to have a material impact in the project

← less warming

more warming →

explore.climatescale.com

Projected wind speed changes

Under **global warming**, it is expected that in regions where Monsoon winds are driven by the land-sea temperature contrast, wind speeds will increase, as land masses are projected to warm faster than oceans[1]. In the ISC where the cooling effect of aerosols seems to be driving a decrease in wind speeds, the resulting changes will reflect the competing effect of warming greenhouse gases and cooling aerosols.

Different SSPs assume specific emissions pathways of Green House Gases (GHG) and aerosols (including those that have a cooling effect on the climate such as SO₂). The only scenario that assumes continuous increase of sulfates globally is SSP3-7.0. SSP2-4.5 and SSP5-8.5 assume a decrease in aerosols from around the 2020s [2].

Over the ISC, SSP3-7.0 is the only scenario that assumes increases in aerosol emissions up to around 2050 due to weak air quality policies and continued reliance on fossil fuels [3]

[1] <https://www.carbonbrief.org/guest-post-why-does-land-warm-up-faster-than-the-oceans/>

[2] Persad et al (2022) Aerosols must be part of climate risk assessments <https://www.nature.com/articles/d41586-022-03763-9.pdf>

[3] Lund et al , 2019, Anthropogenic aerosol forcing under the Shared Socioeconomic Pathways. Atmos. Chem. Phys., 19, 13827–13839, 2019. <https://doi.org/10.5194/acp-19-13827-2019>

Projected wind speed changes

Projected warming over the ISC and surrounding areas shows the expected patterns:

in the short term:

- SSP5-8.5 is the fastest warming scenario
- SSP3-7.0 shows smaller changes of temperature over the ISC.
- SSP2-4.5 and SSP5-8.5 do not show less warming over the ISC (compared to the ocean or the AP), consistent with the assumption of aerosols emissions declining from about the 2020s.
- except for SSP3-7.0, the IO does not warm more than the ISC.

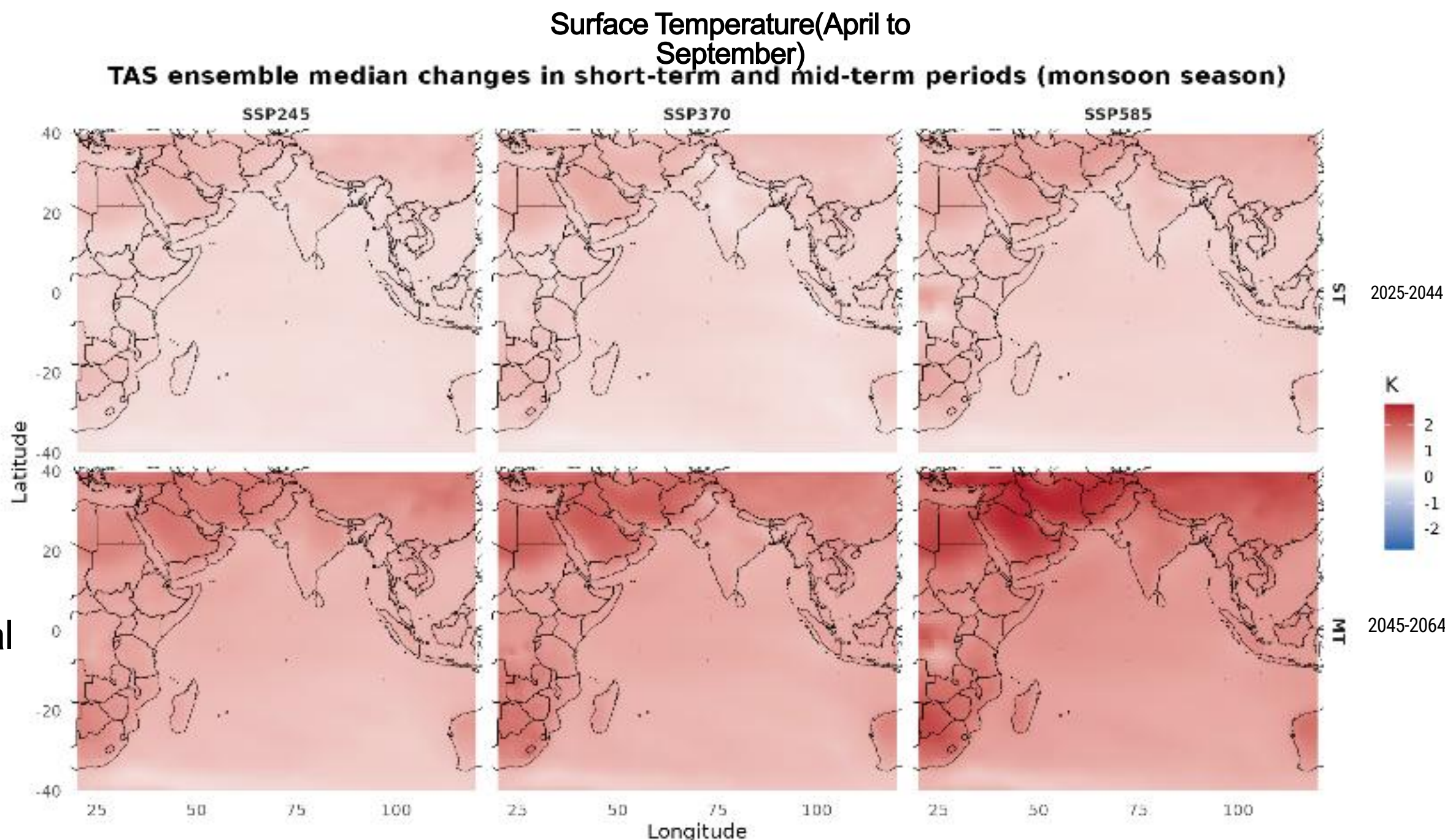
In the medium term

- temperatures increase substantially over ocean and land masses, with the largest increases under SSP5-8.5.
- in spite of corresponding to a scenario with larger greenhouse gas emissions, SSP3-7.0 shows similar levels of warming over the ISC to SSP2-4.5, presumably due to the stronger aerosol emissions.

For all scenarios and periods temperature increases more in the AP than in the ISC, presumably because the AP is drier.

For **SSP4.5 and 8.5** scenarios, relatively weak differential warming of land vs ocean could explain weak changes in wind speeds over most of the ISC.

For **SSP3-7.0** scenario, the competing effects of increased warming attributable to greenhouse gases resulting in stronger winds, and cooling due to aerosols resulting in weakened winds, could explain weak changes in wind speeds over most of the ISC



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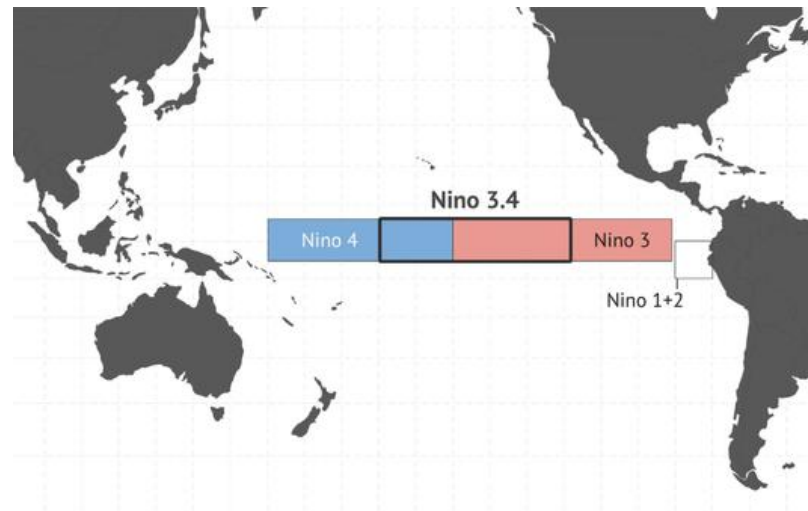
Climate Scale approach and products

Examples of use

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Energy +

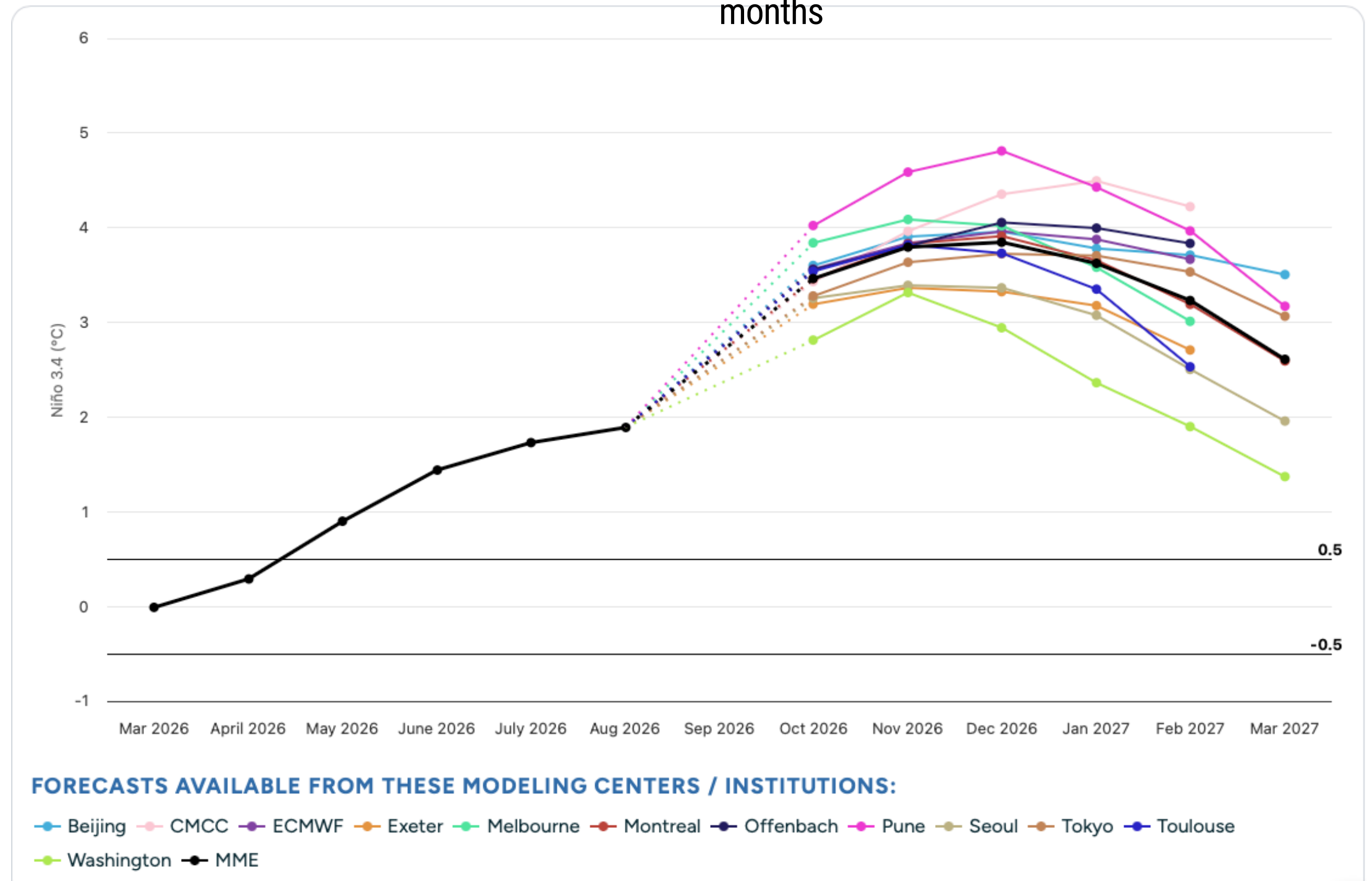
El Niño 2026-2027 is expected to be one (the?) strongest on records.



Niño 3.4: sea surface temperature anomalies over the central Pacific region, relative to a centred 30-year climatology.

Above +0.5°C: El Niño conditions
 +0.5°C to +1°C → weak El Niño
 +1°C to +1.5°C → moderate El Niño
 +1.5°C to +2°C → strong El Niño
 > +2°C → very strong / extreme El Niño

Current Niño 3.4 forecast: initialized Sep 1, 2026 for upcoming 6 months

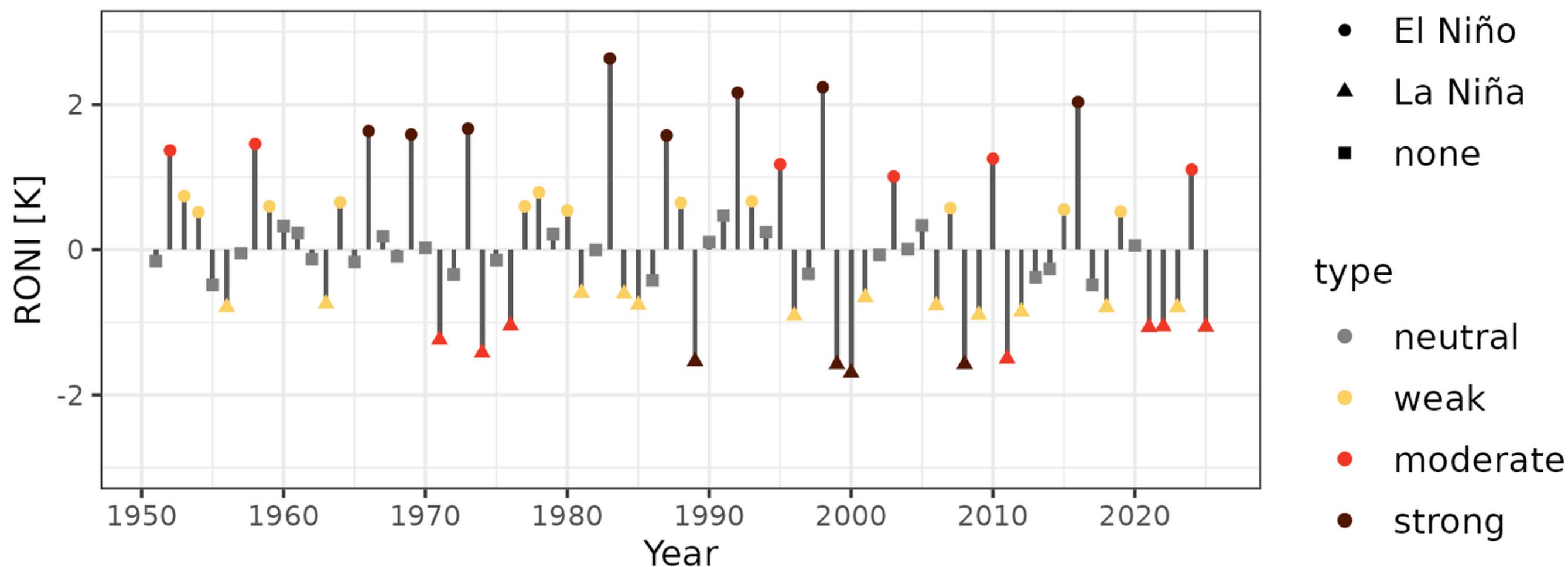


source: <https://climateknowledgeportal.worldbank.org/index.php/ENSO-forecast>

<https://wmo.org/seasonIndicesUI/#>

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El Niño impacts on wind resource

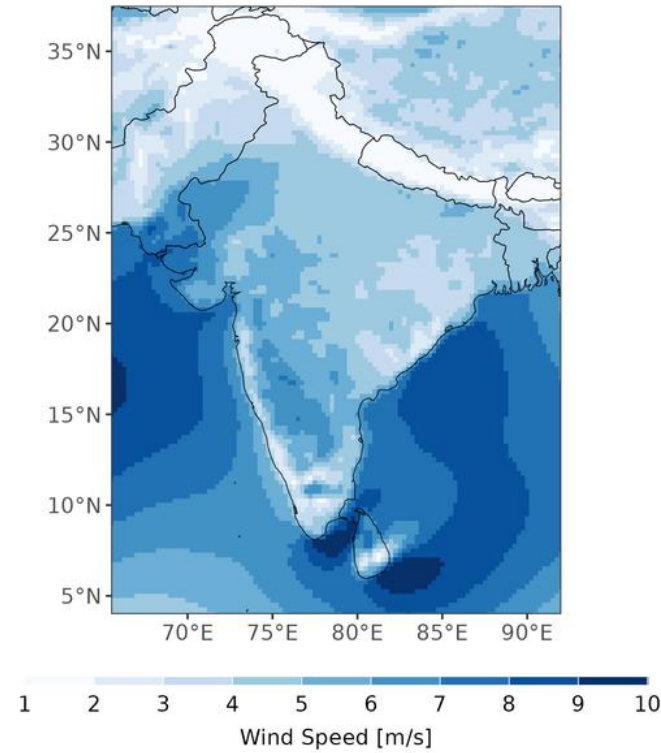


Relative Oceanic Niño Index (RONI): sea surface averages in the Nino 3.4 region with temperature anomalies observed across the tropical oceans (between the latitudes of 20 degrees north and south) subtracted.

DJF seasonal values. Years indicate the center of the season (Jan)

Events are categorised by classes weak (until +0.5C to 1C), moderate (1C to 1.5C) and strong (> 1.5C).

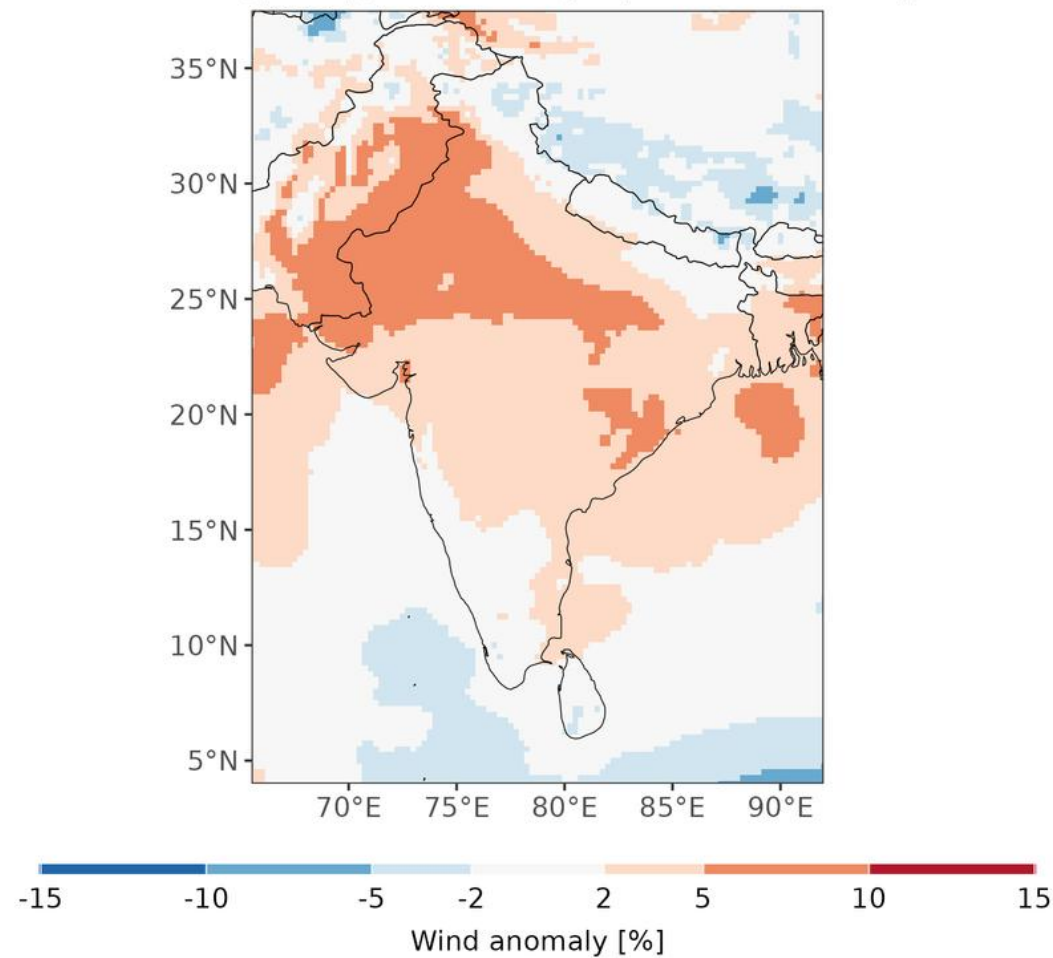
ERA5 wind 100m climatology - April to September (2006 - 2025)



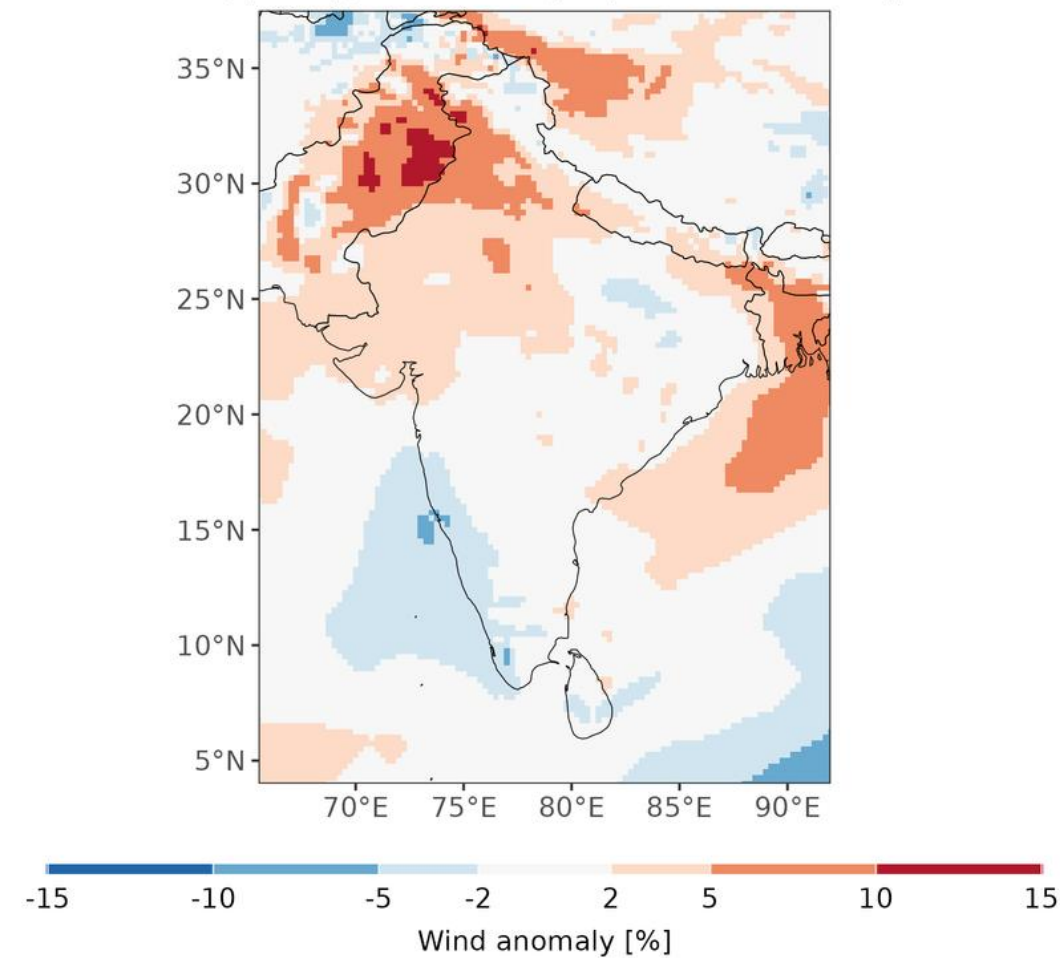
El Niño impacts on wind resource

Bottom figures show composites of wind @100m anomalies for weak (left), moderate (middle) and strong (right) El Niño events, with respect to the 2006-2025 climatology (left figure)

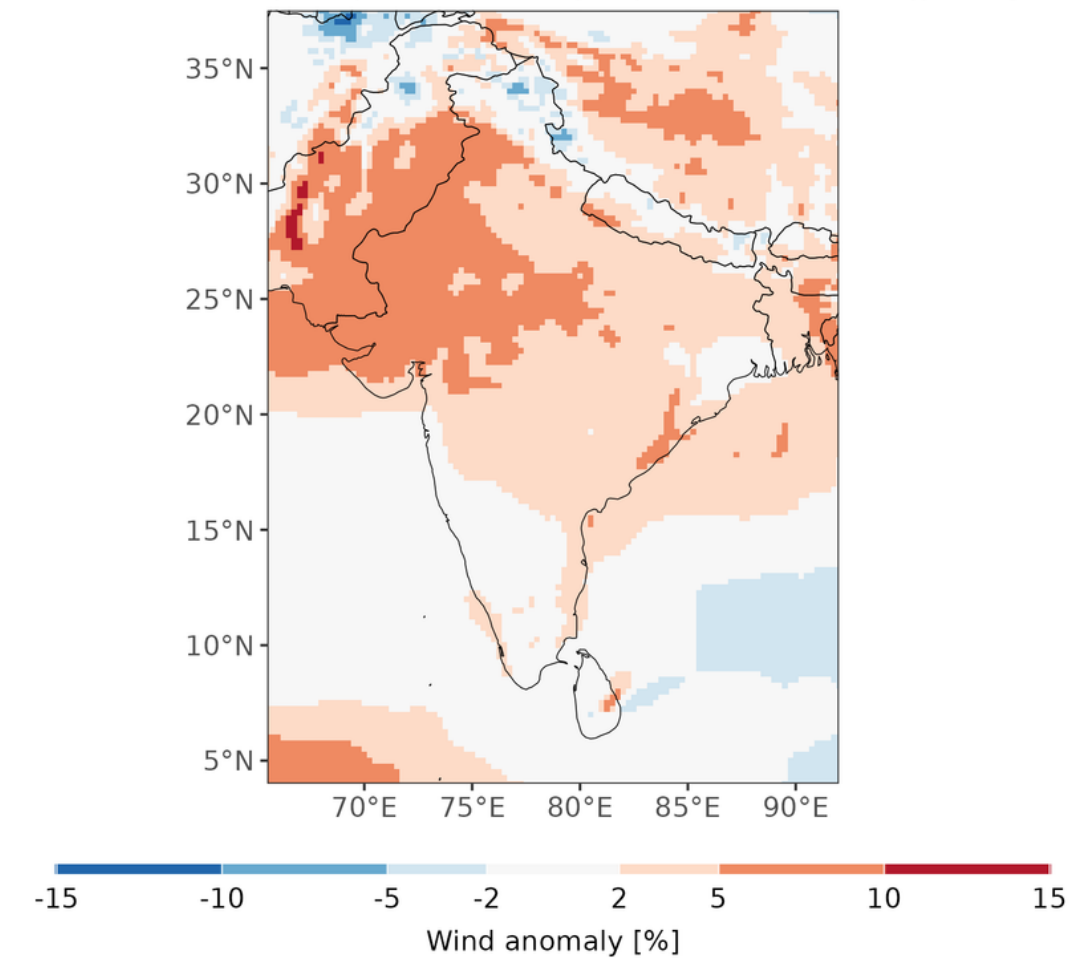
Monsoon season (Apr. to Sep.) Wind 100m anomaly composite for El Niño events of type: weak



Monsoon season (Apr. to Sep.) Wind 100m anomaly composite for El Niño events of type: moderate



Monsoon season (Apr. to Sep.) Wind 100m anomaly composite for El Niño events of type: strong





Level 1
(ordering products)

Level 2
(In depth study report)

Level 3
(mapping tool)

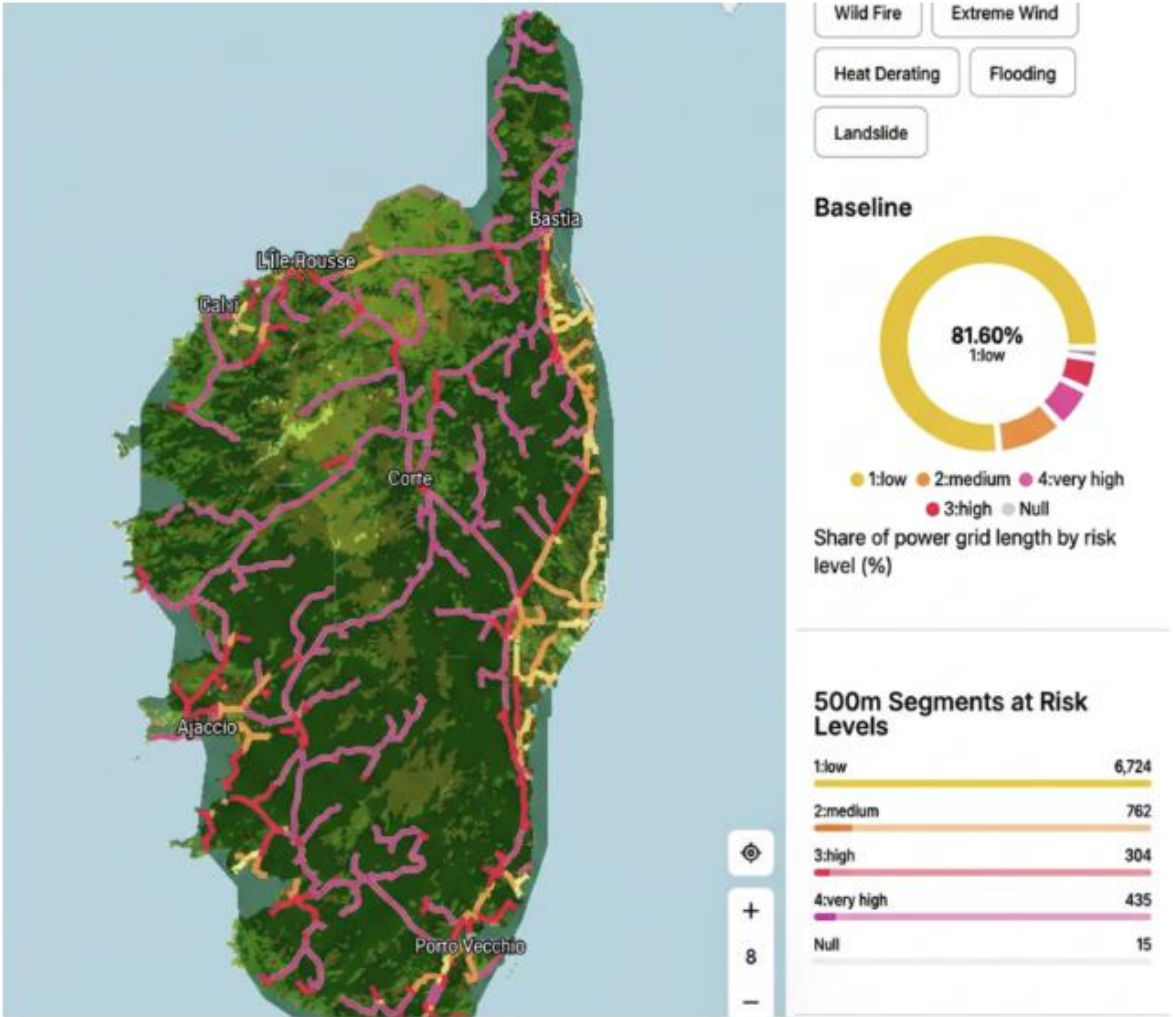
Quantitative data deep diving

Interpretation of signals

Climate driver roles

Adaptation measures

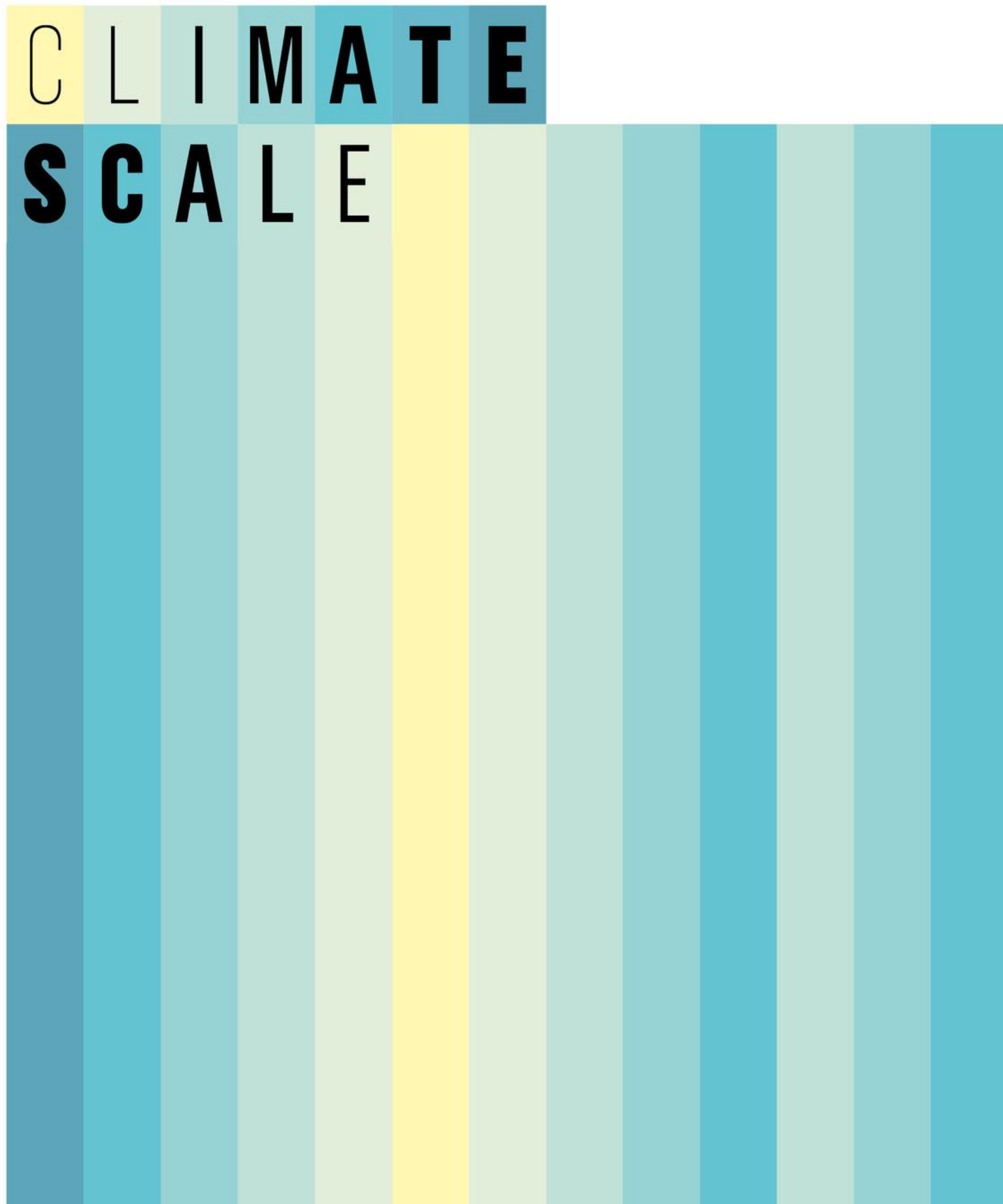
In depth study reports



El Niño impacts on wind resource

Further reading

- <https://www.carbonbrief.org/analysis-super-el-nino-reaches-remarkable-all-time-record>
- <https://interactive.carbonbrief.org/el-nino-explainer/index.html>
- <https://www.theclimatebrink.com/p/the-impacts-of-this-years-record>



The Wind Energy Climate Risk Tool

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