Eventi meteorologici estremi e cambiamento climatico: dal fenomeno della turbolenza aerea all’acqua alta di Venezia

ISTITUTO NAZIONALE
DI GEOFISICA E VULCANOLOGIA

Tommaso ALBERTI

la Repubblica

Clima, superata ufficialmente la soglia di 1,5 gradi. Il 2024 è stato l'anno più caldo di sempre

L'uragano Milton in Florida
(reuters)

Rapporto di Copernicus: infranto il limite indicato dagli accordi di Parigi.

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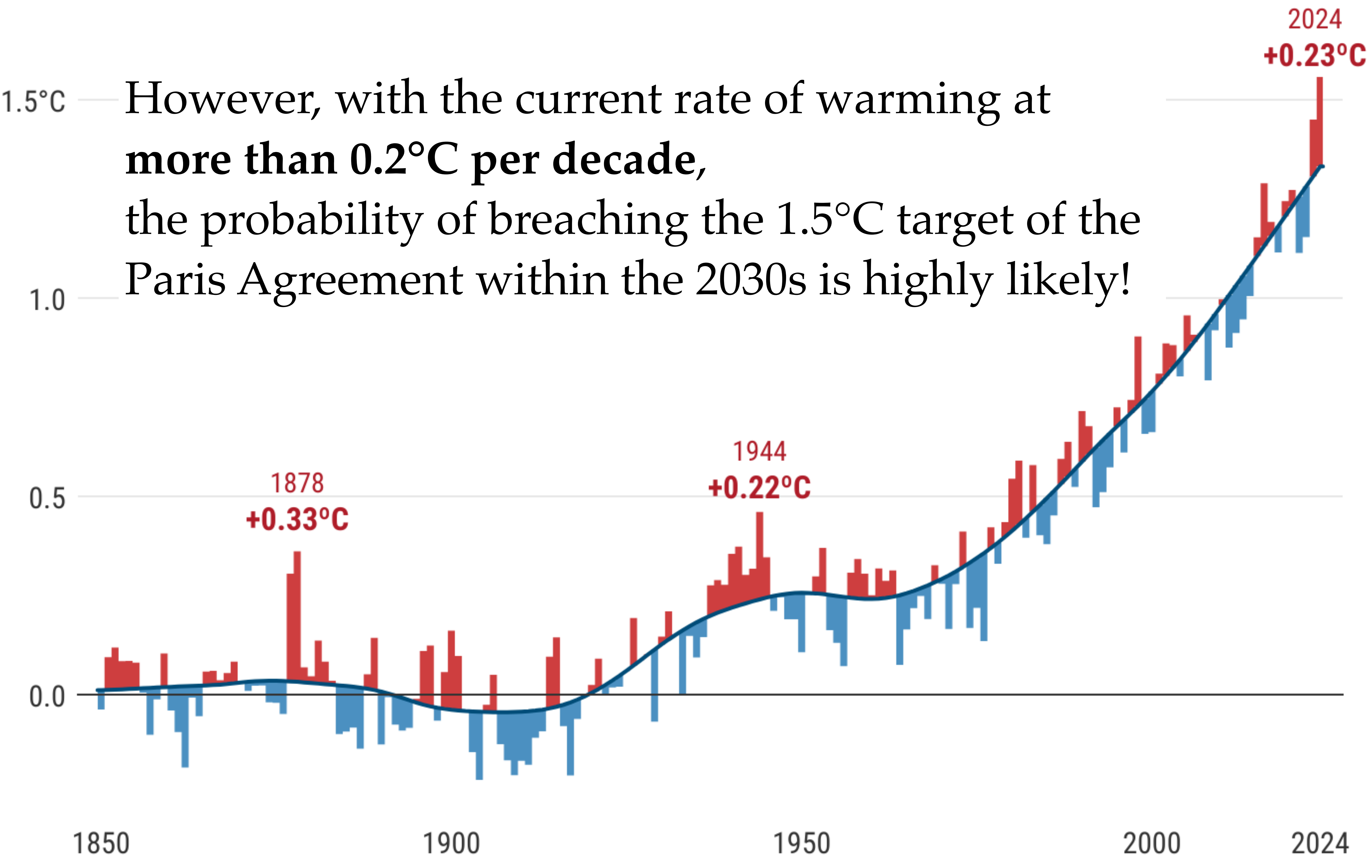
However, **temperatures averaged over two or three decades** are needed to confirm that one or other of these thresholds has been passed.

One or two years that exceed 1.5°C above the pre-industrial level does not imply that the Paris Agreement has been breached.

By how much do annual global temperatures deviate from evolving climatological averages?

Data: average of Berkeley Earth, ERA5, GISTEMPv4, HadCRUT5, JRA-3Q, NOAAGlobalTempv6 • Reference period: pre-industrial (1850–1900) • Credit: C3S/ECMWF

However, with the current rate of warming at **more than 0.2°C per decade**, the probability of breaching the 1.5°C target of the Paris Agreement within the 2030s is highly likely!



Region	Anomaly (vs 1991–2020)	Actual temperature	Rank (out of 85 years)
Globe	**+0.72°C** (+1.60°C vs pre-industrial)	15.10°C	**1st highest** 2nd - 2023
Europe	**+1.47°C**	10.69°C	**1st highest** 2nd - 2020

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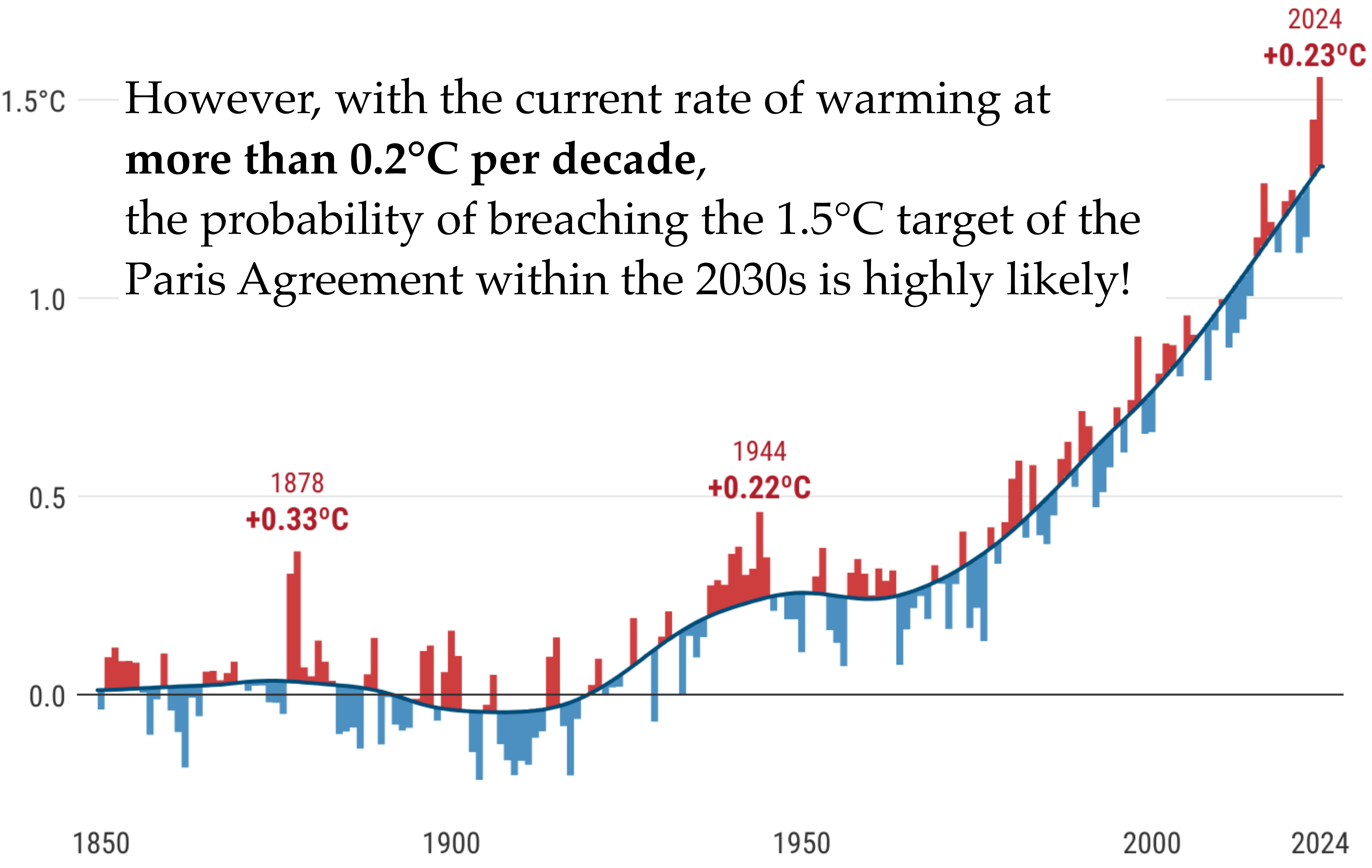

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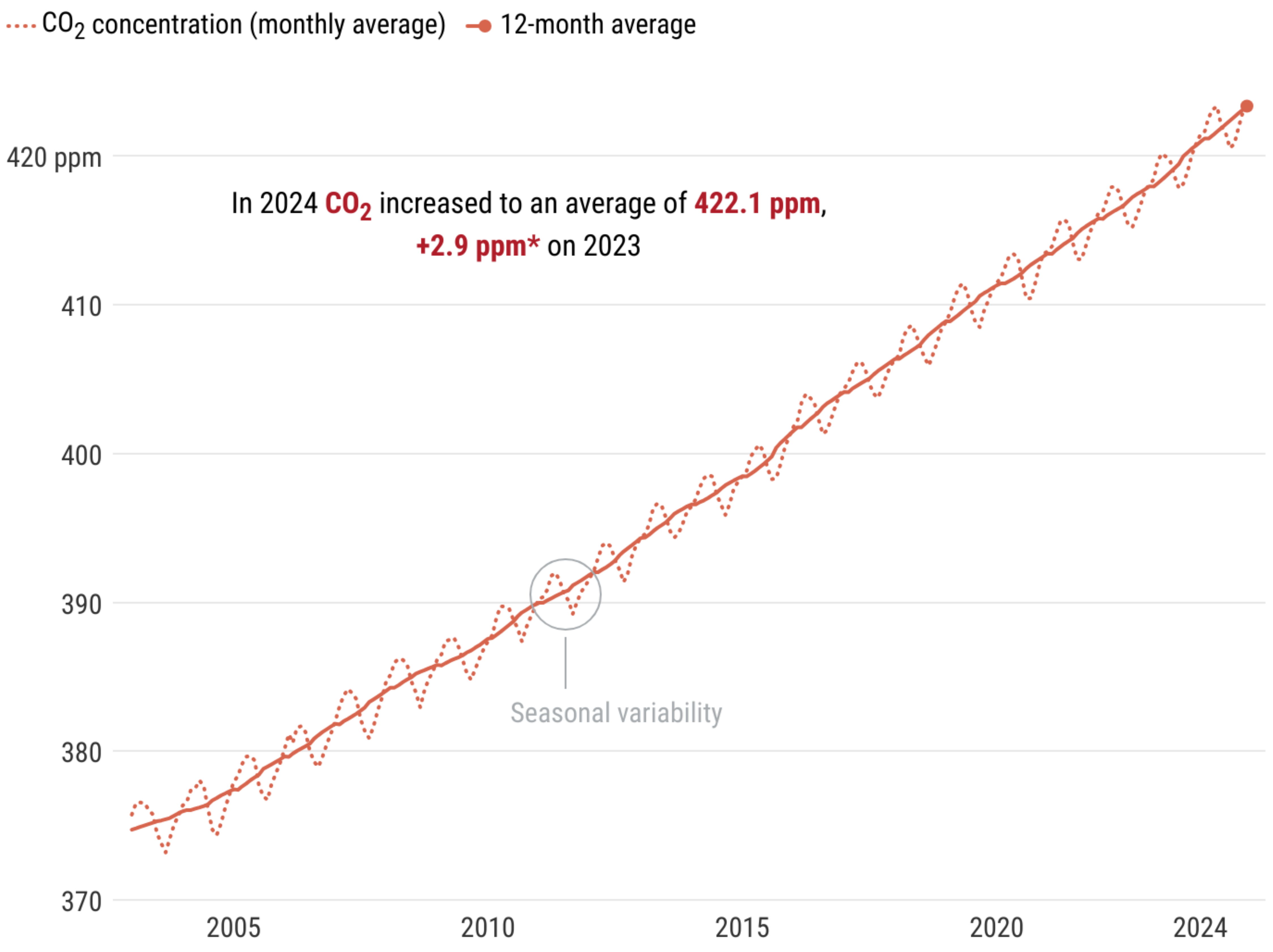
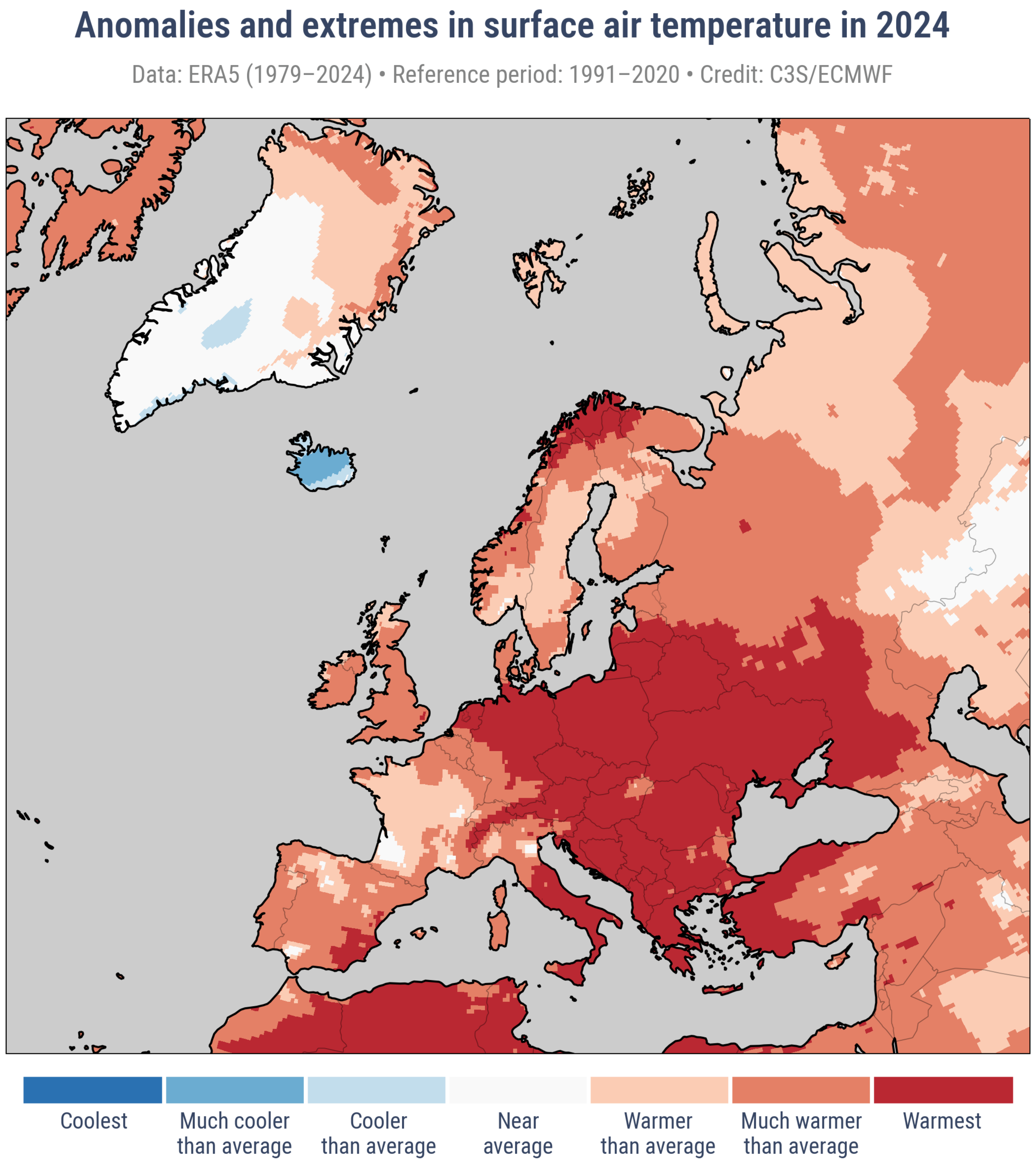
Global atmospheric concentration of carbon dioxide



To limit global warming to 1.5°C, greenhouse gas emissions must peak before 2025 at the latest and decline 43% by 2030

THE EUROPEAN STATE OF THE CLIMATE



PROGRAMME OF THE EUROPEAN UNION

opernicus Europe's eyes on Earth

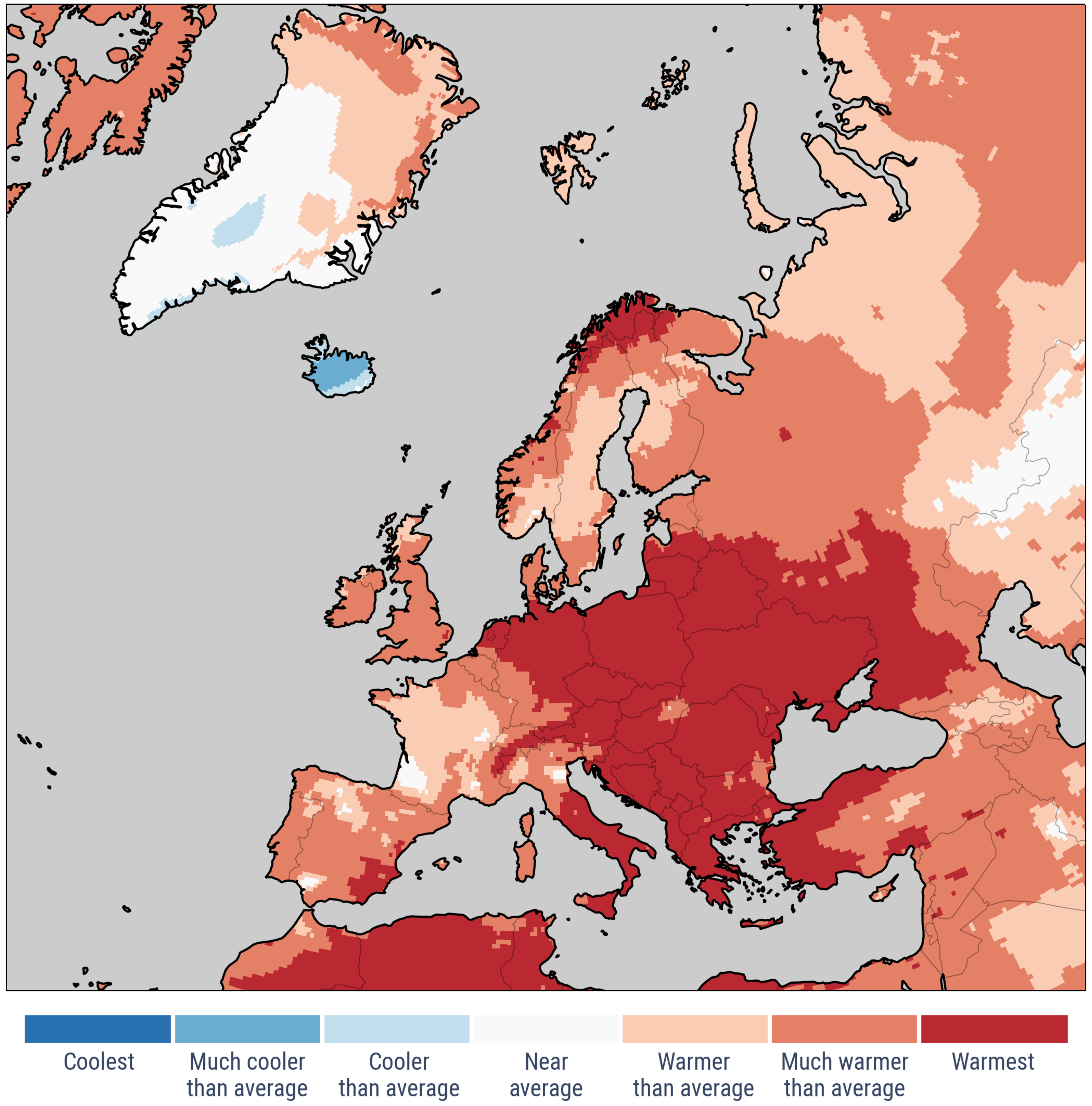
Climate Change Service

IMPLEMENTED BY ECMWF

THE EUROPEAN STATE OF THE CLIMATE

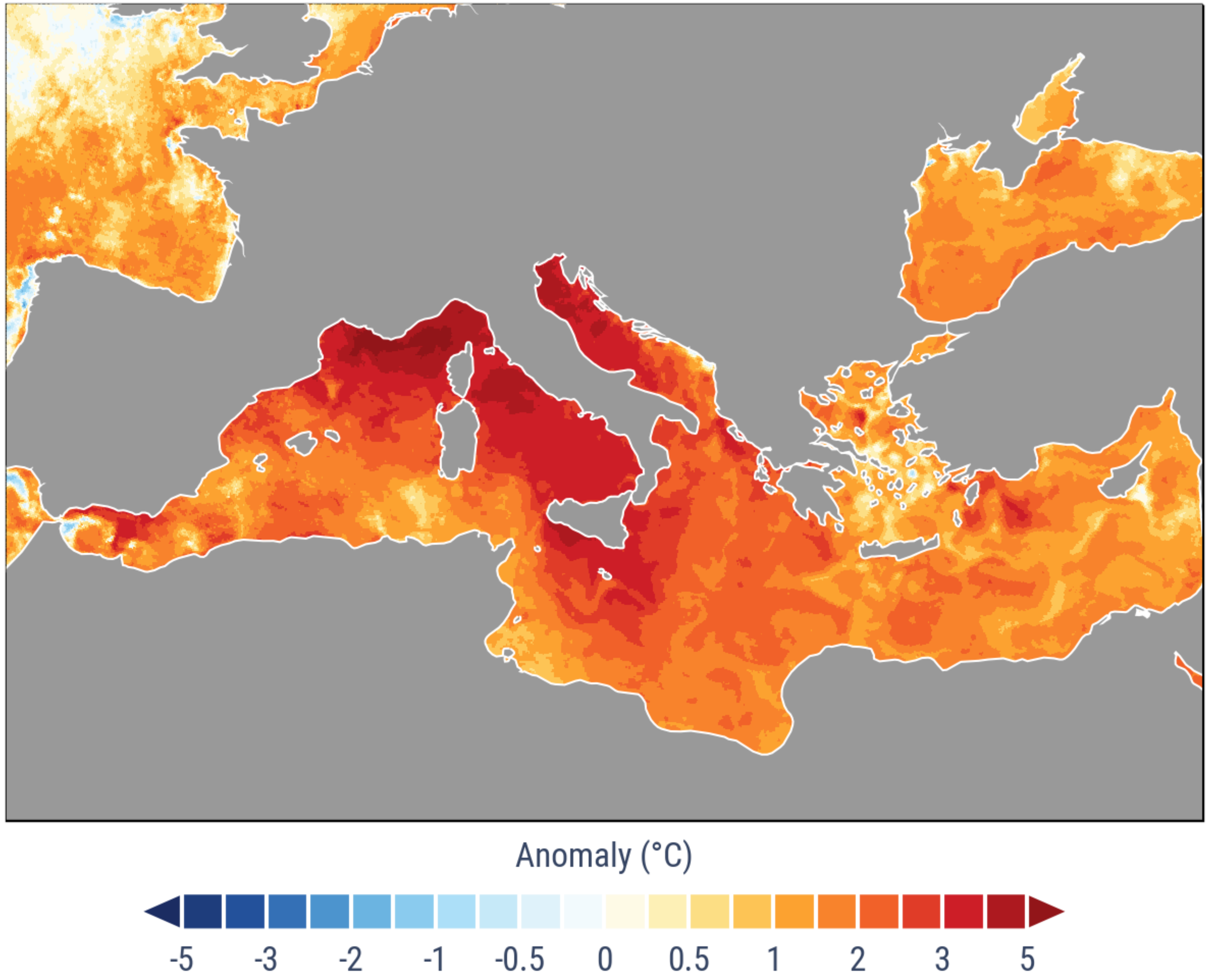
Anomalies and extremes in surface air temperature in 2024

Data: ERA5 (1979–2024) • Reference period: 1991–2020 • Credit: C3S/ECMWF



Mediterranean Sea in August 2024

Anomaly in SST on 13 August 2024



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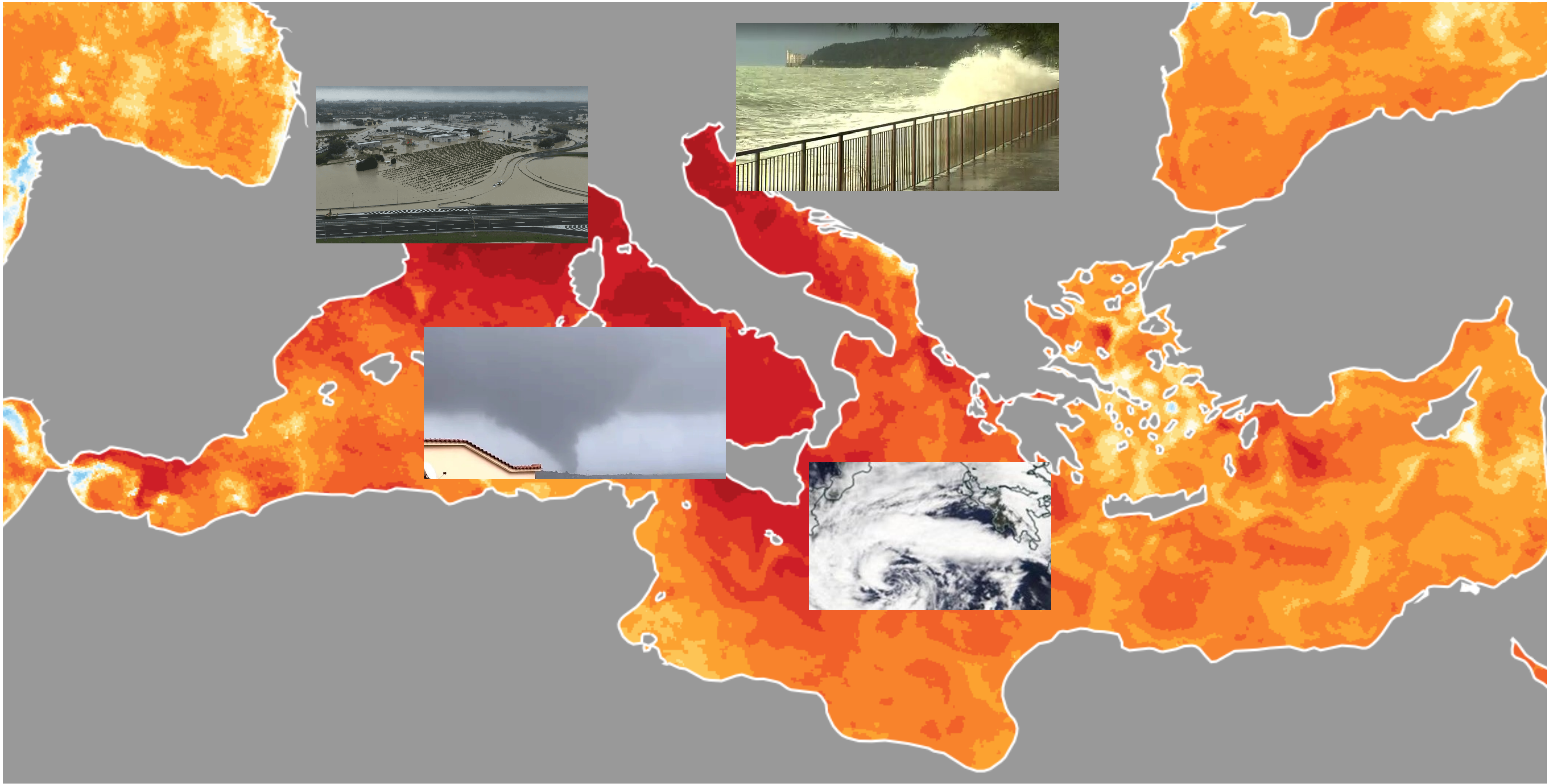
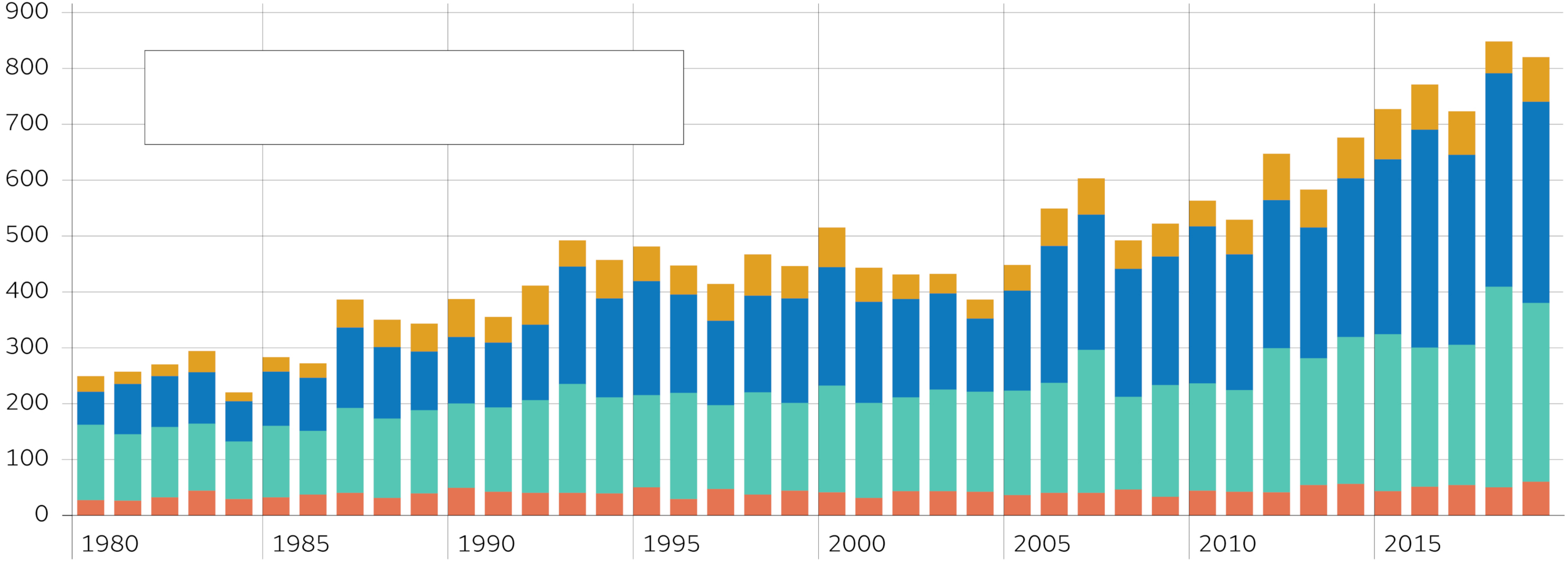
THE CURRENT STATE OF THE CLIMATE
Extreme weather events



Met Office Are extremes becoming more frequent?



Geophysical events
Earthquakes, tsunami, volcanic activity

Meteorological events
Tropical storm, extratropical storm, convective storm, local storm.

Hydrological events
Flood, mass movement.

Climatological events
Extreme temperature, drought, wildfire.

EXTREME WEATHER EVENTS IN ITALY IN 2024

+485%
rispetto al
2015

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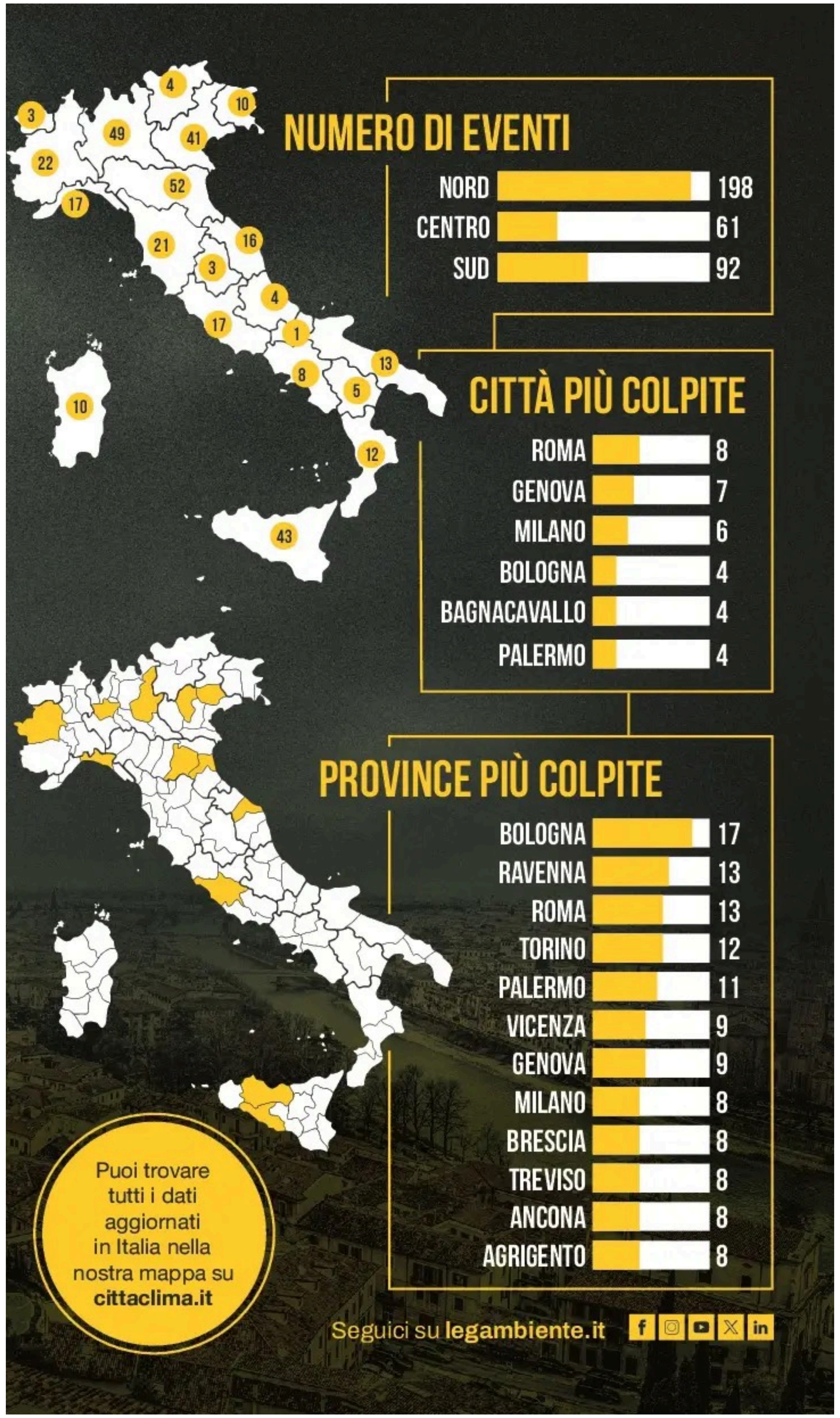

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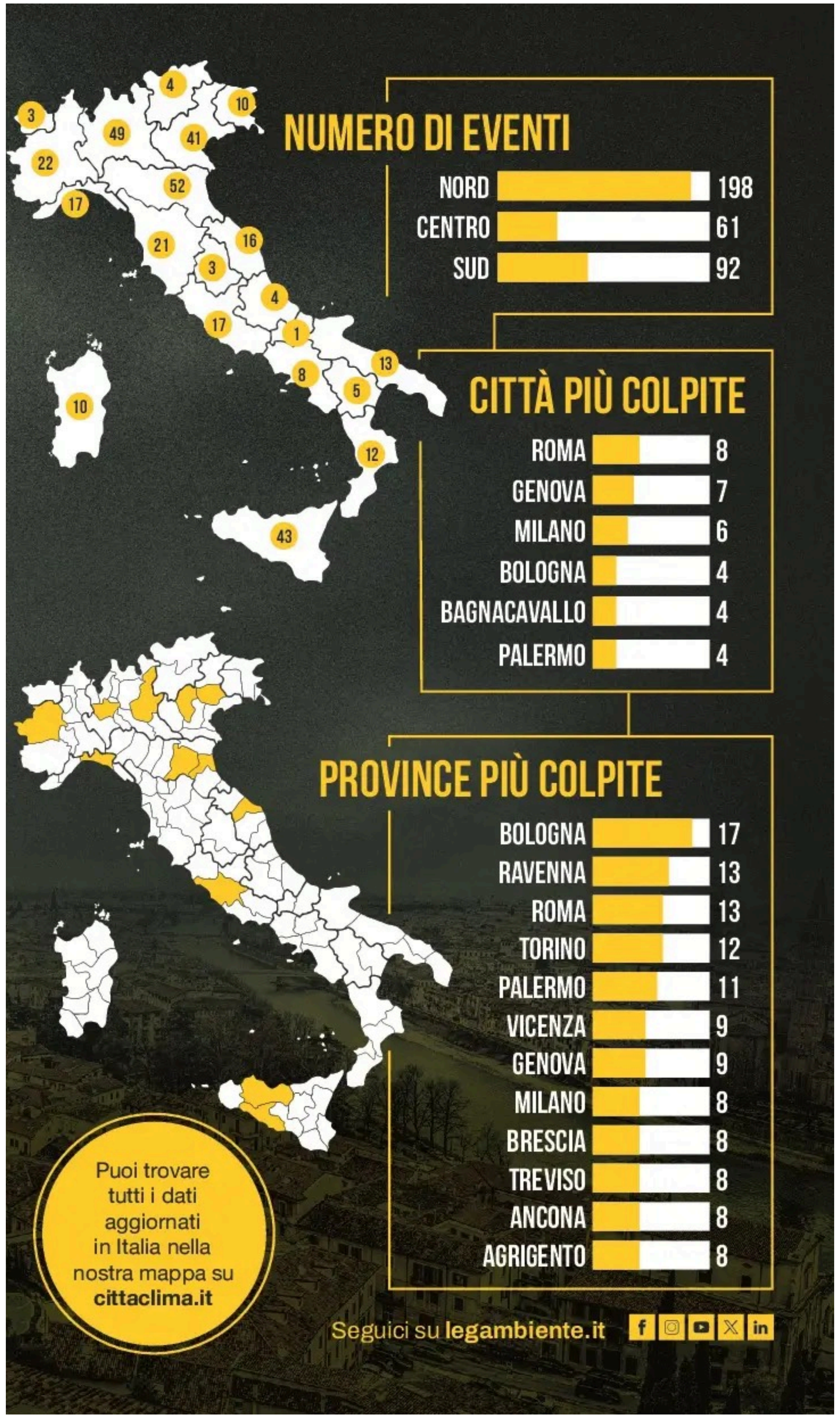

WEATHER HAZARDS FOR COASTAL INFRASTRUCTURES

+2-3 °C compared to 1850-1900

+400% intense rainfall compared to 2018

- Airports, ports, railway networks at risk
- +30% risk of interruption of critical services by 2050

2010–2024: 816 extreme weather events (+14.6%) over coastal zones – flooding from heavy rains, damage from tornadoes and gusts of wind, storm surges and damage to infrastructure

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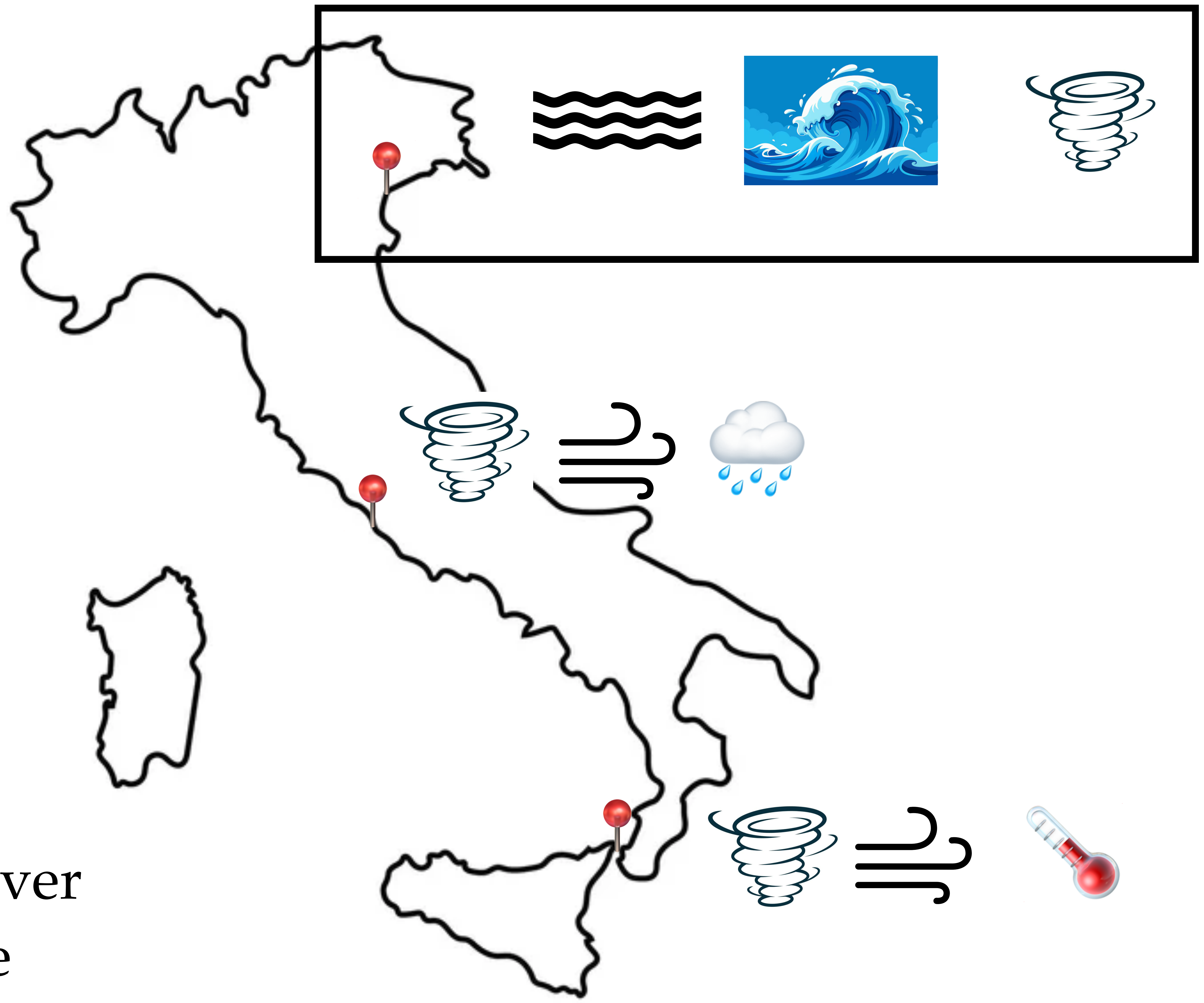

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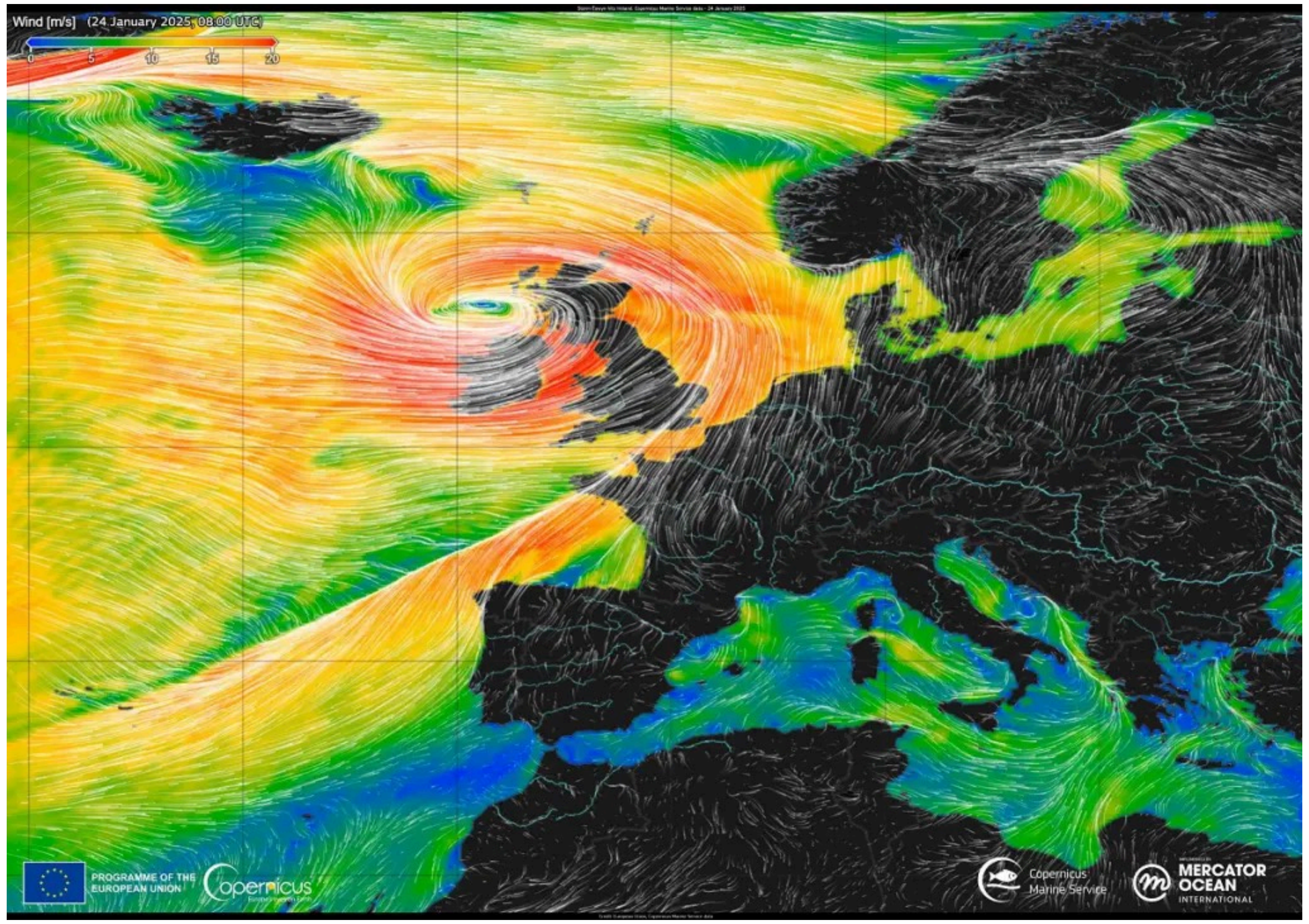
CLIMATE CHANGE IMPACTS ON CRITICAL INFRASTRUCTURES WITH A SPECIAL CASES FOR ITALY: VENICE LAGOON

STORMS, THUNDERSTORMS, STRONG WINDS (lightning, hail, icing, snow)

ULTIM'ORA CRONACA MONDO TV & SPETTACOLO DOSSIER VIDEO

La tempesta Eowyn paralizza Gran Bretagna e Irlanda: oltre 500 voli cancellati

Più di 800mila persone senza elettrictà, scuole e università chiuse. Le raffiche di vento a più di 180 all'ora paralizzano i due Paesi. Dal premier irlandese l'appello ai cittadini: "Siamo nell'occhio del ciclone, non uscite"



⚡ Specific Hazards from Storms

Flooding and Drainage Failure

Intense rainfall can lead to **runway and taxiway flooding**, especially in older coastal infrastructures with insufficient drainage.

➤ In 2018, **Venice Marco Polo Airport** experienced partial flooding, affecting operations for several hours during a heavy storm.

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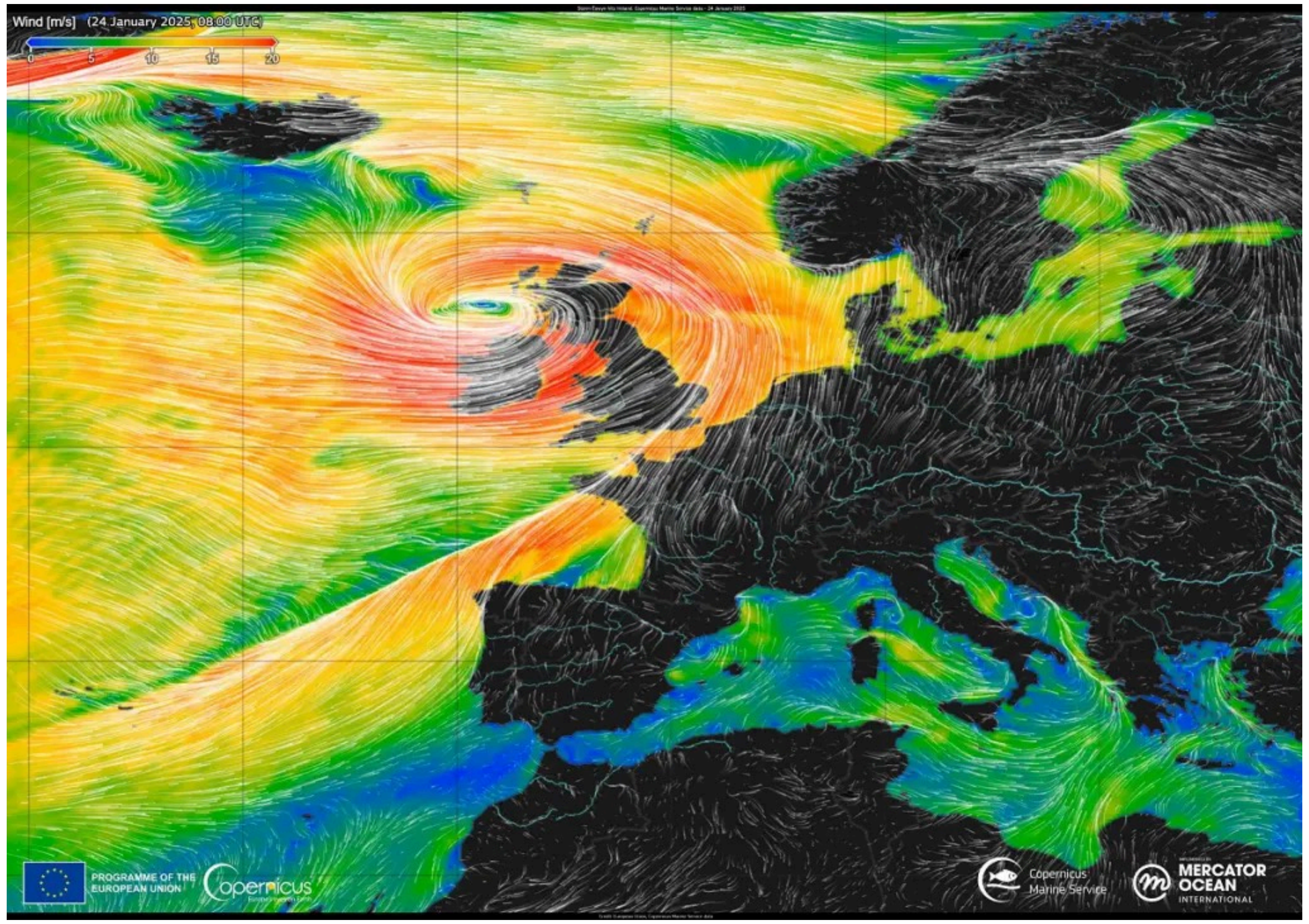

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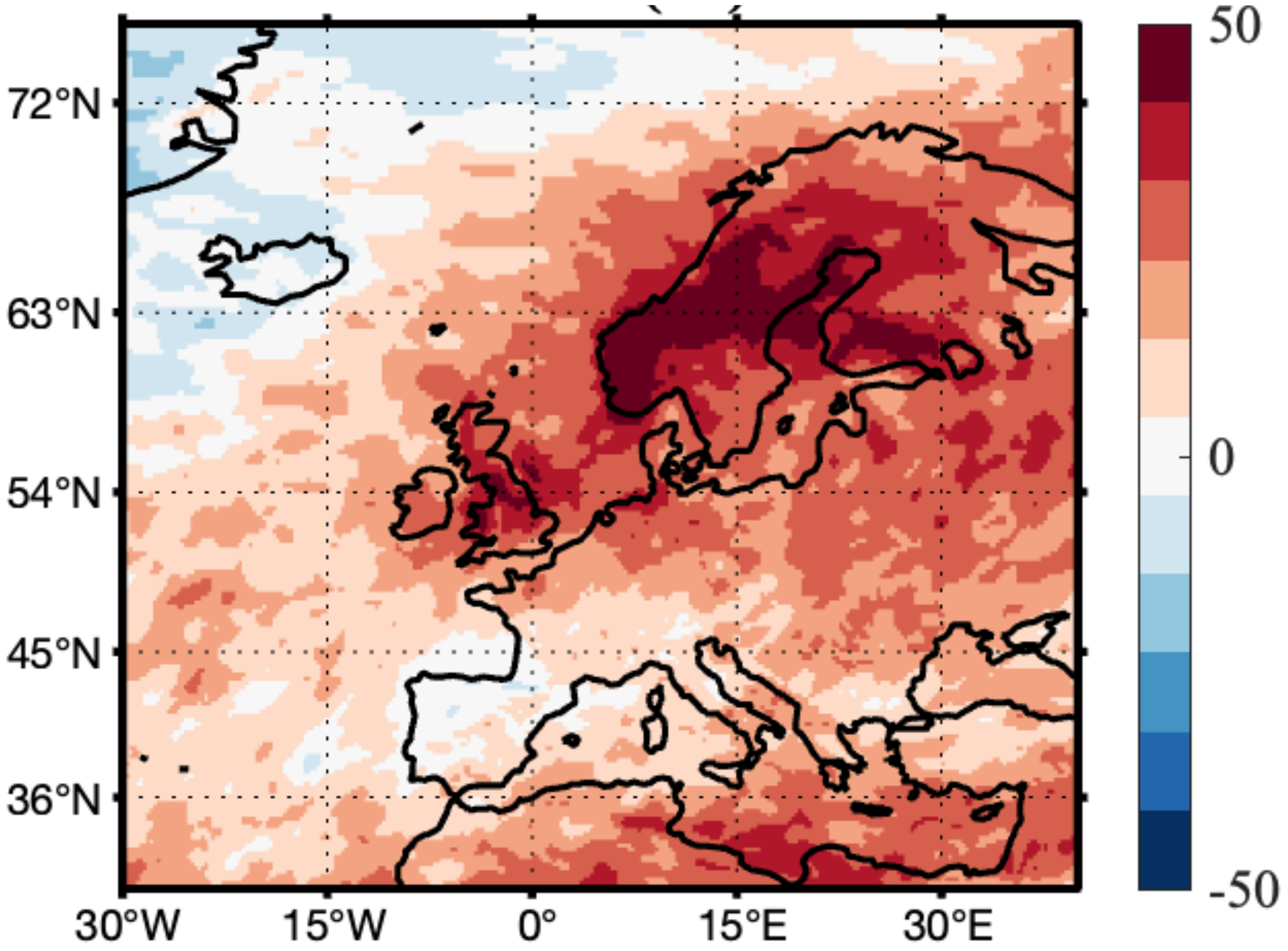
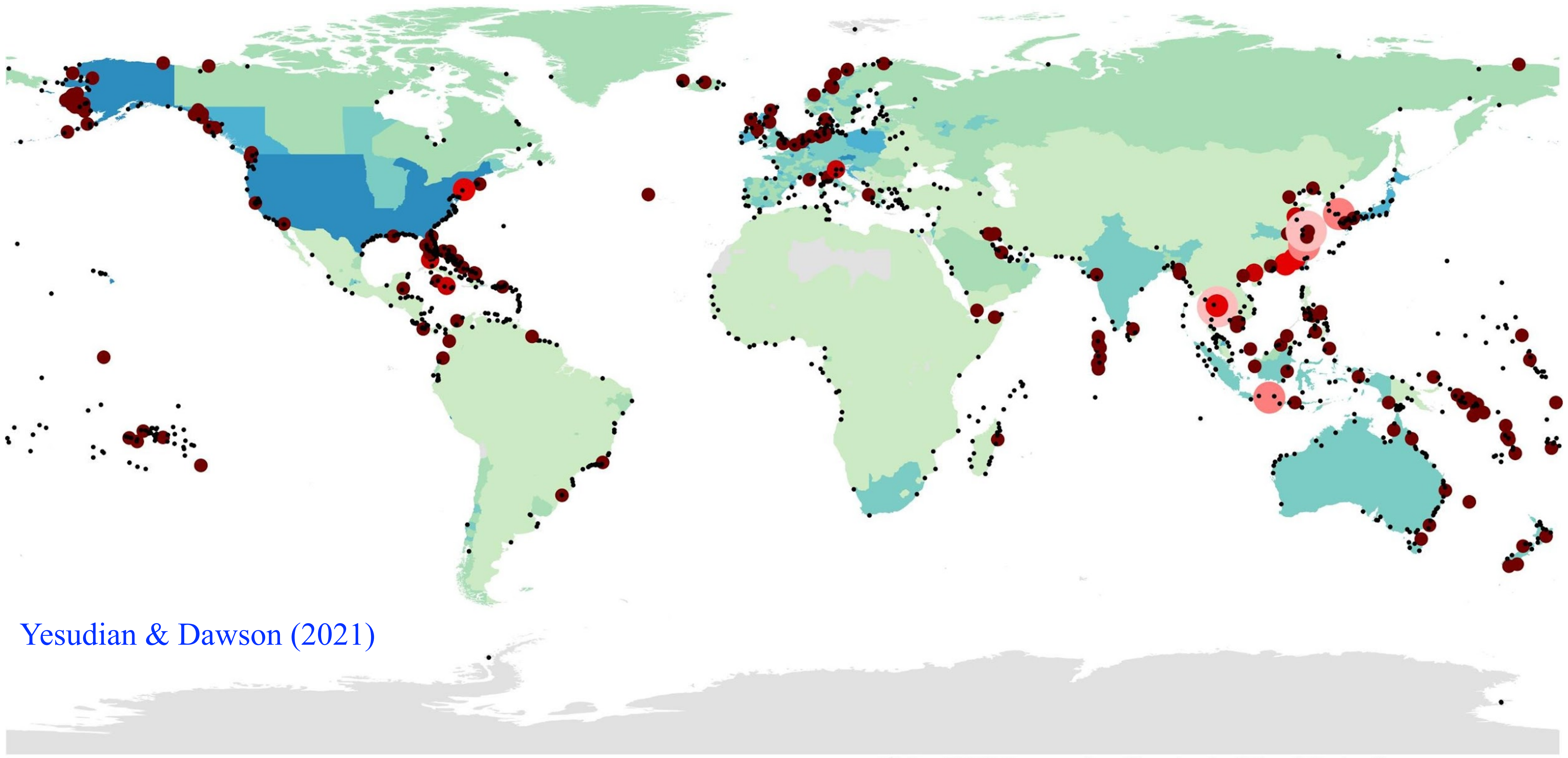
Increases of turbulence up to 50% within Europe!



SEA LEVEL RISE AND STORM SURGE



Yesudian & Dawson (2021)

- <u>100 airports under sea level due to climate change in 2100</u>
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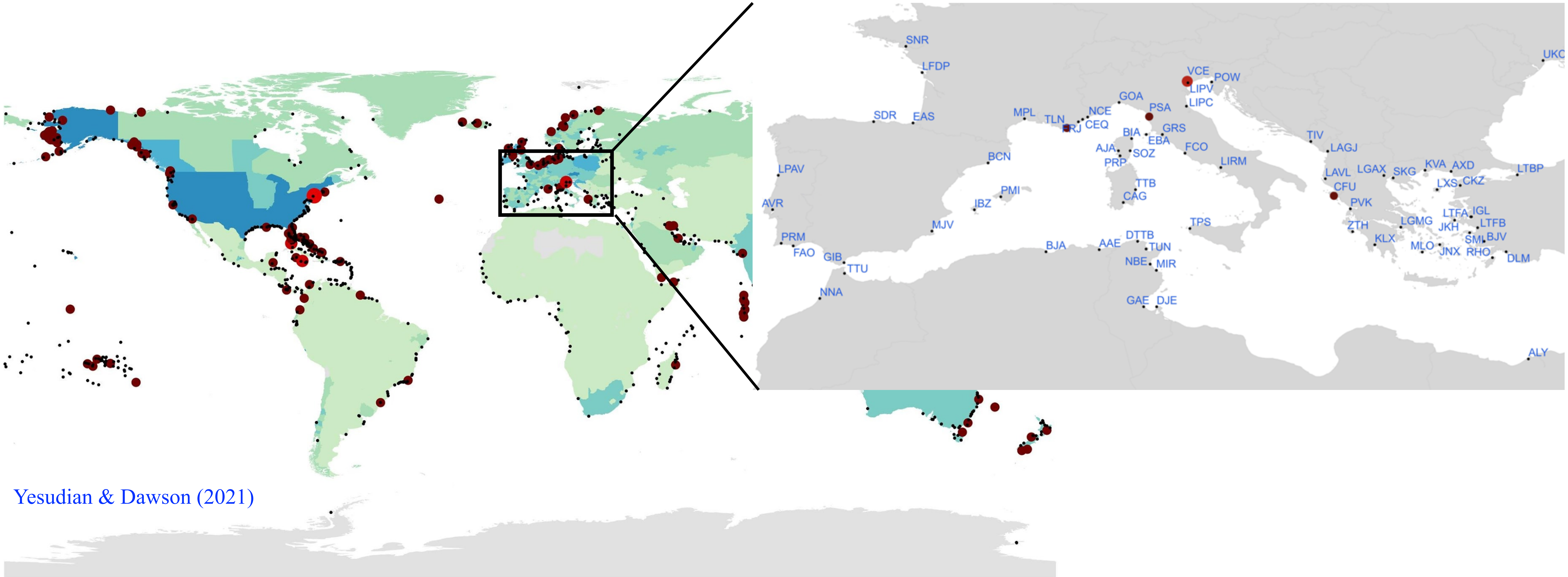

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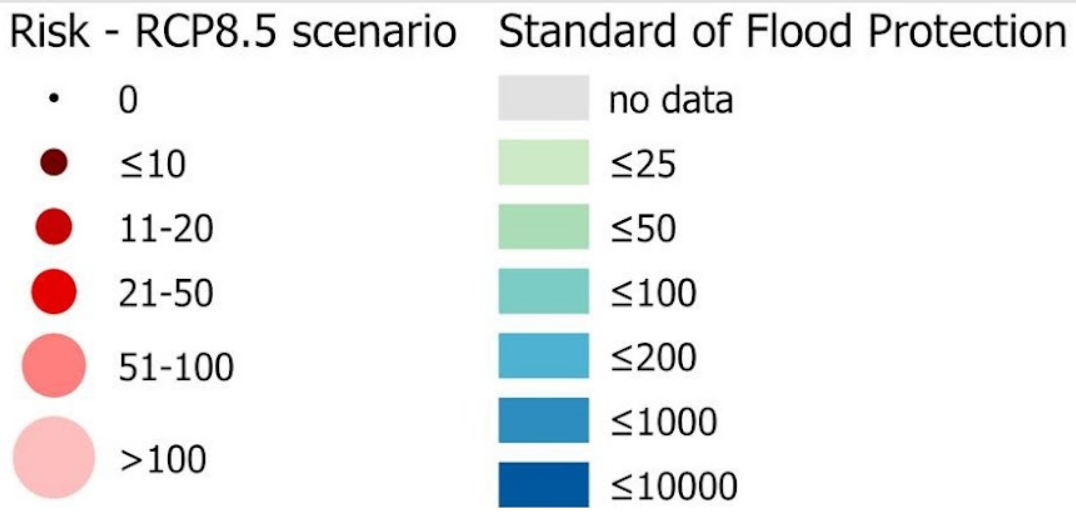

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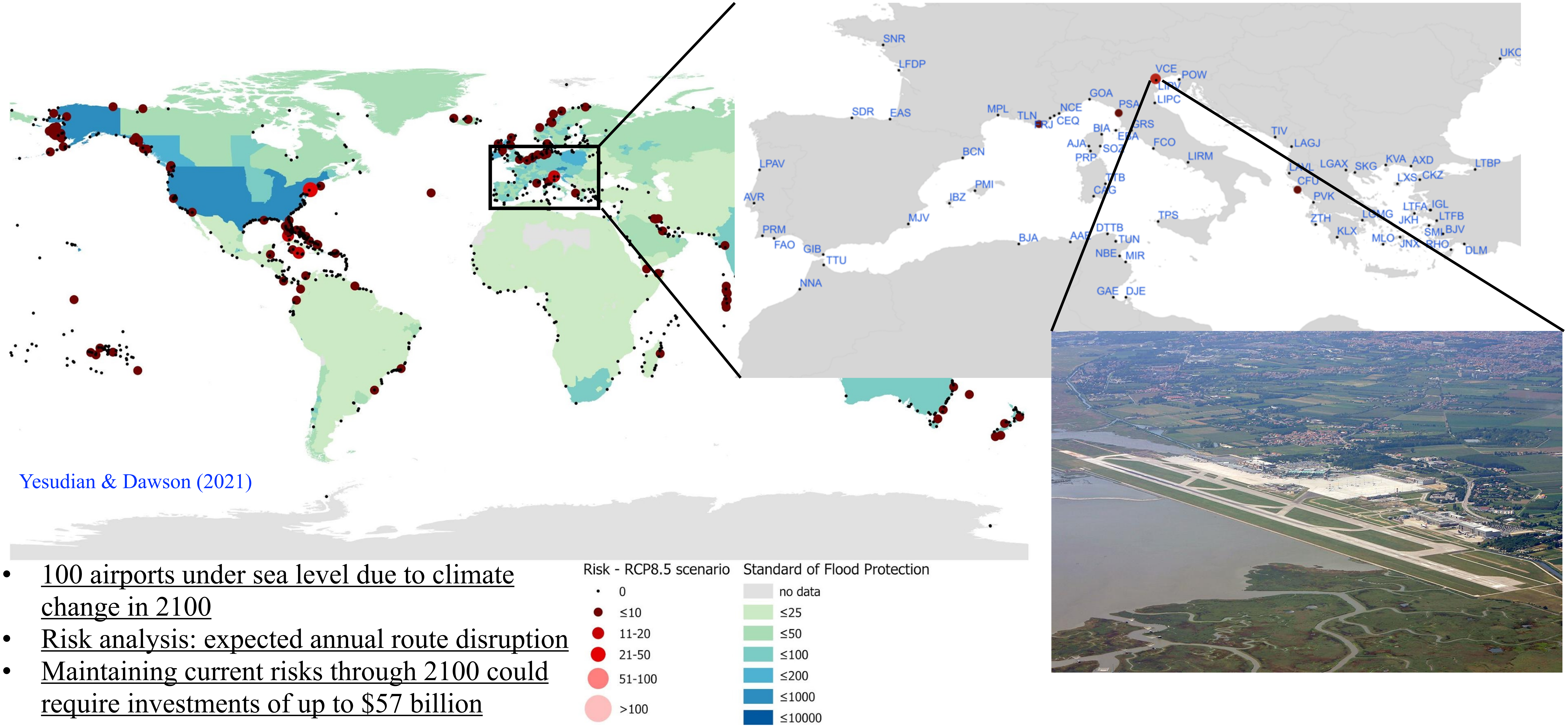

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STORM SURGE

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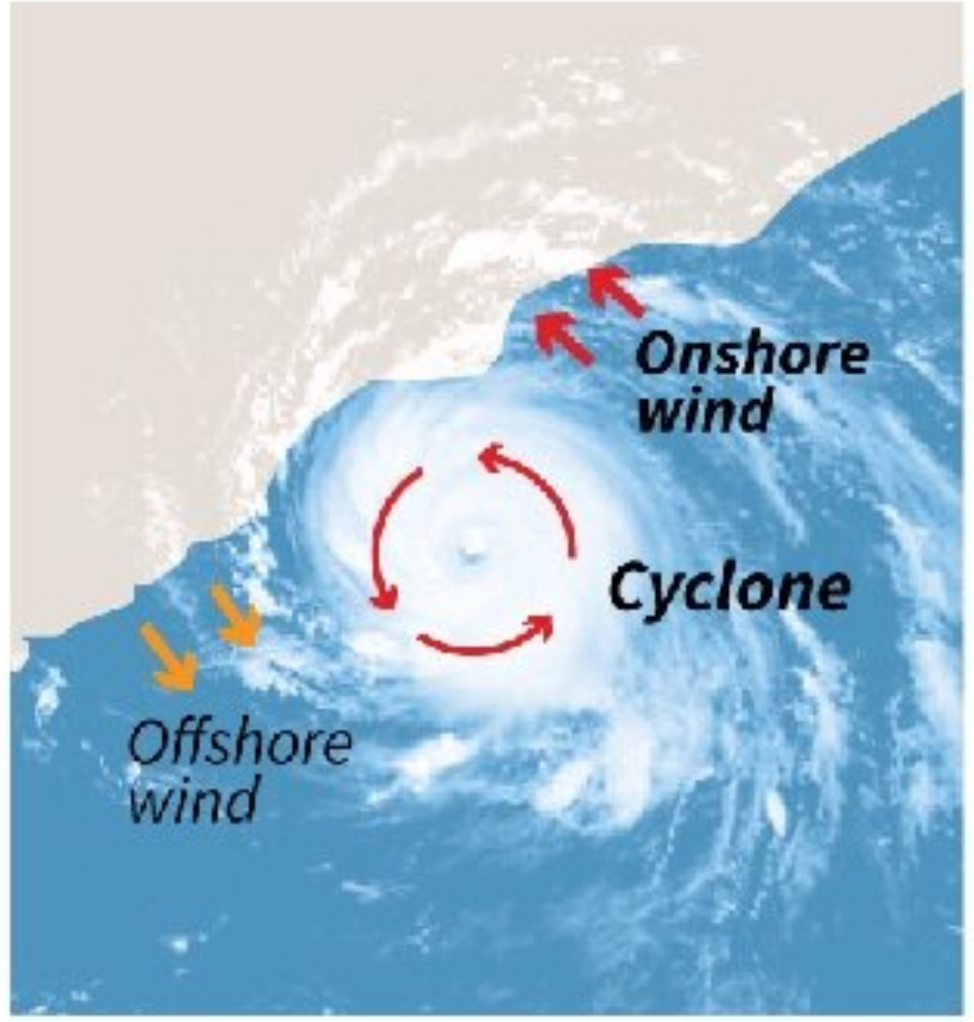
🎯 Main causes:

🌬️ Strong wind: pushing towards the coast

📉 Low atmospheric pressure: every -1 hPa → +1 cm of rise.

■ High winds push sea water towards the coast



Source: NOAA, Met Office

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⚠️ **Main factors**

🌊 **Fetch**: length of the stretch of open sea over which the wind can blow without obstacles.

Longer fetch = higher waves

In the Mediterranean, fetch is limited compared to the oceans, but in basins such as the Ligurian Sea or the Adriatic it can still have significant effects.

🌎 **Local topography** (bathymetry, coastal slope): can amplify the effect.

Areas with low coastal plains are particularly vulnerable, such as Venice.

🌎 **Coastal resonance and configuration**:

Closed or narrow gulfs (e.g. Gulf of Trieste or Venice) can amplify sea level due to resonance effects.

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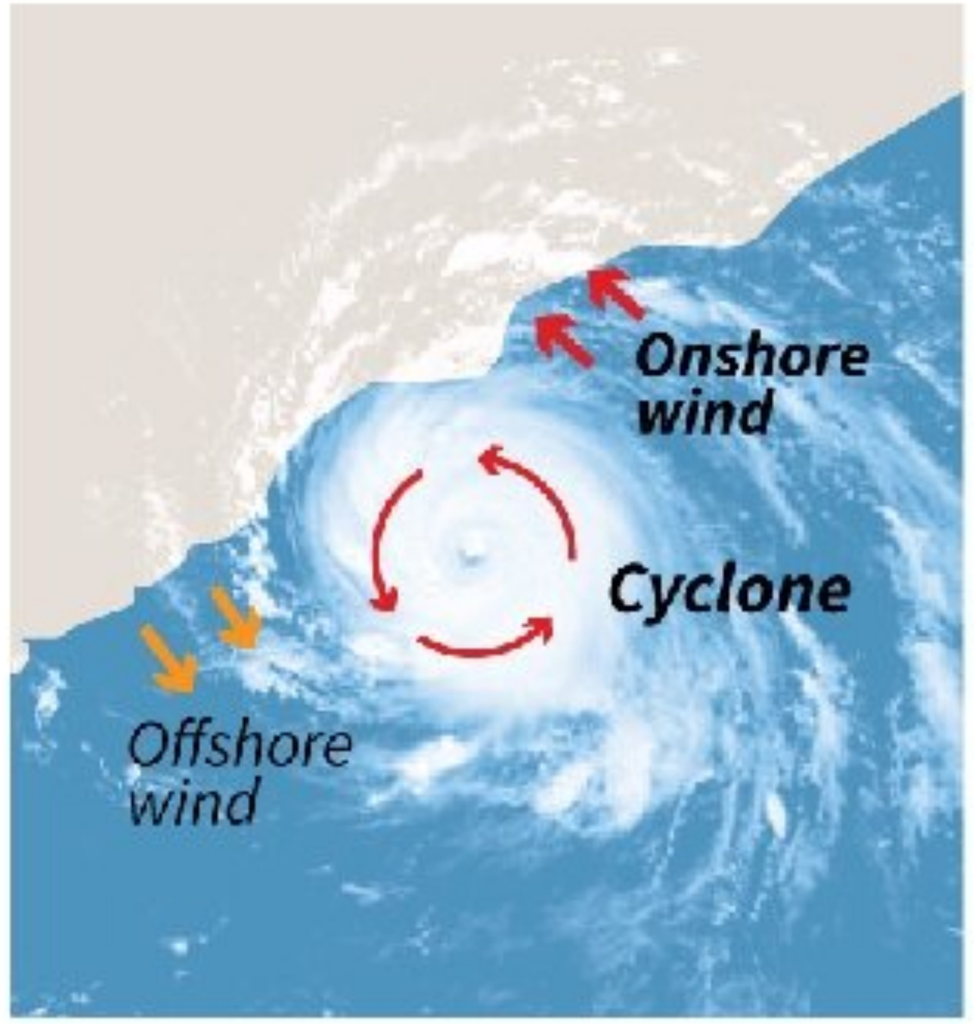
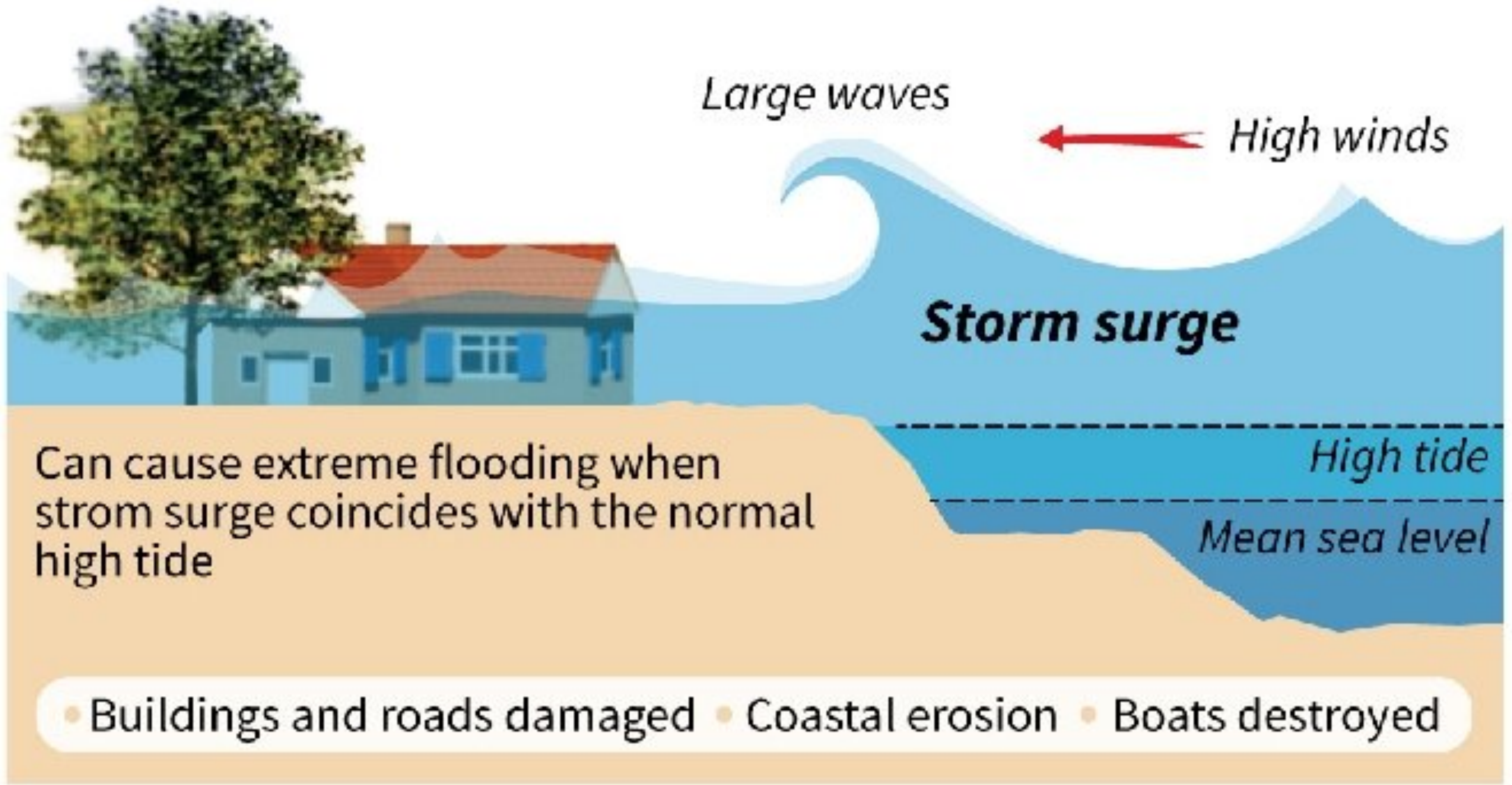


Source: NOAA, Met Office

■ The cyclone makes landfall, water has nowhere to go but inland



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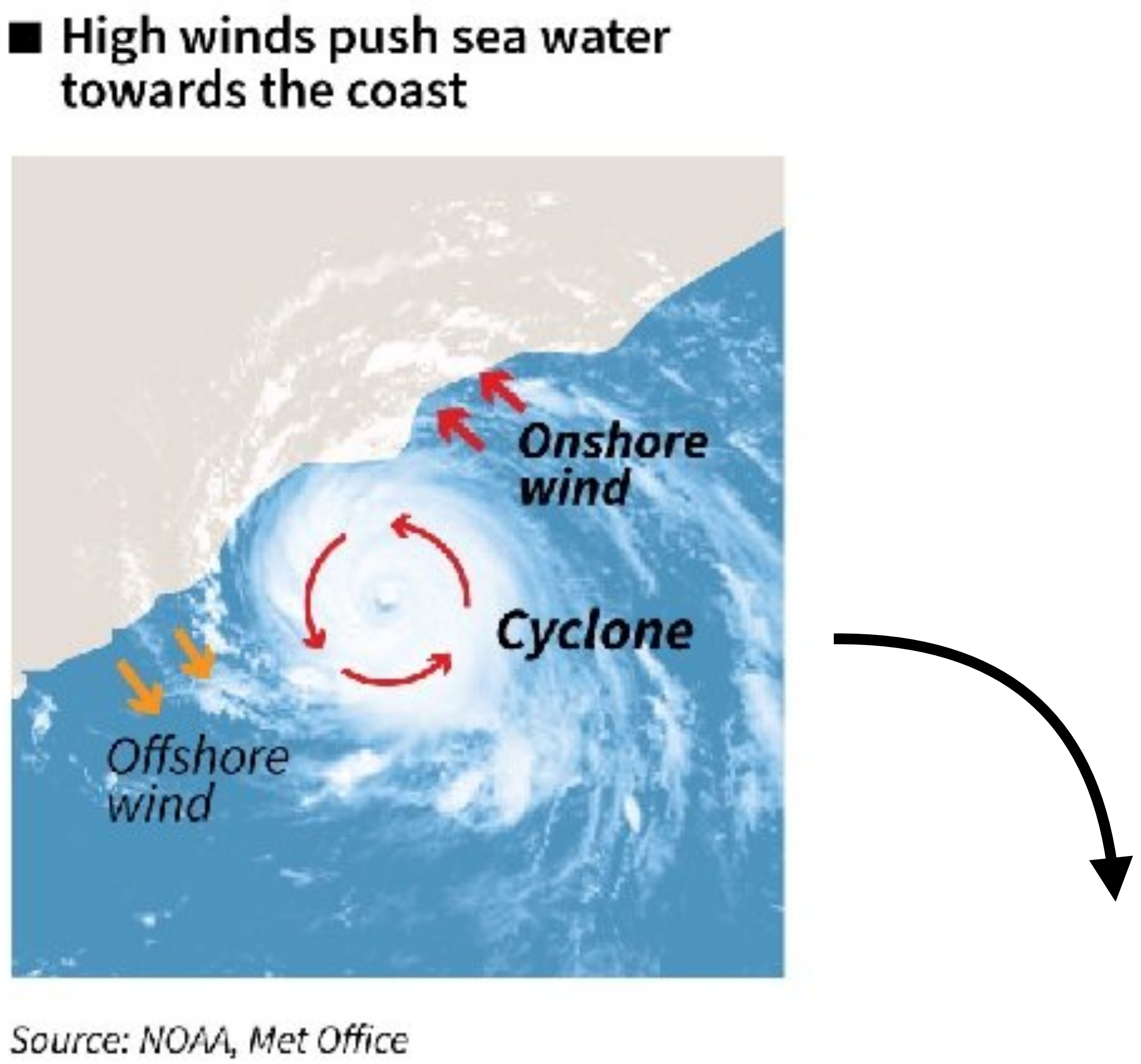
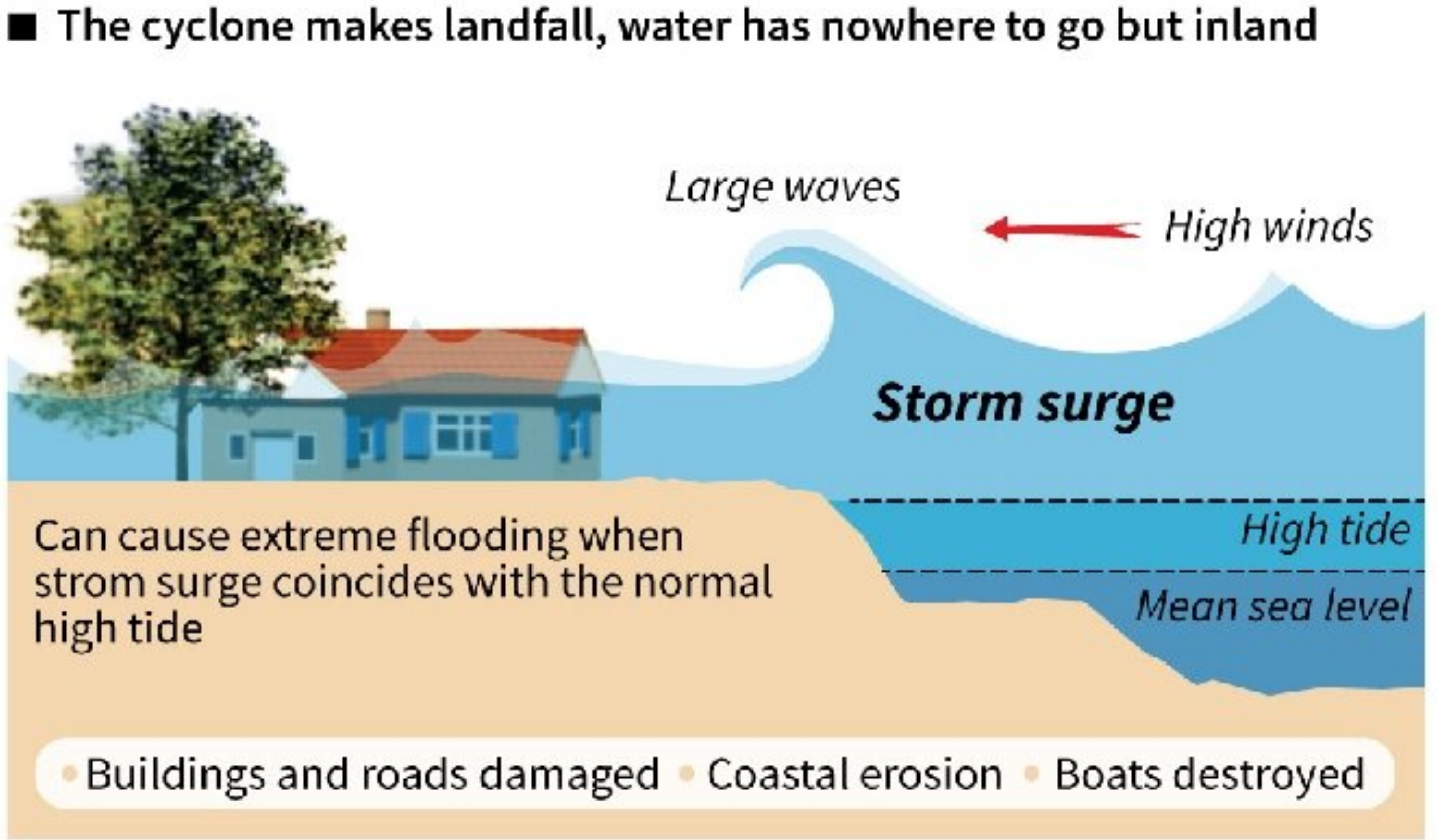


⚠️ Effects on the coast:

- Extreme flooding even in the absence of heavy rain.
- Damage to infrastructure, coastal erosion, soil salinization.
- In combination with high tide (storm tide) → devastating effects.

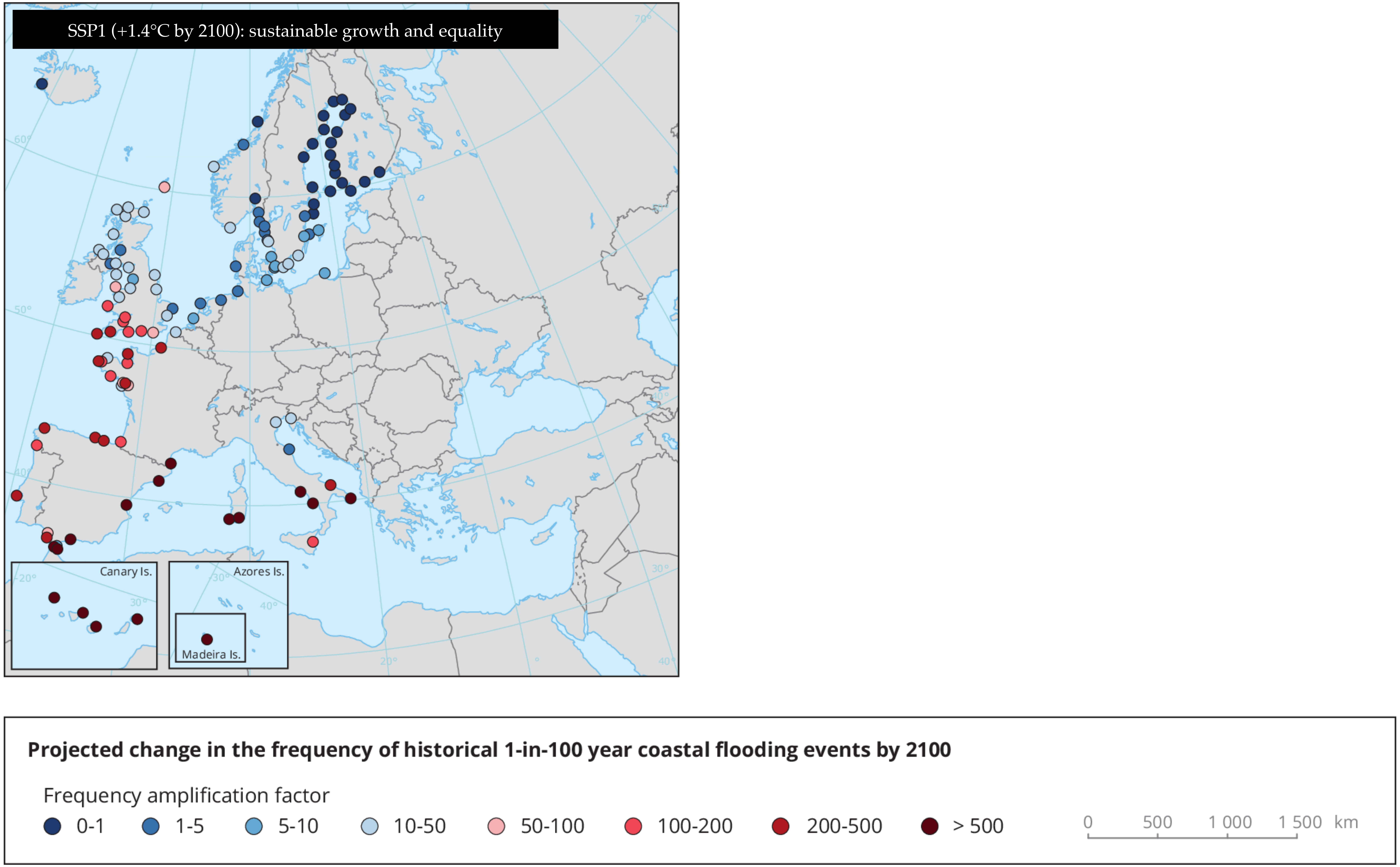


📈 Amplifying factors:

- 🌡️ Rising mean sea level (anthropogenic climate change)
- 🔄 Increased frequency of intense storms (anthropogenic climate change)
- 🏞️ Coastal morphology and long fetch (land-use, urbanization, human-driven climate change)

💡 Note: Although less intense than in the oceans, storm surges in the Mediterranean can be highly destructive in densely populated areas

STORM SURGE: 100-yr RETURN TIME PROJECTED OVER EUROPE



Estimated change in the frequency of 1-in-100-year flooding events in 2100 under the low- and high-emissions scenarios

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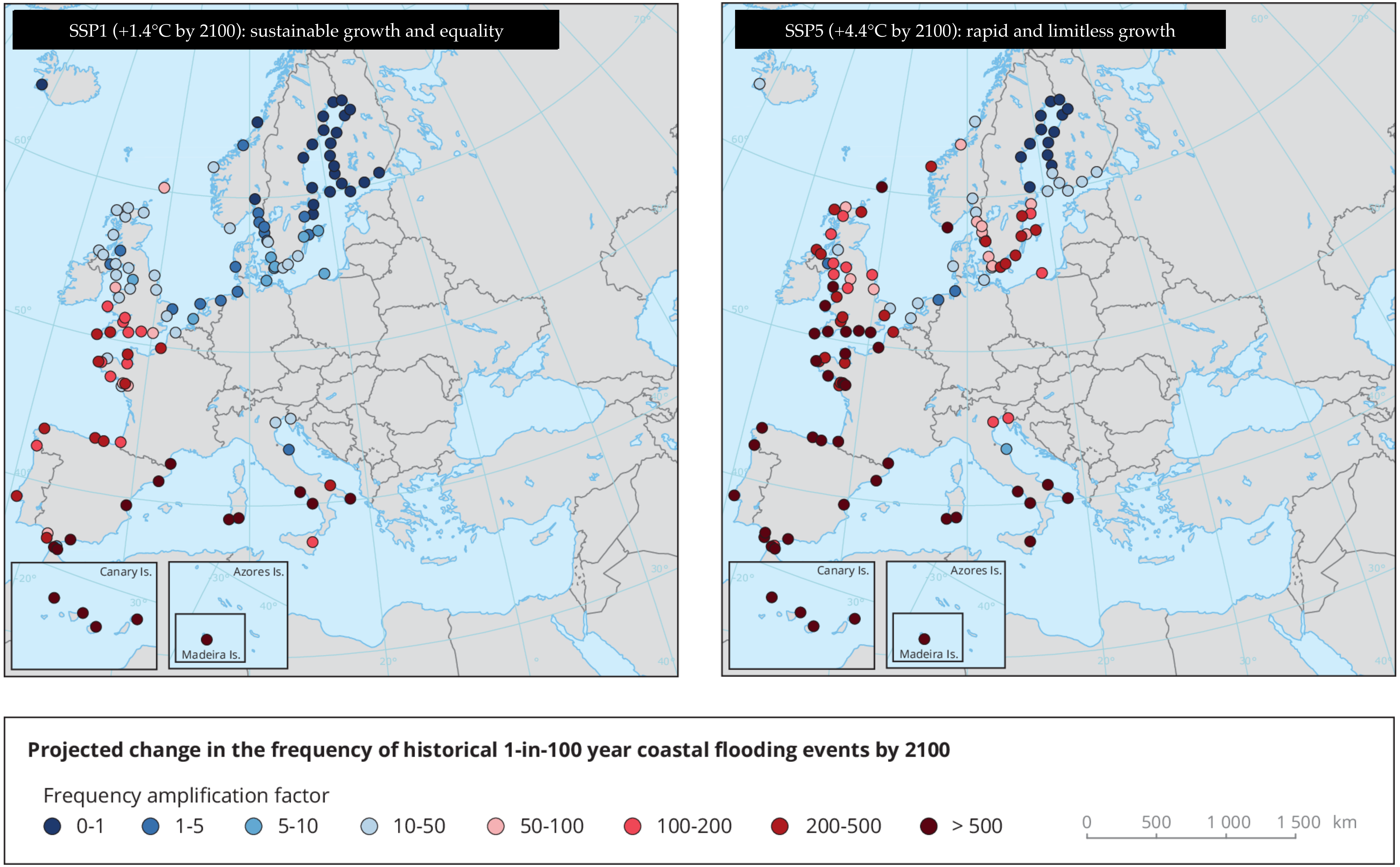

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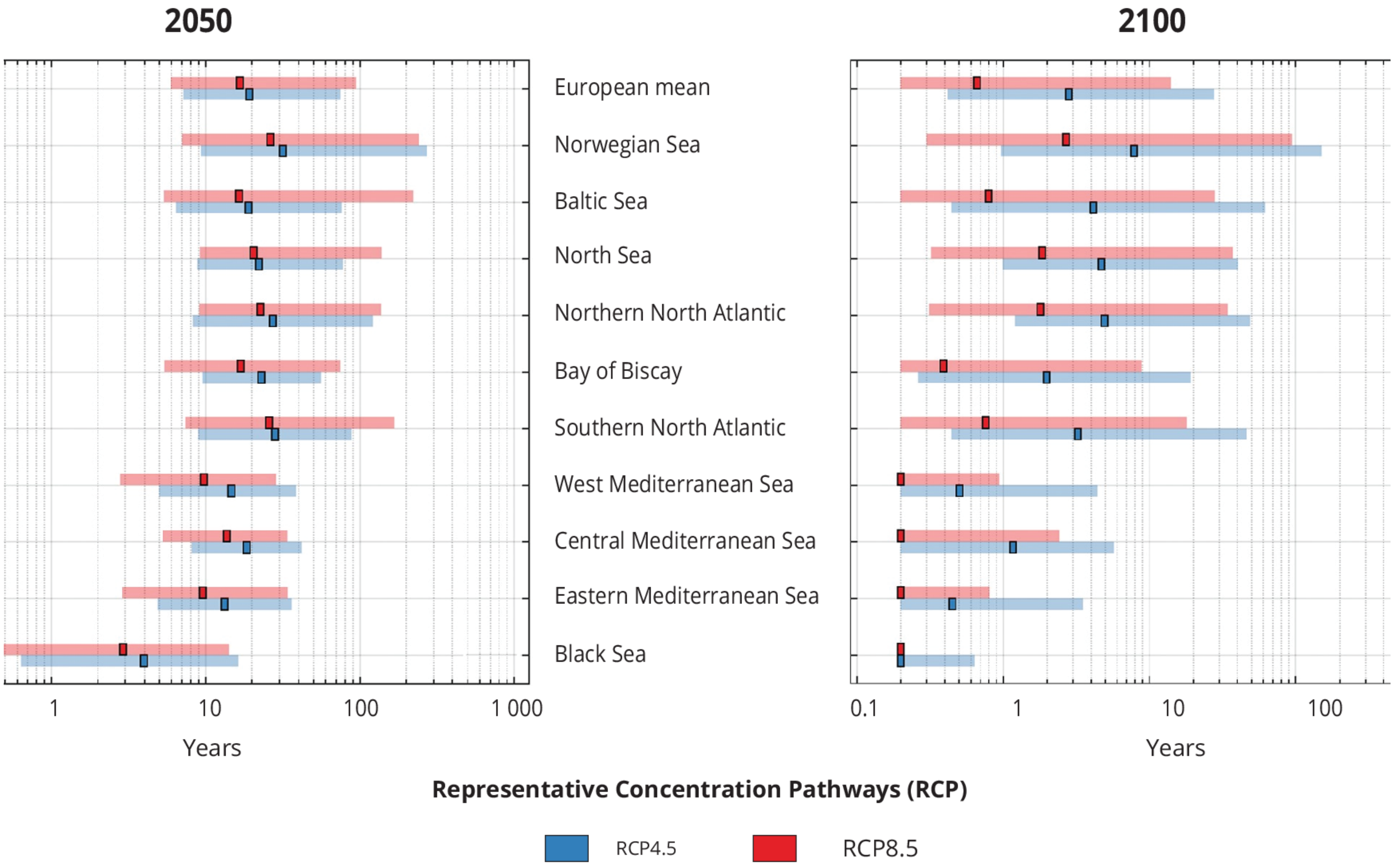

Return period of current 100-year extreme sea levels for European coasts

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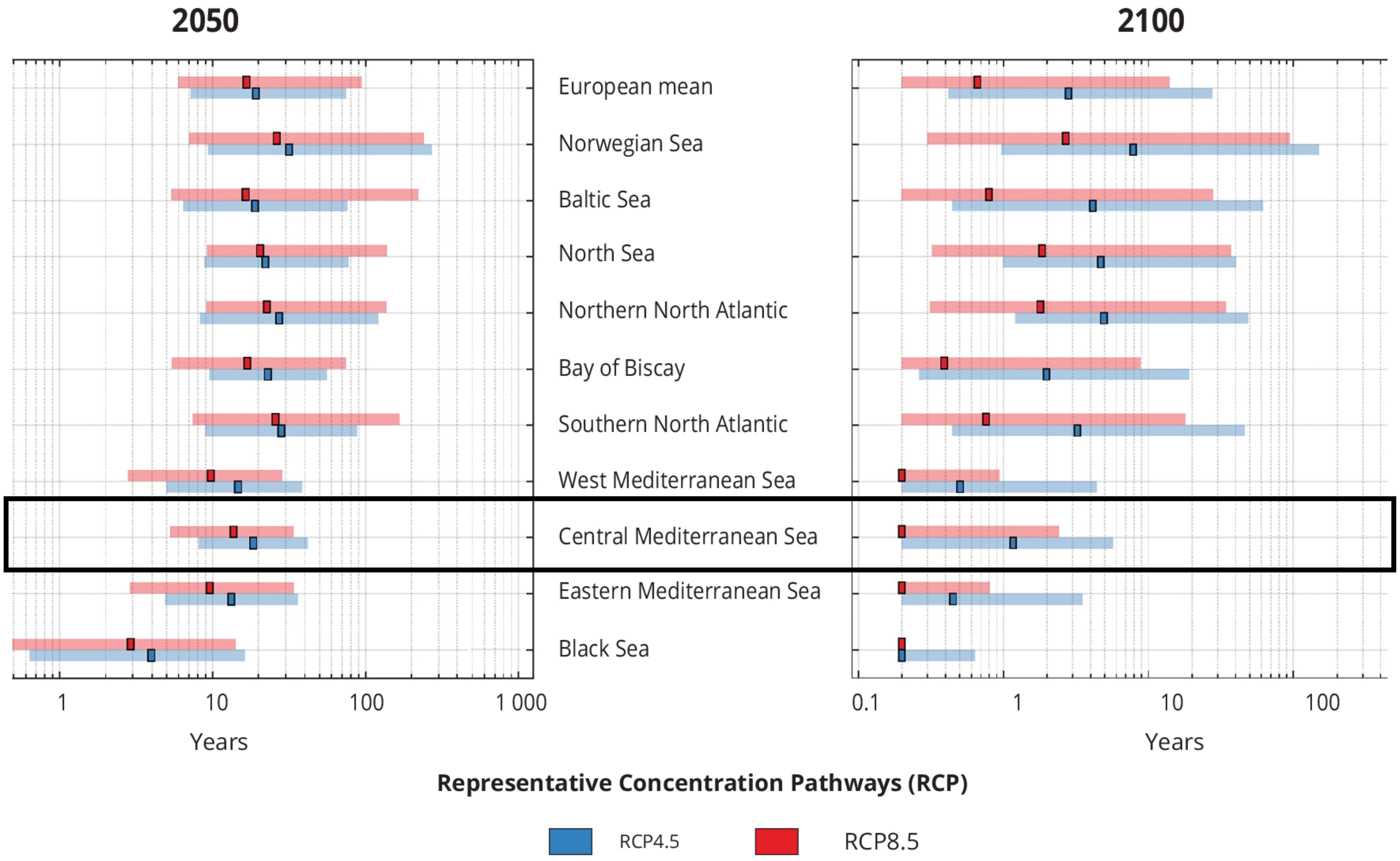

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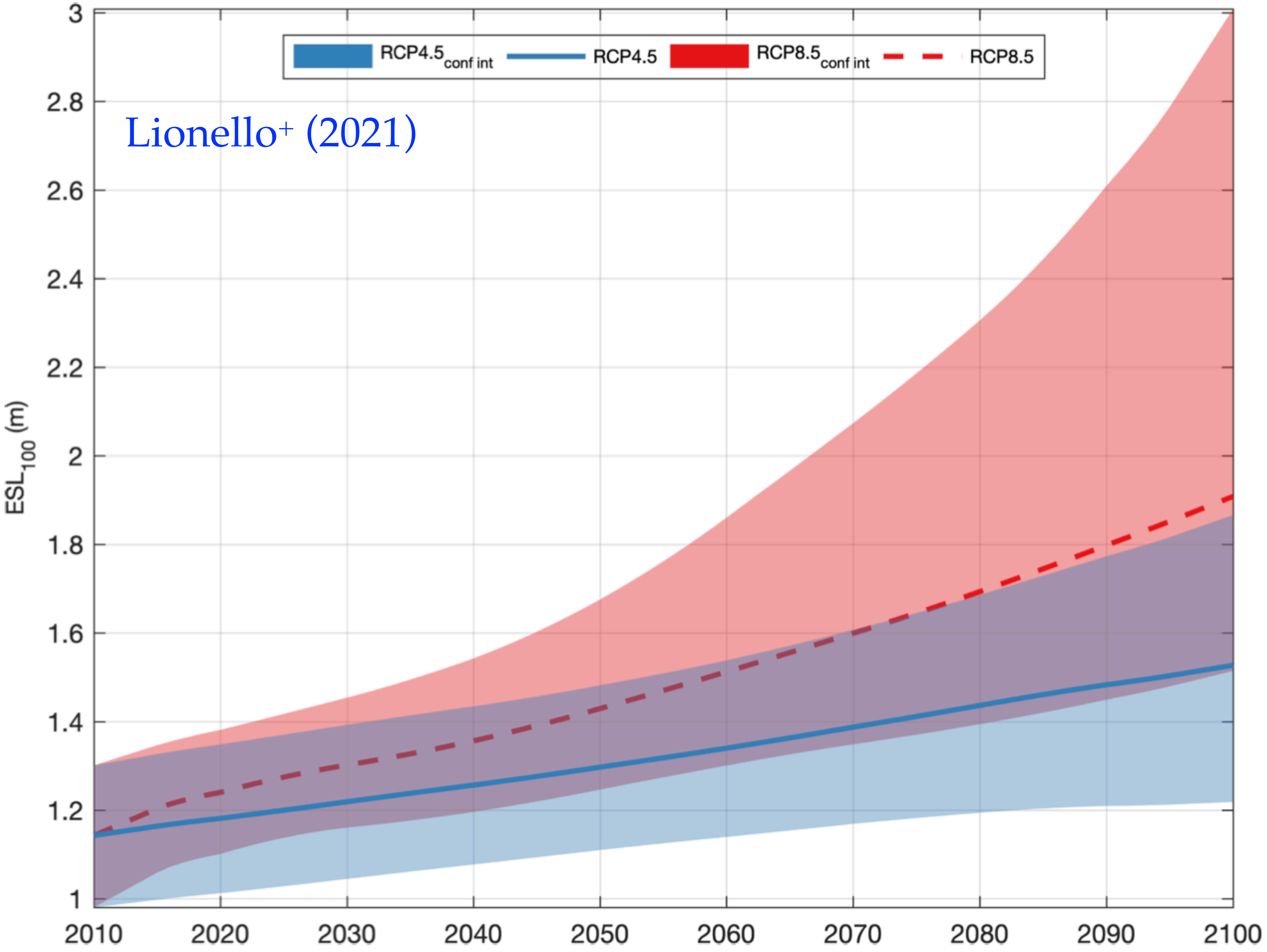
STORM SURGE: 100-yr RETURN TIME PROJECTED OVER THE ADRIATIC SEA

🌊 **100-Year Extreme Sea Level (ESL) – North-Western Adriatic Sea**



📅 **By 2050:**

Under **RCP4.5** (moderate emission scenario):
→ ESL is **very likely** to rise by **12–17 cm**

Under **RCP8.5** (high emission scenario):
→ ESL is **very likely** to rise by **26–35 cm**.

📅 **By 2100:**

Under RCP4.5:
→ Rise of **24–56 cm**.

Under RCP8.5:
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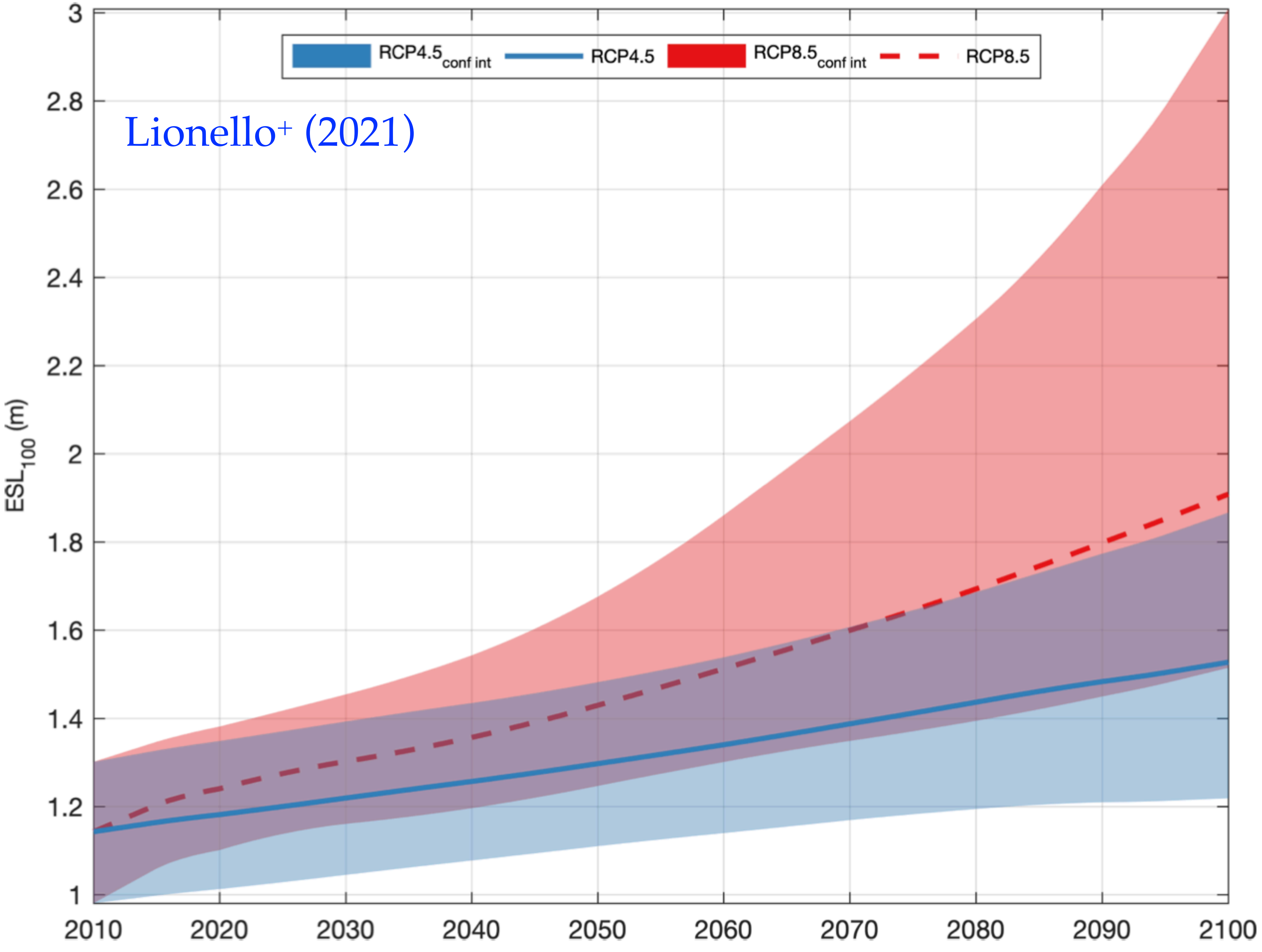

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🔁 **Frequency of Current 100-Year Events:**

🕒 **By 2050:**

Events of today's 100-year severity may occur:

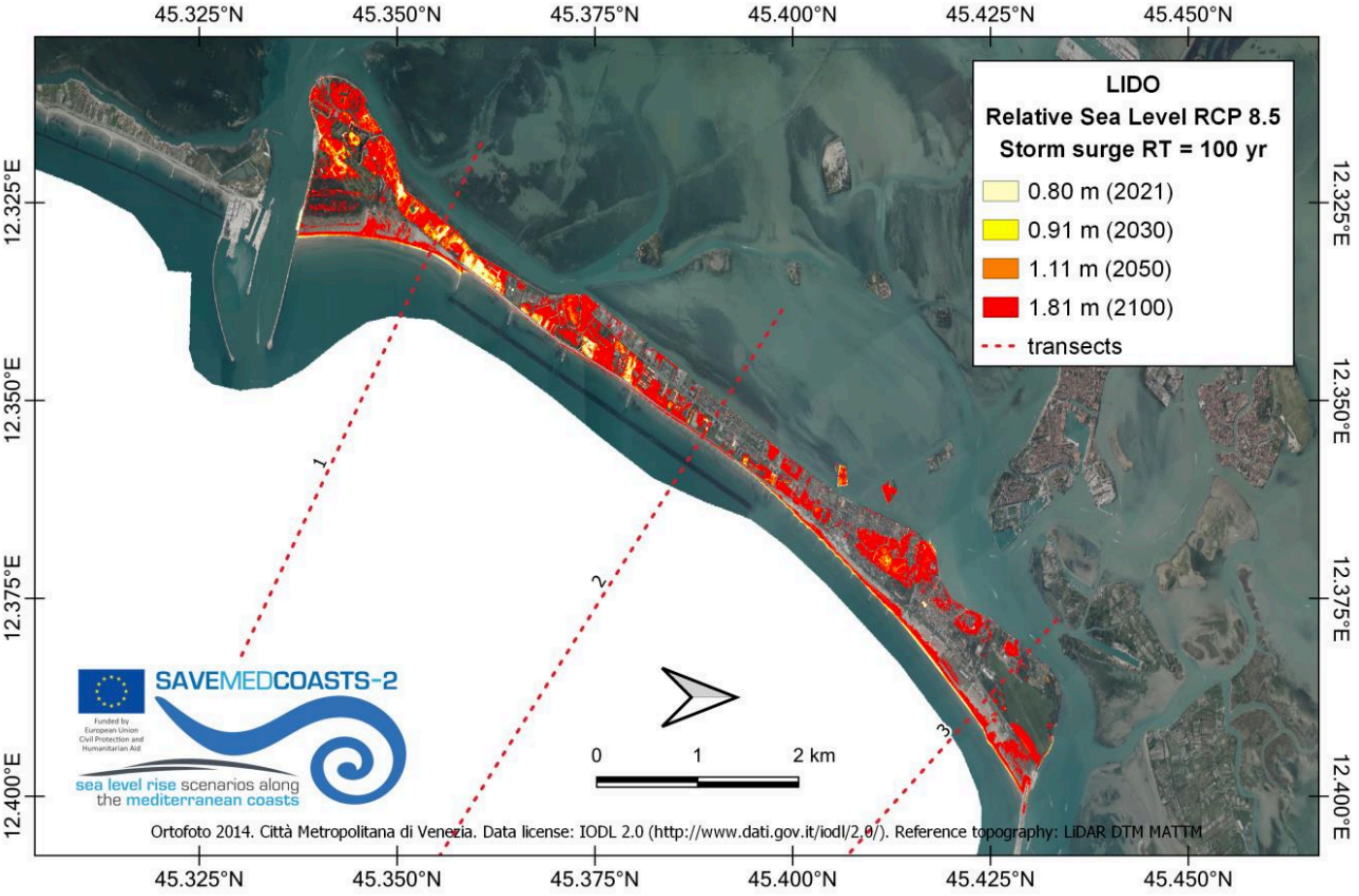
- **Every 50 years** (RCP4.5).
- **Every 10 years** (RCP8.5).

🕒 **By 2100:**

These events may occur:

- **At least every 5 years** (RCP4.5).
- **Every year** (RCP8.5).

STORM SURGE: 100-yr RETURN TIME PROJECTED FOR VENICE



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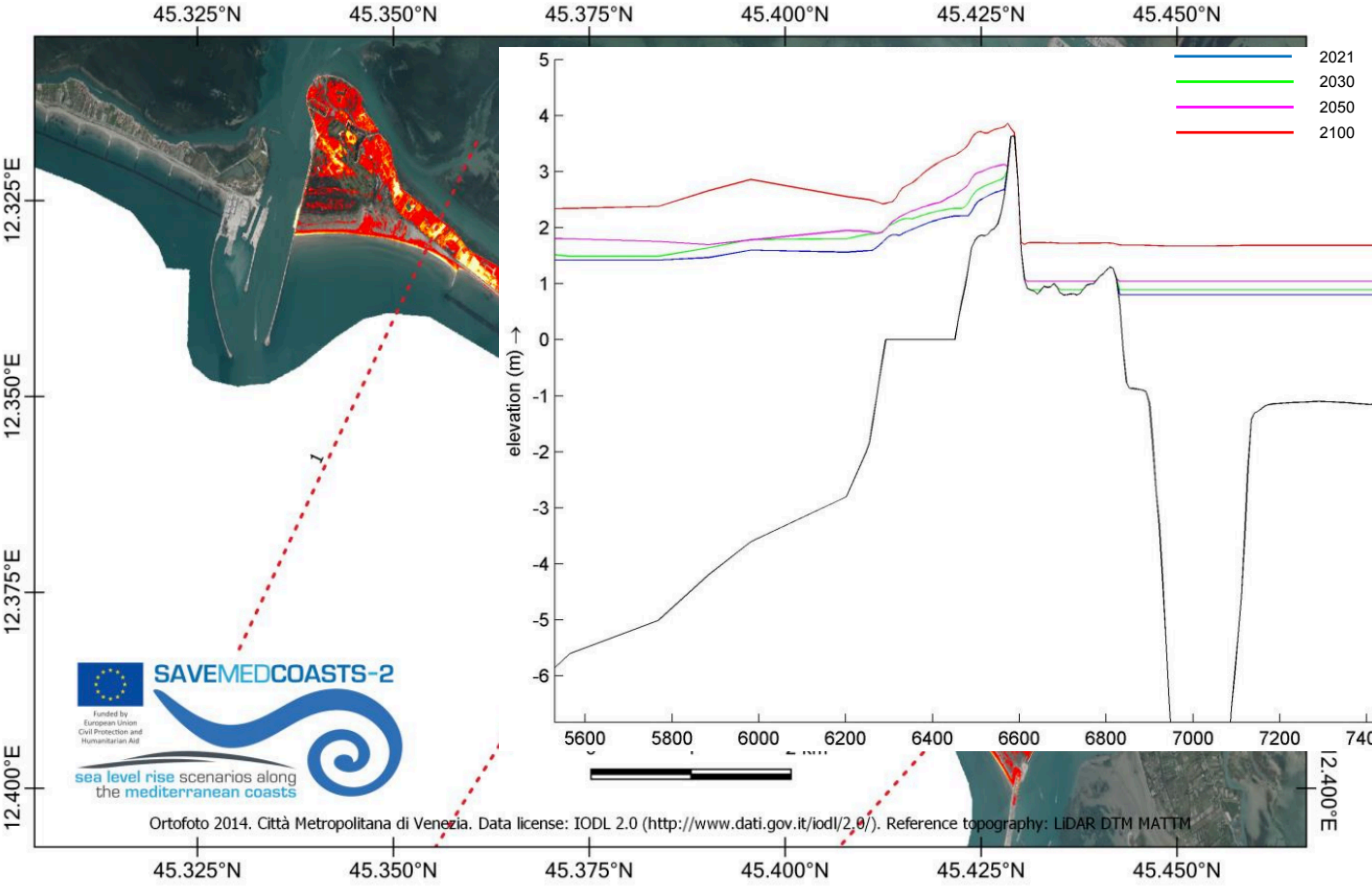

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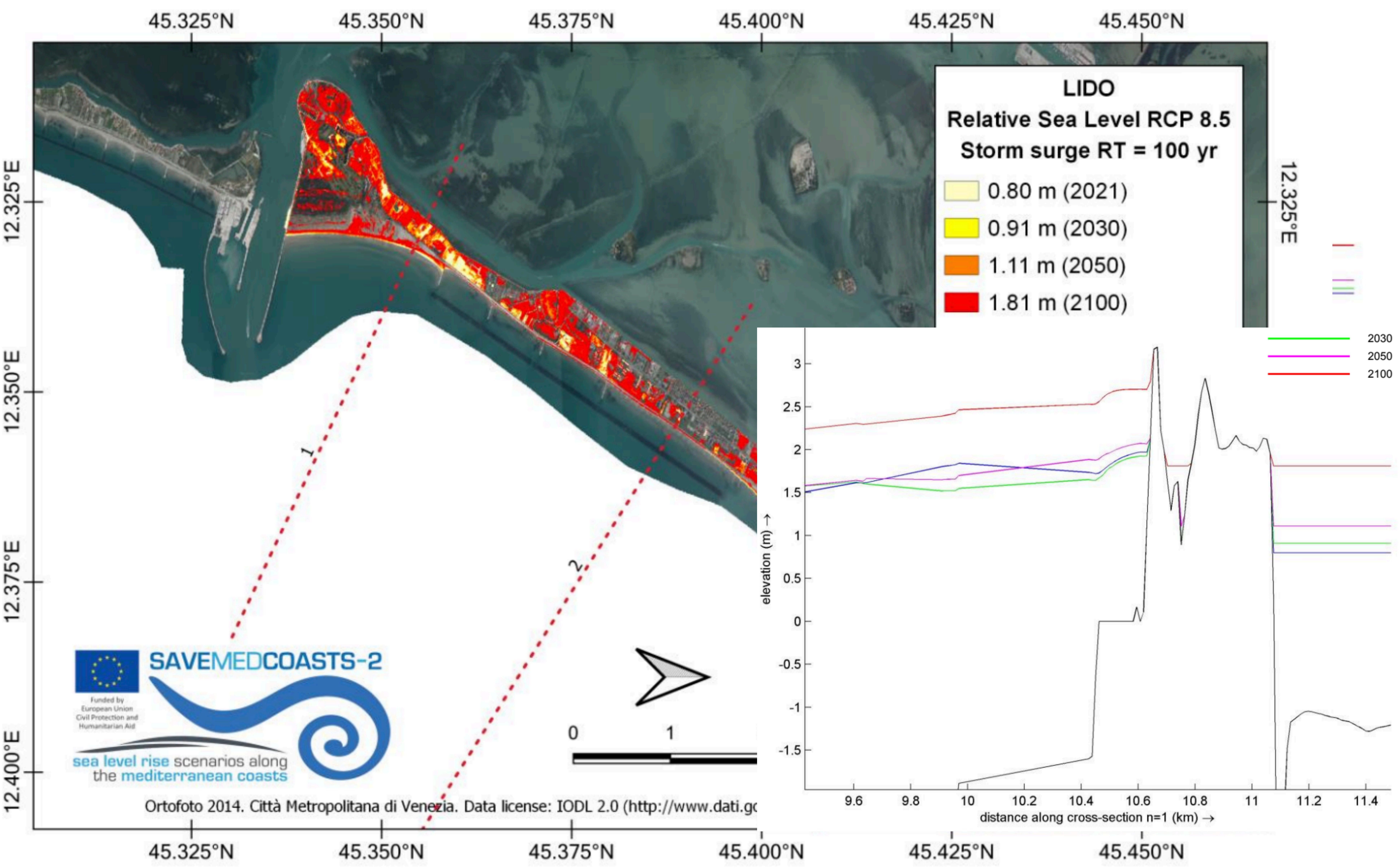

STORM SURGE: RETURN TIME
Is it significant?

Summary:

- Due to climate change, the frequency and intensity of storm surge events are expected to increase in the coming decades.
- The Mediterranean is particularly vulnerable due to its morphology and the density of coastal areas.

Future projections:

- Under high greenhouse gas emissions scenarios, the probability of 100-year return events could increase significantly, with the risk that storm surge events could occur several times per year by the end of the century.

Implications for coastal protection:

- Coastal infrastructure design need to take into account the increasing frequency of these events.

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REASSESSING RETURN PERIOD VALIDITY
The Emilia-Romagna case

🌧️ **Recent Flood Events**

02 May 2023: severe flooding in Emilia-Romagna, with 23 rivers overflowing, 250 landslides, and over €10 billion in damages.

16 May 2023: another major flood event, with 65,000 landslides and breaches in 23 rivers, flooding 540 km².

18-19 September 2024: another flood event due to Storm Boris, over 300 mm of rain in just 48 hours, evacuation of over 1,000 residents.

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Both events sequentially: 500 years

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IS THIS THE "NEW" NORMAL? ARE WE PREPARED FOR THAT?

1966 Acqua Alta in Venice

- Highest recorded sea level: 194 cm

- Caused by strong Scirocco winds, a powerful depression

- Power outages, flooded streets, destroyed boats, and businesses

- Sant'Erasmo vanished under 4-meter waves

- Murano's glass factories nearly entirely destroyed.

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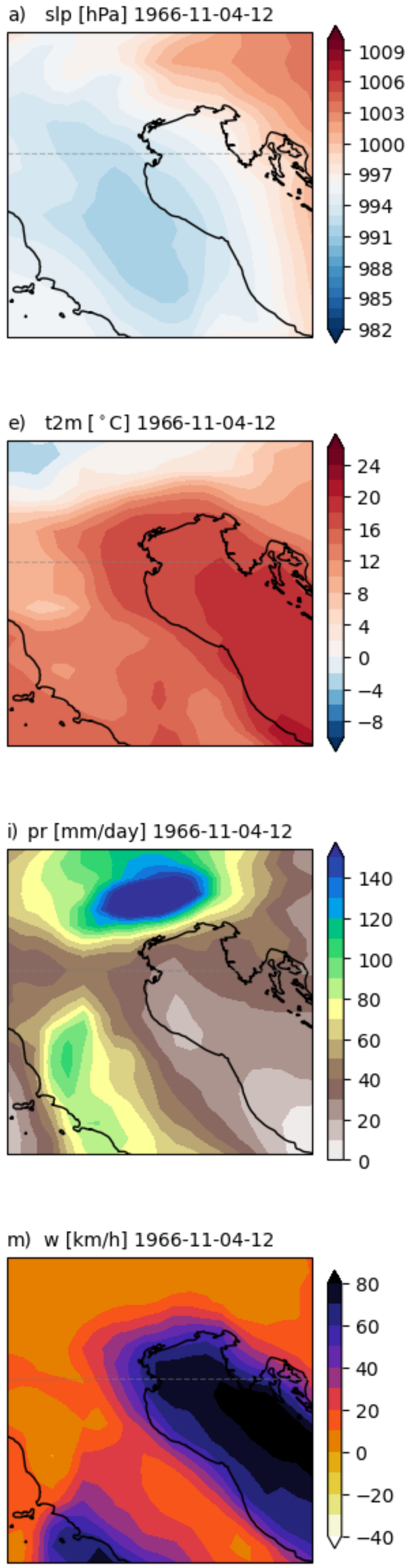

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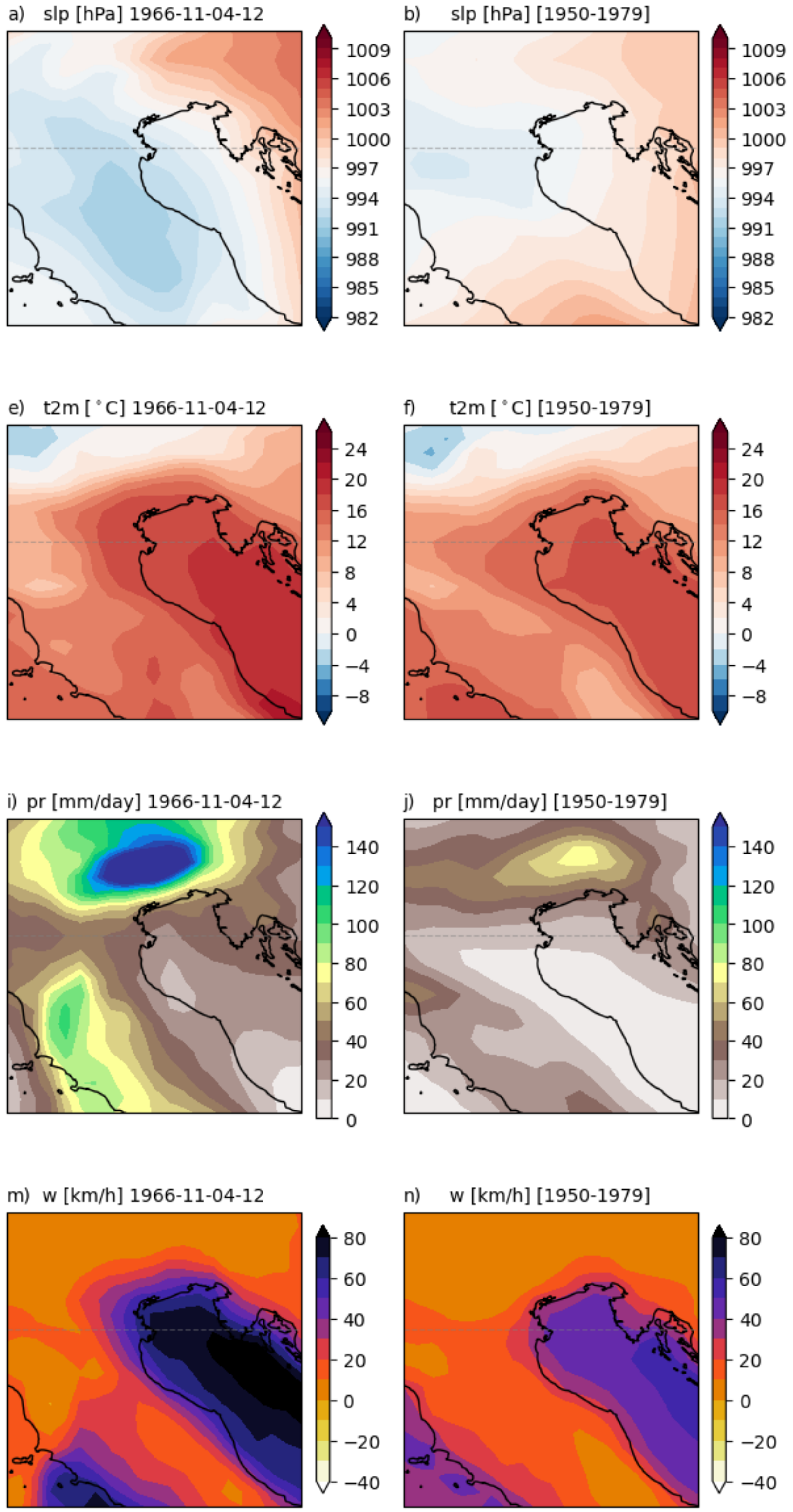

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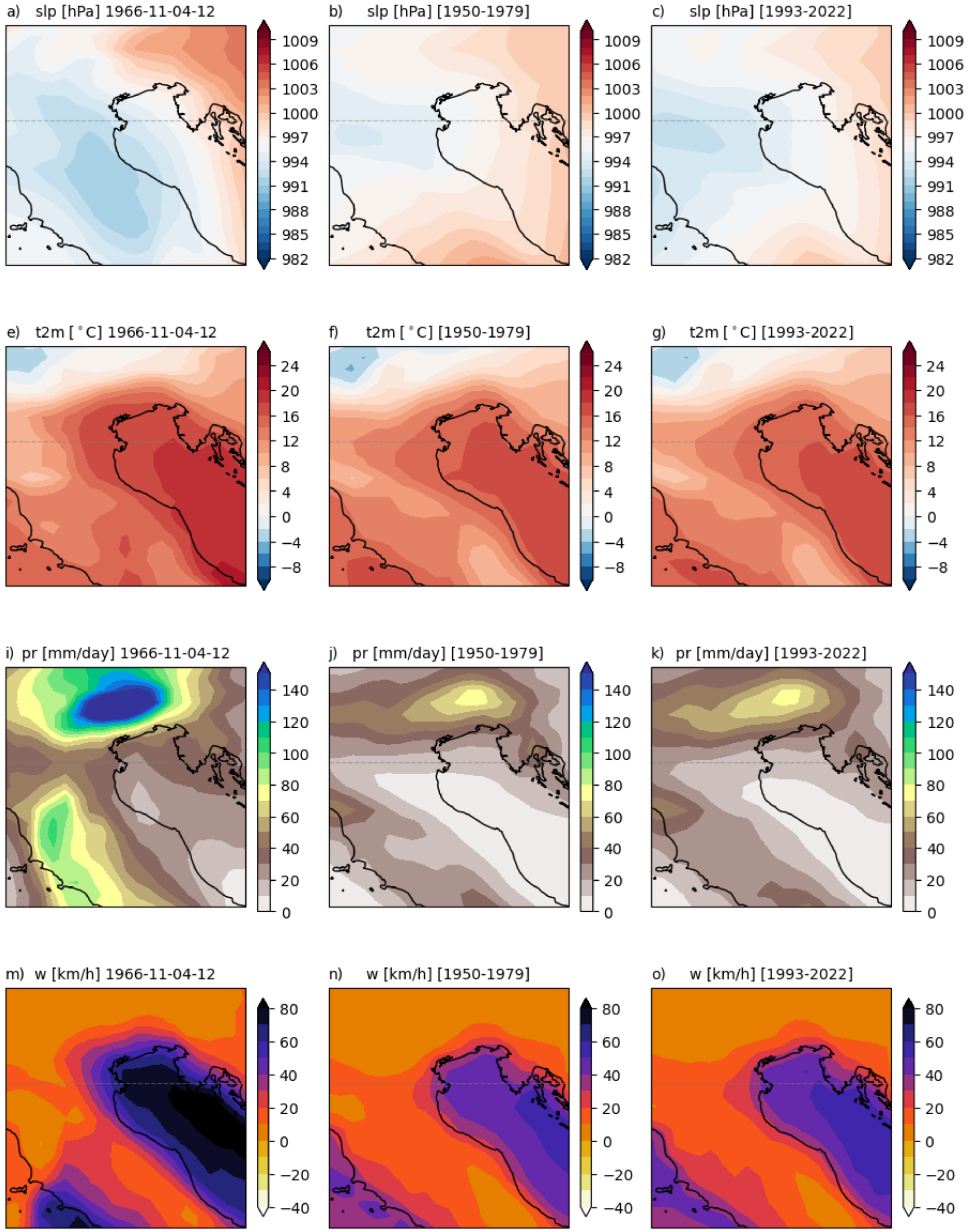

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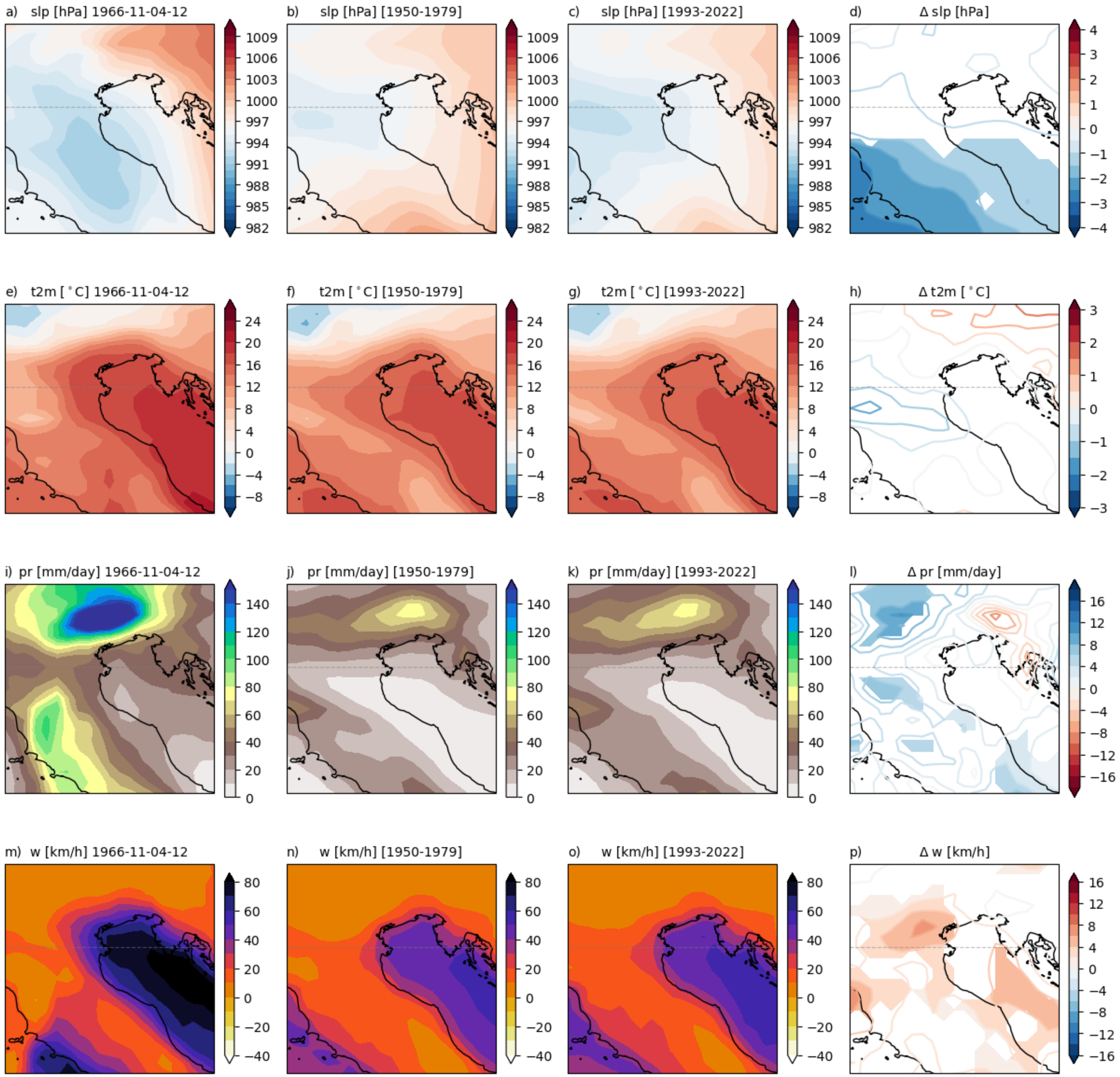


📍VENICE LAGOON

🚧 MoSE System: a safeguarding system implemented in Venice to protect against acqua alta.

🔧 MoSE operations: started its test-phase service on 03-10-2020 aiming to mitigate extreme flooding events in the city.

MO SE

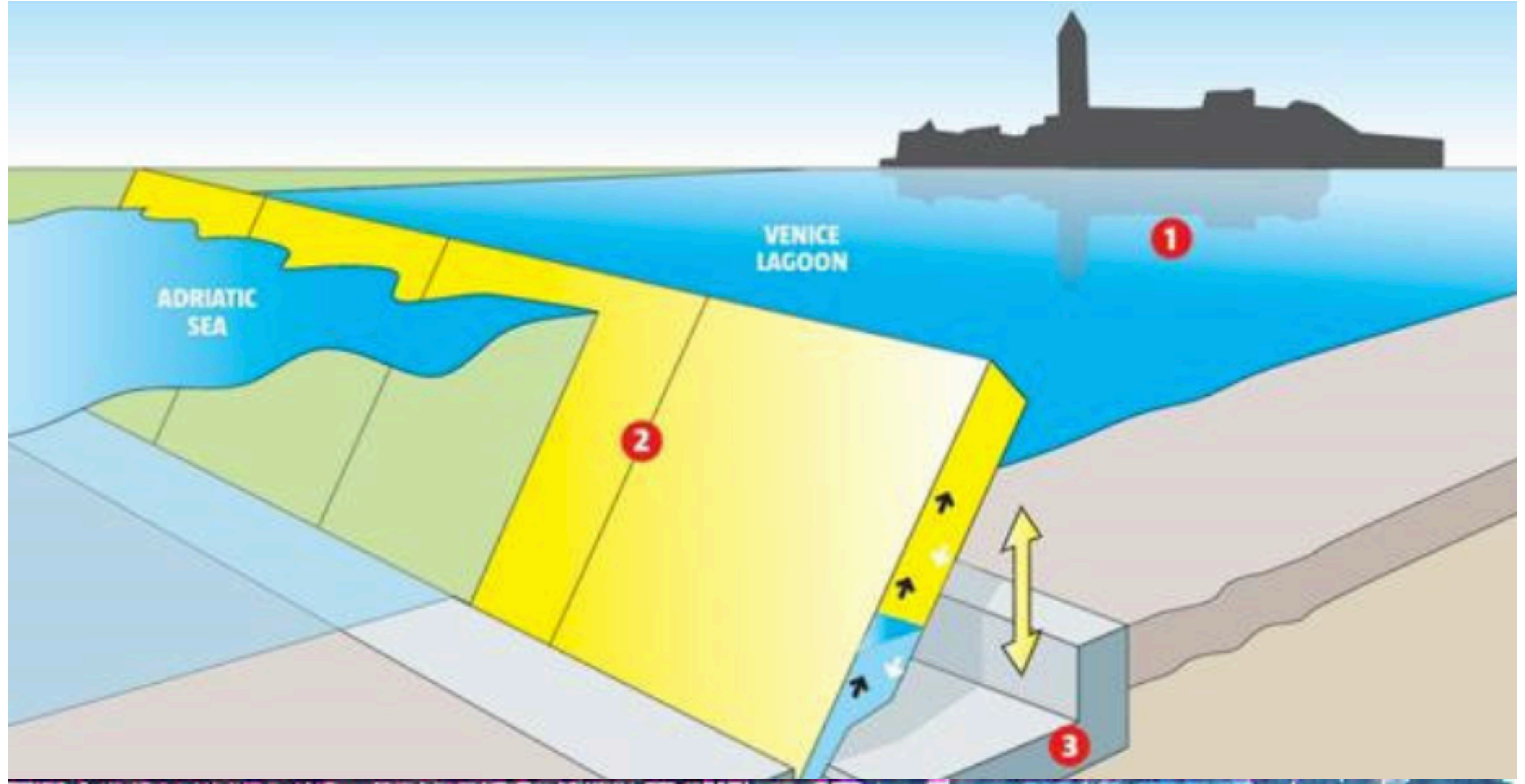
PER LA DIFESA DI VENEZIA
E DELLA LAGUNA DALLE ACQUE ALTE

MOSE · LAGUNA · CONSORZIO TRASPARENTE · BANDI DI GARA · SIN · CONTATTI

PARATOIE TOTALI	BARRIERE MOBILI	BOCCHE DI PORTO LAGINARI	METRI DI MAREA FRONTEGGIABILI
78	4	3	3

✅ Activation frequency: has been activated >100 times to safeguard Venice from high water levels.

Il Mose: 100 alzate per proteggere Venezia da danni per oltre 2,6 miliardi

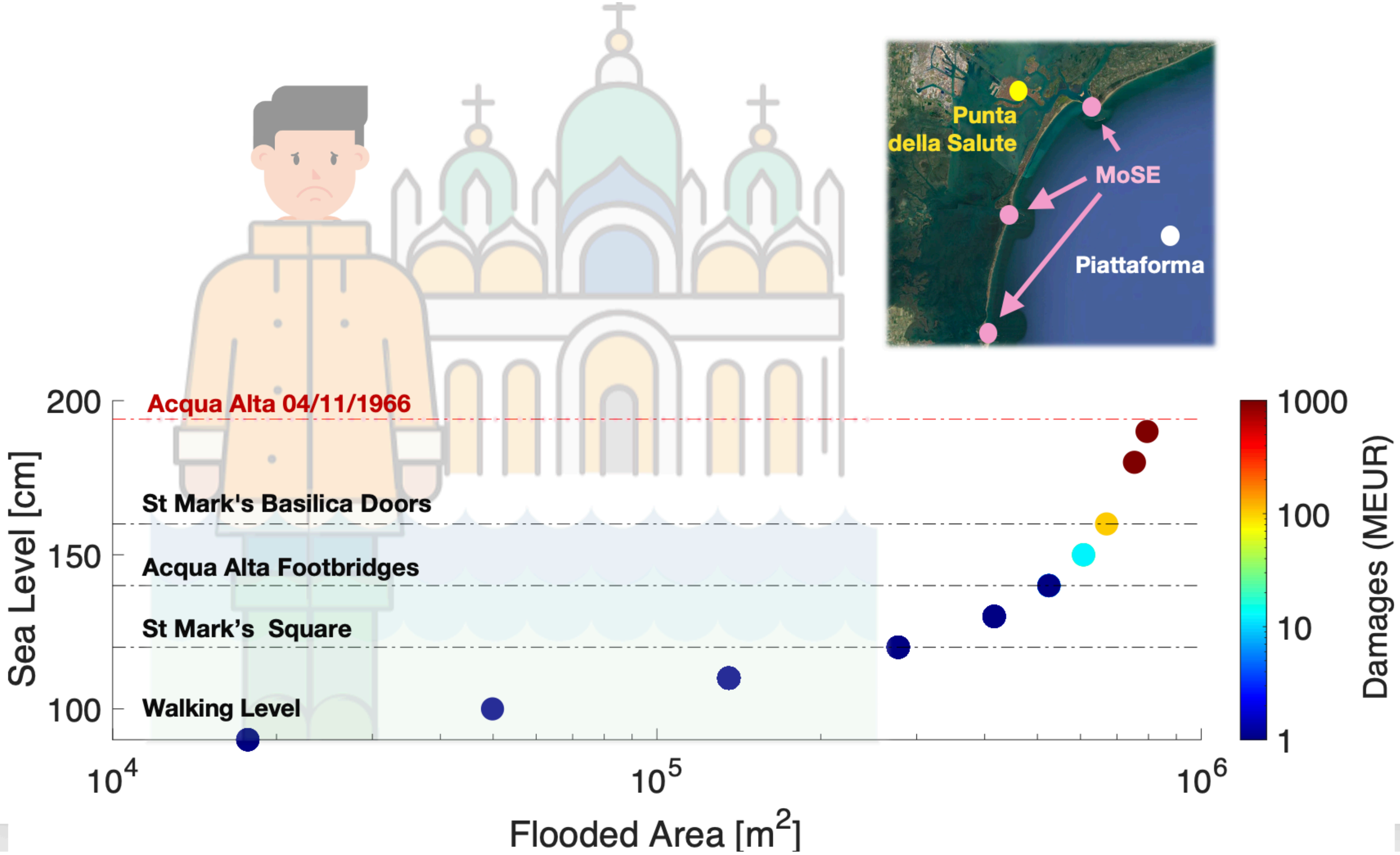


EFFECTIVENESS OF THE MoSE

1) To evaluate what would have happened **without MoSE, we use the measurement of Piattaforma**

2) We compute **damages** with an exponential model

3) If **MoSE is activated** for a given analogues date, we add a 0.025 MEUR cost (operational costs of the MoSE in 2023)



EVALUATING THE EFFECTIVENESS OF THE MoSE

	# MoSE	Variables	Event	[1993–2022] With MoSE	[1993–2022] No MoSE
1966	11 (40%)	SL [cm][b]	194	111 (59, 156)	123 (107, 156)
		Damages [MEUR]	4.5	0.25 (0.07, 28)	0.45 (0.06,28)

MoSE effectiveness 🚧❓

The analysis shows successful protection against the 1966 extreme event and just activated for 11 events analogues to the 1966

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MoSE effectiveness 🚧❓

The analysis shows successful protection against the 1966 extreme event and just activated for 11 events analogues to the 1966

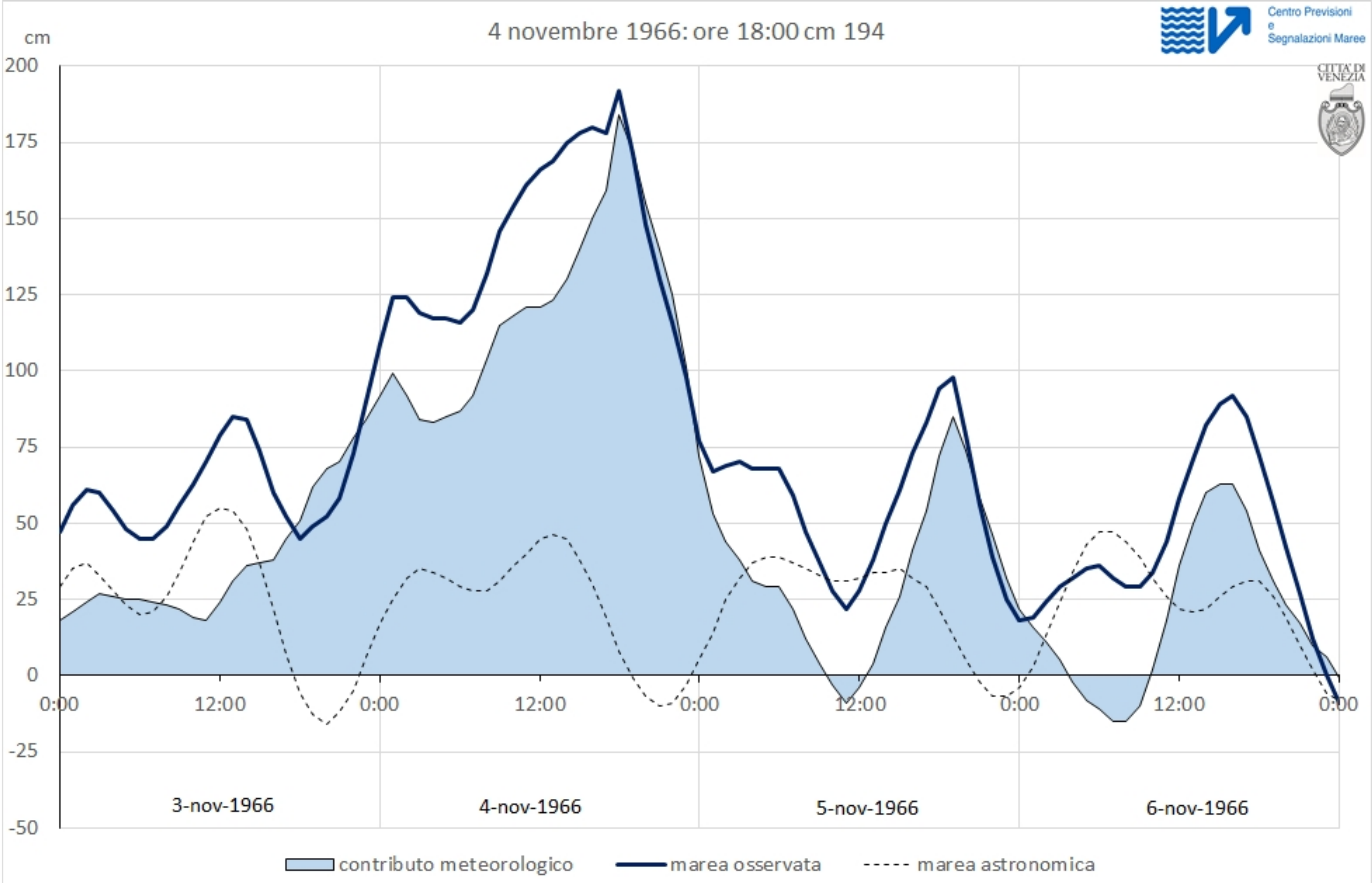
🌀 Minimum pressure: ~985 hPa

+

🌬️ Scirocco wind: 80 km/h

=

🌊 Direct storm surge: 50 cm



EVALUATING THE EFFECTIVENESS OF THE MoSE IN 2100
“New” storm surge

Direct storm surge: 50 cm

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Climate change contribution:

- 12-17 cm for medium emission
- 26-35 cm for high emission

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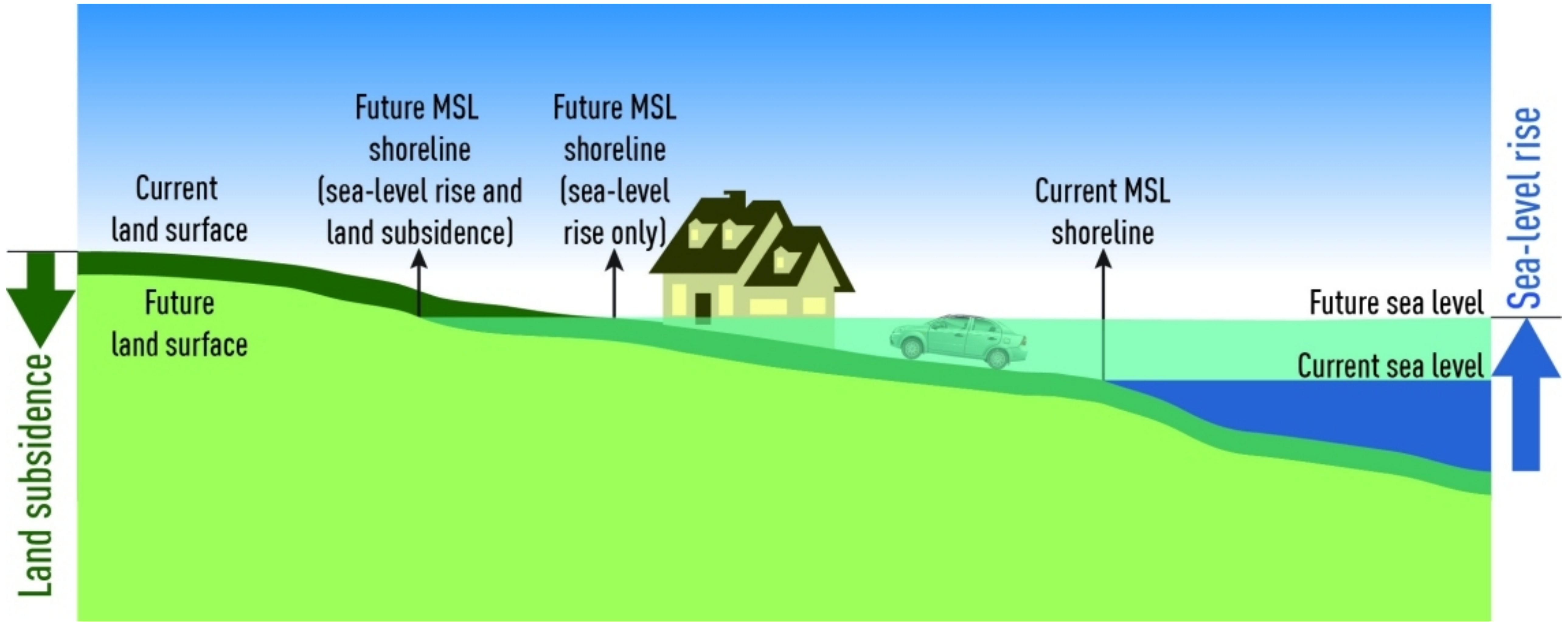
but…

Average rate: 5 mm/yr

→ 40 cm (2100)



Average sea level rise:
→ 60-100 cm (2100)

EVALUATING THE EFFECTIVENESS OF THE MoSE IN 2100
“New” storm surge

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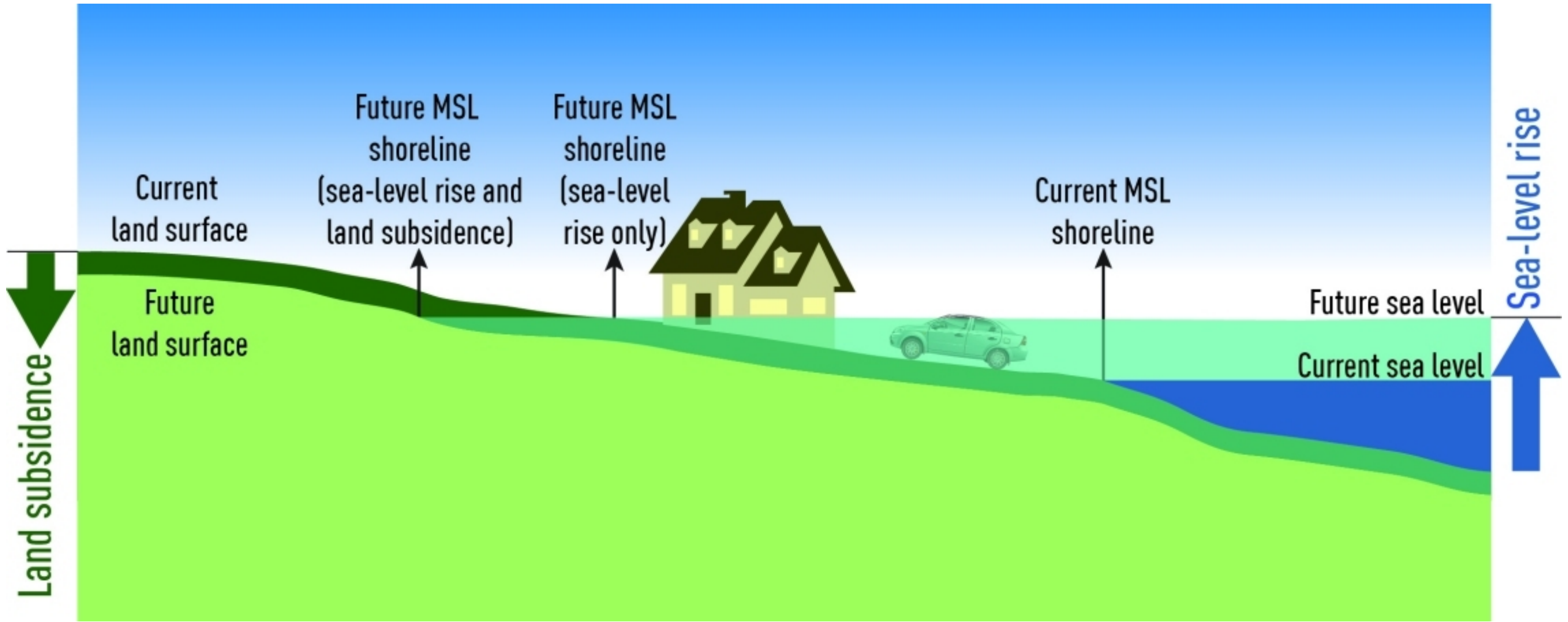
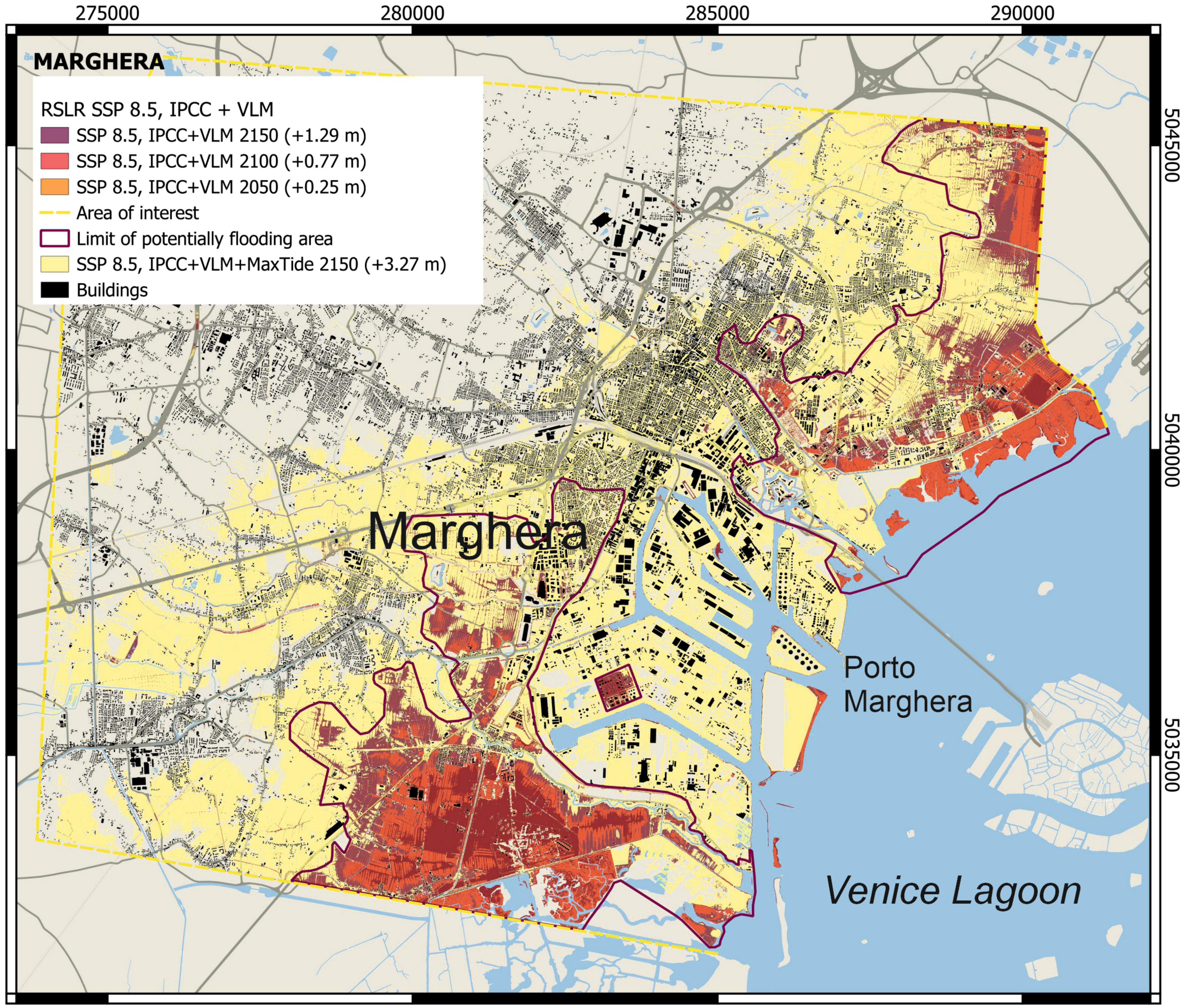


Average sea level rise:
→ 60-100 cm (2100)

Acqua Alta 2100: >300 cm

MoSE effectiveness 🚧❌

EVALUATING THE EFFECTIVENESS OF THE MoSE IN 2100
“New” flooding scenarios



- SL could rise up to 3.21 m in the high-emission scenario, corresponding to about 78 km^2 of flooded land.

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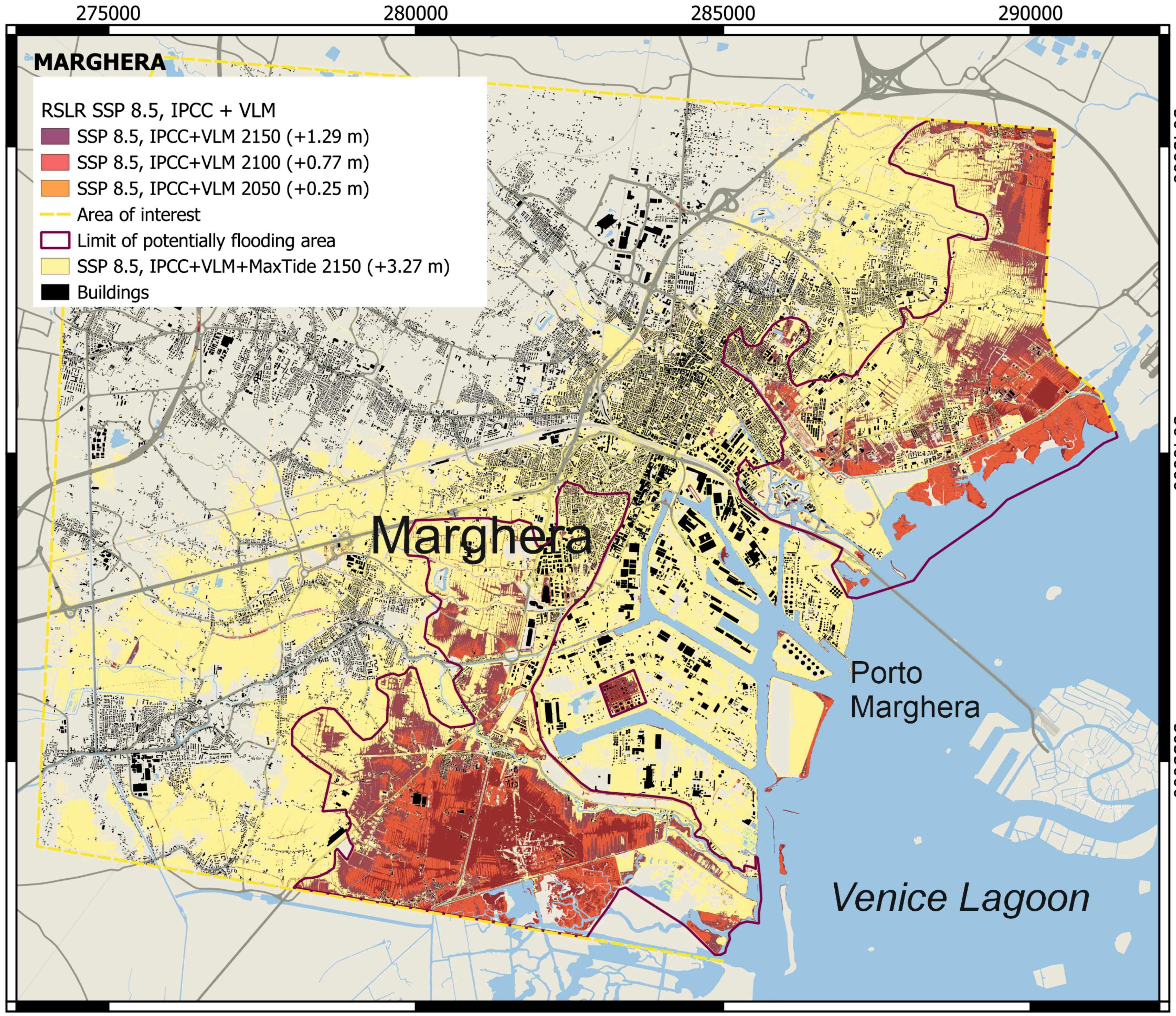
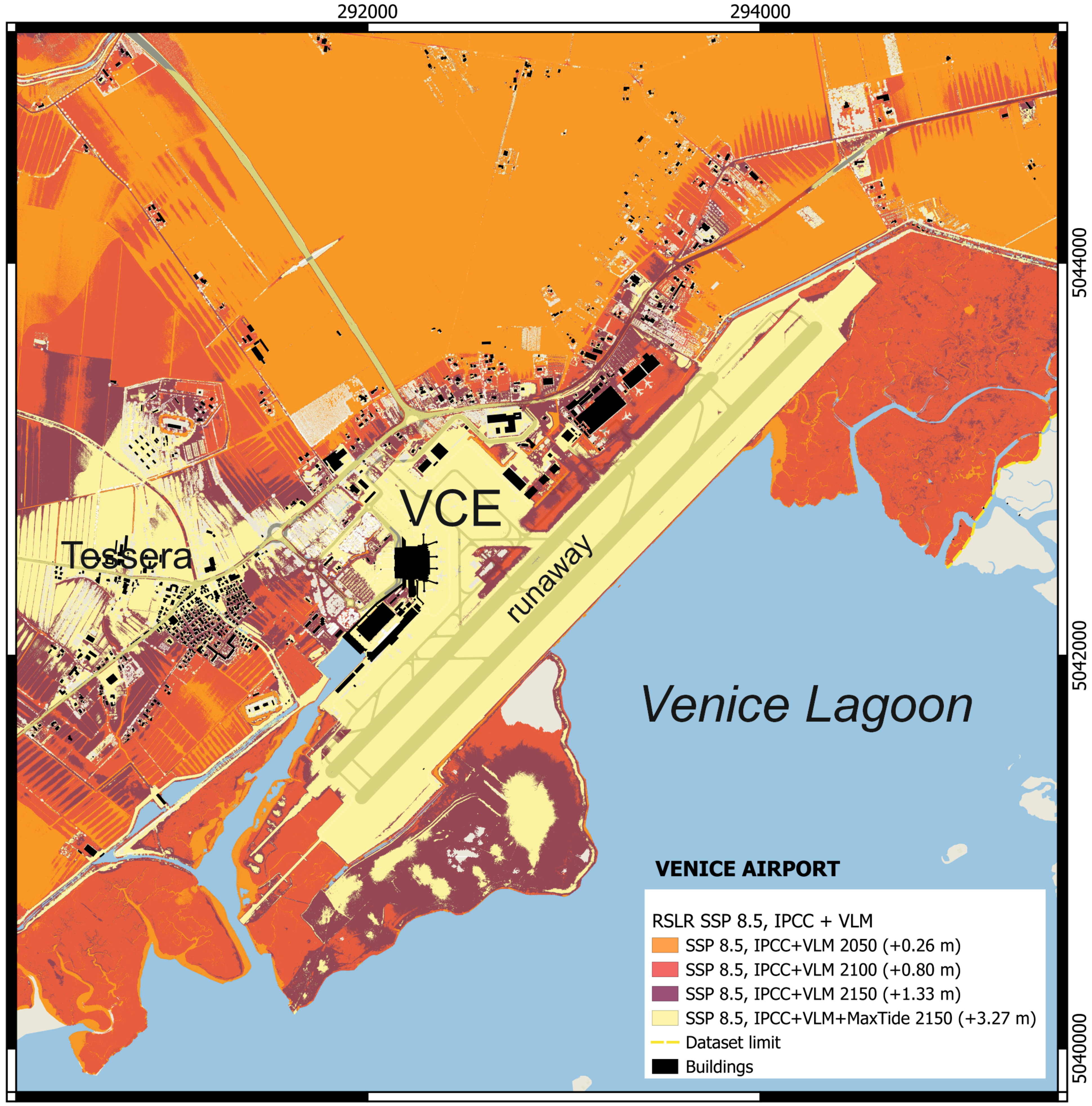
“New” flooding scenarios





- SL could rise up to 3.21 m in the high-emission scenario, corresponding to about 78 km² of flooded land.

- SL would rise up to 3.25 m, thus flooding about 92% of the area.
- Runways will be completely submerged, and >800 buildings

NOT SIMPLY CYCLONES…MEDICANES

Medicanes (Mediterranean hurricanes) are tropical or subtropical-like cyclones that form in the Mediterranean.

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🌡️ **Sea surface temperatures:** above 26°C can favor their formation and intensification

🌀 **Pressure:** minimum depression up to 950-960 hPa
→ +25 cm storm surge

🌬️ **Wind:** gusts between 60 and 120 km/h, peak 150 km/h (Qendresa, Nov 2014)
→ +15-30 cm fetch

⛈️ **Precipitation:** more than 200 mm/day (>monthly precipitation)

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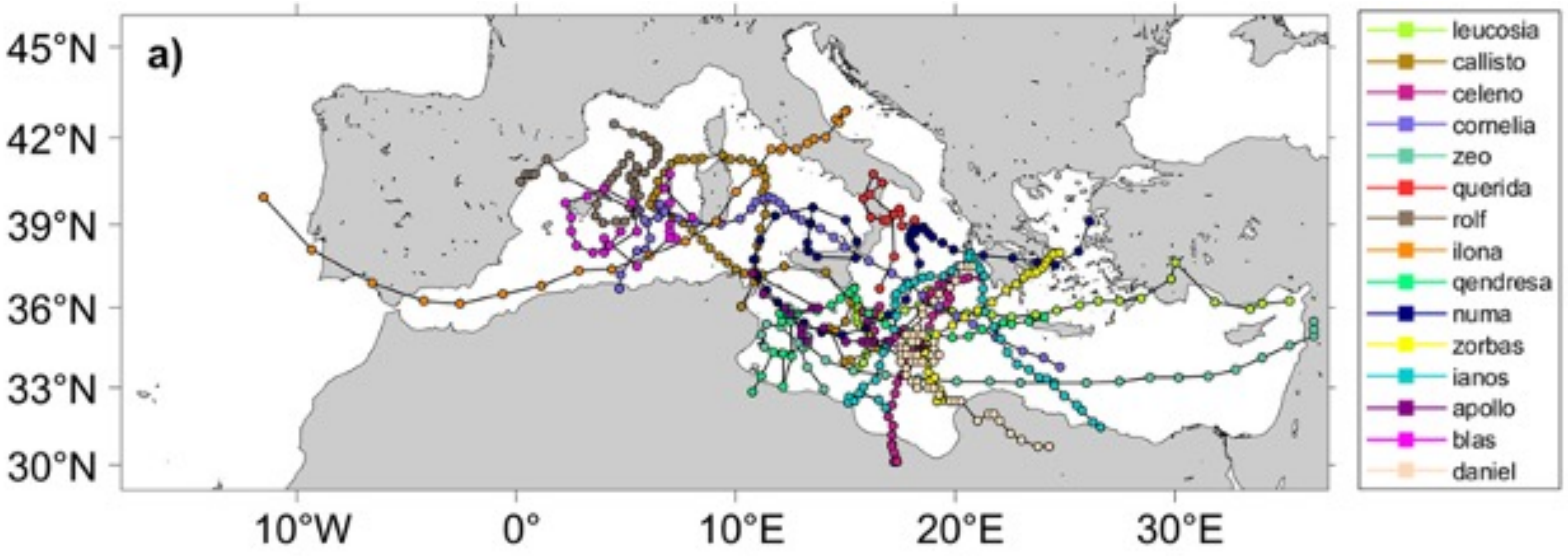
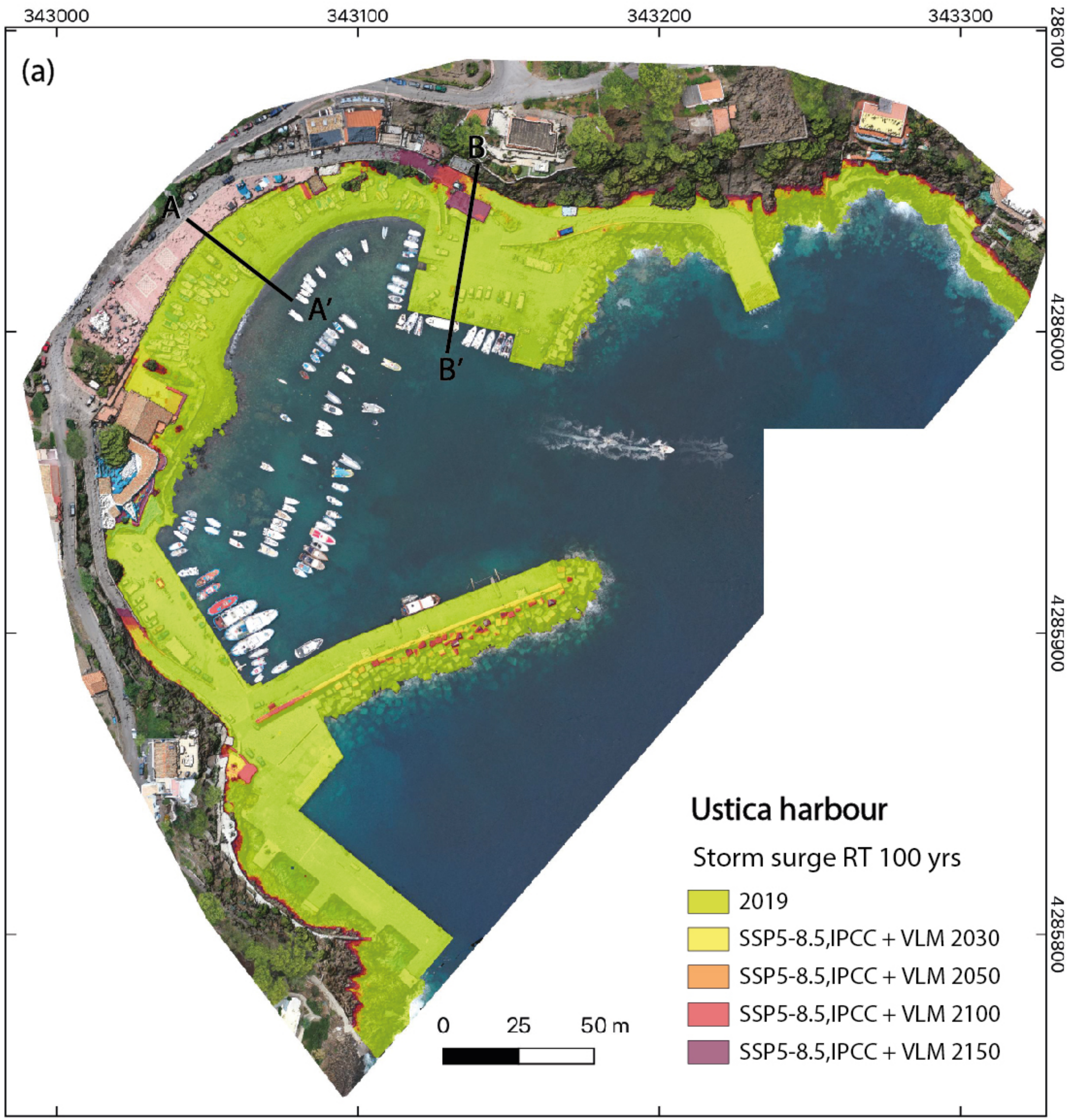


🚧 **Risks for infrastructure:** flash floods, especially in coastal or mountainous areas, storm surge, lightnings, …

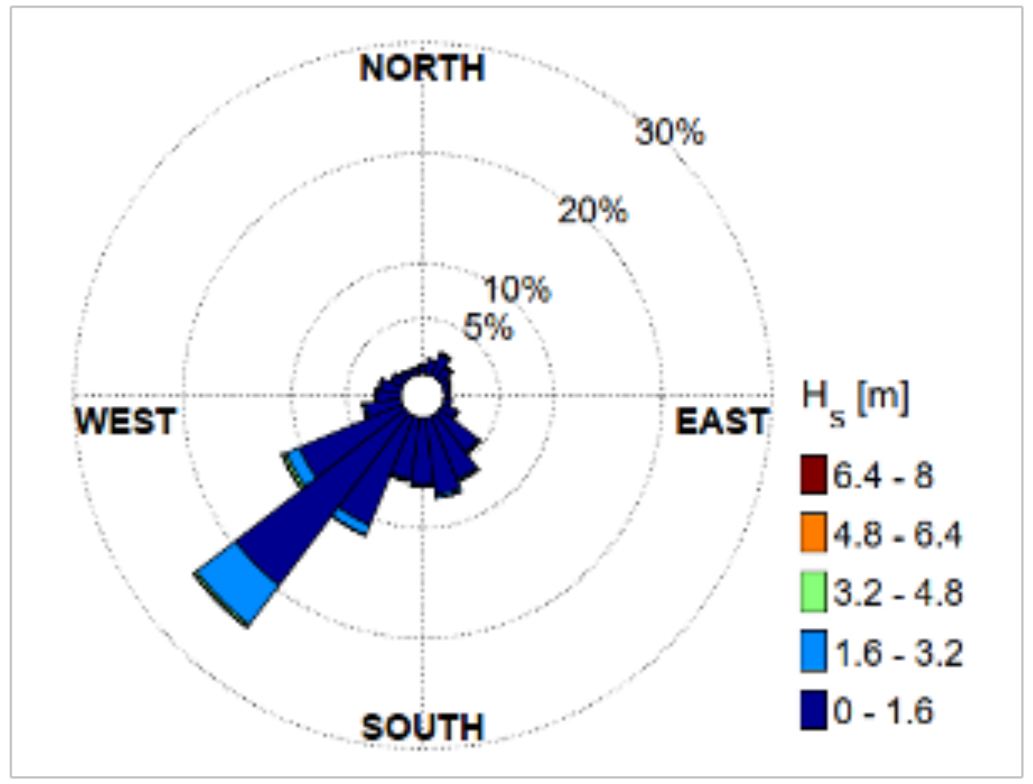
STORM SURGE IN USTICA
Likely exposed to Medicanes

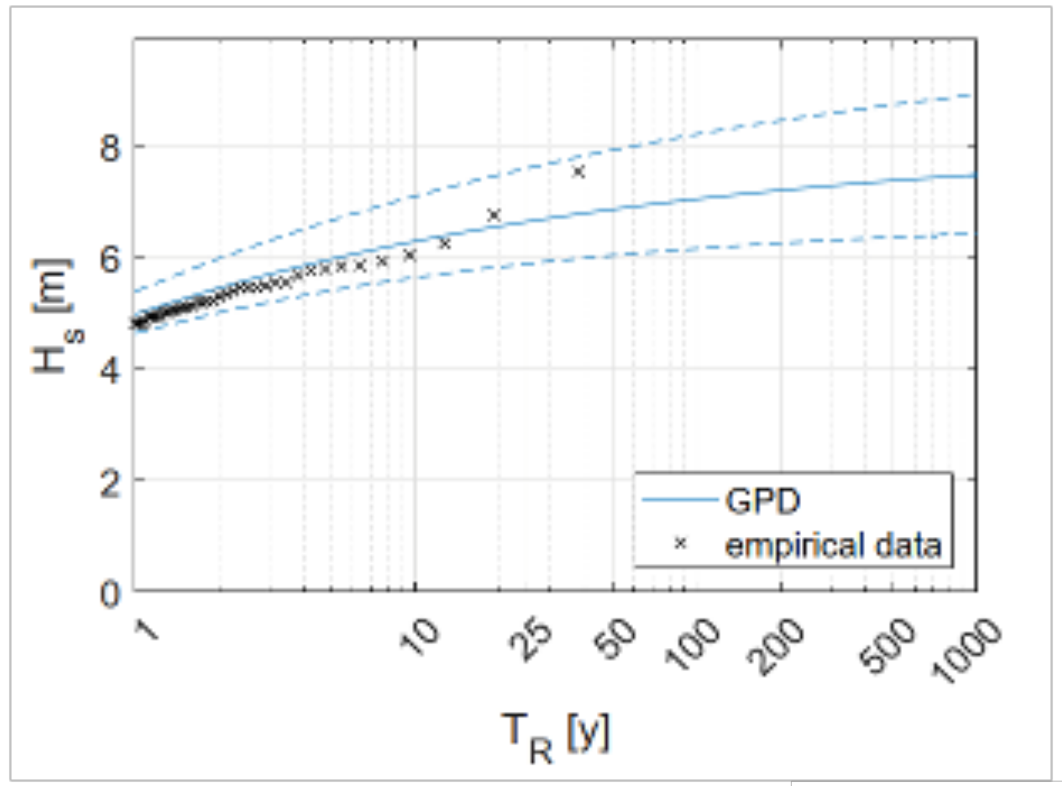
- In the harbor area, current storm surges can **raise water levels up to 5.4 meters**, nearly four times the relative sea-level rise (RSLR, 1.3 meters under ordinary conditions).
- During an extreme storm surge event (return time of 100 years), **up to 50% of the land** (based on the 2019 reference) **and 56%** (based on the 2150 reference) may be affected by seawater.
- Critical infrastructure—including the road to the harbor, the dock, tourist facilities near the coastline, the beach, and the breakwater—would be submerged under such conditions.

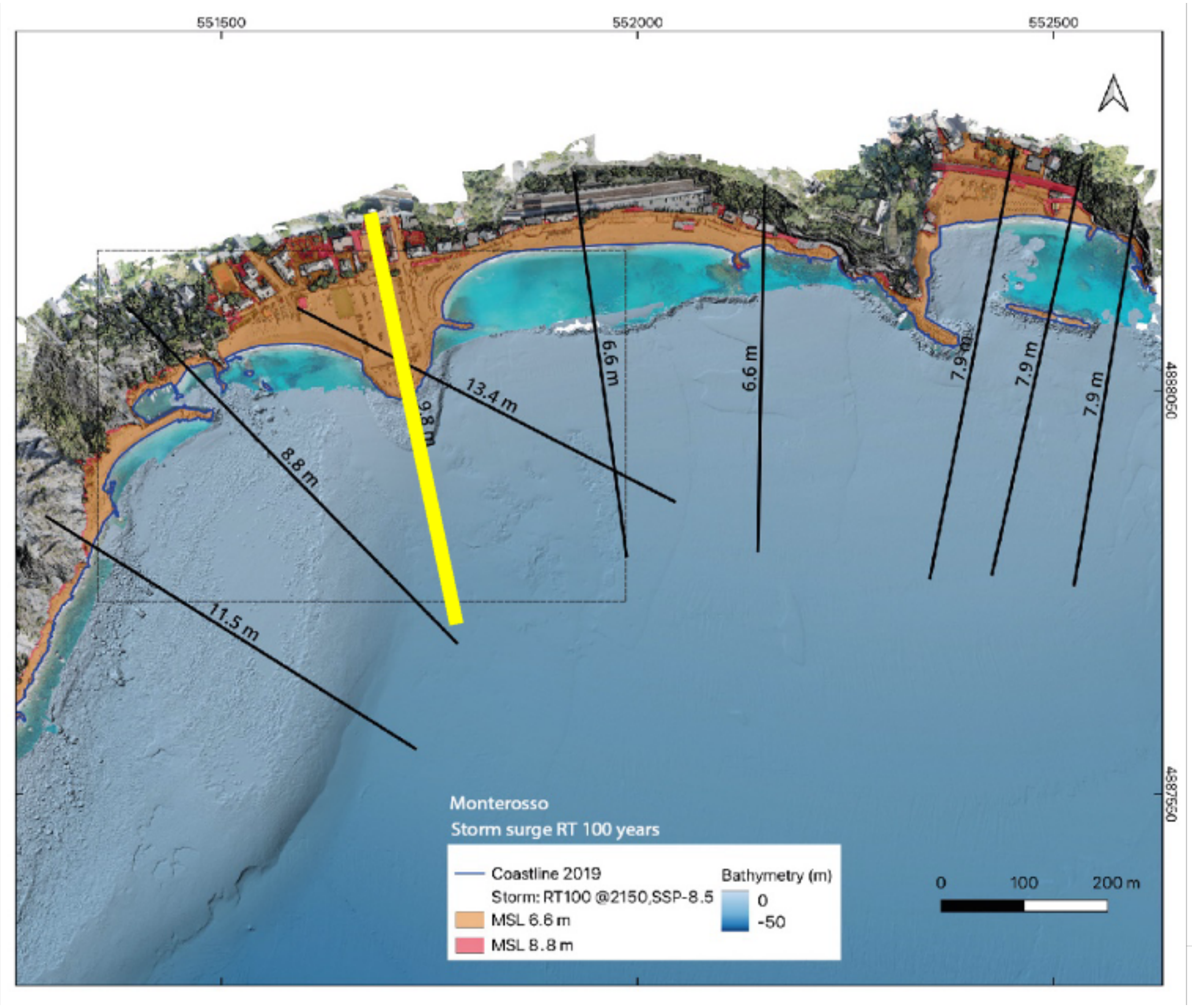


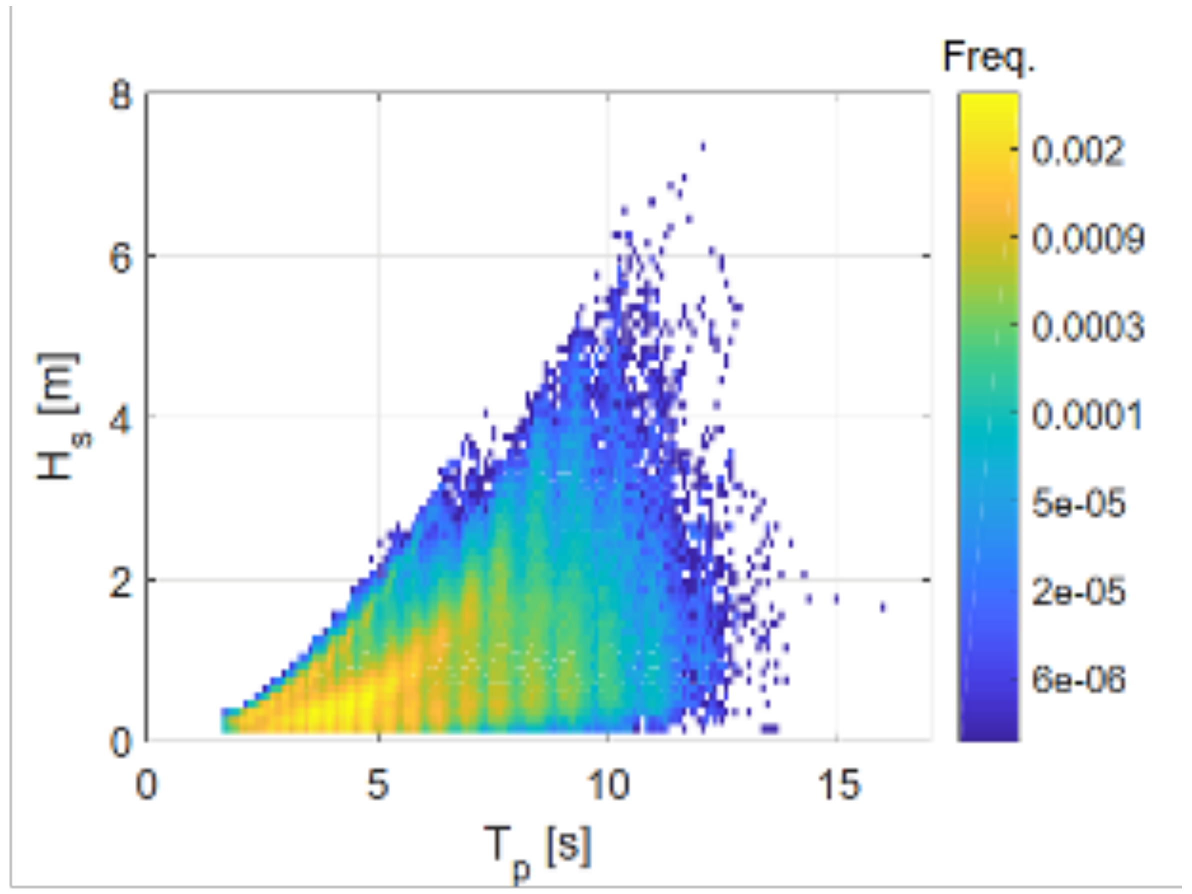
STORM SURGE IN MONTEROSSO
Exposed to Genoa Low depressions

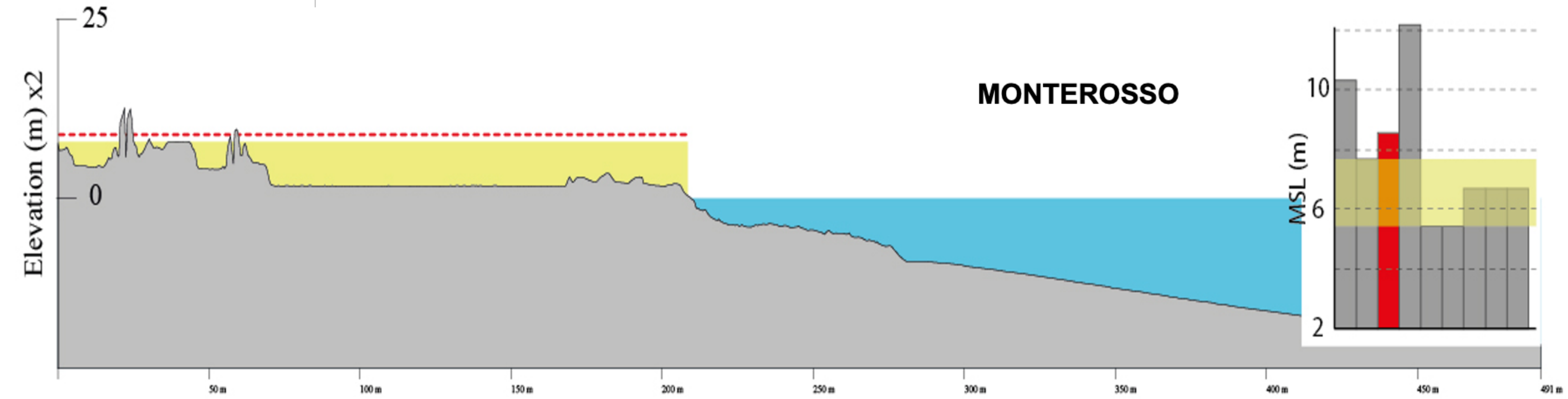
- Potential maximum water level (max WL) for a storm surge with a return time (RT) of 100 years for the SSP5-8.5 climatic scenario for the year 2150 across Monterosso coast.



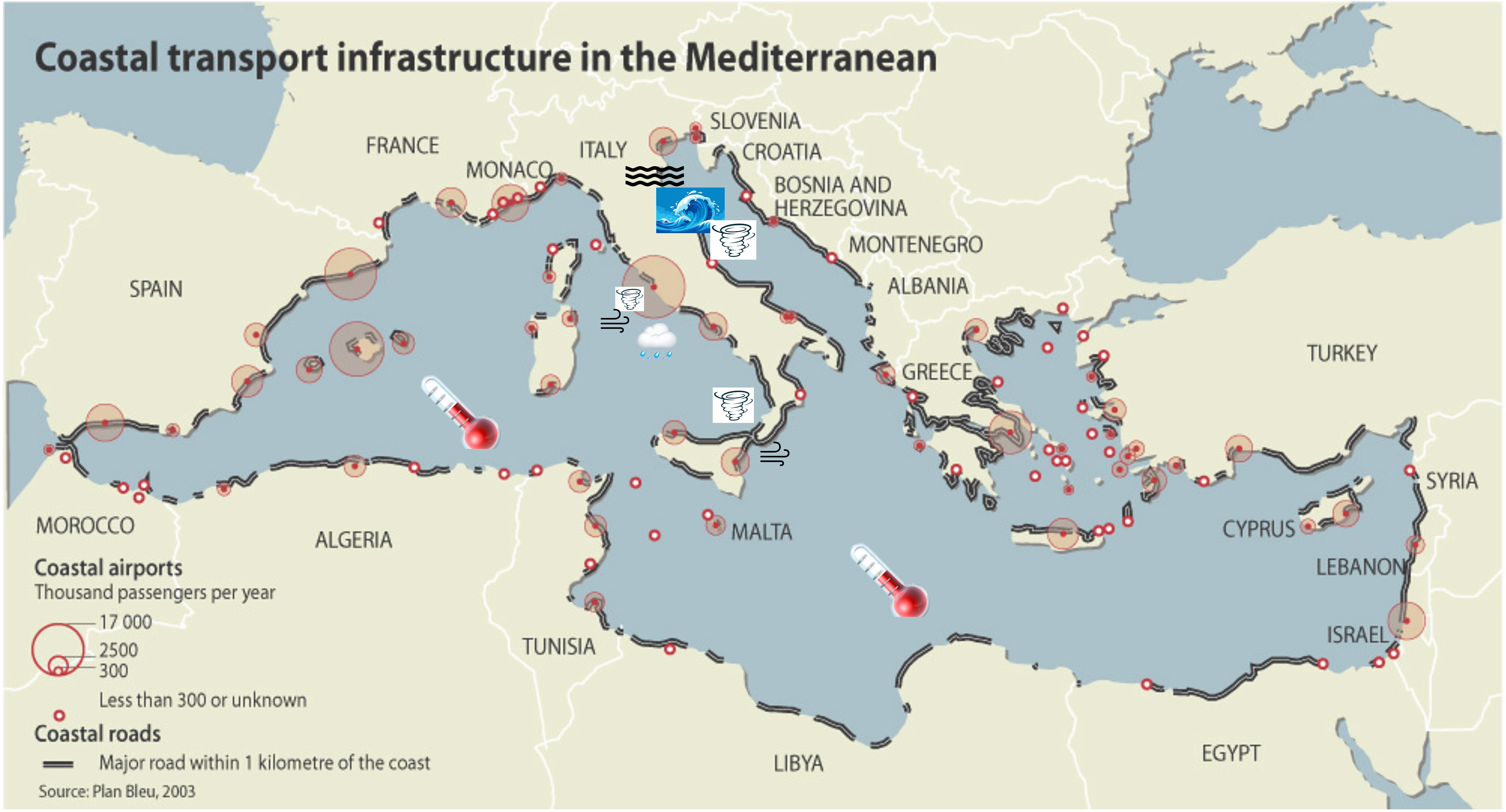








CONCLUSIONS



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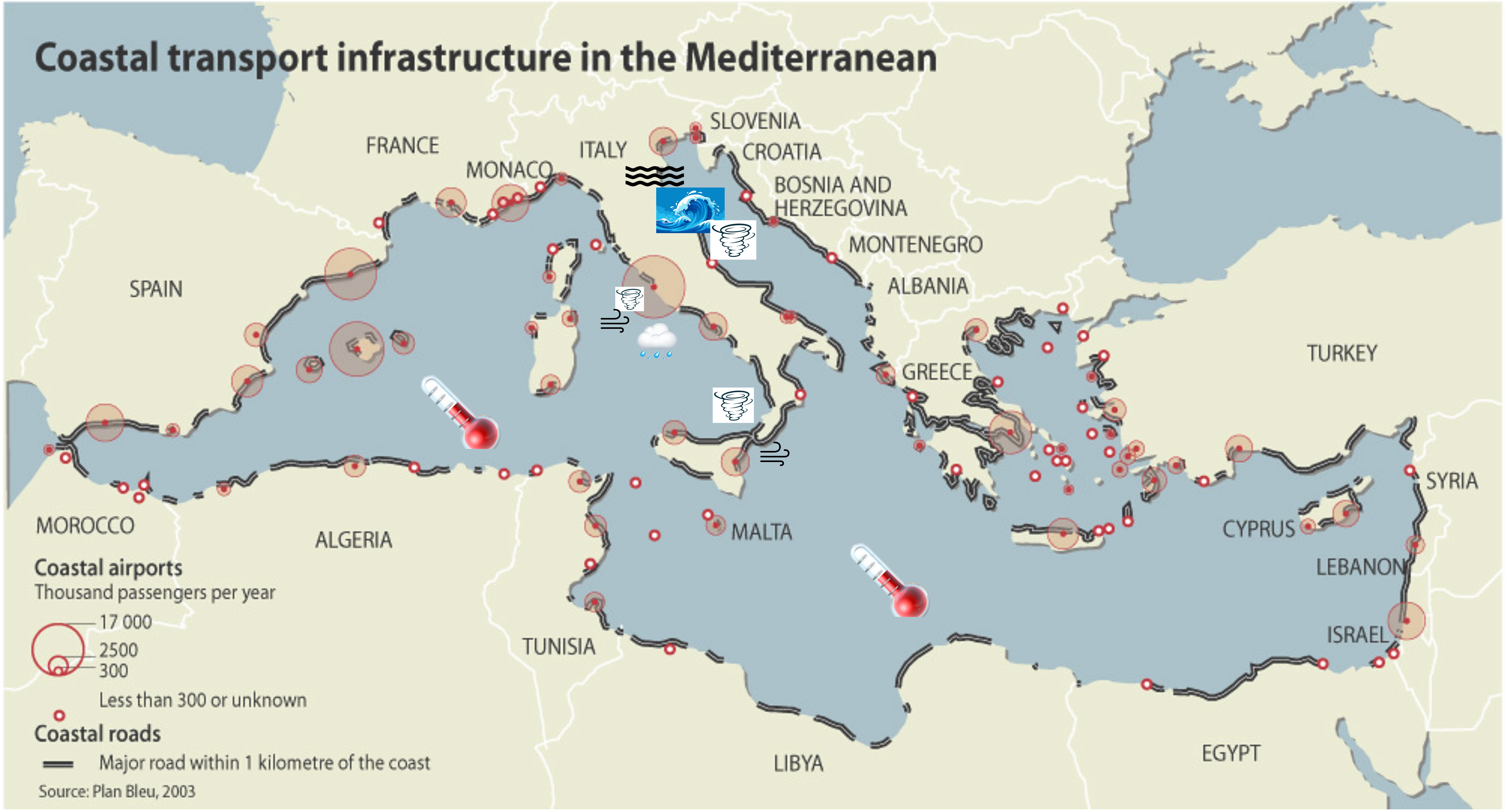

🏗 Implications for Building Practices

- Existing infrastructure and <u>building codes may not account for the increased frequency and intensity of storm surge events due to more frequent cyclones, new events (Medicanes), stronger winds</u>

- There is a need for <u>updated building regulations that consider shorter return periods and incorporate climate change projections</u>.

THANKS FOR THE ATTENTION!

ClimaMeter
Understanding Extreme Weather in a Changing Climate

11

Weather and Climate Extreme Events in a Changing Climate

Coordinating Lead Authors:
Sonia I. Seneviratne (Switzerland), Xuebin Zhang (Canada)

Lead Authors:
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Geophysical Research Letters

RESEARCH LETTER
10.1029/2024GL111618

Impacts of Changing Atmospheric Circulation Patterns on Aviation Turbulence Over Europe

Tommaso Alberti[1], Davide Faranda[2,3,4], Lia Rapella[2,5], Erika Coppola[6], Fabio Lepreti[7], Bérengère Dubrulle[8], and Vincenzo Carbone[7]

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Key Points:
- Changing atmospheric circulation due to climate change increases turbulence over Europe
- Turbulence peaks in winter, linked to wind shears from the subtropical jet stream over the Southern Mediterranean
- Most increasing episodes are related to clear air turbulence, occurring unexpectedly at flight cruise altitudes

scientific reports

Check for updates

OPEN

Dynamical diagnostic of extreme events in Venice lagoon and their mitigation with the MoSE

Tommaso Alberti[1]✉, Marco Anzidei[1,2], Davide Faranda[3,4,5], Antonio Vecchio[6,7], Marco Favaro[8] & Alvise Papa[8]

Weather Clim. Dynam., 5, 959–983, 2024
https://doi.org/10.5194/wcd-5-959-2024

Weather and Climate Dynamics

Open Access

CCP4

Mediterranean Region

Cross-Chapter Paper Leads: Elham Ali (Egypt), Wolfgang Cramer (France)

Cross-Chapter Paper Authors: Jofre Carnicer (Spain), Elena Georgopoulou (Greece), Nathalie Hilmi (Monaco), Gonéri Le Cozannet (France), Piero Lionello (Italy)

Cross-Chapter Paper Contributing Authors: Ahmed Abdelrehim (Egypt), Mine Cinar (USA), Islam Abou El-Magd (Egypt), Shekoofeh Farahmand (Iran), François Gemenne (Belgium), Lena Reimann (Germany), Alain Safa (France), Sergio Vicente-Serrano (Spain), Francesca Spagnuolo (Italy), Duygu Sevgi Sevilgen (Monaco), Samuel Somot (France), Rémi Thiéblemont (France), Cristina Tirado (USA), Yves Tramblay (France)

Cross-Chapter Paper Review Editors: Karim Hilmi (Morocco), Marta Rivera-Ferre (Spain)

Cross-Chapter Paper Scientist: Duygu Sevgi Sevilgen (Monaco)

ClimaMeter: contextualizing extreme weather in a changing climate

Davide Faranda[1,2,3], Gabriele Messori[4,5,6], Erika Coppola[7], Tommaso Alberti[8], Mathieu Vrac[1], Flavio Pons[1], Pascal Yiou[1], Marion Saint Lu[1], Andreia N. S. Hisi[1,11], Patrick Brockmann[1], Stavros Dafis[9,10], Gianmarco Mengaldo[12,13], and Robert Vautard[1]

npj | climate and atmospheric science

www.nature.com/npjclimatsci

ARTICLE OPEN

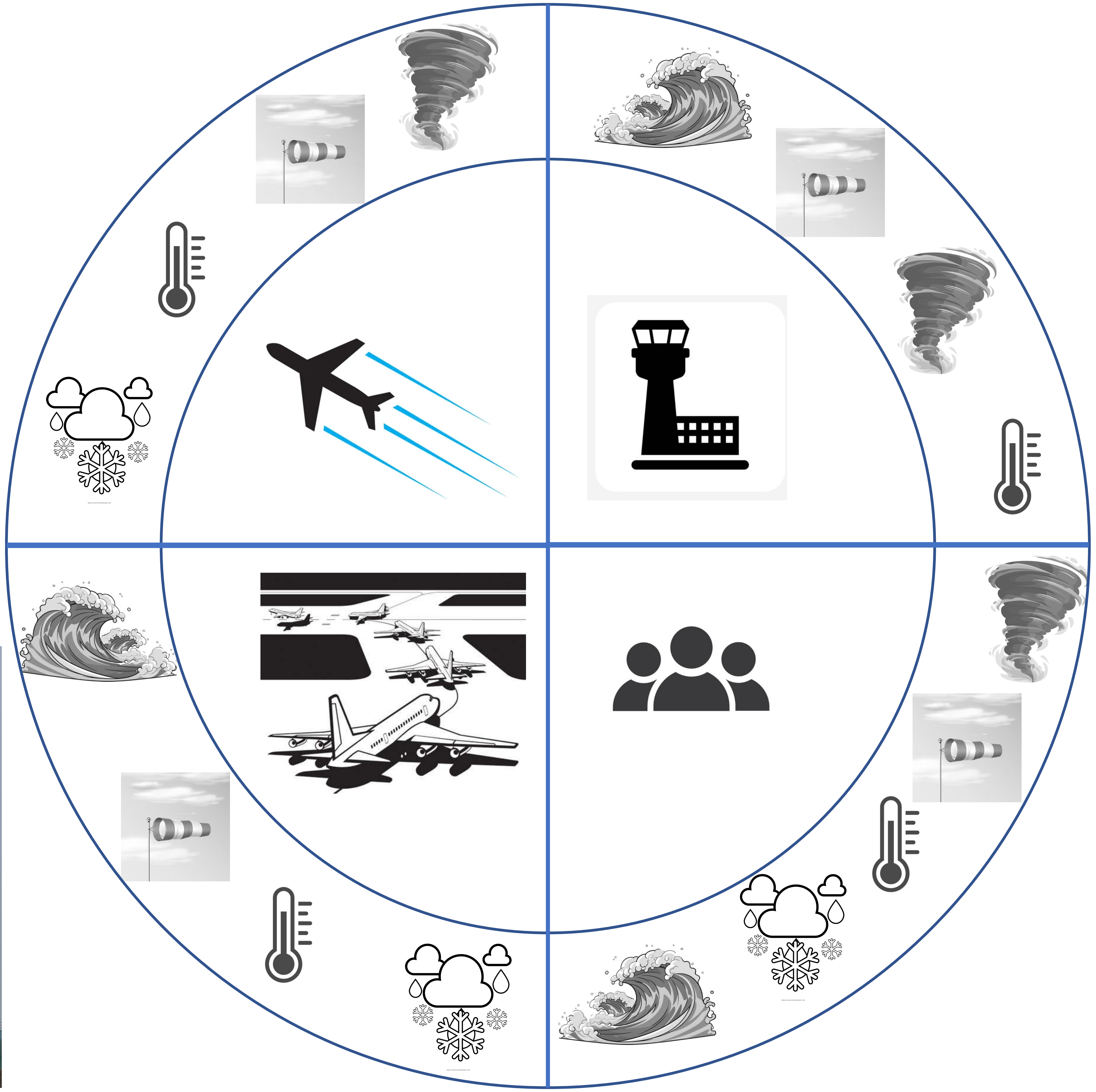
Check for updates

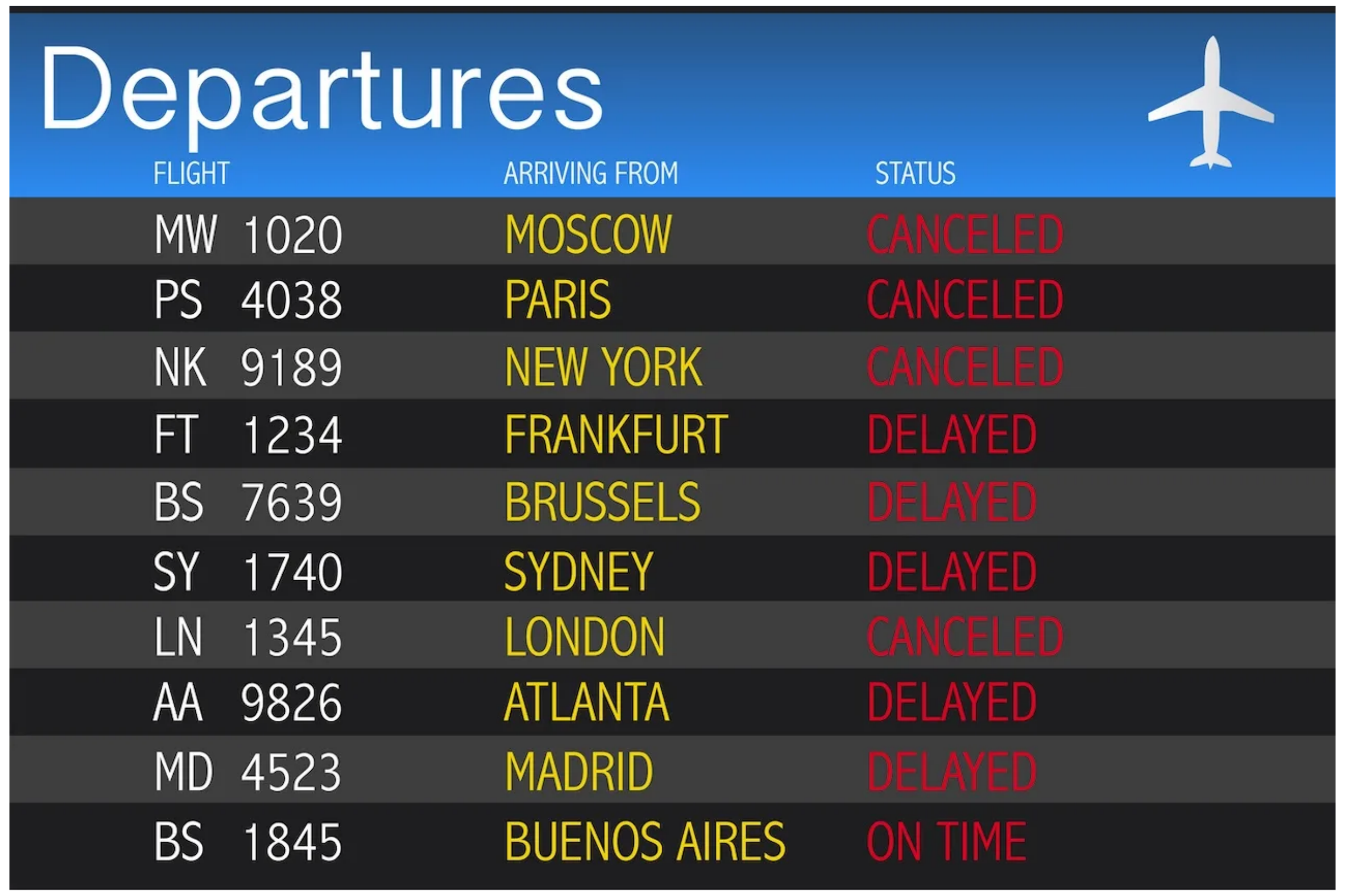
Attributing Venice Acqua Alta events to a changing climate and evaluating the efficacy of MoSE adaptation strategy

Davide Faranda[1,2,3]✉, Mireia Ginesta[1], Tommaso Alberti[4], Erika Coppola[5] and Marco Anzidei[4]

Back-up slides

CLIMATE CHANGE IMPACTS ON AVIATION





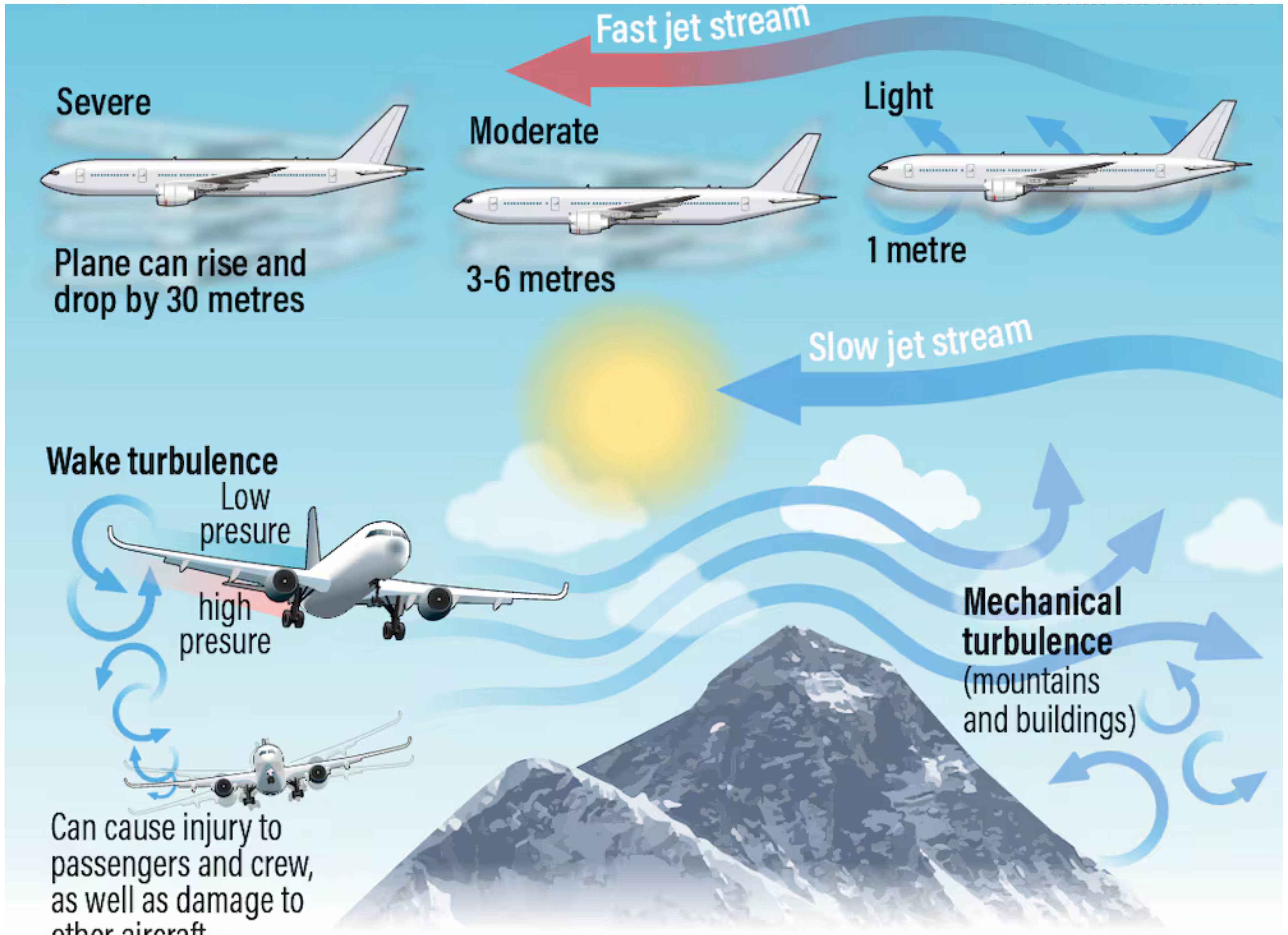
LETTERS
PUBLISHED ONLINE: 8 APRIL 2013 | DOI:10.1038/NCLIMATE1866
nature climate change

Intensification of winter transatlantic aviation turbulence in response to climate change

Paul D. Williams[1]* and Manoj M. Joshi[2]

This first 2013 study, opened the way for understanding how turbulence is affected by climate change

Warmer surface
⇒ increased energy and thermal gradients
⇒ wind shears
⇒ more turbulence (especially CAT)



Graphic: Roy Cooper, The National

Geophysical Research Letters
RESEARCH LETTER
10.1029/2023GL103814

Key Points:

Evidence for Large Increases in Clear-Air Turbulence Over the Past Four Decades

Mark C. Prosser[1], Paul D. Williams[1], Graeme J. Marlton[2], and R. Giles Harrison[1]

Geophysical Research Letters
RESEARCH LETTER
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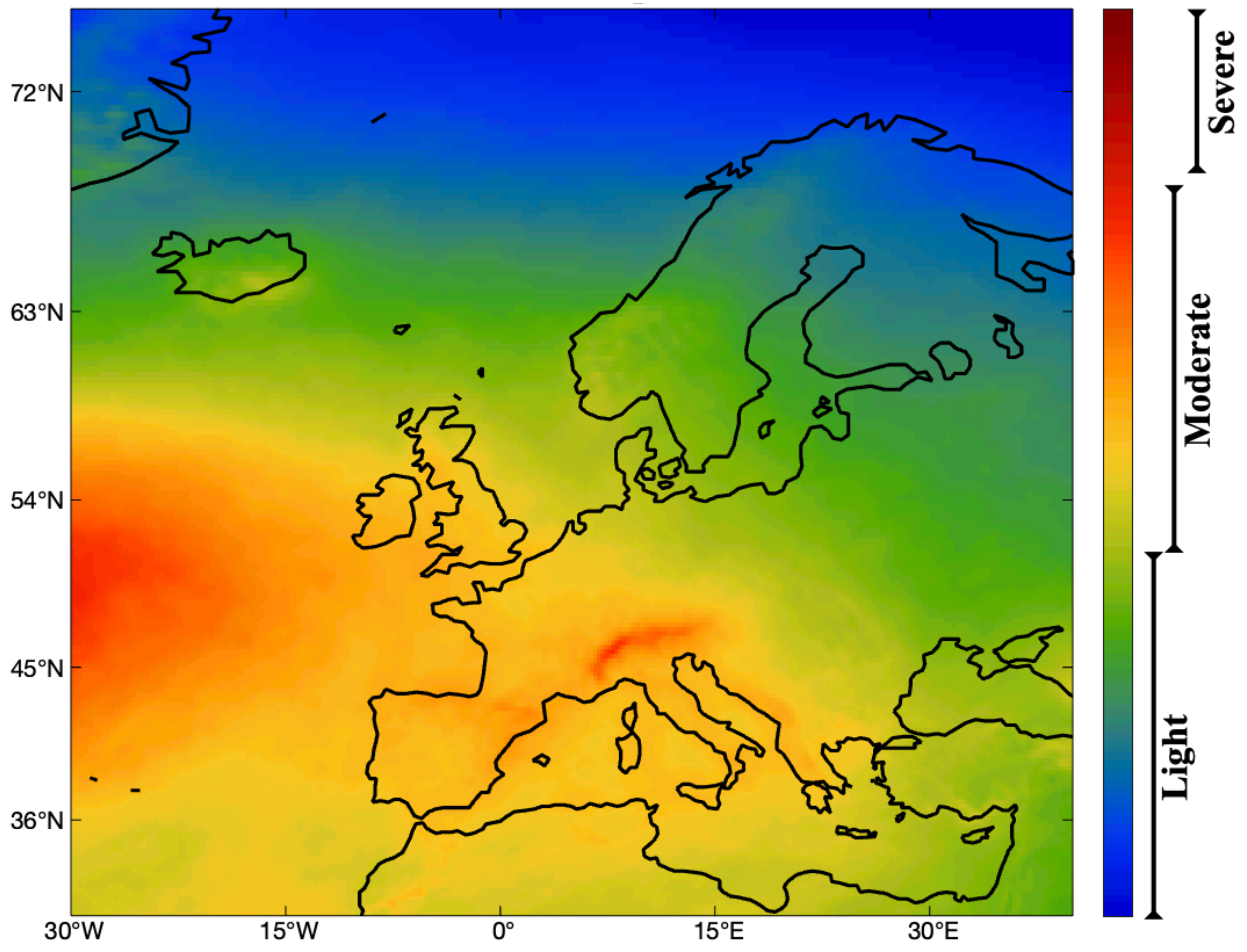
ATTRIBUTION RESULTS
Moderate-or-greater (MOG) turbulence

Typical patterns unchanged under climate change



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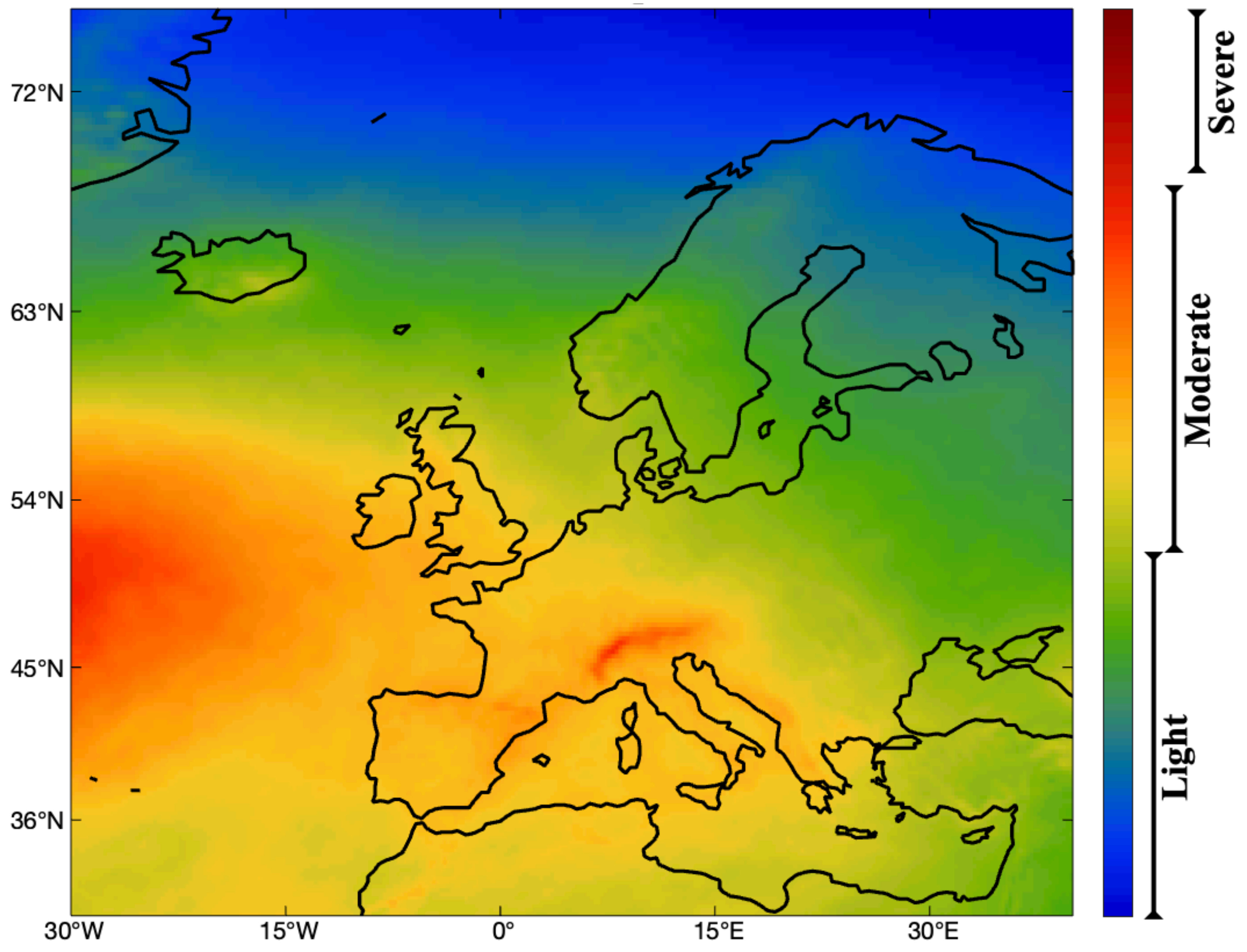
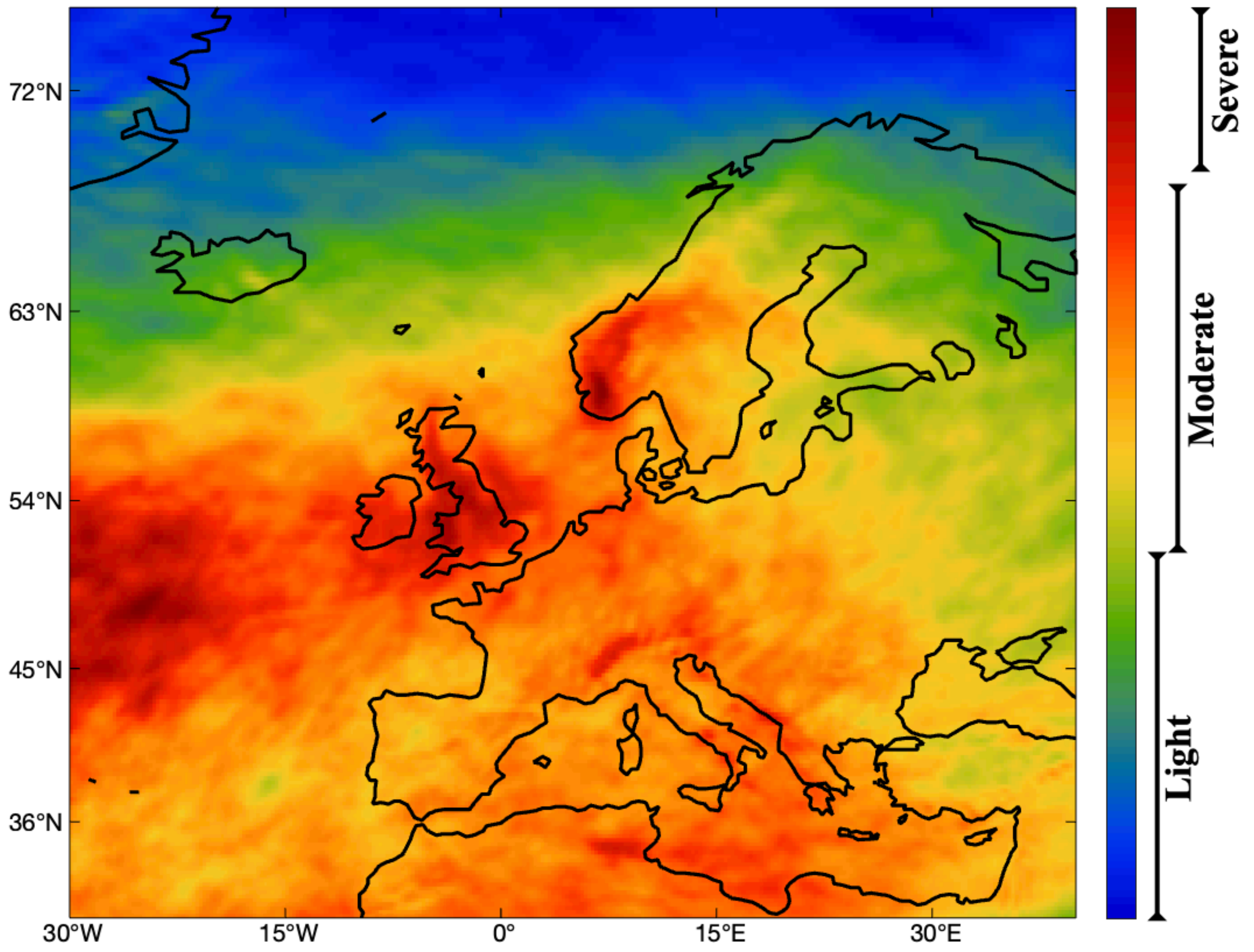
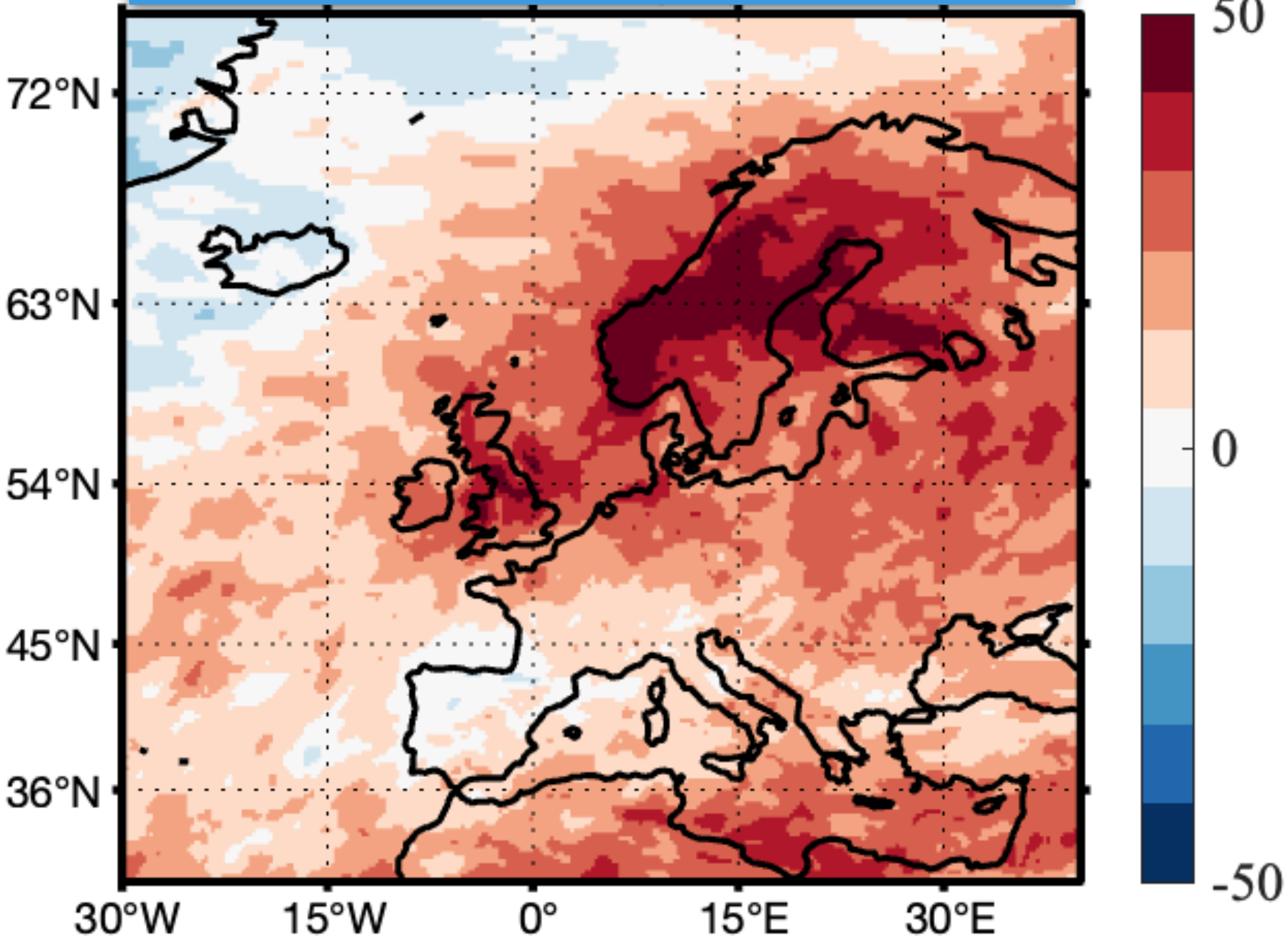


Most-frequent patterns changing under climate change



ATTRIBUTION RESULTS
Moderate-or-greater (MOG) turbulence

Increases up to 50% within Europe!



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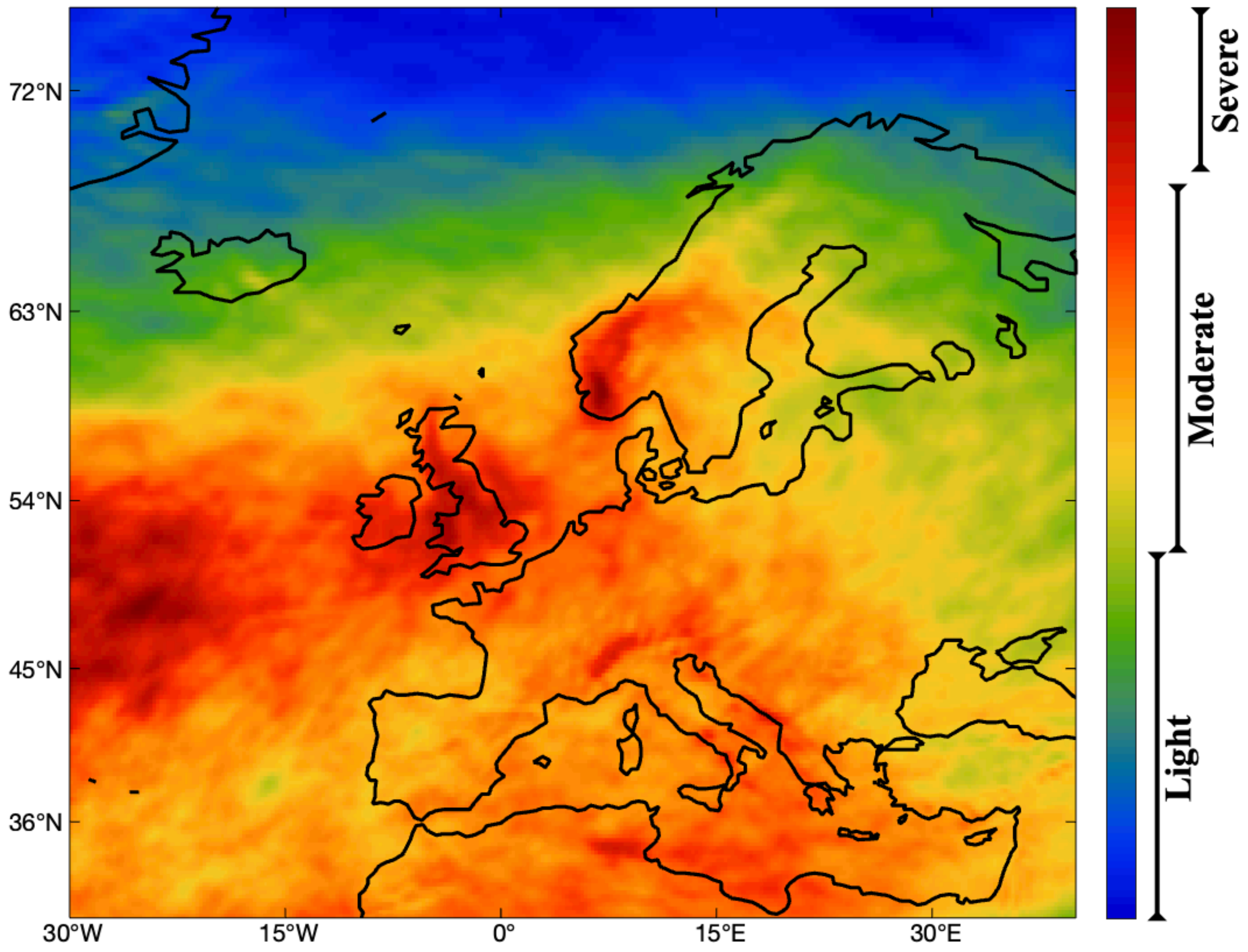
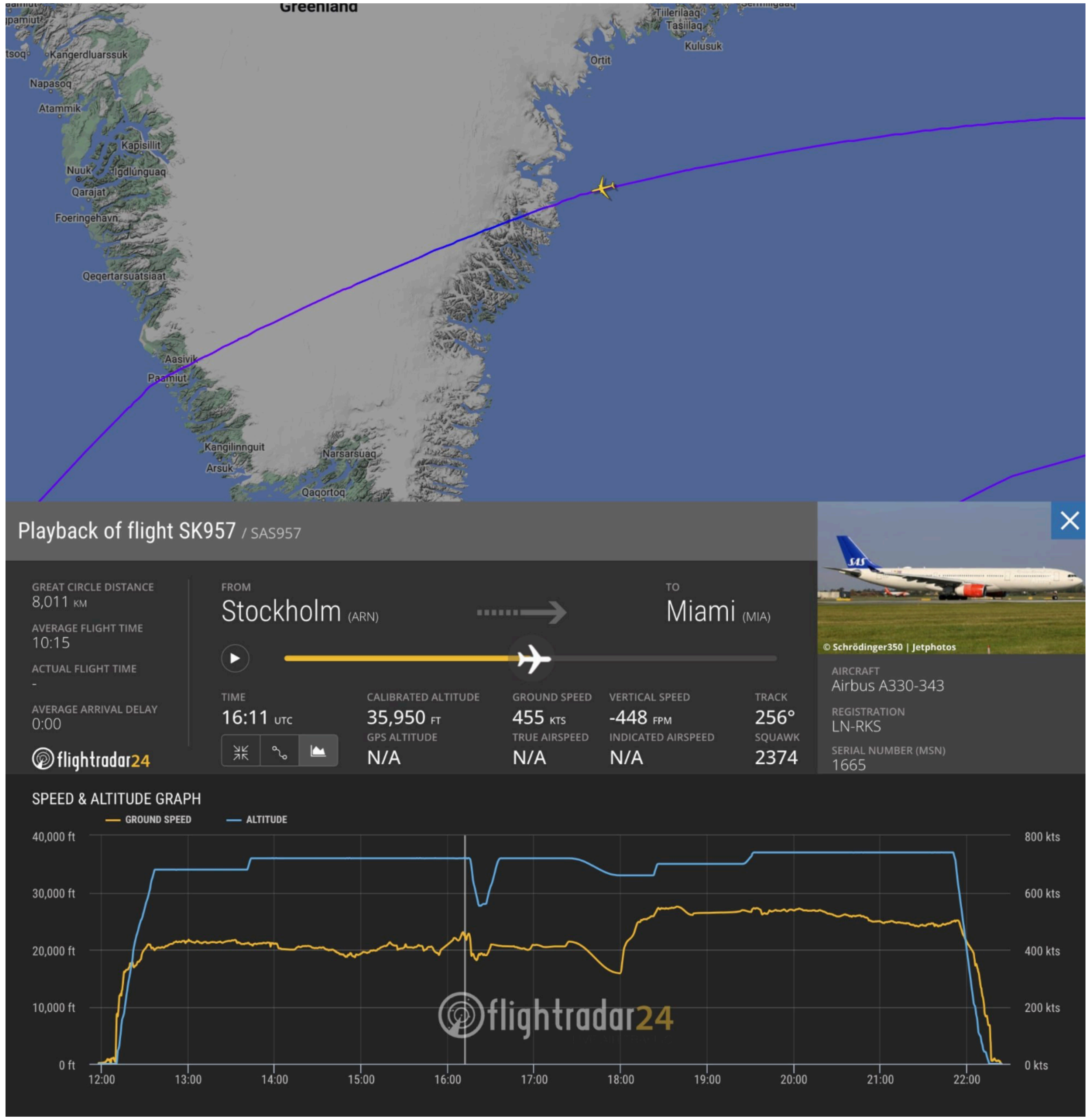


SCANDINAVIAN AIRLINES FLIGHT SAS957

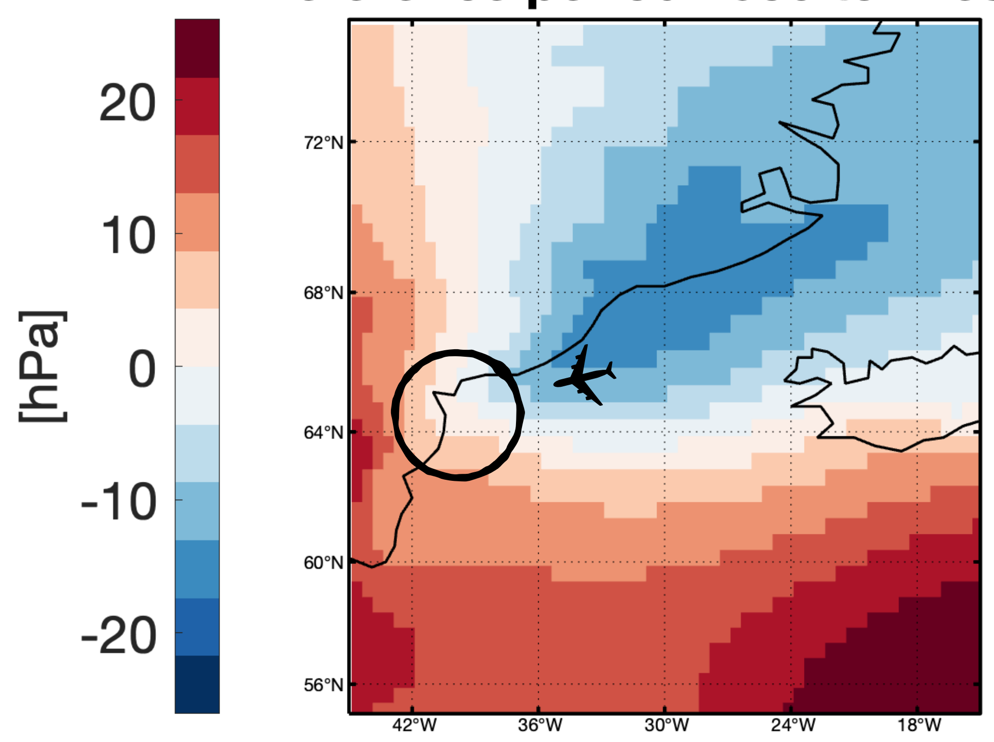
CNN travel | Destinations | Food & Drink | News | Stay | Video

Severe turbulence forces Scandinavian Airlines flight to return to Europe, airline says



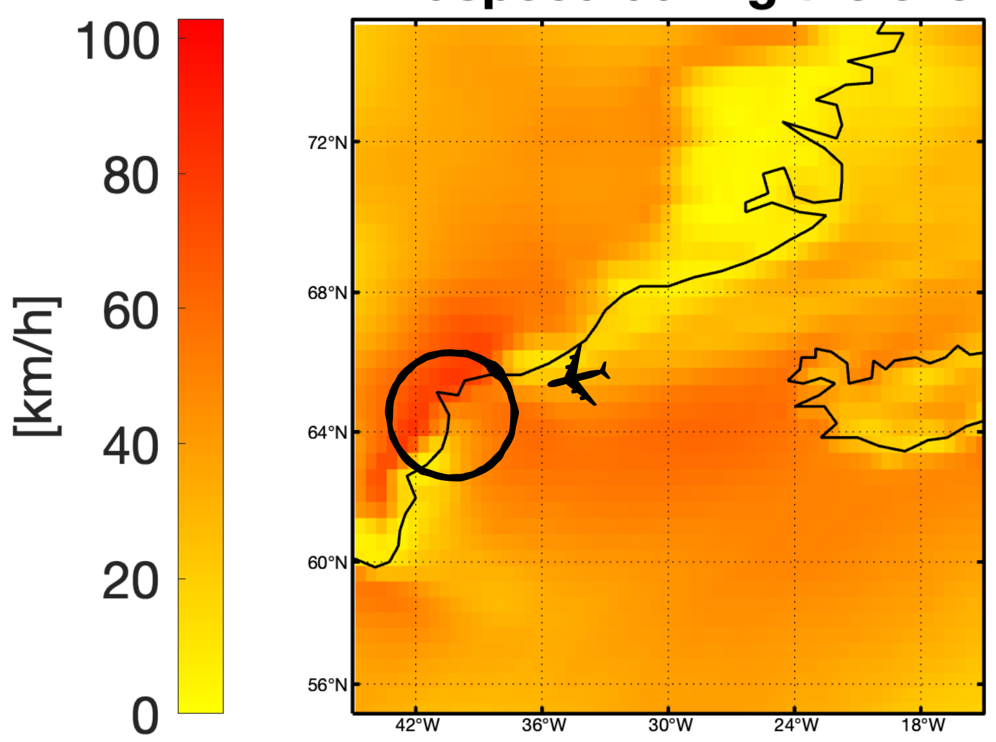
Surface Pressure Anomalies

Reference period:1950 to Present



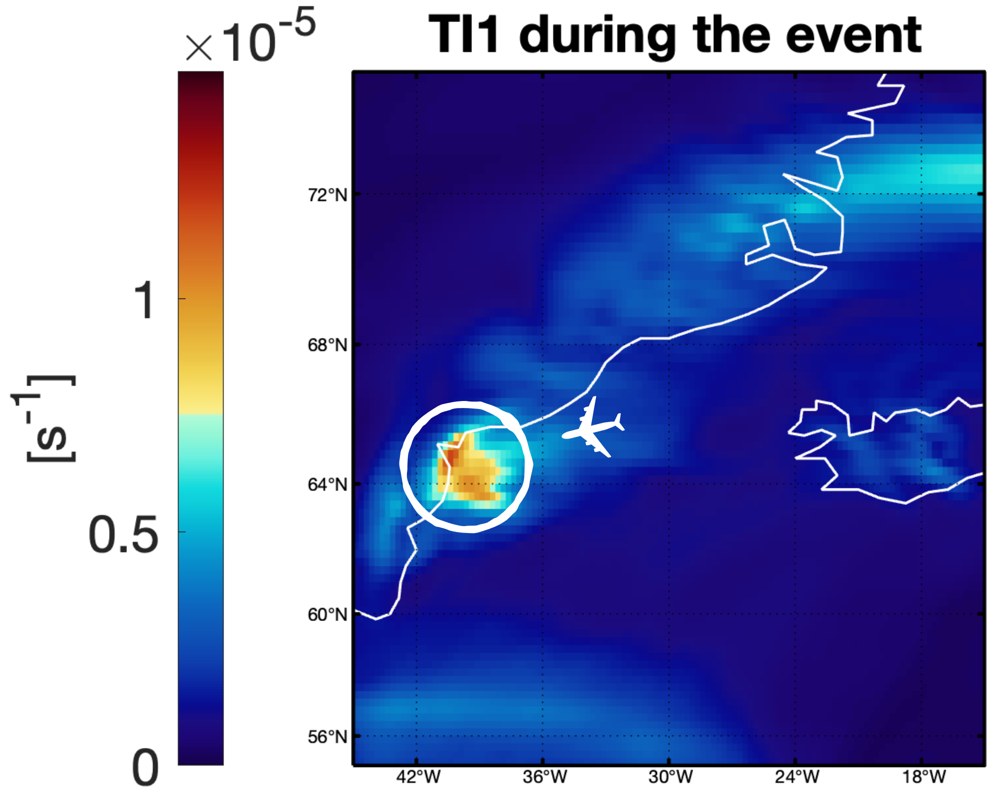
Windspeed Data

Windspeed during the event



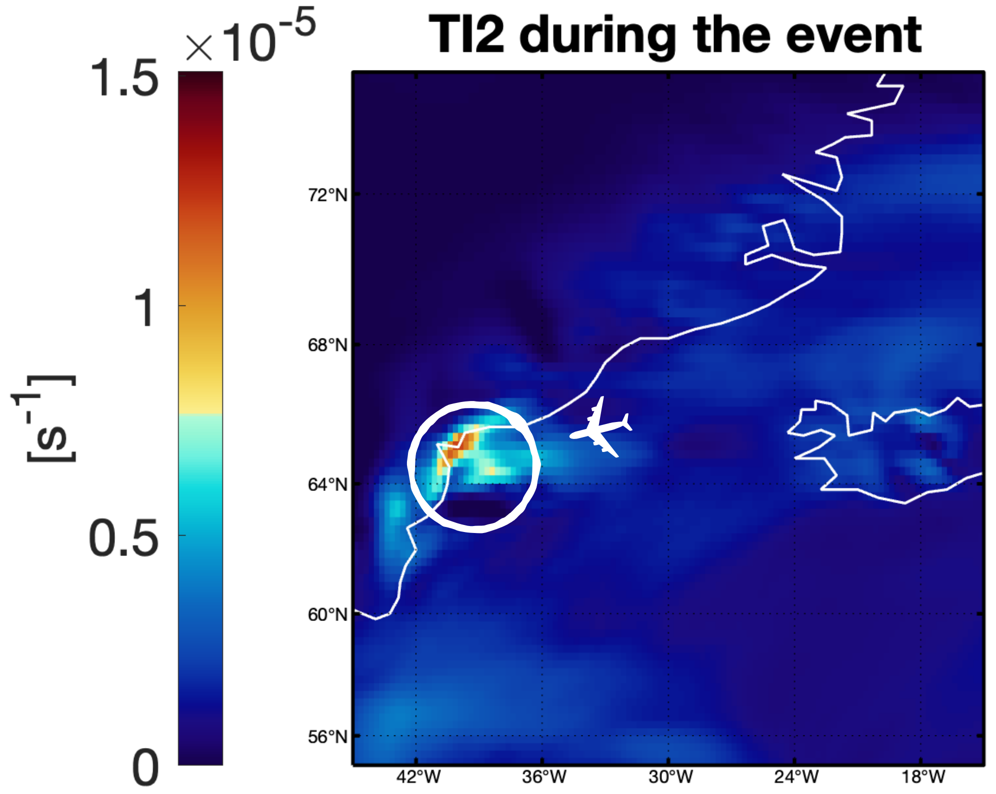
Ellrod index TI1

TI1 during the event



Ellrod index TI2

TI2 during the event



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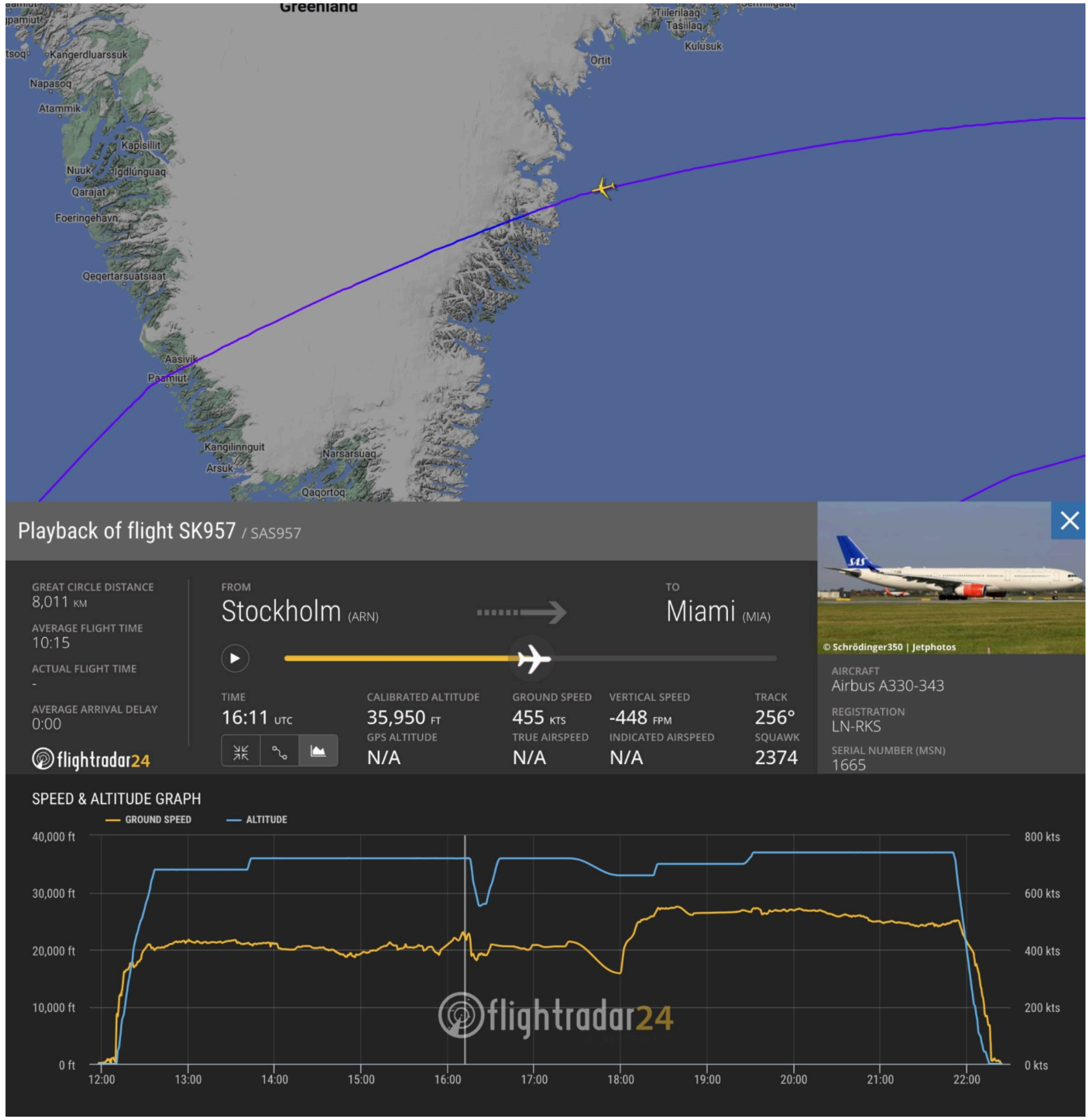
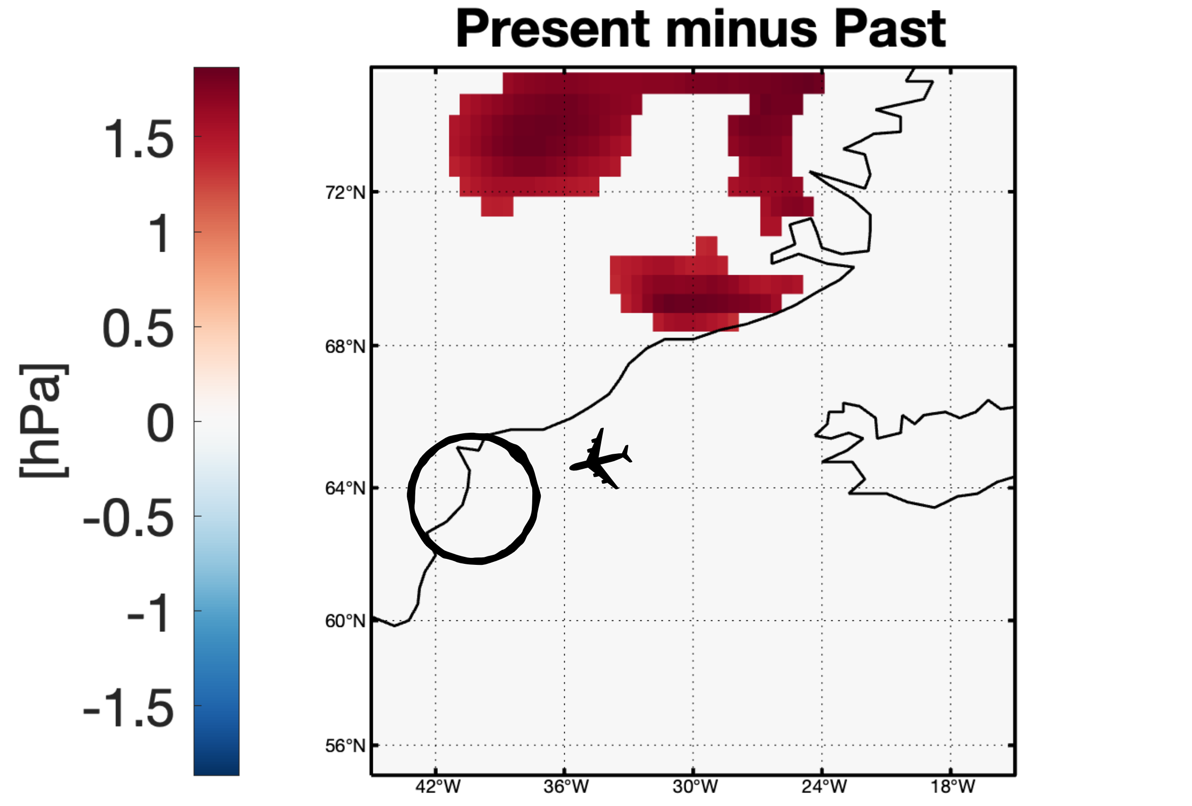
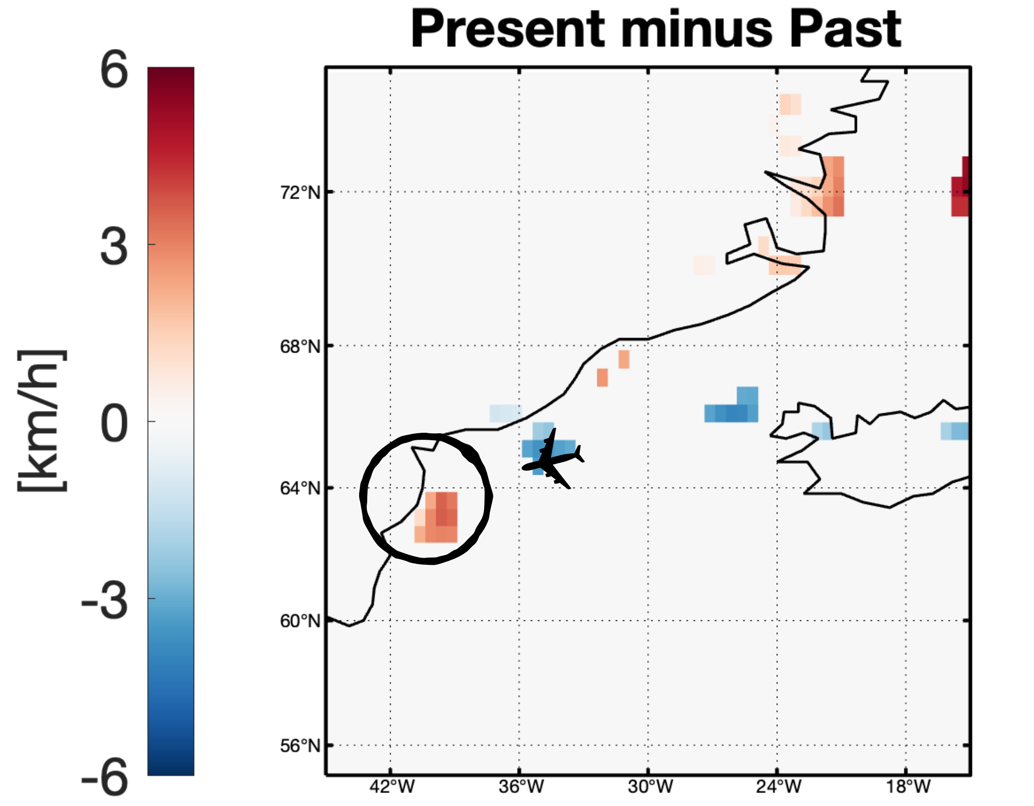


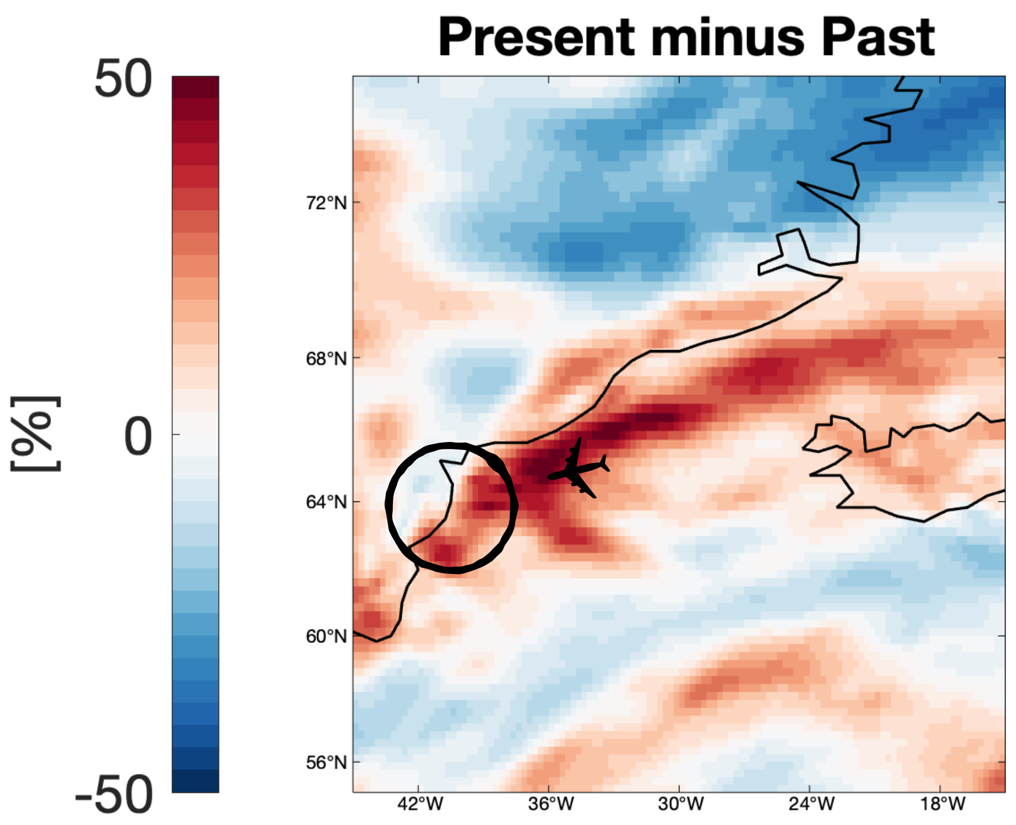
Surface Pressure Changes



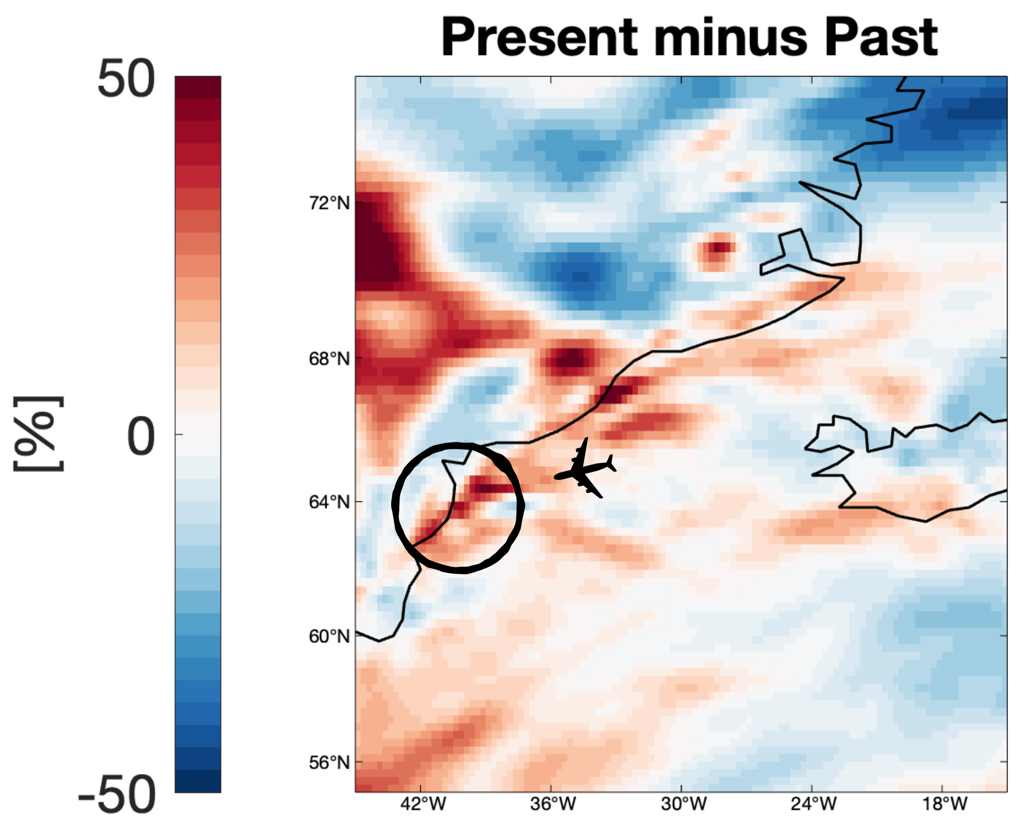
Windspeed Changes



TI1 Changes

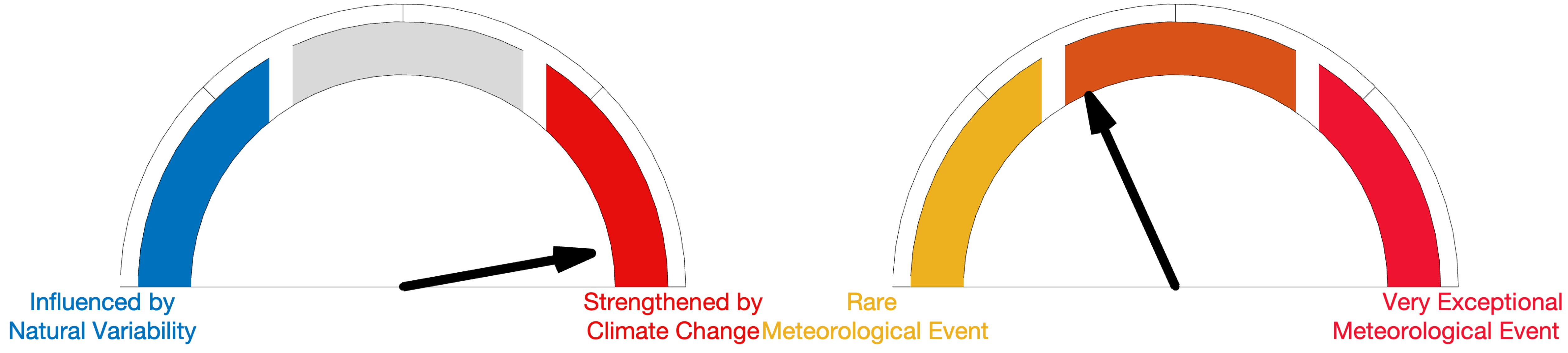


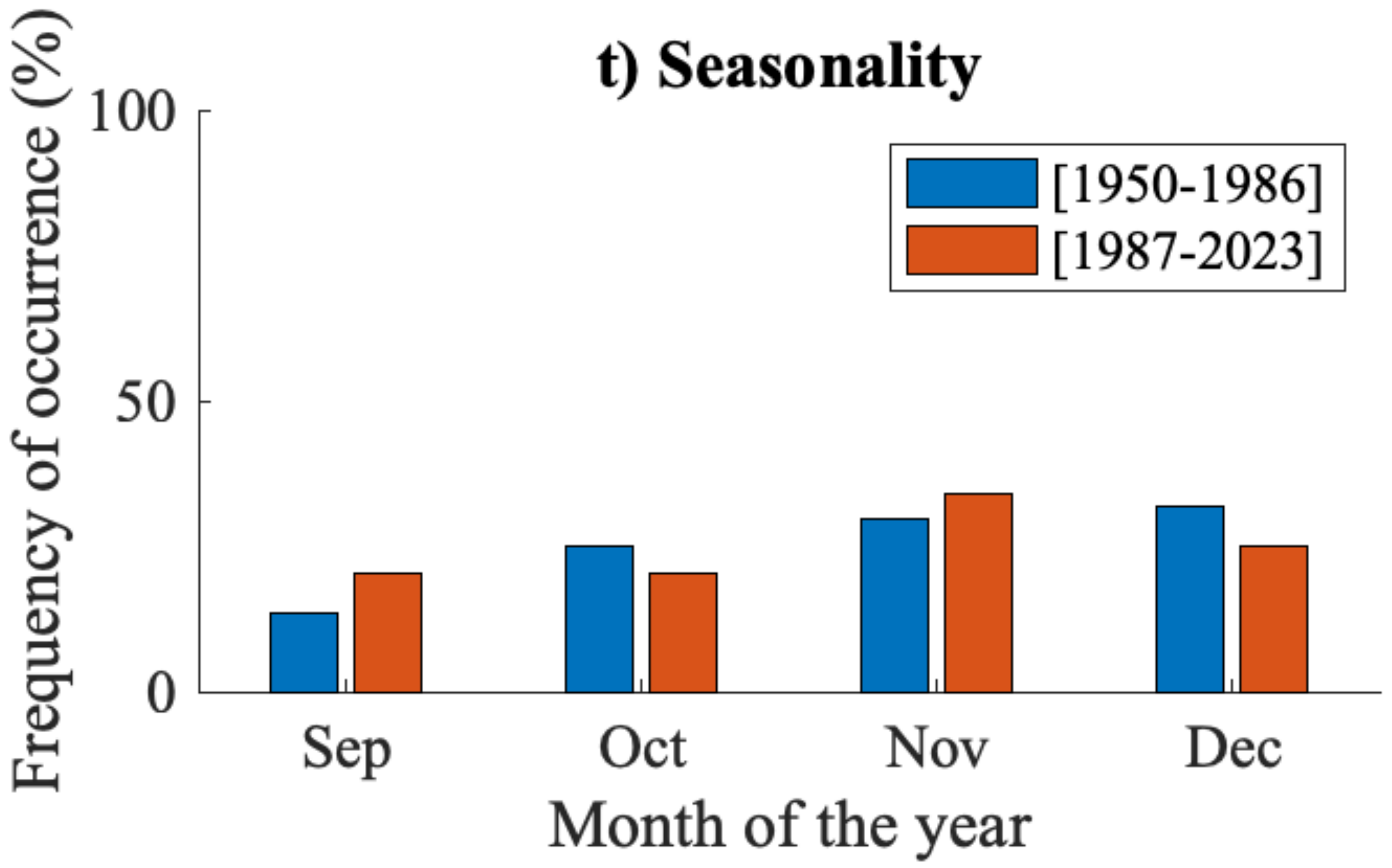
TI2 Changes



SCANDINAVIAN AIRLINES FLIGHT SAS957

TurboMeter for SAS957
14-Nov-2024





- Turbulence on SAS957 was <u>mostly increased by anthropogenic climate change</u>
- <u>Natural variability alone cannot explain the increase</u> in turbulence on SAS957
- This turbulence event was triggered by <u>exceptional meteorological conditions</u>

NOT ONLY IN VENICE…
Fiumicino Airport

- **"Leonardo da Vinci" International Airport (Fiumicino)**, located near the Tyrrhenian coast, at an altitude of less than 1 m above sea level.
- **Size:** Covers an area of 29 km²; it is the largest airport in Italy and the third largest in Europe.
- **Passenger traffic:** 49.2 million passengers in 2024.
- **Connections:** Served by over 100 airlines, connecting around 200 destinations in more than 70 countries.
- **Potentially flooded area by 2150:** approximately 62 km².
- **Land at risk:** Represents about 51% of the land below 4 m a.s.l., totaling around 122 km².
- **Buildings at risk:** Around 19,500 buildings with a surface area greater than 20 m² potentially affected within the expected flood area.