Turbulence, Aviation and Climate Change

Davide Faranda

Tommaso Alberti, Davide Faranda, Lia Rapella, Erika Coppola, Fabio Lepreti, Bérengère Dubrulle, Vincenzo Carbone

Presentation prepared with the help of Tommaso Alberti

Please Fasten your Seat-Belt! We will departly shortly

1. 🛬 **Turbulence Overview**
2. ✈️ **From Reynolds to Wright, why can we fly?**
3. 🍱 **Meal Service (Break and Game)**
4. ⛈️ **Meteorology and Climate Change**
5. 🛬 **Climate change for Aviation Turbulence**

Questions from Students will have SkyPriority for all the lecture!

The Navier Stokes equations

The **Navier-Stokes equation** for an incompressible Newtonian fluid is:

$$\rho \left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = -\nabla p + \mu \nabla^2 \mathbf{u} + \mathbf{F}$$

where:

- ρ is the fluid density,
- $\mathbf{u}$ is the velocity field,
- p is the pressure,
- μ is the dynamic viscosity,
- $\nu = \frac{\mu}{\rho}$ is the kinematic viscosity,
- $\mathbf{F}$ represents external forces.

The Terms in the Navier Stokes equations

The **Navier-Stokes equation** for an incompressible Newtonian fluid is:

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t}+\mathbf{u}\cdot\nabla\mathbf{u}\right)=-\nabla p+\mu\nabla^2\mathbf{u}+\mathbf{F}$$

From this equation, we identify:

1. **Inertial forces** (from the left-hand side):

$$F_{\text{inertial}}\sim\rho U^2/L$$

where:

- U is a characteristic velocity,
- L is a characteristic length scale.

2. **Viscous forces** (from the diffusion term $\mu\nabla^2\mathbf{u}$):

$$F_{\text{viscous}}\sim\mu U/L^2$$

The Reynolds number

The Reynolds number is obtained by taking the ratio of inertial forces to viscous forces:

$$\frac{F_{\text{inertial}}}{F_{\text{viscous}}} = \frac{\rho U^2 / L}{\mu U / L^2}$$

Simplifying:

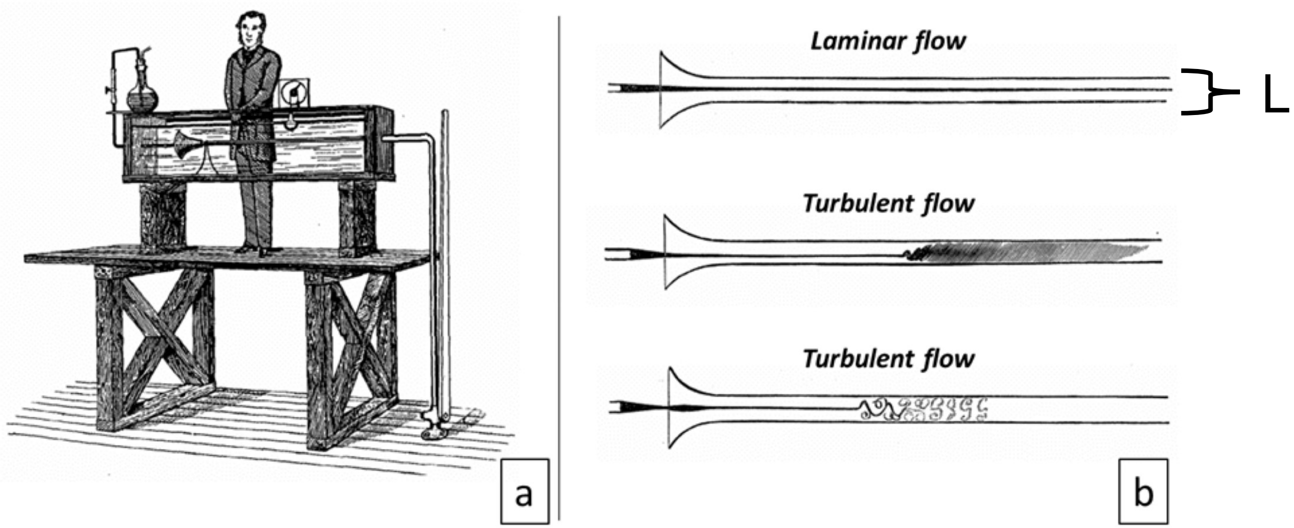
$$Re = \frac{\rho U L}{\mu} = \frac{U L}{\nu}$$

- Re is the **Reynolds number**,
- $\nu = \frac{\mu}{\rho}$ is the **kinematic viscosity**.

.

- If $Re \gg 1$, **inertial forces dominate** over viscous forces, leading to turbulent or nearly inviscid flow.
- If $Re \ll 1$, **viscous forces dominate**, leading to laminar or creeping flow (e.g., Stokes flow in very viscous fluids).

Turbulence in fluids, the first key observation by Reynolds (1883)



For Low Reynolds Numbers (Re < 2000):

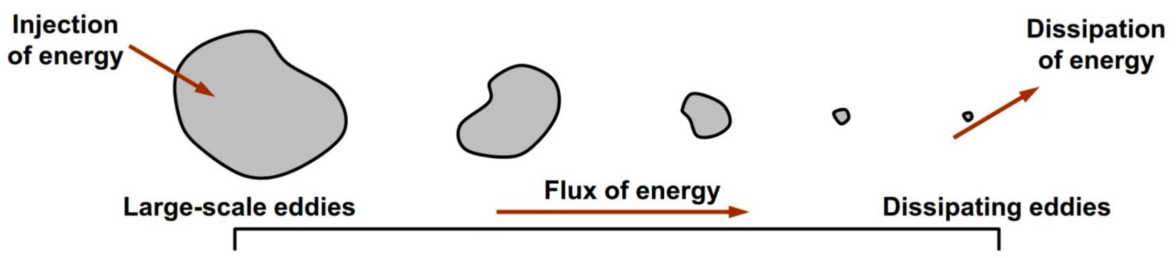
- **Laminar flow** dominates, where fluid moves in smooth, parallel layers with minimal mixing.

For High Reynolds Numbers (Re > 4000):

- **Turbulent flow** occurs, where the flow becor chaotic with eddies, vortices, and complex patterns of motion.

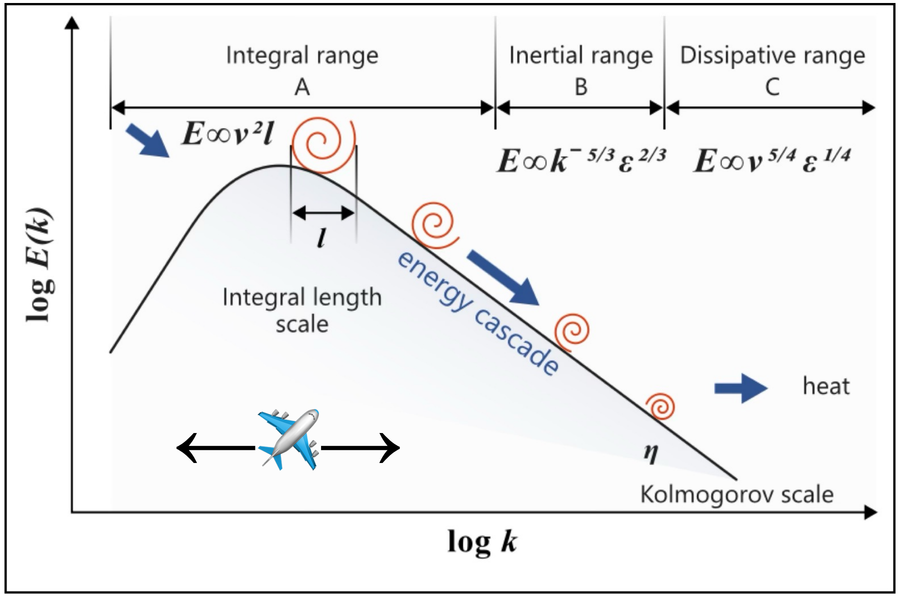
From Reynolds (1883) to Lewis Fry Richardson (1922)

- **Small Length Scales (Small L):**
  When the characteristic length L is small (e.g., small pipes, narrow channels), viscous forces dominate because the ratio between inertial forces and viscous forces (Re) is low. This results in **laminar flow** where the fluid moves in smooth, orderly layers.
- **Large Length Scales (Large L):**
  As the characteristic length L increases (e.g., large pipes, wings of an aircraft), the inertial forces become more significant. At higher Reynolds numbers (Re), inertial forces dominate over viscosity, and the flow becomes **turbulent**. The larger the system, the more likely it is that the flow will become turbulent, as the inertial forces can lead to chaotic fluid motion.



The Kolmogorov Cascades

- **Kolmogorov's Self-Similarity Assumption**:
  - In the inertial range, the **velocity fluctuations** $\delta u(\ell)$ across a length scale ℓ behave similarly, regardless of the actual scale.
  - The distribution of energy across different scales follows a **universal form**.



The Kolmogorov Cascades

- The **energy spectrum** $E(k)$ describes how the turbulent energy is distributed across different wave numbers (scales). In the inertial range, the spectrum follows a **power law** given by Kolmogorov's theory:

$$E(k) = C_{\varepsilon}\varepsilon^{2/3}k^{-5/3}$$

  Where:

  - $E(k)$ is the energy per unit wave number k.
  - C_{ε} is a constant
  - k is the wave number (related to the inverse of the length scale).

- The **Kolmogorov 5/3 Law**:
  - Kolmogorov showed that in the **inertial range**, the energy spectrum follows a **power law** with an exponent of **-5/3**.
  - This means that the energy decreases as the wave number increases, and larger scales carry more energy.

The Eddy dissipation rate

- The **EDR** ε is related to the **energy spectrum** $E(k)$ of the turbulence in the **inertial range**. According to Kolmogorov, the energy spectrum $E(k)$ follows the **5/3 law**:

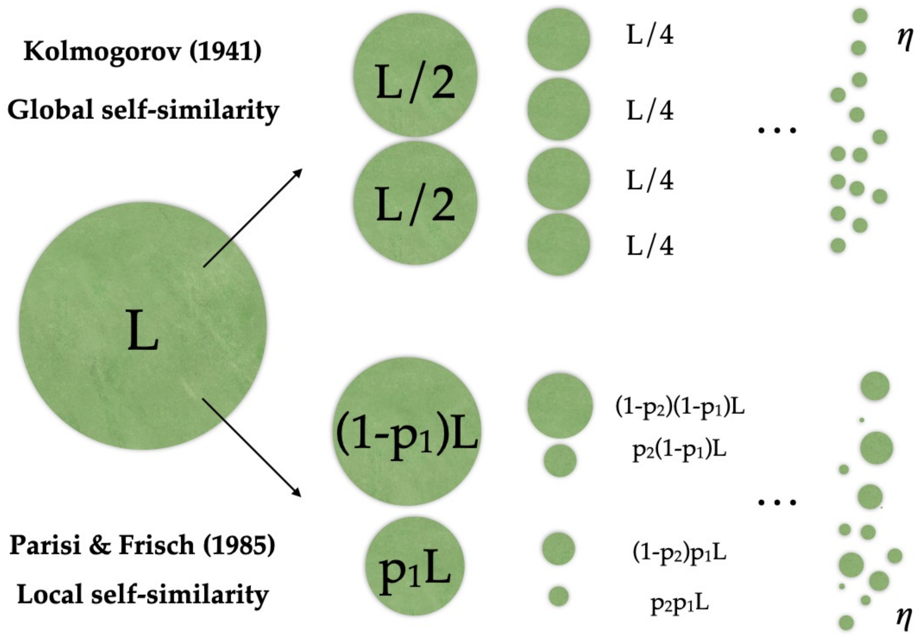
  $$E(k) \sim \varepsilon^{2/3} k^{-5/3}$$

  Where:

  - k is the wave number (related to the length scale).
  - ε is the energy dissipation rate.

- The EDR is directly proportional to the energy that is dissipated per unit mass and per unit time. At the **Kolmogorov scale**, the energy from larger eddies is transferred and eventually dissipated by viscosity, where the dissipation rate ε provides a measure of this energy loss.

From Kolmogorov to Parisi & Frisch (1985)



3. **The amount of energy** from the mothers eddies to the daughters **must be preserved**

$$\varepsilon_L = \varepsilon_r = \frac{\Delta v_r^3}{r} = \varepsilon_\eta$$

EDDY DISSIPATION RATE

$$\text{EDR} = \varepsilon_\ell^{1/3} = \left(\frac{\Delta v_\ell^3}{\ell}\right)^{1/3}$$

3. **The amount of energy** from the mothers eddies to the daughters **is not preserved**

$$\varepsilon_L \neq \varepsilon_r \neq \frac{\Delta v_r^3}{r} \neq \varepsilon_\eta$$

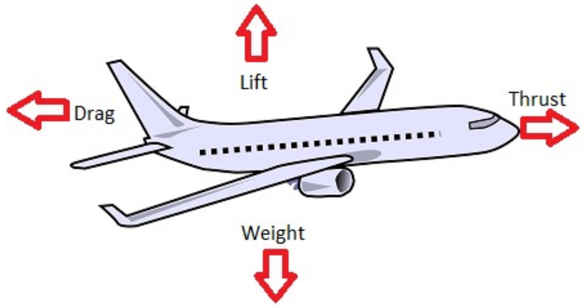
Frisch & Parisi refined the Kolmogorov hypothesis from global self-similarity to local self-similarity

=> EDR is not a constant

From Reynolds to Wright Brothers 1903 First Flight

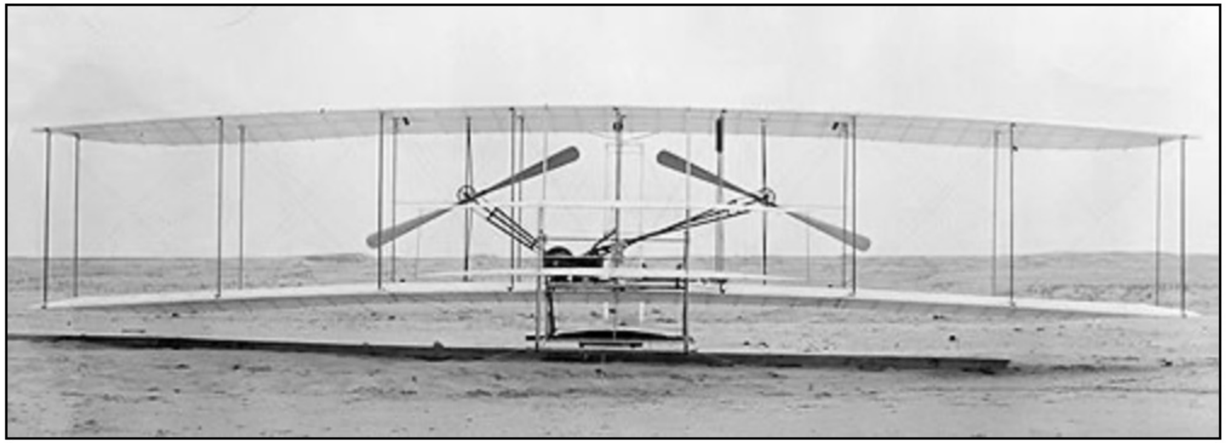
There are four main forces involved in flight:

- **Lift** (L): The upward force that counteracts weight.
- **Weight** (W): The downward force due to gravity.
- **Thrust** (T): The forward force provided by the engines.
- **Drag** (D): The resistance force opposing motion.



For stable flight:

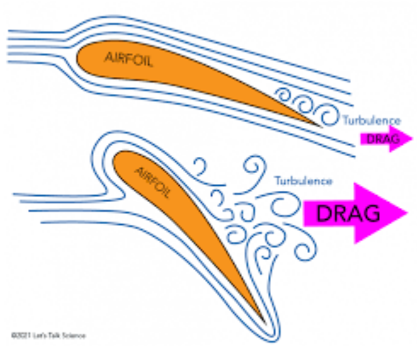
$$L = W \quad \text{and} \quad T = D$$



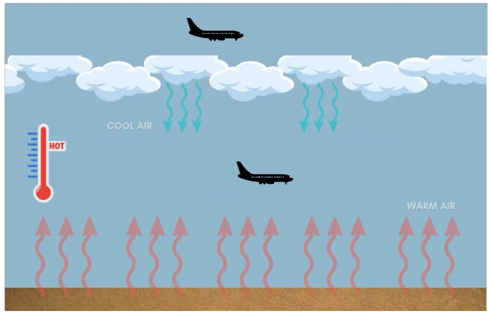
Wright flyer, 1903

How Turbulence affect Flights?

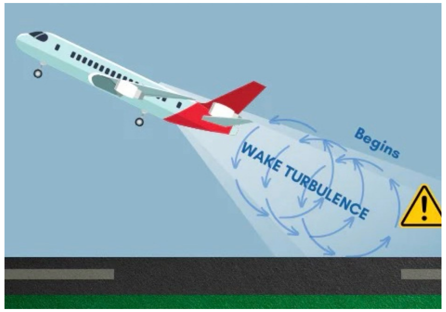
- **Lift** is generated by the pressure difference between the top and bottom surfaces of the wing, governed by **Bernoulli's principle** and **Newton's third law**.
- **Turbulence** can decrease **lift** and increase **drag**, especially through **flow separation** and **wake turbulence**.
- **Drag** increases due to **turbulent boundary layers** and **viscous effects**.
- **Aircraft stability** is affected by **turbulent air** conditions, requiring careful management by pilots to avoid **stall** and maintain smooth flight.



Thermal Turbulence

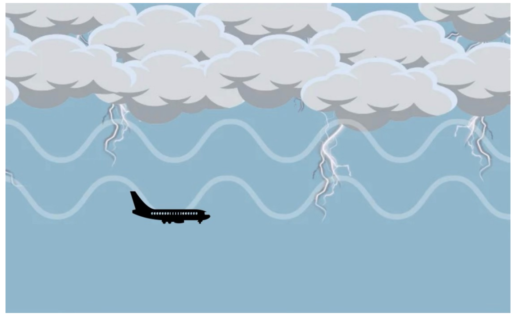


Wake Turbulence



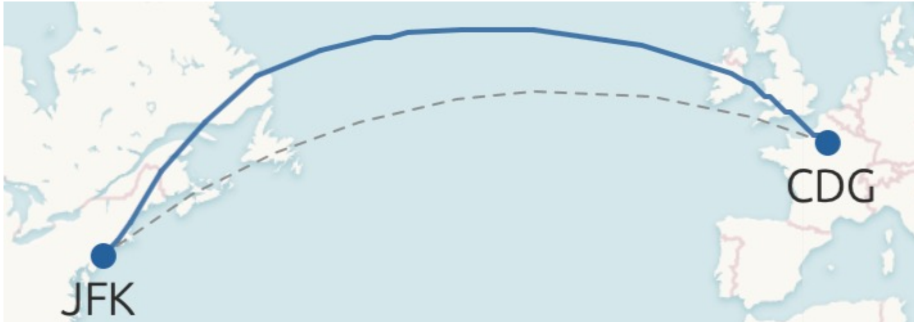
Clear Air Turbulence

Thundestorms



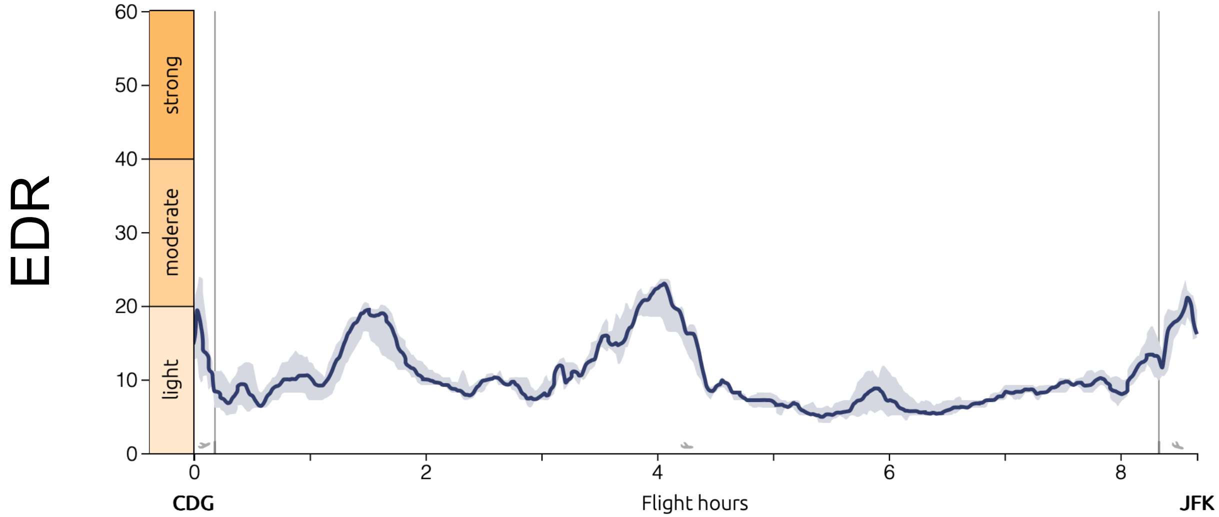
How do we quantify turbulence during flights?

- **EDR** measures energy loss in turbulence (heat dissipation).
- **Turbulent flow** increases **drag** and reduces **lift**.
- **EDR** helps calculate **induced drag** and **flow separation**.
- High **EDR** = higher drag, less efficient flight.



EDDY DISSIPATION RATE

$$\mathrm{EDR} = \varepsilon_\ell^{1/3} = \left(\frac{\Delta v_\ell^3}{\ell}\right)^{1/3}$$



Turbli.com for Paris (CDG) - New York (JFK)
Flight AF 8 16:30 - 19:10 09/02/2025

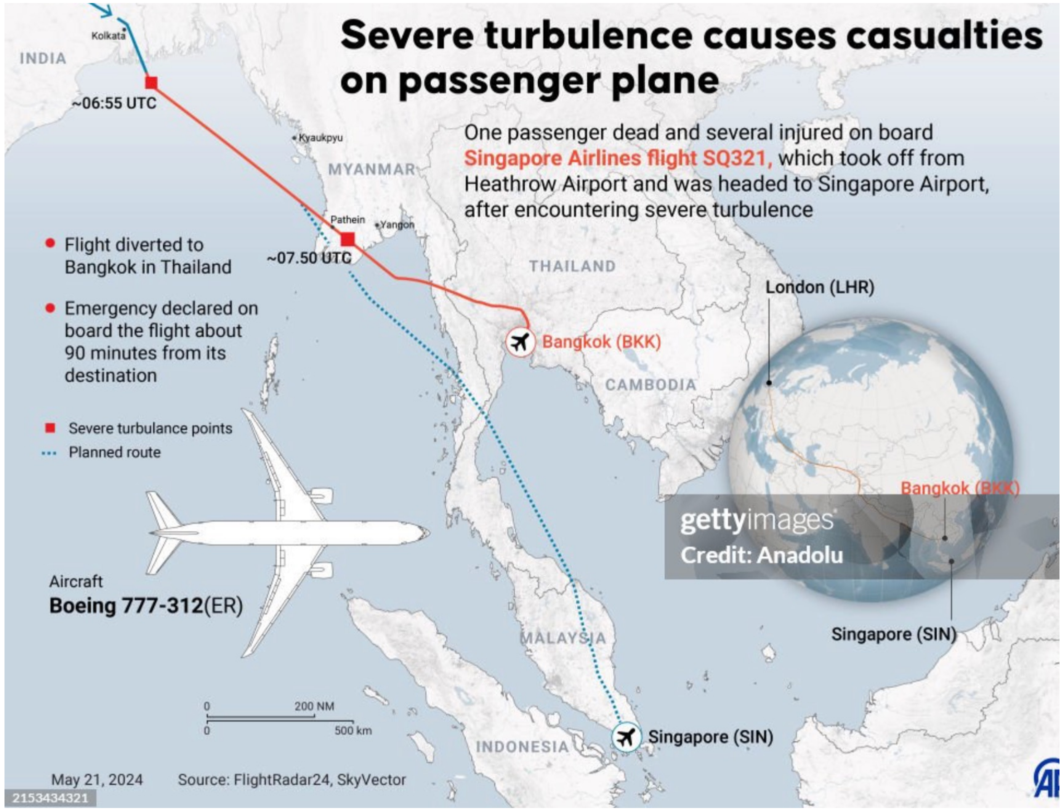
Plane Turbulence, is the worst yest to come?

•In US , **turbulence-related incidents cost the aviation industry up to $500 million** annually.

•These costs stem from increased aircraft wear and tear, passenger and crew injuries, and flight delays.

•Turbulences lead **to higher fuel consumption and increased CO_2 emissions.**

•In 2022, global **air travel emitted over 780 million tons of CO_2, accounting for about 2% of global energy-related CO_2 emissions.**



Is Climate Change to blame for increased turbulence?

LETTERS

PUBLISHED ONLINE: 8 APRIL 2013 | DOI: 10.1038/NCLIMATE1866

nature climate change

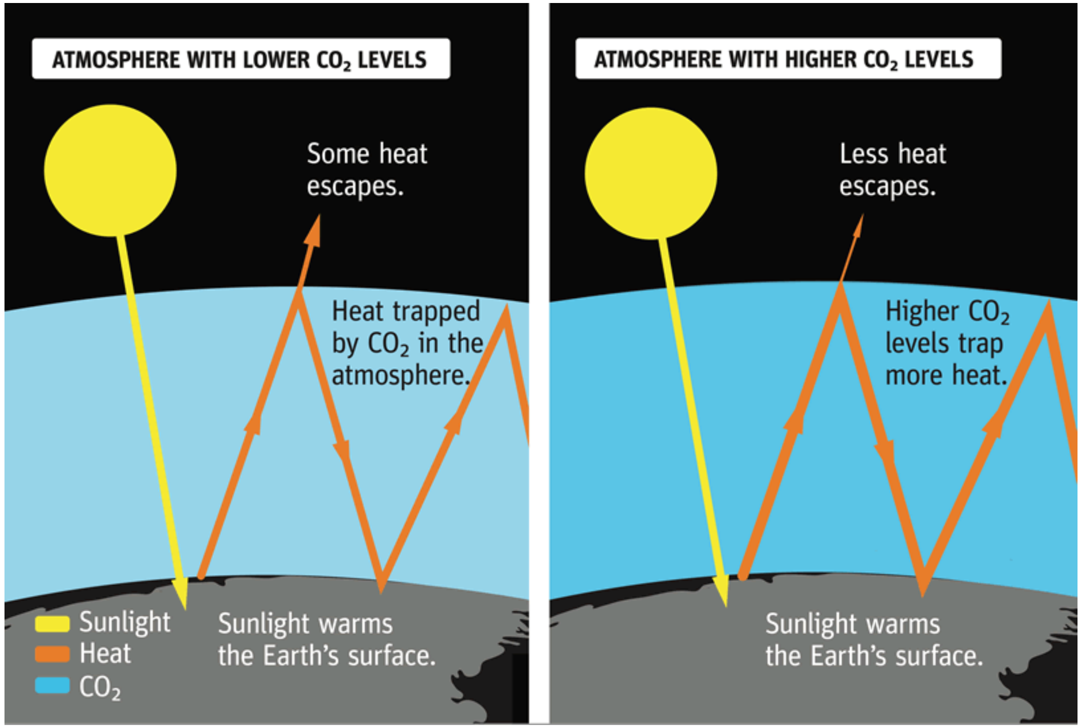
Intensification of winter transatlantic aviation turbulence in response to climate change

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

=> let's make a step back to understand these results

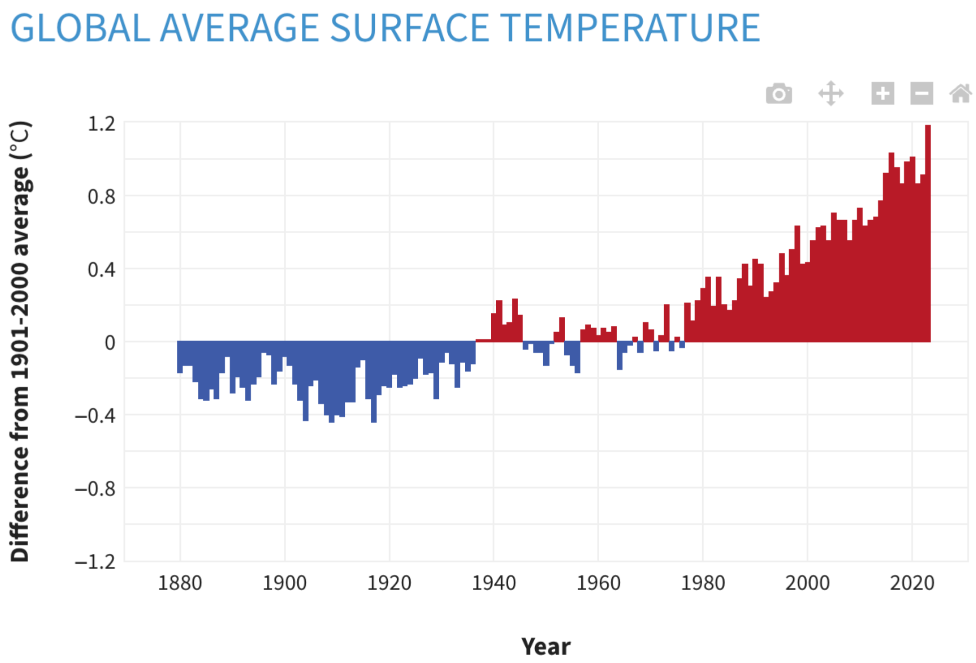
Climate Change, the Physical Basis



Sunlight warms the surface of the Earth. But Earth stays warm even at night because of a layer of carbon dioxide, or CO2, in our atmosphere. CO2 acts like a heat-trapping blanket, absorbing the heat and holding it in.

There are other heat-trapping gases. These include methane (CH4), water vapor, nitrous oxide (N2O), and some fluorinated gases.

CLIMATE CHANGE CONTRIBUTING FACTORS - LAST 10 YEARS

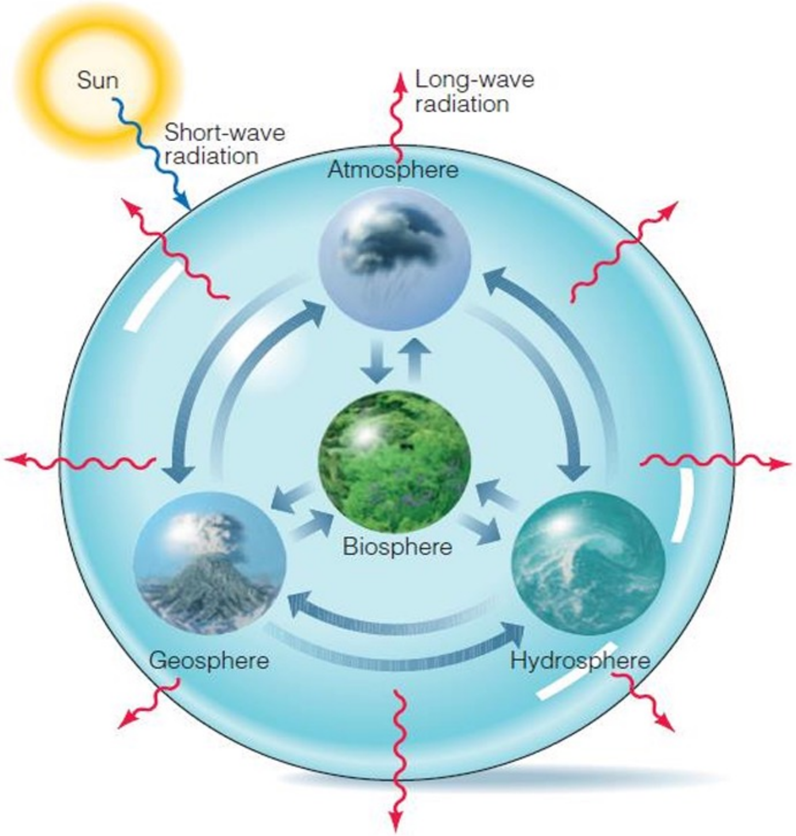


Yearly surface temperature from 1880–2023 compared to the 20th-century average (1901-2000). Blue bars indicate cooler-than-average years; red bars show warmer-than-average years. NOAA Climate.gov graph, based on data from the National Centers for Environmental Information.

The anthropogenic warming is responsible for the majority of the warming in the last 10 years, but El Niño also had a very clear effect. The solar cycle, the eruption of Hunga Tonga, and the reduction in maritime air pollution may also have played a small role in the records of 2023."

- BERKELEY EARTH

Climate as a «closed » Physical System



- **Earth is a closed system,** but all of its innumerable smaller parts are interconnected;
- When **CO_2 perturbs this steady state, the atmosphere, hydrosphere, biosphere, and geosphere react creating extreme events in each** sphere

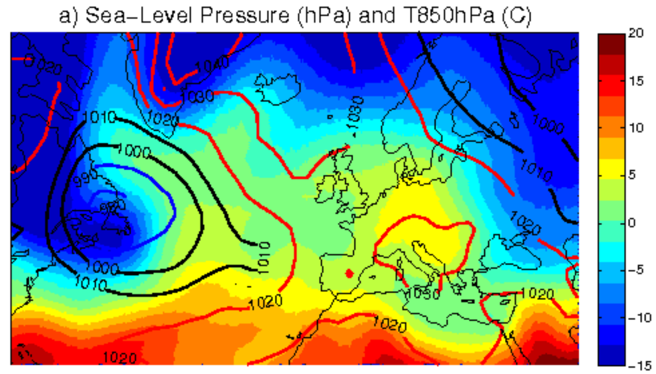
Source: bbec.ac.in

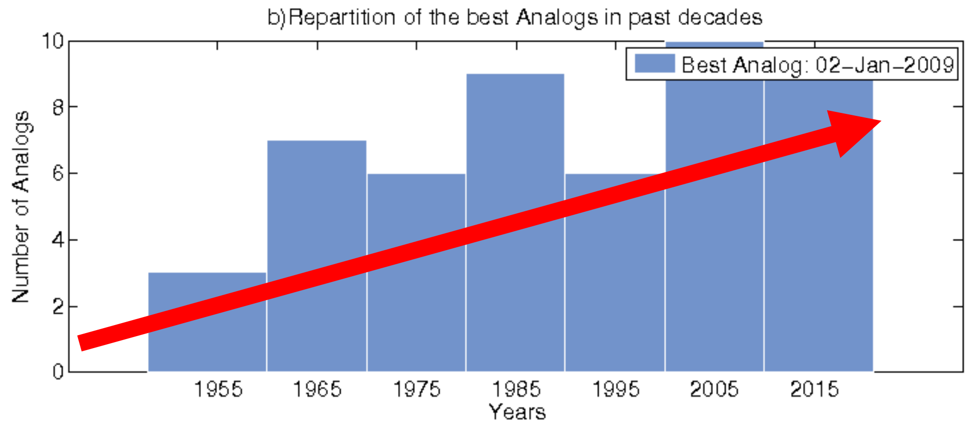
Using analogs frequency changes to detect long-term dynamical changes

1.We select alternatively **all ERA5 Sea-level Pressure maps over the North Atlantic** from 1950-2021

2. For each map we compute the Euclidean distance between daily maps, and define **a high quantile to select the analogues**.

3. We count the **number of analogues per decade and we select those having an increasing trend and a decreasing trend**





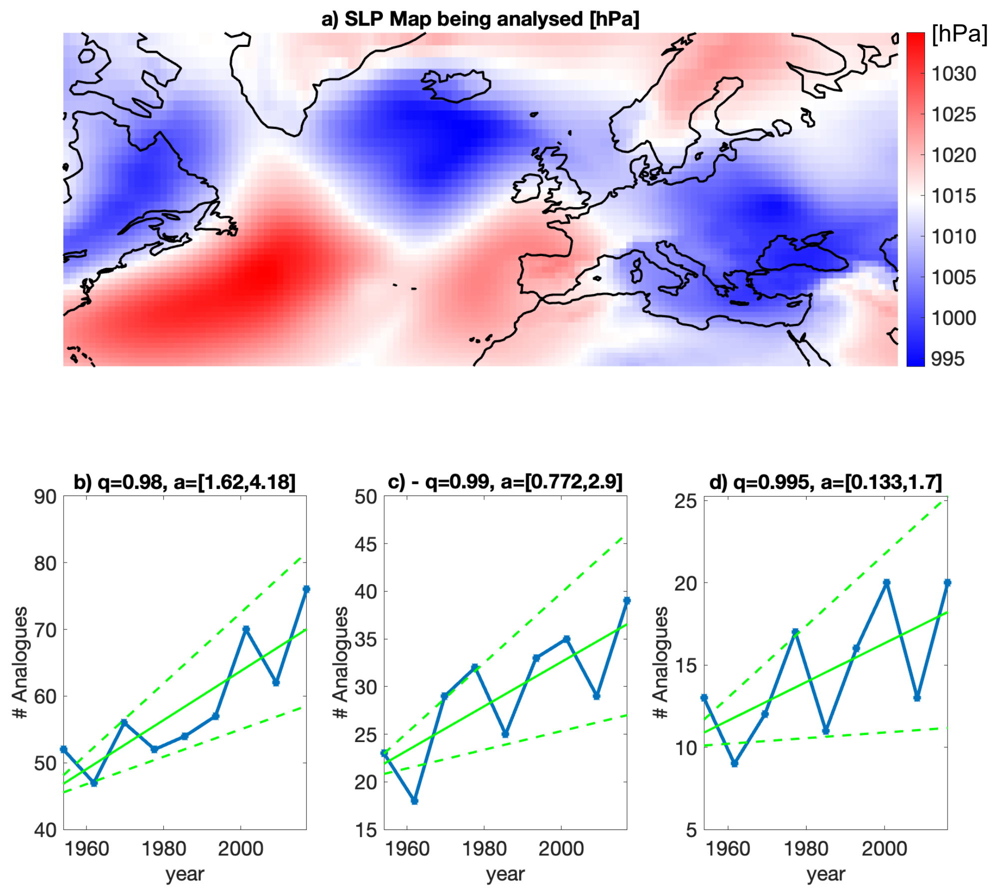
Ensuring Robustness of Changes

1. For each SLP map (a) **we take the best 2% (b), 1% (c) and 0.5% (d) analogues** in daily sea-level pressure maps from ERA5 starting in January 1950.

2. The **# Analogues counted in each decade** are then obtained (blue dots, panels b--d).

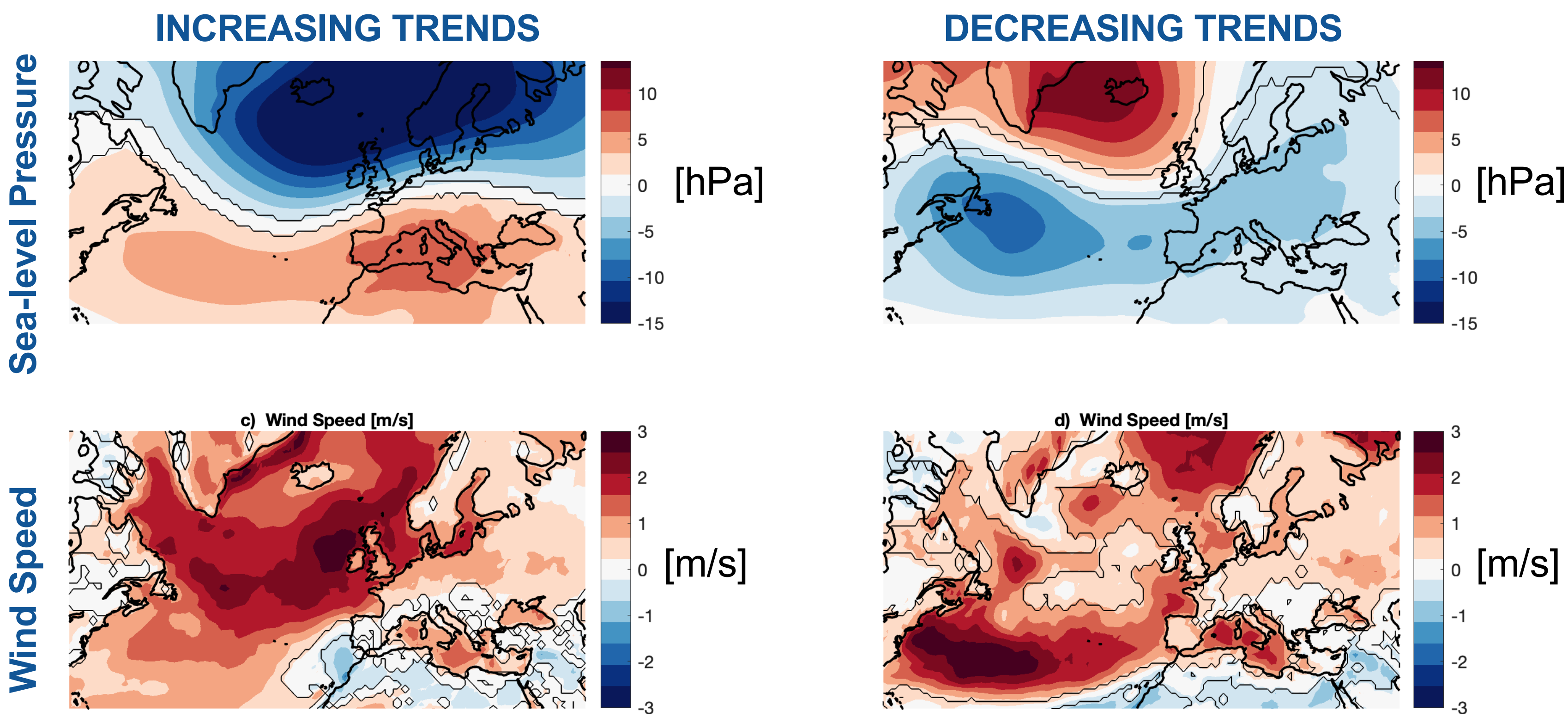
3. **A linear fit is performed (solid line) and the confidence intervals** for the slope are computed (dotted lines).

4. **Only if all confidence intervals have a positive slope, the map has increasing frequency**



Results: Winter

The vast majority (92.7%) of circulation patterns show no significant occurrence trend in the historical period; 5.1% show increasing trends and 2.2% show decreasing trends

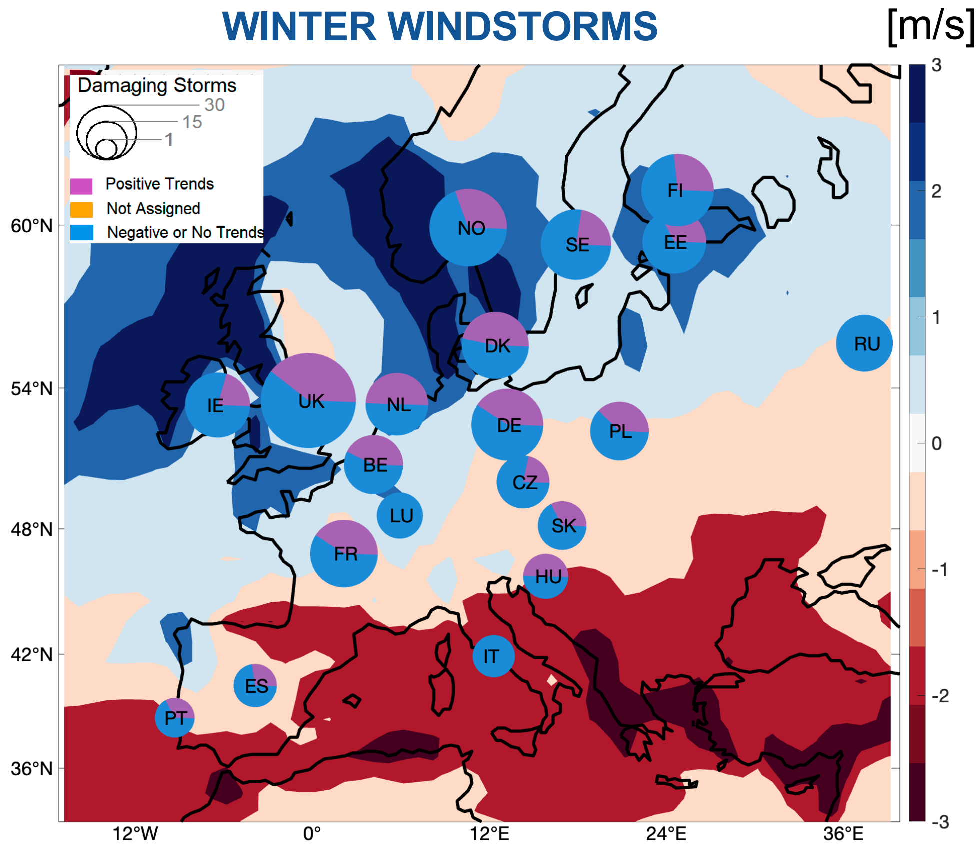


Faranda et al. PNAS, 2023

Linking frequency changes to impactful extreme events

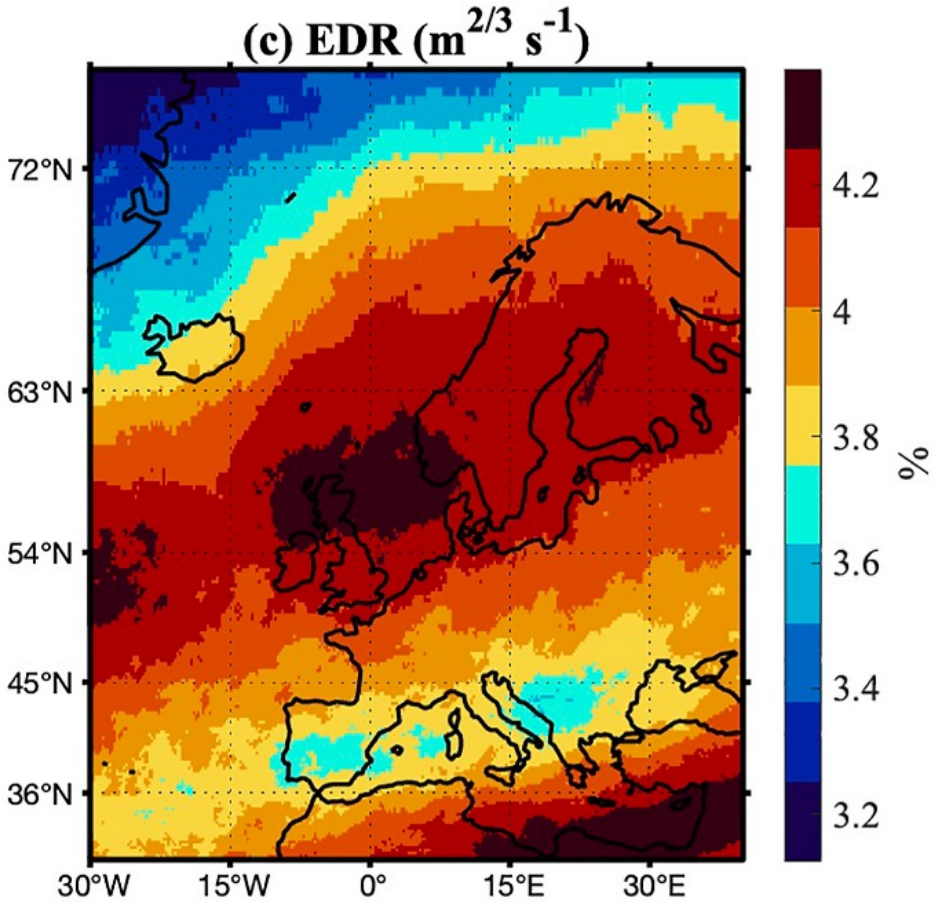
- We find that **large scale atmospheric patterns which favor wintertime windstorms** over large parts of the continent are becoming increasingly frequent
- **We cannot explain the changes with natural variability,** the main hypothesis is climate change!
- What are **the implications for turbulence in aviation?**

WINTER WINDSTORMS



Faranda et al. PNAS, 2023

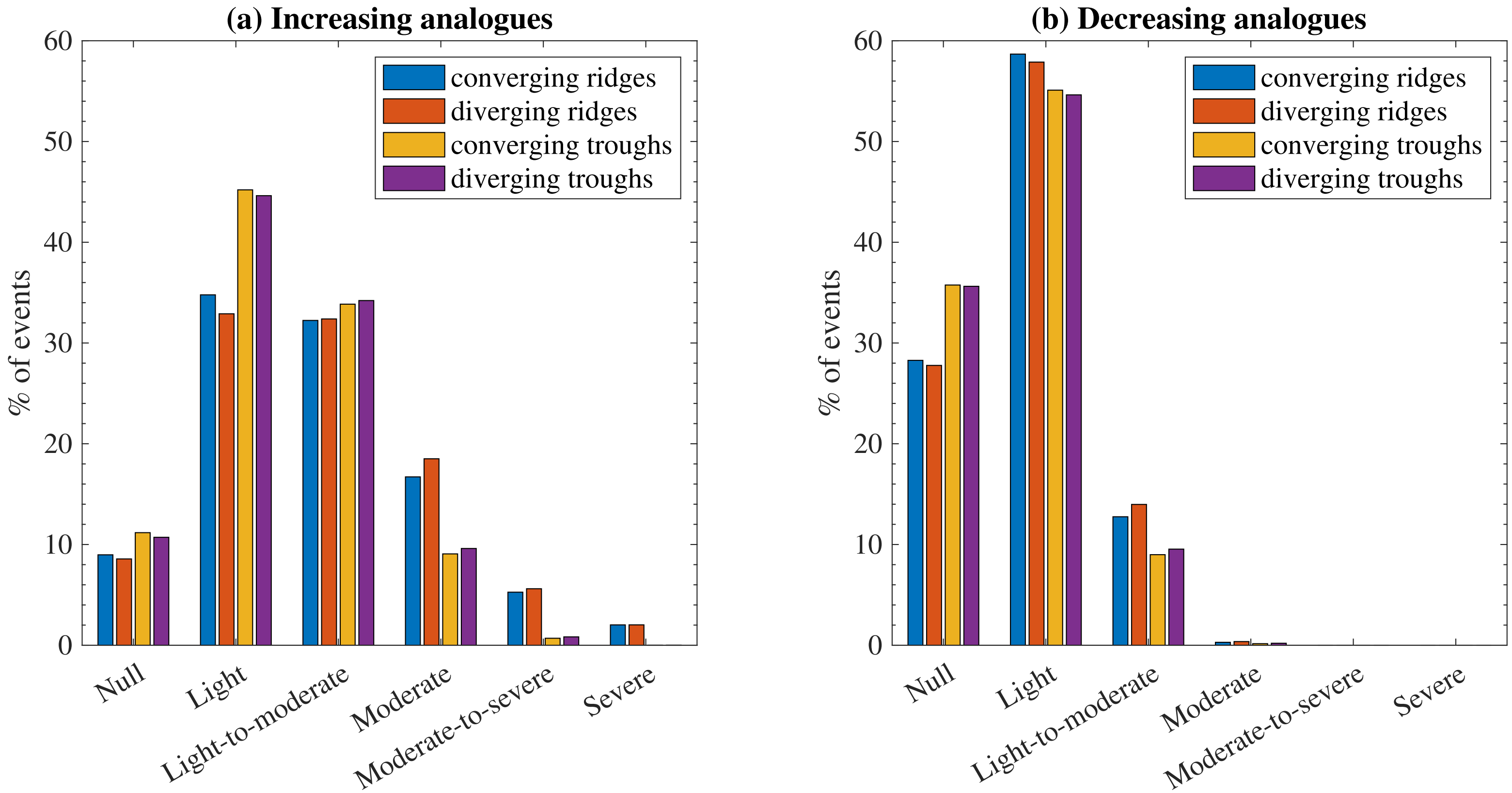
Eddy Dissipation Rate (EDR) changes with climate change



This is the frequency increase of EDR during pattern that become more frequent **=> how much time we spend in more turbulent flight**s!

Alberti, Faranda et al. GRL 2024

How turbulent is getting because of climate change?



More events featuring moderate to severe turbulence levels, especially associated with atmospheric ridges and clear air turbulence episodes

Alberti, Faranda et al. GRL 2024

Can we detect the influence of Climate Change on a single Flight?

Attribution: The process of determining the causes of observed changes in climate and extreme events in terms of natural climate variability or greenhouse gases emissions

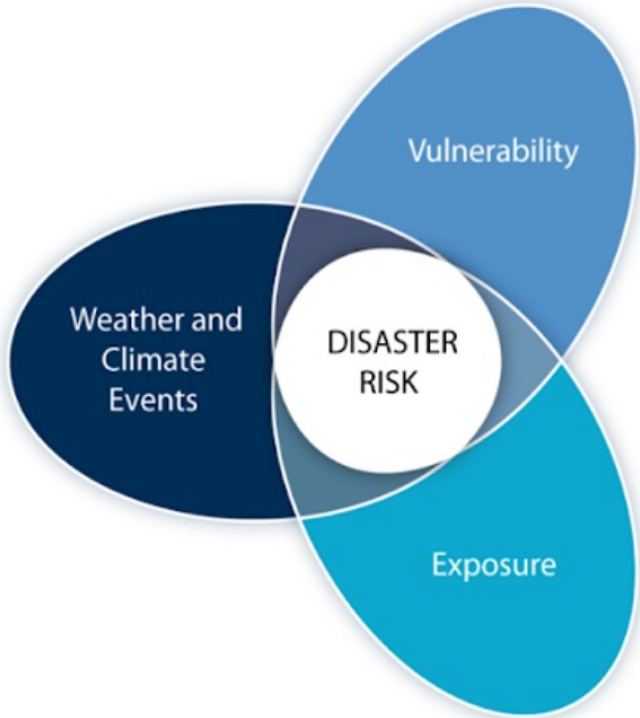
"I wonder what would happen if I halved the global warming...?"

Which Extreme Events need Attribution?

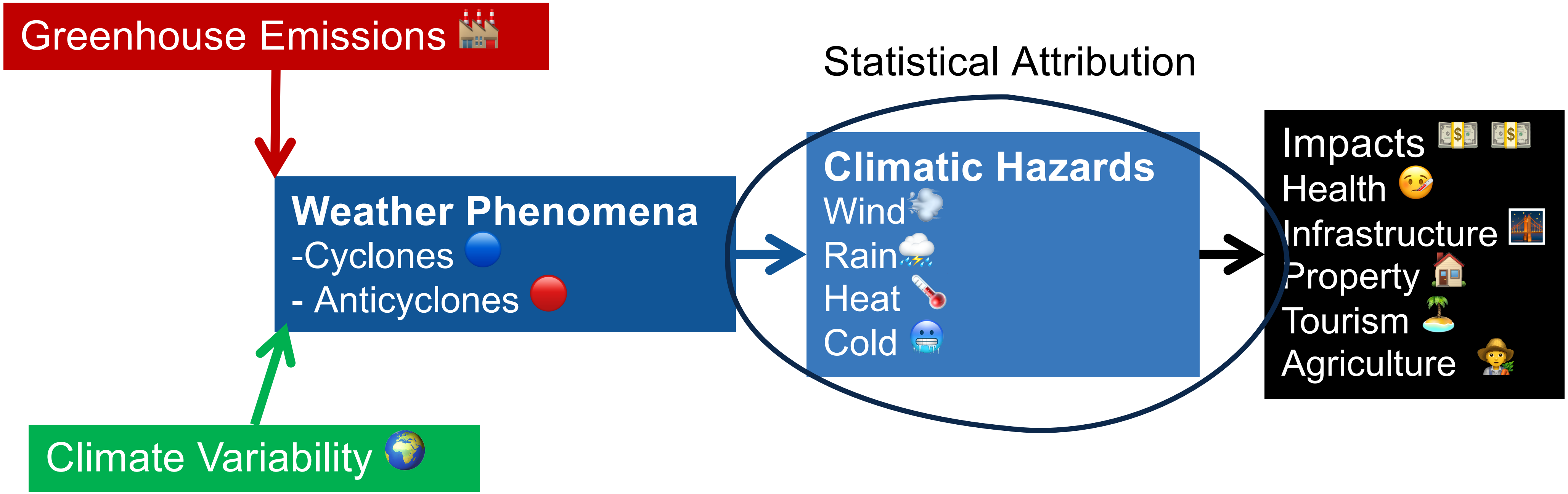
Weather extreme events may disrupt daily life, damage infrastructure, and have long-lasting effects on communities and ecosystems. This depends on:

Vulnerability: accounts for the susceptibility to damage of the assets exposed to the forces generated by the hazard.

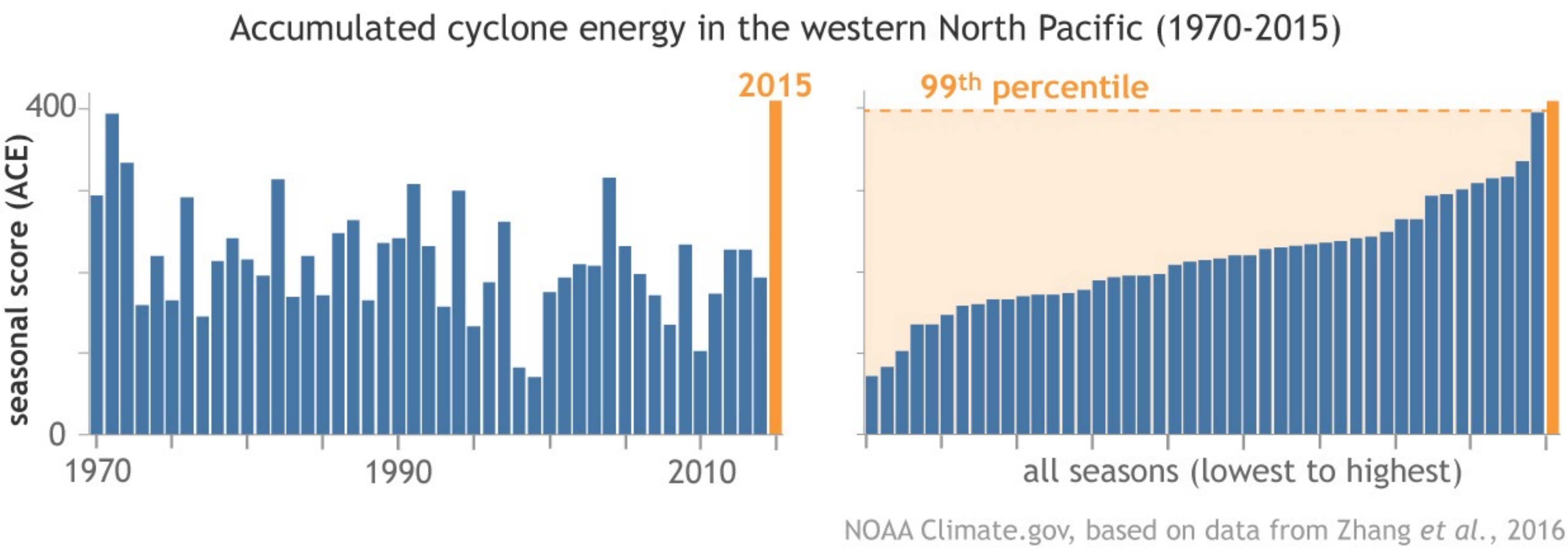
Exposure: represents the stock of property and infrastructure exposed to a hazard, and it can include socioeconomic factors.



A General Pathway to Attribution

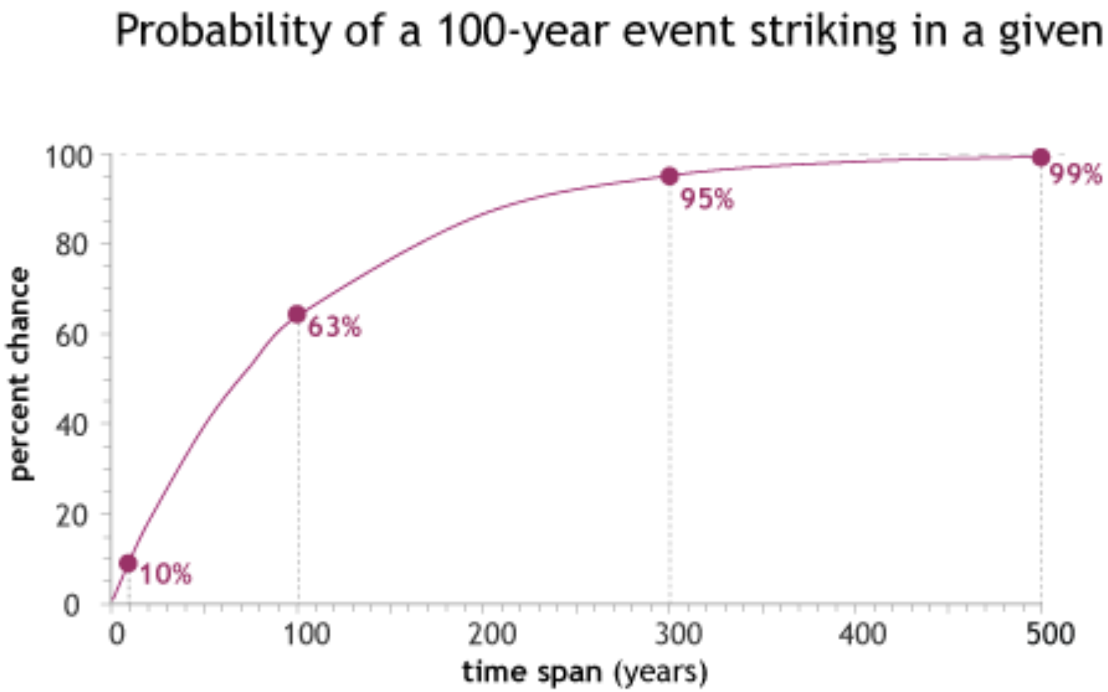


Statistical Attribution #1 : Detection



1. Define a quantiy that can track the extreme events: here cyclone energy
2. Sort our record and locate the percentile of our event

Statistical Attribution #2 : Characterization Of The Event



TIME SPAN years	PROBABILITY % chance
1	1
5	5
10	10
20	18
50	40
75	53
100	63
200	87
300	95
400	98
500	99.3
800	99.97
1000	99.996

By definition, the probability that a 100-year event will occur in any single year is 1%. That means the probability that it won't happen that year is 99%

Statistical attribution #3 : results

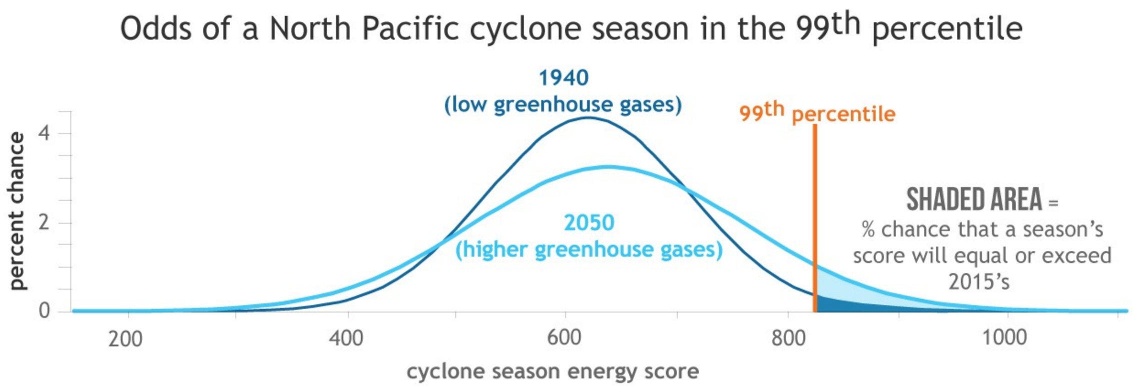
For attribution we can use changes in model projections of identiftied observables:

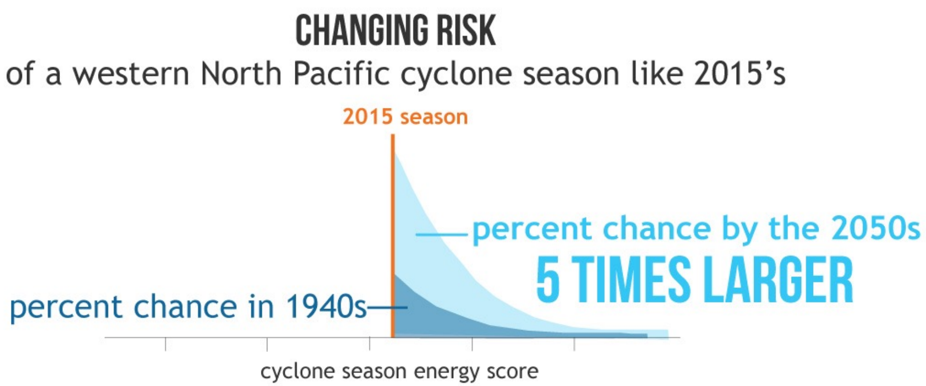
-1940-1970 (dark blue line) show cyclone energy for the world with low greenhouse gases emissions

-2020-2050 (light blue line) showt he changing frequency of 99th percentile events.

We conclude that Global warming due to rising greenhouse gases has increased the risk of an extreme North Pacific hurricane season like 2015's by a factor of 5

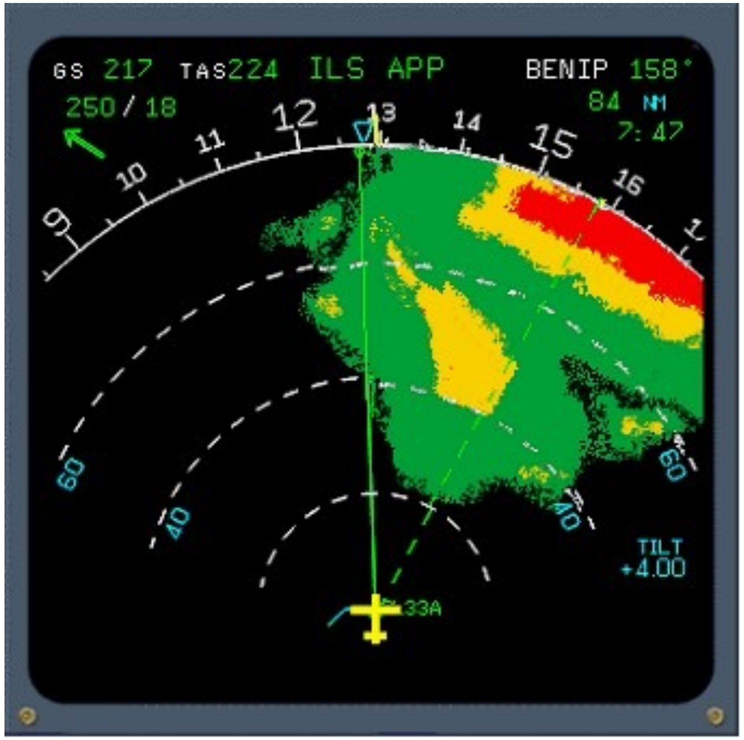
NOAA Climate.gov graphic adapted from Zhang *et al*., 2016.



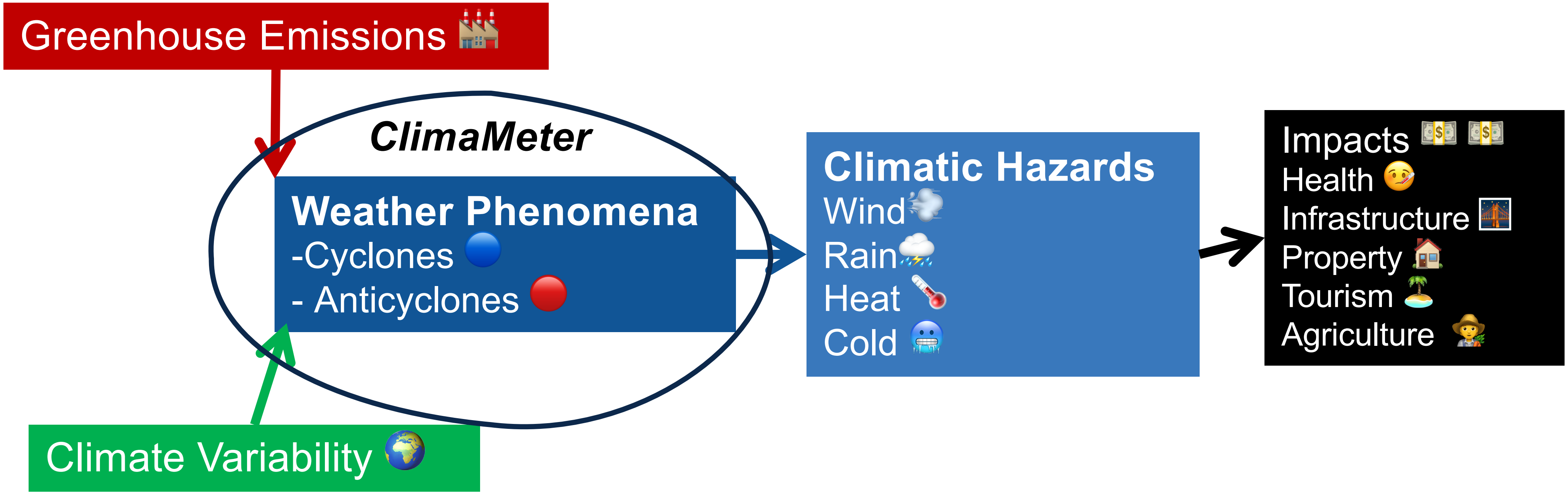


Can Statistical Attribution work on Flights turbulence?

- Statistical Attribution is concerned with observables averaged over a certain region
- It **does not take into account the spatial and temporal extension** of the phenomena ot attribute
- **It does not account for the physical causes of changes** that we observe in the climate system



ClimaMeter Attribution Pathway

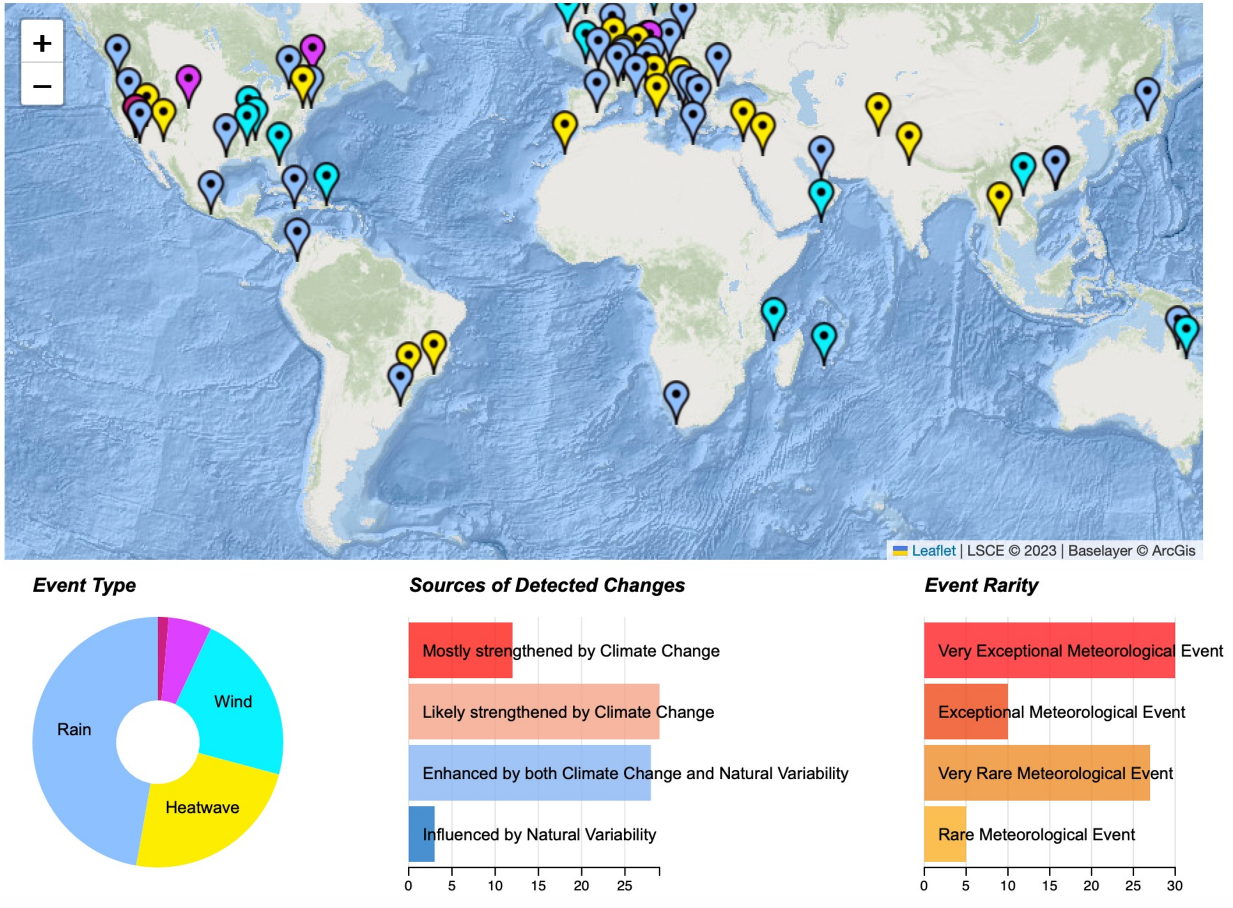


ClimaMeter

- **ClimaMeter is a rapid attribution framework** for putting weather extremes in a climate perspective, developed by IPSL-CNRS

- **ClimaMeter is a consortium of scientists** coming from several institutions all over the world.
-
- **Report ready about 48 hours after the event. All reports availabe on Zenodo**

- **We have analyzed 65 events in 15-months**, with over 2000 international press articles



The Methodology used in ClimaMEter

🌐 **Data**: gridded data from reanalyses based on ERA5 (1950 to Present)

🌀 **Event Definition**: Time averaged Surface Pressure Anomalies map in a lon-lat box

🔍 **Analogues Analysis**: Assess differences in Present vs. Past Analogues

⏰ **Periods**: Split into two periods

- 🏞️ Past: Barely affected by Climate Change
- 🏜️ Present: Highly affected by Climate Change

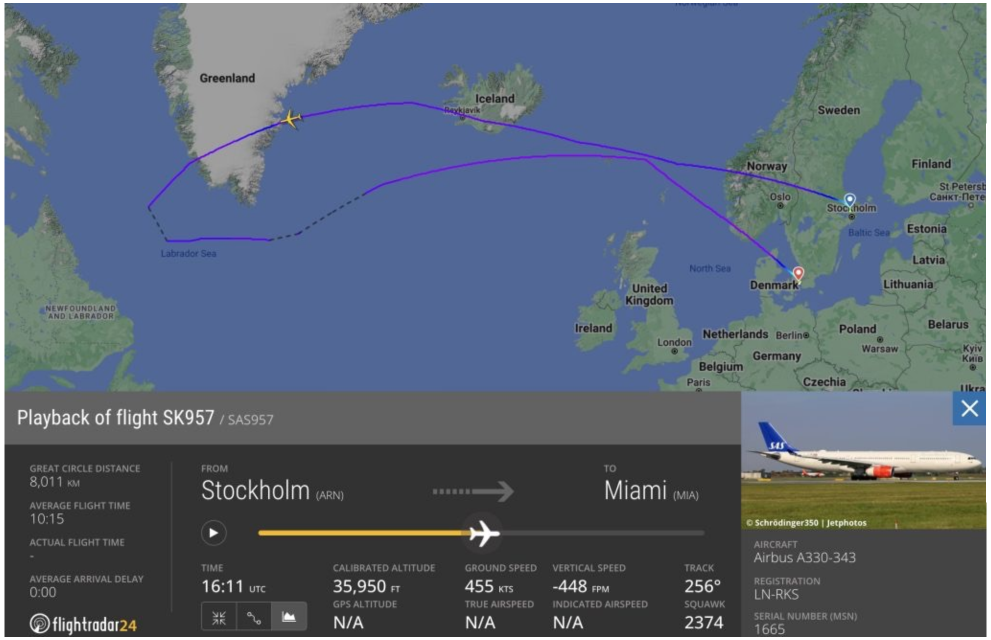
📊 **Diagnosed Changes:** Pressure**,** Temperature, Precipitation, Winds

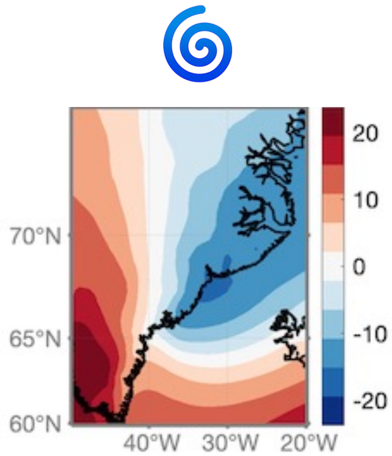
🌍 **Natural Variability Modes Change of phase in analogues:** ENSO, AMO, PDO

Example of Turbulence Attribution: SAS Flight 957 14/11/2024

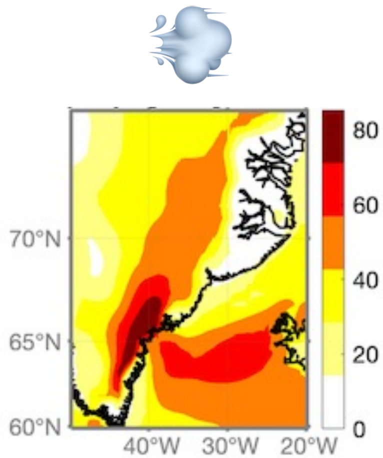
CNN travel | Destinations | Food & Drink | News | Stay | Video

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





[hPa]



[km/h]

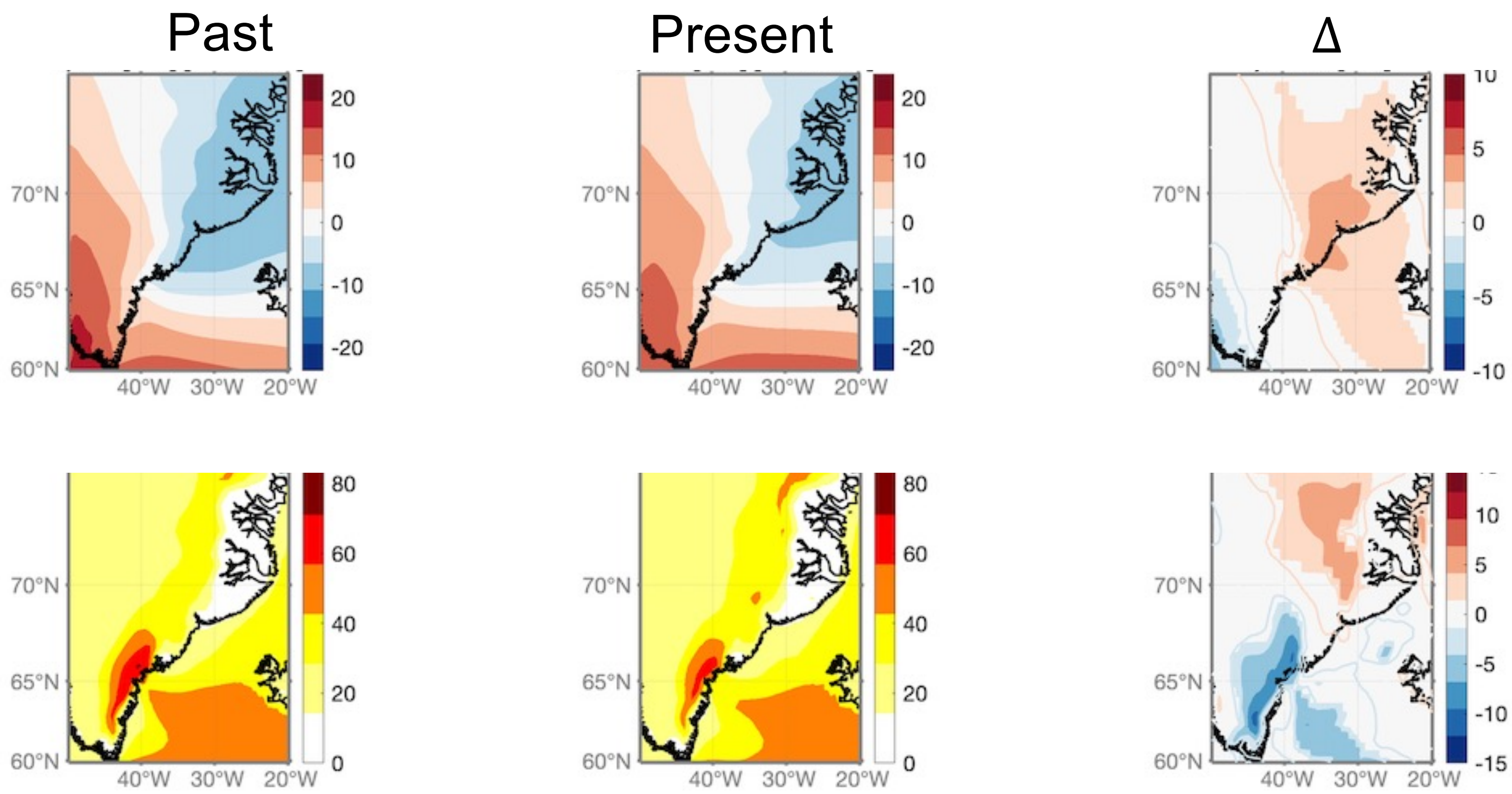
Example of Turbulence Attribution: SAS Flight 957 14/11/2024

Pressure

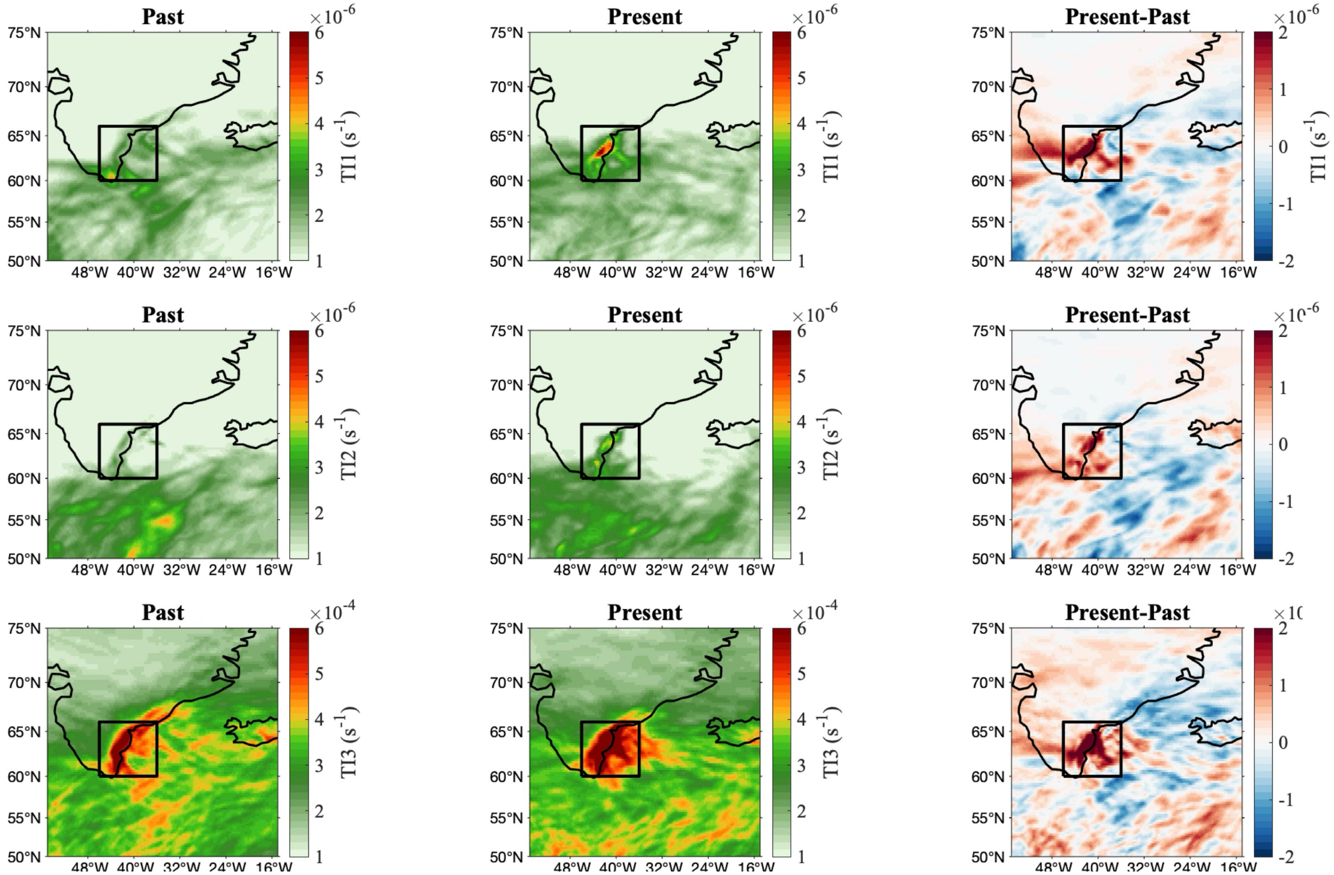
[hPa]

Wind 10m

[km/h]



Example of Turbulence Attribution: SAS Flight 957 14/11/2024



Reynolds Stress Tensor Components between 200 and 250 hPa Flight levels

- $T11$ (or τ_{11}):

$$T11 = \overline{u'_1 u'_1} = \overline{u'_x u'_x}$$

- $T12$ (or τ_{12}):

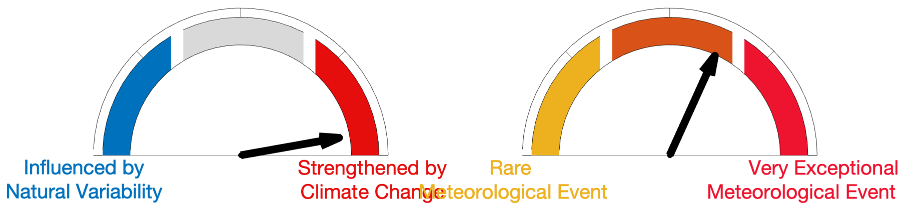
$$T12 = \overline{u'_1 u'_2} = \overline{u'_x u'_y}$$

- $T13$ (or τ_{13}):

$$T13 = \overline{u'_1 u'_3} = \overline{u'_x u'_z}$$

Analyses provided by Tommaso Alberti

Example of Turbulence Attribution: SAS Flight 957 14/11/2024



- **Turbulence on SAS Flight 957 was mostly increasead by anthropogenic climate change.**
- **Natural variability alone cannot explain the increase in turbulence** on SAS 957
- This turbulence **was triggered by exceptional meteorological conditions**

Conclusions

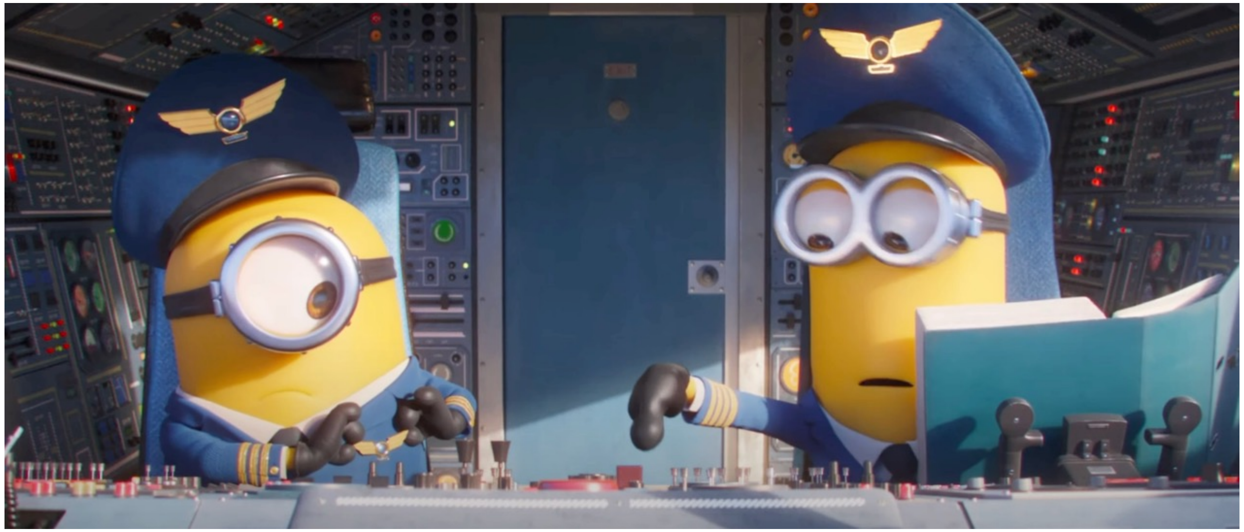
- We can **detect the climate change signal on atmospheric turbulence** in avearage and on single events.
- Knowing in advance how climate change affects flight turbulence may **help in reducing the (huge) impact of aviation on global warming.**
- Don't worry, airplanes are designed to withstand even extreme turbulence... ***your comfort is all in the hands of pilots!***

Y-a-t-il un pilote dans l'avion? 1980

If you liked this presentation… and Rome!

Researcher positions will be soon available on the project “Mediterranean Extreme Events and Tipping elements in a changING climate on multiple spatiotemporal scales” recently financed by MUR (Italy equivalent of ANR)

=> Contact Tommaso.Alberti@ingv.it



🙏 Thanks for your attention!

- Alberti, T. et al. (2024) Impacts of Changing Atmospheric Circulation Patterns on Aviation Turbulence Over Europe GRL.
- Faranda et al. (2023). Atmospheric circulation compounds anthropogenic warming and impacts of climate extremes in Europe. PNAS, 120(13), e2214525120.
- Faranda, D et al (2024) : ClimaMeter: Contextualising Extreme Weather in a Changing Climate, Weather and Climate Dynamics, 2024

www.climameter.org

climameter@lsce.ipsl.fr

EDIPI has received funding from the European Union's Horizon 2020 research and innovation programme under Marie Skłodoawska-Curie grant No. 95639

Xaida has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003469.