An emergent constraint for the future frequency of European windstorms

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Aims

Projections of windstorm frequency vary significantly across climate models, with realizations often giving equal and opposite future trends. Climate models have different representations of the historical climate, with these biases often propagating into their projections. We utilize these biases, and emergent constraint analysis, to reduce uncertainty in projections.

Data

- CMIP6 models with historical (1980-2014), and SSP3-70/5-85 (2015-2100). Cyclones tracked using Hodges (1994) scheme
- Footprints constructed from max gust over 72-hour (Fig. 1)
- Gusts must exceed the local 95th percentile
- Trends in DJF frequency calculated using Generalized Linear model (Priestley et al., 2024; Figure 2a-c)

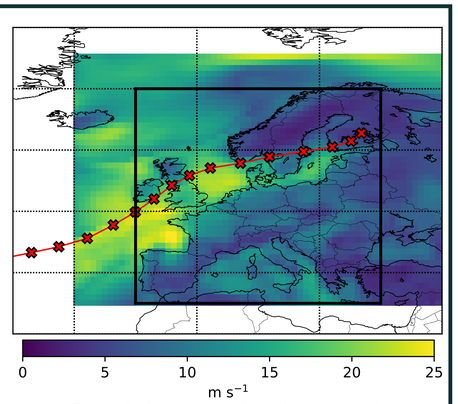

Figure 1. Cyclone track and associated windstorm footprint from a CMIP6 model

Global Zonal Index

- Model trends vary significantly (Figure 2a-c) and are correlated with mean sea level pressure in the middle and high latitudes (Figure 2d).
- Define the **Global Zonal Index (GZI)** as the globally averaged midlatitude pressure gradient.

$$\mathrm{GZI} = \frac{1}{2}\left[\left(\overline{P}_{30°\mathrm{N}-60°\mathrm{N}} - \overline{P}_{60°\mathrm{N}-90°\mathrm{N}}\right) + \left(\overline{P}_{30°\mathrm{S}-60°\mathrm{S}} - \overline{P}_{60°\mathrm{S}-90°\mathrm{S}}\right)\right]$$

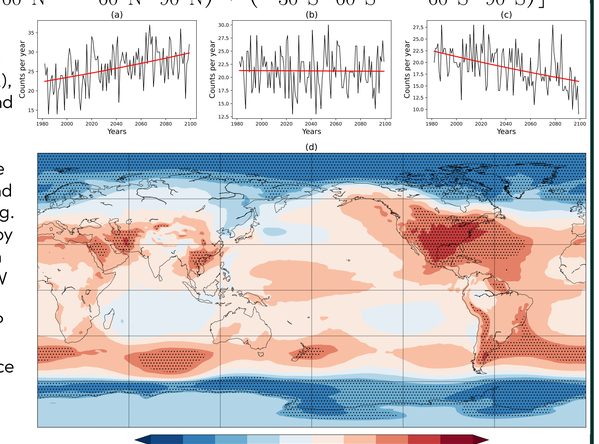

Figure 2. (a-c) Trends for a positive (a - BCC-CSM2-MR), neutral (b - GISS-E2-1-G) and negative trend model (c - MIROC6). Timeseries of frequency are the black line for historical (1980-2014) and SSP5-8.5 (2015-2100) forcing. Trend estimates are shown by the red line. (d) Correlation across CMIP6 models of NW Europe windstorm trends (1980-2100) and DJF MSLP (1950-2014). Stippling indicates areas of significance at the 95% level.

Constraining Projections

- The model variability in trends is significantly related to the GZI (r=0.76)
- The real-world GZI (HadSLP; 8.6 hPa [±0.6]) allows for trends to be constrained

Constrained trend = -3.92% °C^{-1} [±3.3]

Total uncertainty reduced by 32%

Probability of a positive forced trend reduced by a factor of 3

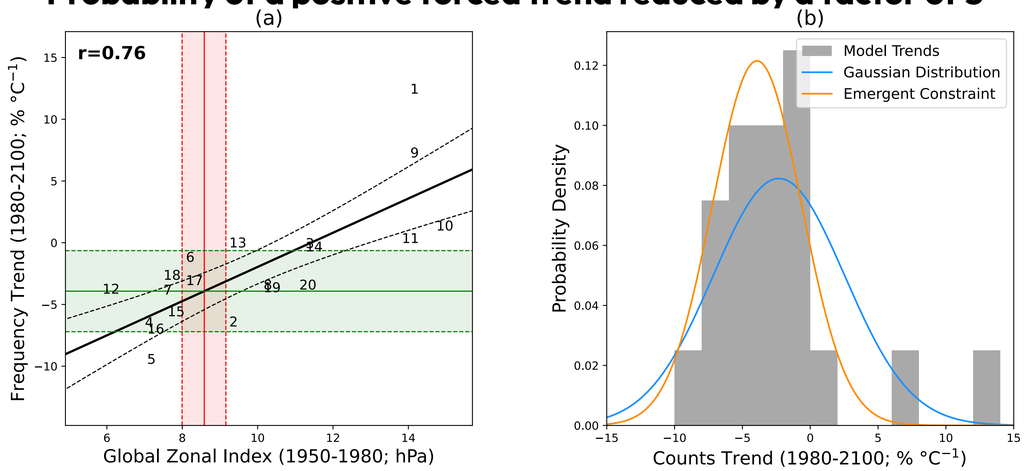

Figure 3. (a) Scatter plot of CMIP6 model GZI against future windstorm frequency trend. Emergent relationship (and associated uncertainty) is shown by the black solid/dashed lines. Vertical red line and shading is the observed GZI. Horizontal green line and shading shows the emergent constraint. (b) Distribution of historical trends (grey bars) and associated gaussian distribution (blue curve) and emergent constraint (orange curve).

A physical mechanism

- GZI strength modifies ocean state in the N. Atlantic, driving an atmospheric response
- Models with a stronger GZI have deeper mixed layers, which is associated with a more intense warming hole at the end of the century
- The stronger NAWH modifies baroclinicity, resulting in a jet extension over Europe
- Models with a weaker GZI have a lower baroclinicity increase and weaker jet anomaly

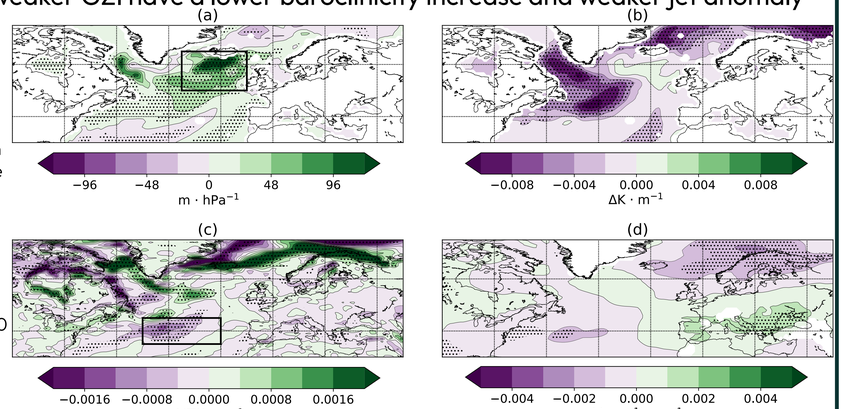

Figure 4. Atmosphere-ocean regressions across CMIP6 models for the North Atlantic sector. (a) Model mean mixed layer depth regressed on mean GZI Index. (b) SST change regressed on historical mixed layer depth in the black box in (a). (c) Surface temperature gradient response regressed on historical mixed layer depth. (d) 850 hPa zonal wind response regressed on historical mixed layer depth.

The bias originates in the atmosphere

- Construct the GZI in coupled and atmosphere-only simulations
- Biases are proportional in both experiments so do not originate from ocean biases/coupling
- Candidates are gravity wave drag, Hadley Cell strength

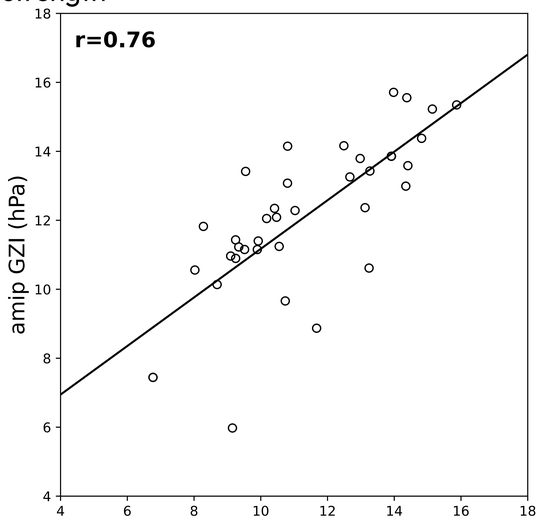

Figure 5. Climatological GZI in coupled *(historical)* and atmosphere-only *(amip)* CMIP6 models for the 1950-1980 period.

Key Points

Climate model variability in future windstorm frequency is explained by the climatological midlatitude pressure gradient. Model spread is constrained using observed GZI, with uncertainty reduced and the probability of positive trends reducing 3x. Atmosphere-ocean coupling modulates the model responses, with more positive trend models having larger NAWH and baroclinicity anomalies, strengthening the jet into Europe.

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References
- Hodges (1994), Monthly Weather Review
- Priestley et al. (2024), Q. J. Royal Met Society