Why are future projections of European windstorms so model-dependent?

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Celebrating 20 years Willis Research Network

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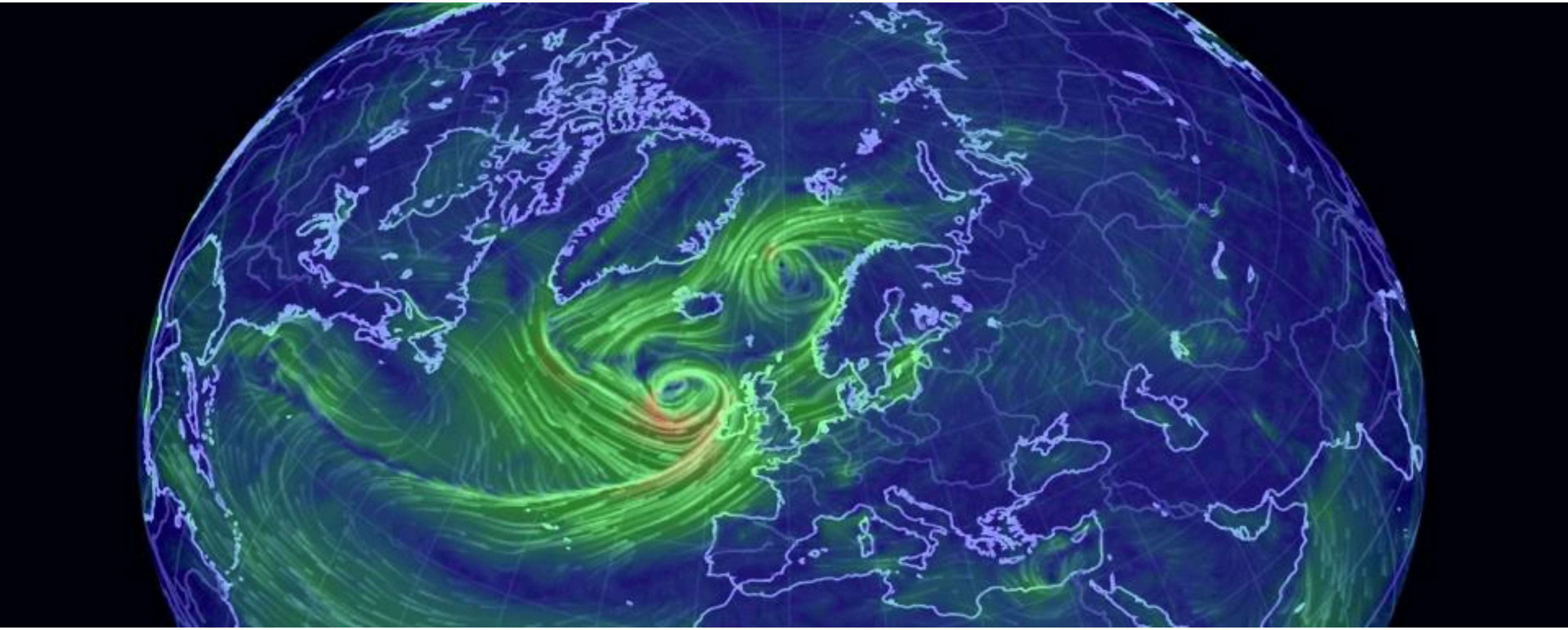


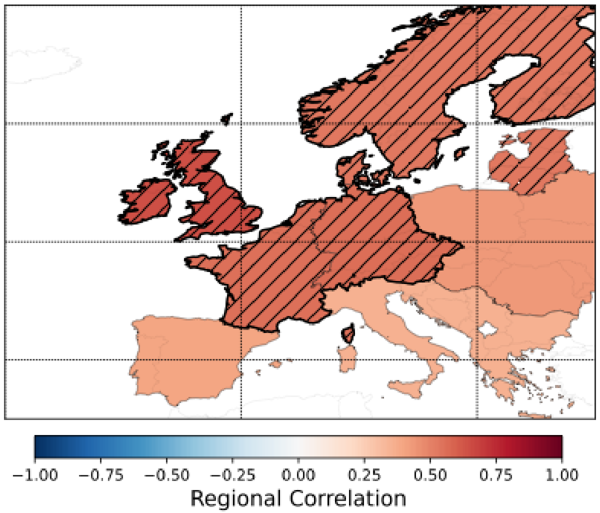
11th European windstorm workshop, Delft, 17-19 June 2026

Climate projections of storm frequency

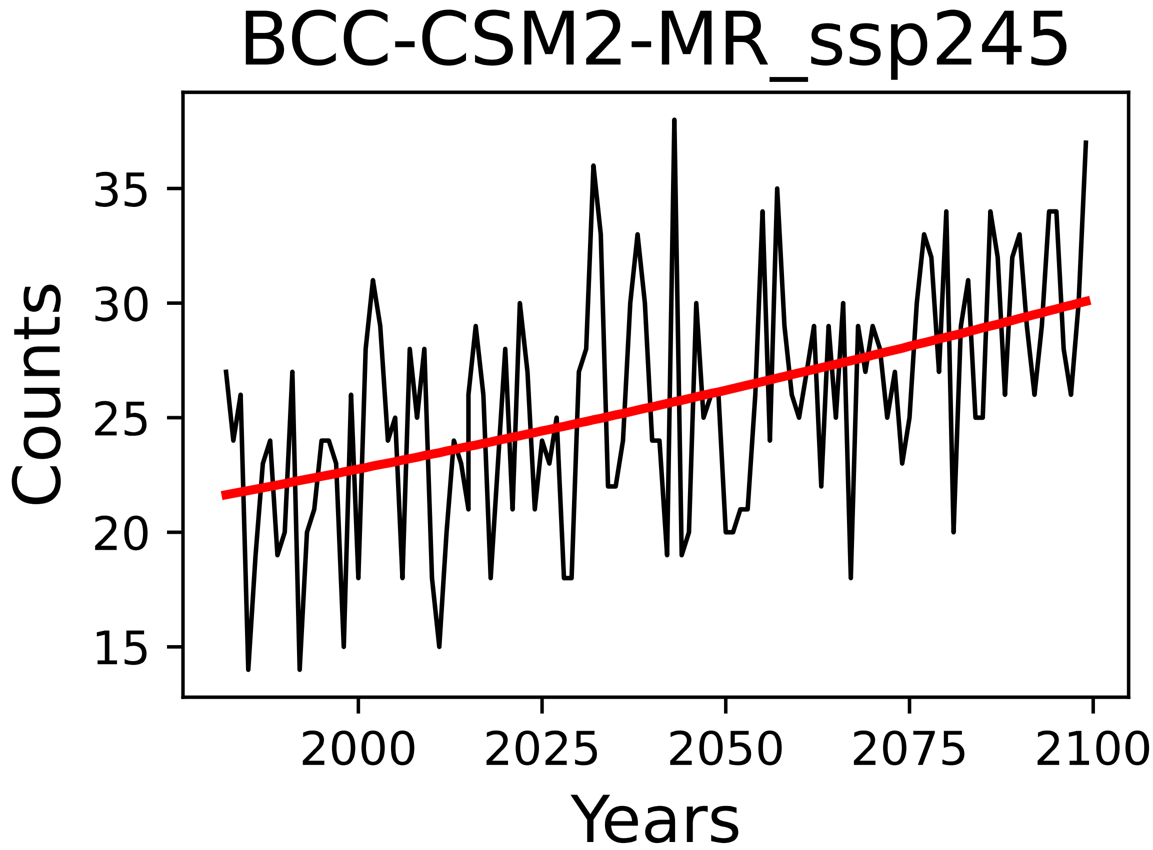
Number	Model Name	SSP2-4.5	SSP5.8.5	Windstorm Trend (% °C^{-1})	AO (hPa)
1	BCC-CSM2-MR	X		12.07	14.05
2	EC-Earth3	X		-6.78	9.25
3	GISS-E2-1-G	X		-0.42	11.27
4	KACE-1-0-G	X		-6.83	7.01
5	MIROC6	X		-9.81	7.07
6	MPI-ESM1-2-HR	X		-1.54	8.10
7	MPI-ESM1-2-LR	X		-4.20	7.50
8	MRI-ESM2-0	X		-3.79	10.16
9	BCC-CSM2-MR		X	6.91	14.05
10	CMCC-CM2-SR5		X	0.99	14.74
11	CMCC-ESM2		X	-0.02	13.83
12	CNRM-CM6-1-HR		X	-4.13	5.88
13	EC-Earth3		X	-0.38	9.25
14	GISS-E2-1-G		X	-0.70	11.27
15	HadGEM3-GC31-MM		X	-5.96	7.61
16	MIROC6		X	-7.36	7.07
17	MPI-ESM1-2-HR		X	-3.43	8.10
18	MPI-ESM1-2-LR		X	-3.00	7.50
19	MRI-ESM2-0		X	-4.01	10.16
20	NESM3		X	-3.79	11.11

- Track all Dec-Feb storms in the 20 simulations
- Calculate 72-hour max wind footprints for 10^{o} around each track
- Count an event if max wind speed exceeds 95th percentile at any land location in the region

→ Counts extreme storms that could create damage somewhere over land in NW Europe



Estimation of trend from 1980-2100

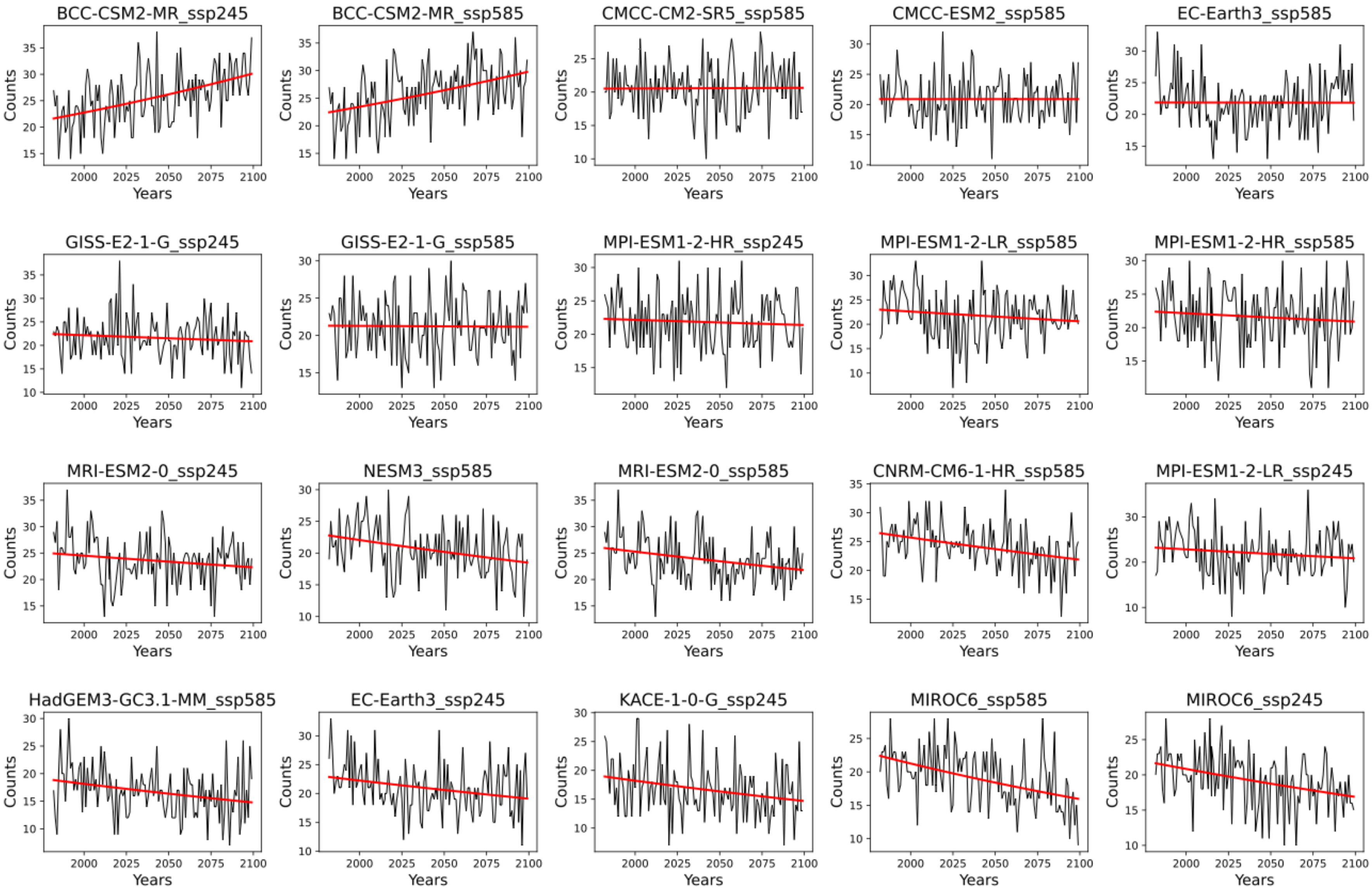


Time trend is estimated by fitting a Generalized Linear Model to the whole time series from each climate model:

N~Poisson(rate) with log(rate)=a+b*x

x = years OR global mean temperature

Models give very different projections



→ Huge spread in model trend estimates from 12.1%/^{o}C to -9.8%/^{o}C

How much variation in the trends is natural?

Standard deviations of trends from 10,000 bootstrap resampled ensembles from CMIP6 ensemble (model variability) and MPI-ESM1-2-LR (natural variability).

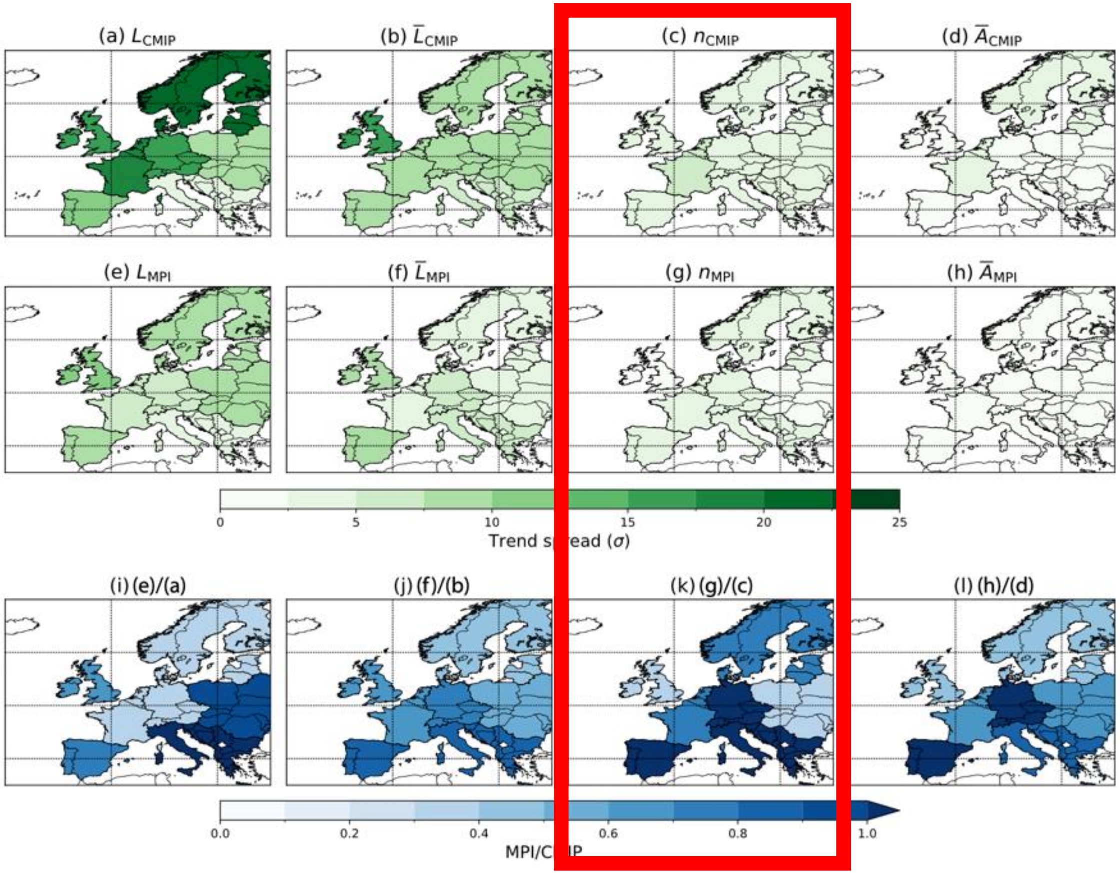


FIGURE 8 Relative importance of internal variability compared with total variability in windstorm trends: (a, e) the seasonal aggregate severity (L); (b, f) the storm average severity ($\overline{L}$); (c, g) the frequency of windstorms (n); (d, h) the storm average footprint area ($\overline{A}$). (a–d) Total variability from the CMIP6 multimodel ensemble. (e–h) Internal variability from MPI-ESM1-2-LR ensemble. Bottom row shows the size of internal variability relative to total variability. Spread is represented as the standard deviations (σ) of the 10,000 bootstrap sample estimates of the trend. Units of the top two rows are %.

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RESEARCH ARTICLE

Forced trends and internal variability in climate change projections of extreme European windstorm frequency and severity

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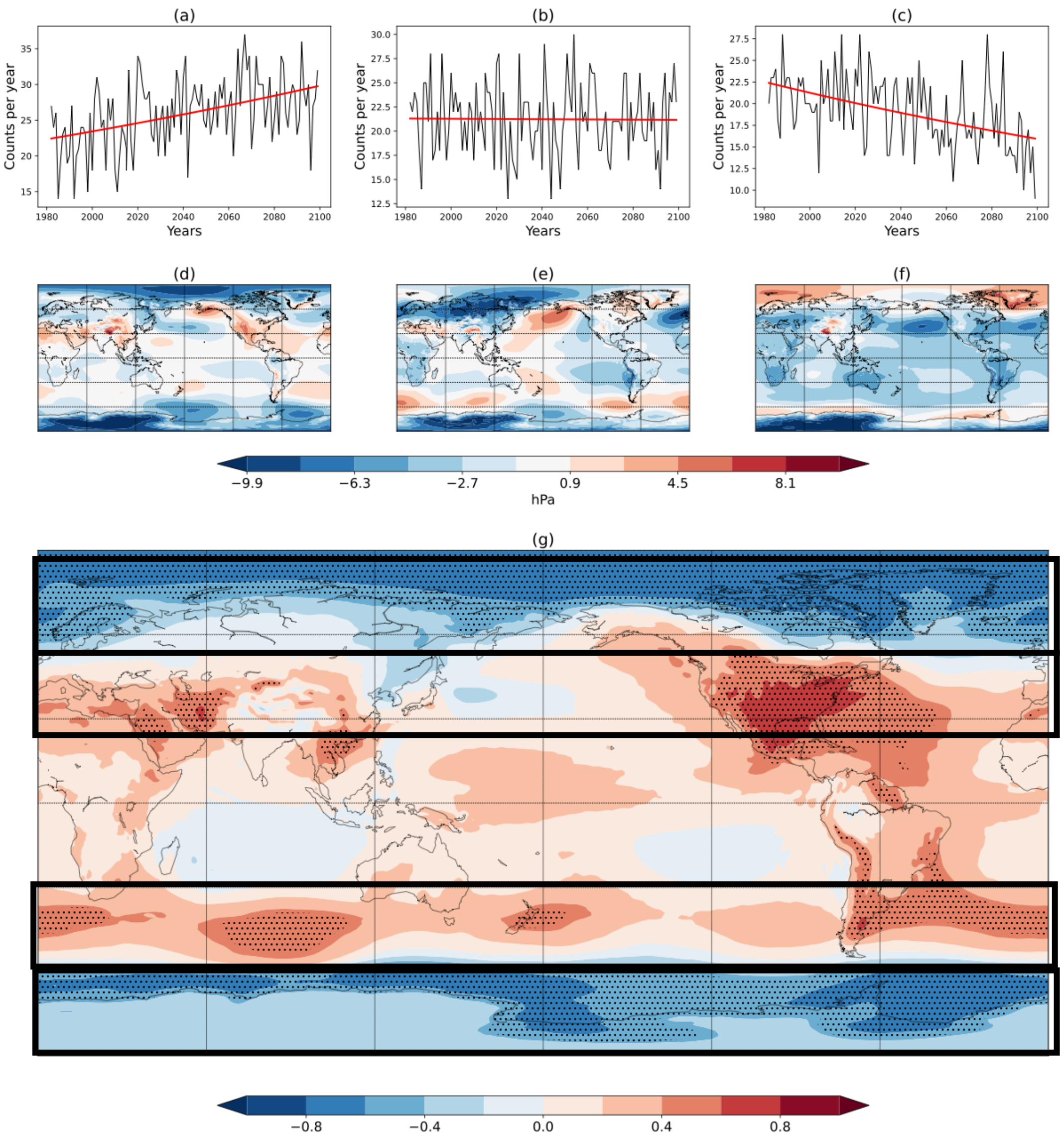
→ More than half of total variability is from model differences rather than natural

Trends depend on model climatology!



Example of of storm counts and historical SLP for 3 contrasting models:
BCC-CSM2-MR, EC-Earth3, MIROC6

Correlation of count trends 1980-2100 on winter SLP (1950-2014)

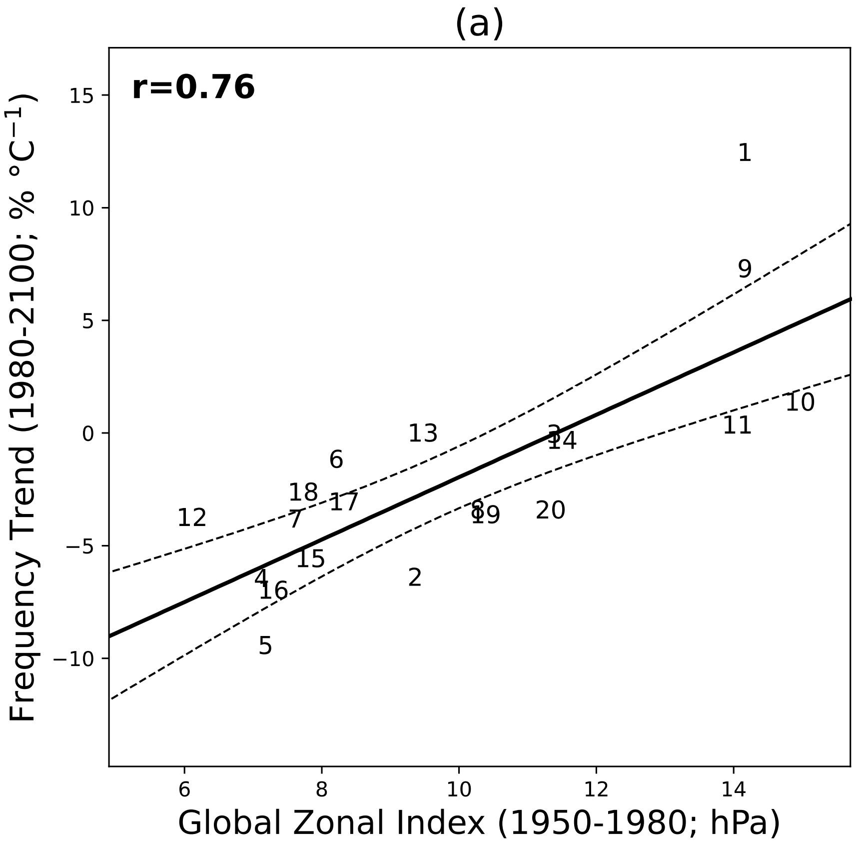
This pattern can be captured using a Global Zonal Index as a measure of the strength of the westerly flow.

GZI defined as the difference in mean sea-level pressure averaged between latitudes 30-60^o and 60-90^o in the Northern and Southern Hemispheres (Gong and Wang, 1999)

→Different models give very different trends – beware if you use only a few models!

Emergent constraint with the zonal index

regression of trend on global zonal index

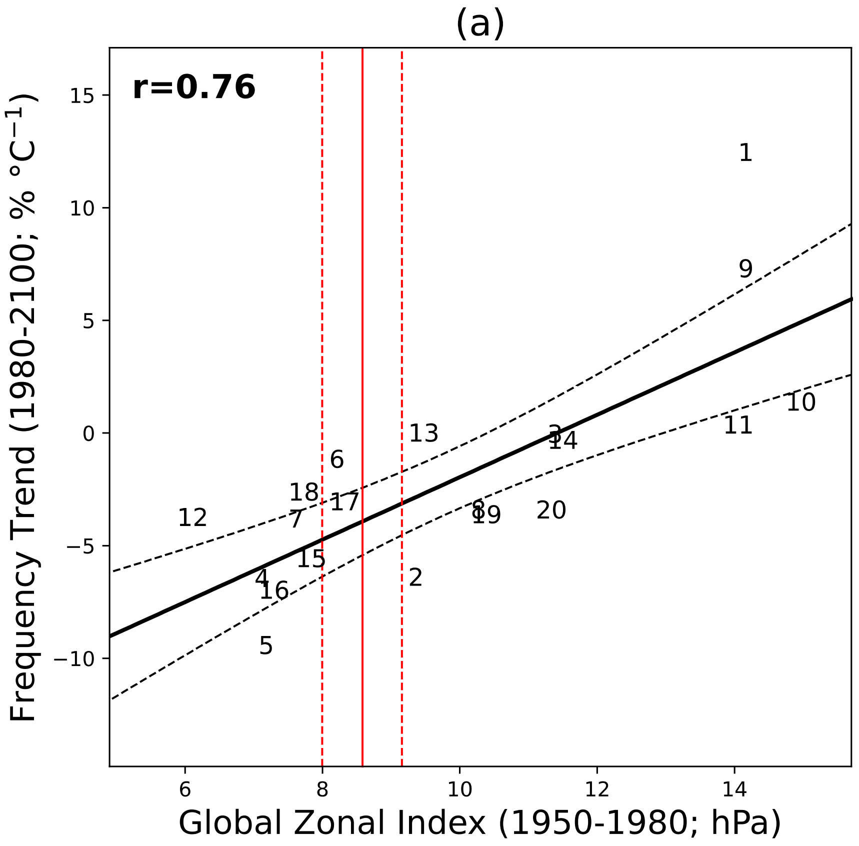


- A strong positive linear association can be noted between the frequency trends and the global zonal index in CMIP6

Around r^2=60% of variance in the trends explained by GZI.

Emergent constraint with the zonal index

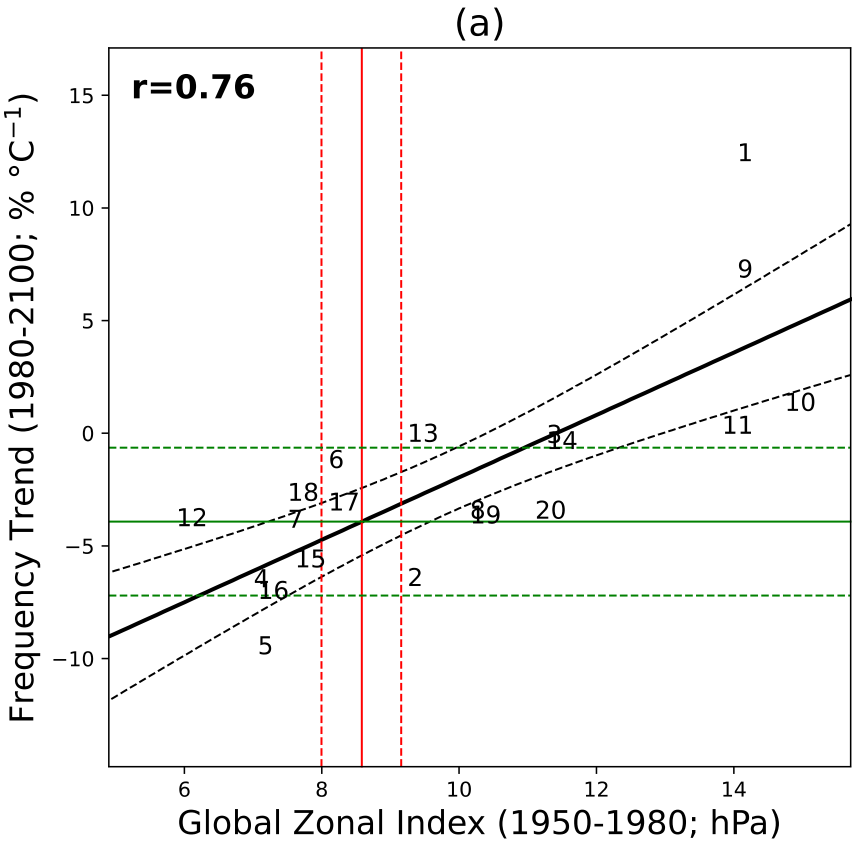
regression of trend on global zonal index



- Estimate the real-world GZI from historical observations from 1950-1980

Emergent constraint with the zonal index

regression of trend on global zonal index



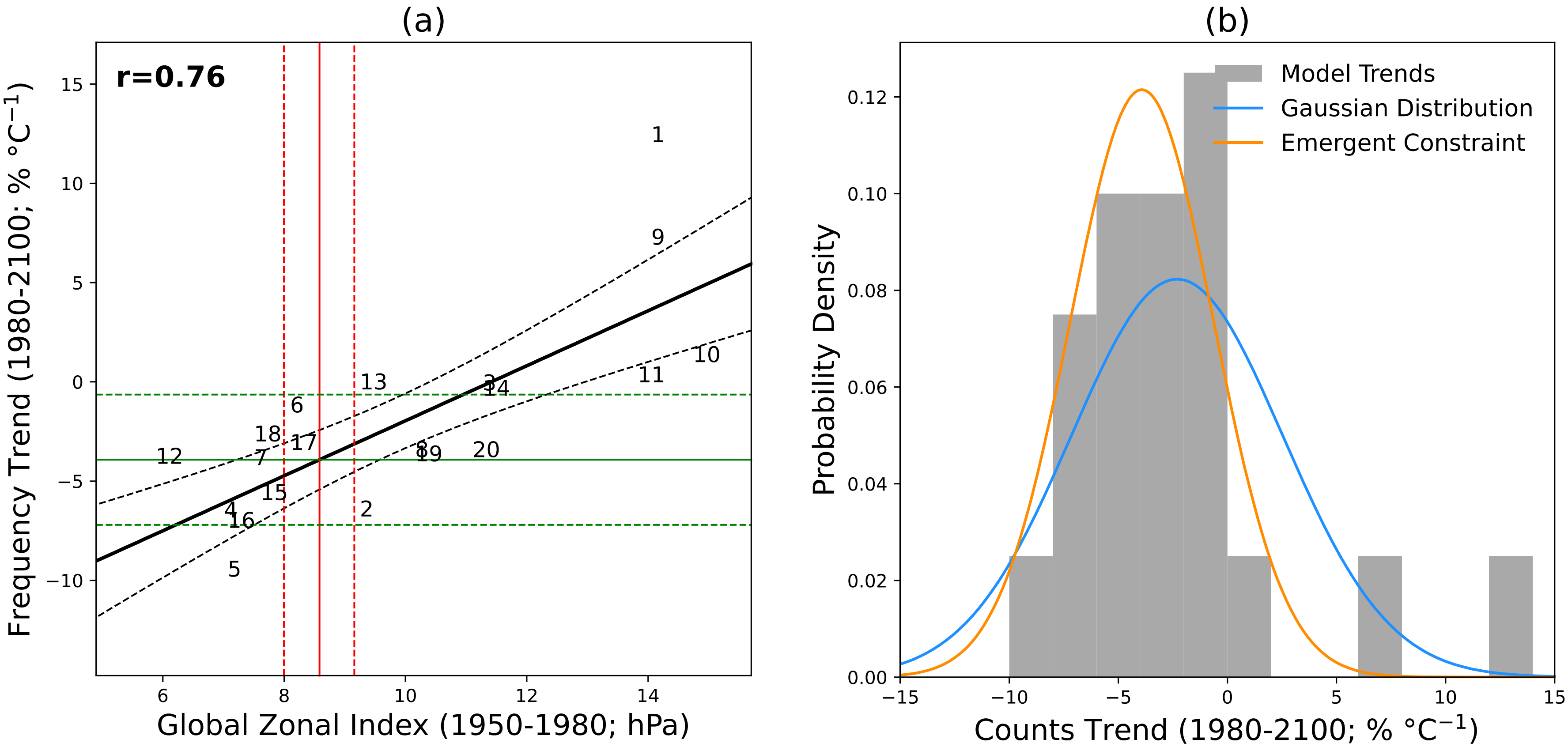
- Use the regression relationship to get a prediction of the constrained trend

→Best estimate of -3.9%/ºC compared to -2.3%/ºC from ensemble mean

→95% confidence interval of [-10.3,2.5]%/ºC compared to [-12.0,7.4]%/ºC from ensemble mean.

Emergent constraint with the zonal index

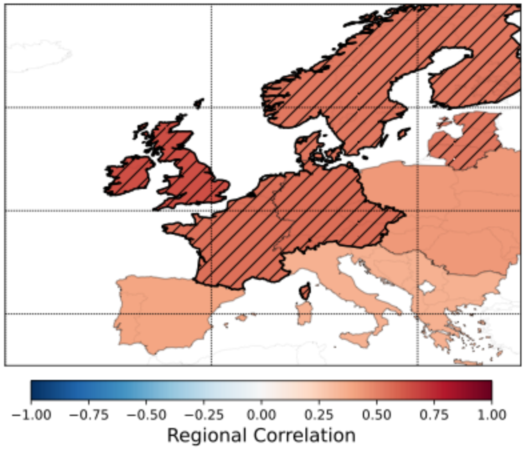
regression of trend on global zonal index



Predicted trend distribution becomes sharper with the standard deviation reducing by one third from 4.9 to 3.3%/°C (more confident projections).

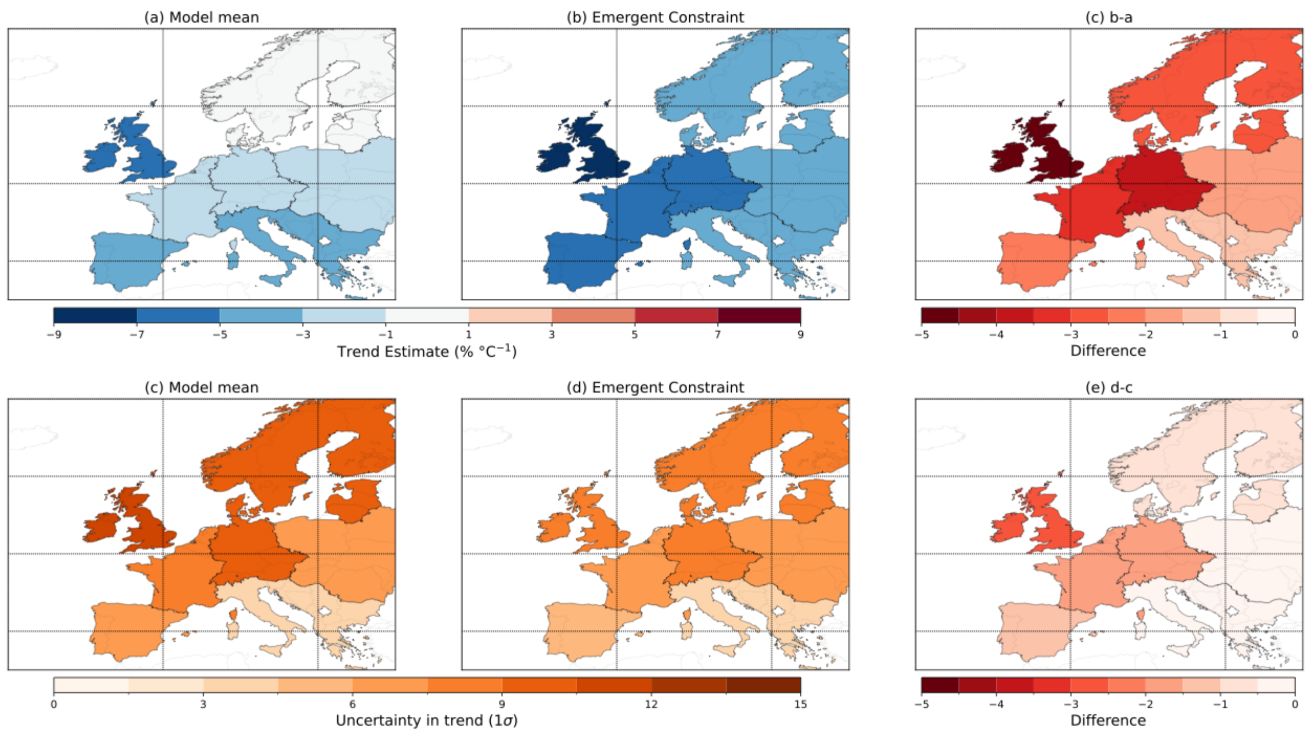
Chance of trends greater than 5%/°C substantially reduced.

Emergent constraint with the zonal index



Correlation of national trends with zonal index

Trend estimates with and without zonal index emergent constraint



What is the physical mechanism?

Differential warming over the N. Atlantic

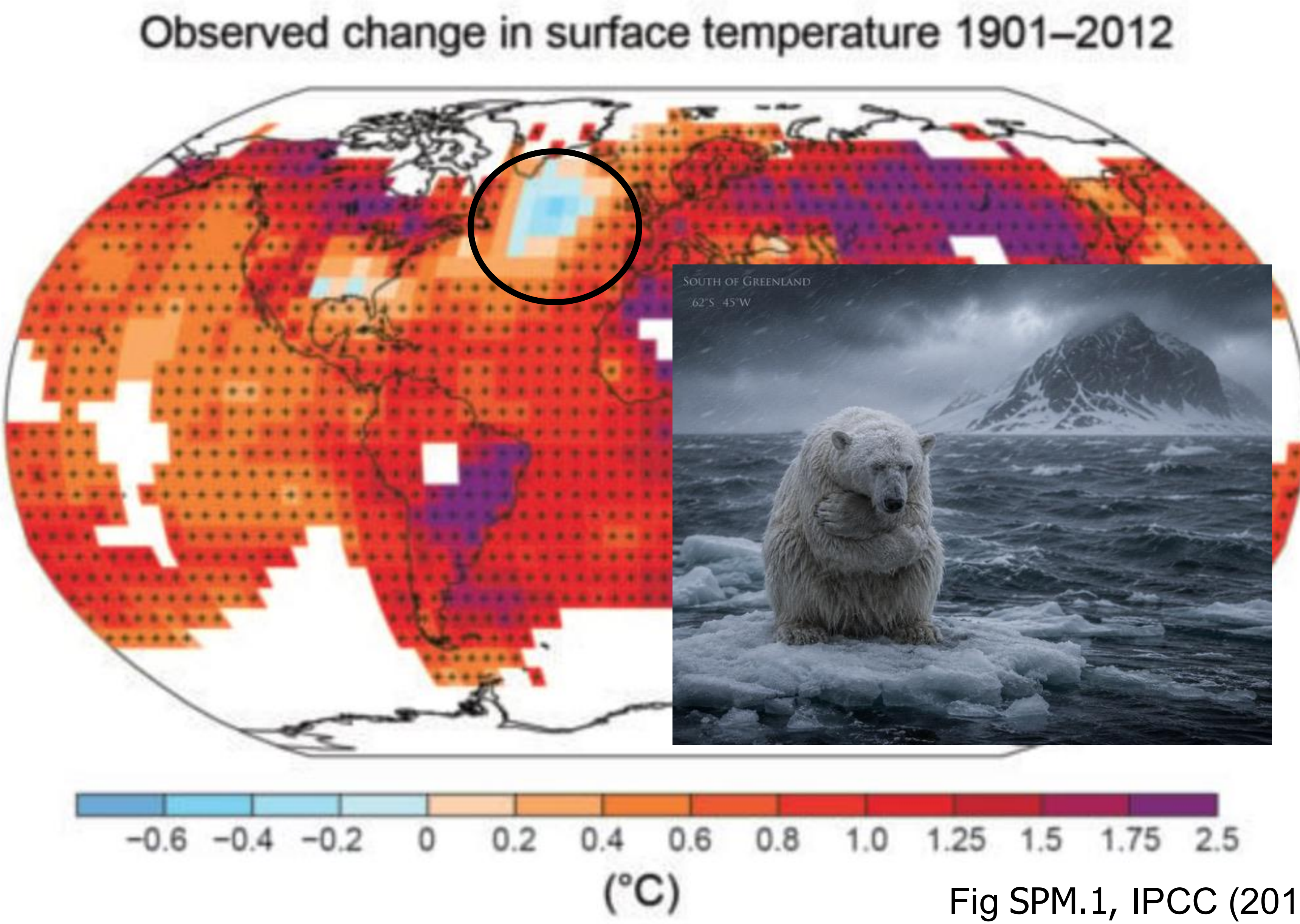
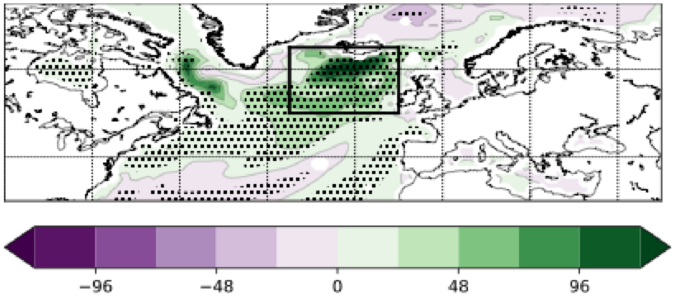


Fig SPM.1, IPCC (2014)

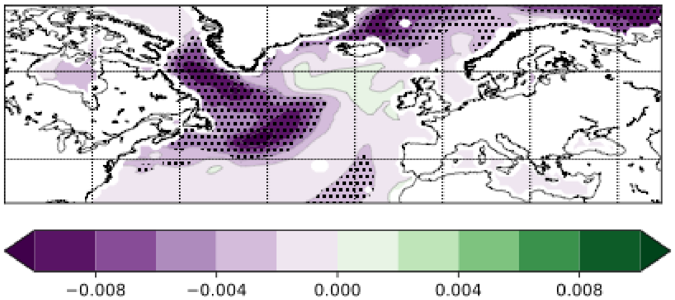
A possible mechanism

Regression slope of mixed-layer depth on GZI



Models with a stronger zonal flow have deeper mixed layers in the North Atlantic

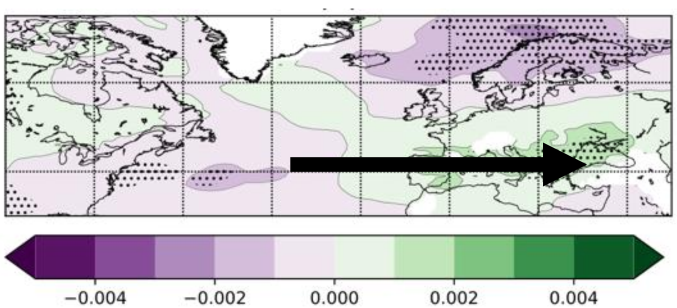
Regression slope of SST change on MLD



Models with deeper mixed-layers do not warm up as much in the N. Atlantic

Less warming leads to greater increase in local latitudinal temperature gradient

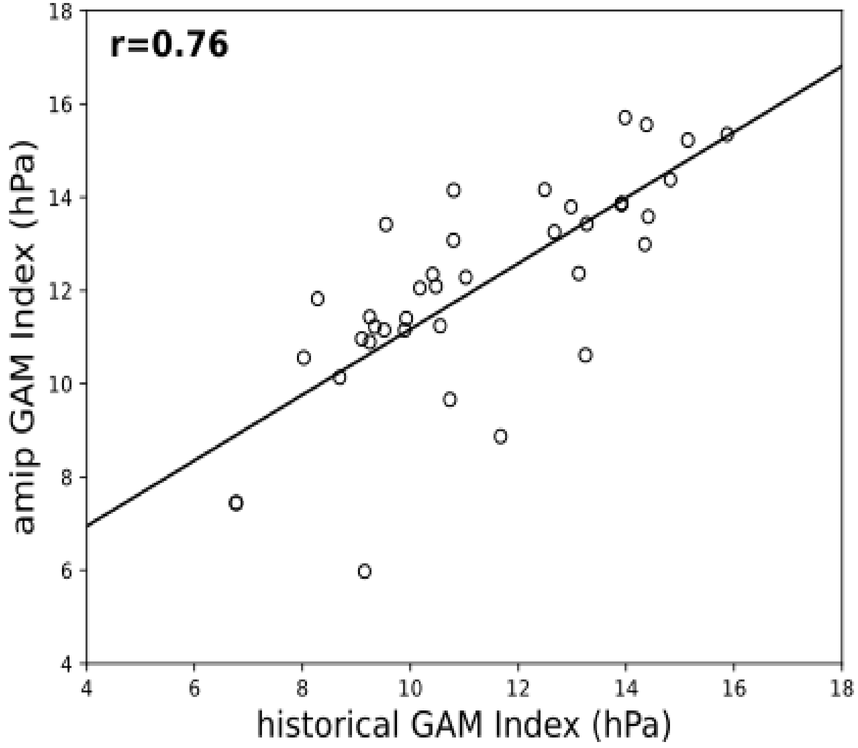
Regression slope of 850hPa u on Irminger MLD



Greater increase in local temperature gradient leads to greater increase in westerlies and storm track over Europe.

Origin of zonal flow differences: the atmosphere models

Historical zonal flow in coupled and atmosphere-only models



→ Strong correlation between the atmosphere-only (prescribed SST) and coupled model historical states

→ Suggests the differences are due to differences in the atmosphere models

Summary

- Different climate models give widely different trend projections for storminess. Much of this variation is related to the strength of the zonal flow in the models.

- Models with stronger zonal flows are found to have deeper ocean mixed-layers south of Greenland, which in turn leads to slower rates of warming in this region. The decreased warming causes meridional temperature gradients to be greater further south over the N. Atlantic ocean thereby increasing baroclinicity and strengthening the jet and storm track.

- This can be used as a constraint to have more confidence in what the real-world trend might be (i.e. most likely a decreasing trend)

Thank you for your attention
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Emergent constraint indicates forced decline in European windstorm frequency, Environmental Research Letters (in review).