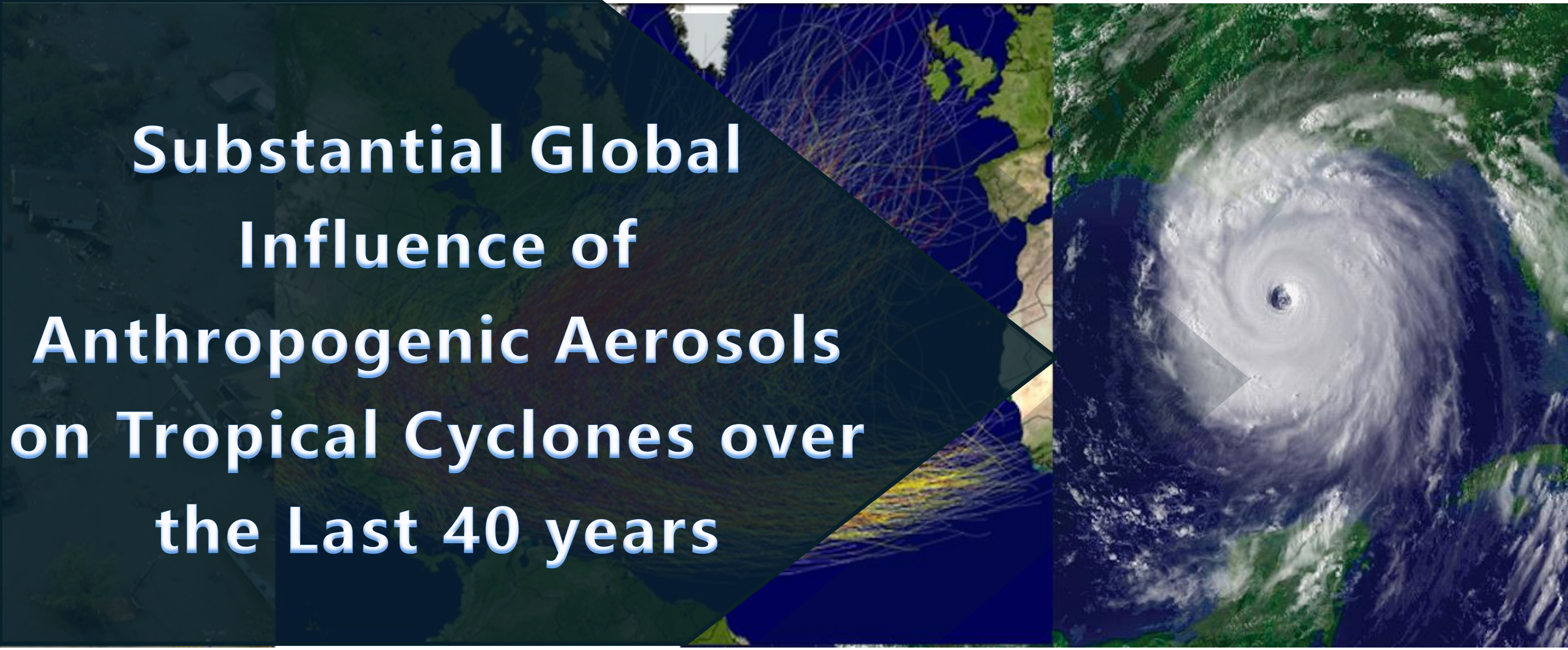
Substantial Global Influence of Anthropogenic Aerosols on Tropical Cyclones over the Last 40 years



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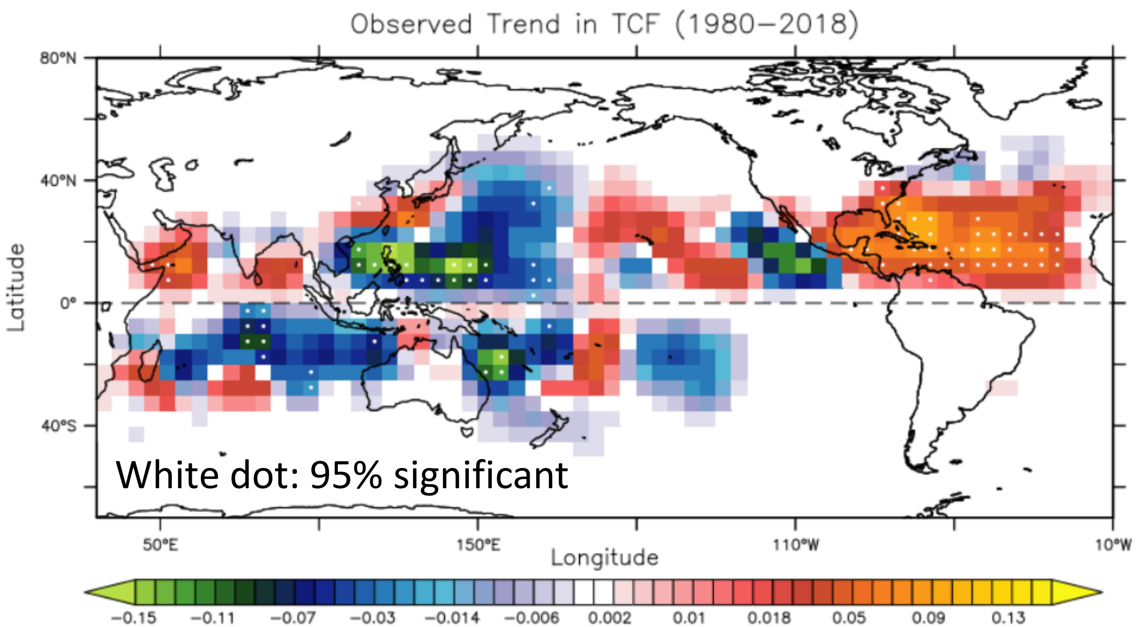
IDAG Meeting 07/04/2023

Observed Trend in Global TC Activity (1980-2018)



Decreasing Frequency

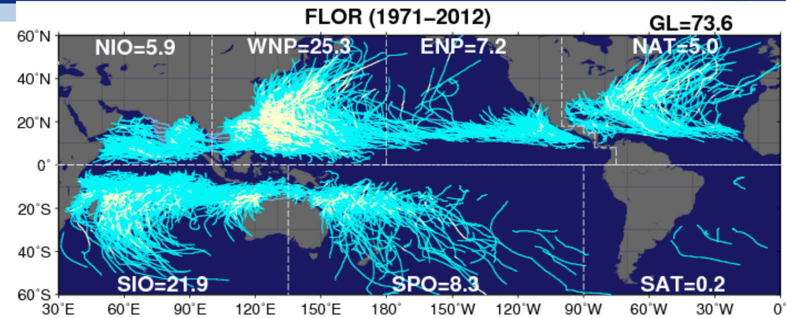
Increasing Frequency

Murakami et al. (2020, *PNAS*)

- TCF (or TC density) is defined as the total TC frequency of occurrence for every 5x5 degree grid cell.
- TCF shows significant negative and positive trends depending on region over 1980-2018.
- **Is this spatial pattern of the trends due to the external forcing or internal variability?**

GFDL-FLOR & SPEAR –High-Resolution Climate Model–

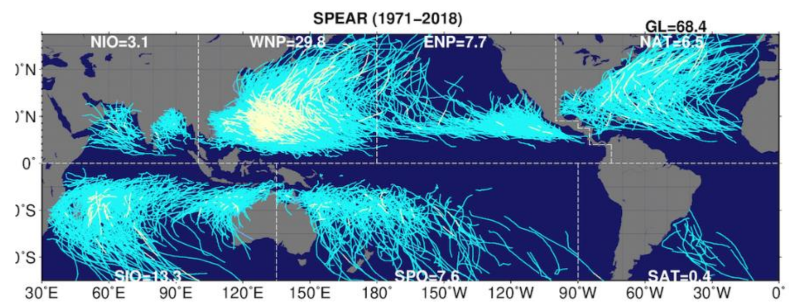
GFDL-FLOR
Vecchi et al. (2014)



A modified version of CM2.5 (Delworth et al. 2012):

- 50km cubed-sphere atmosphere (Same as CM2.5)
- 1° ocean/sea ice (low res enables prediction work; 0.25° for CM2.5)
- Former operational seasonal forecast model for NMME (Vecchi et al. 2014)

GFDL-SPEAR
Delworth et al. (2020)



A modified version of AM4 (atmosphere) & MOM6 (ocean) & SIS2 (ice) & LM4 (land)

- 50km cubed-sphere atmosphere for SPEAR-MED (Same as FLOR)
- 1° ocean/sea ice (Same as FLOR)
- Current operational seasonal forecast model for NMME (Lu et al. 2020)

TC tracks are detected using 6-hourly outputs considering maximum wind speed (15.75m/s), warm core (1K), and duration (36 hours) (Harris et al. 2016).

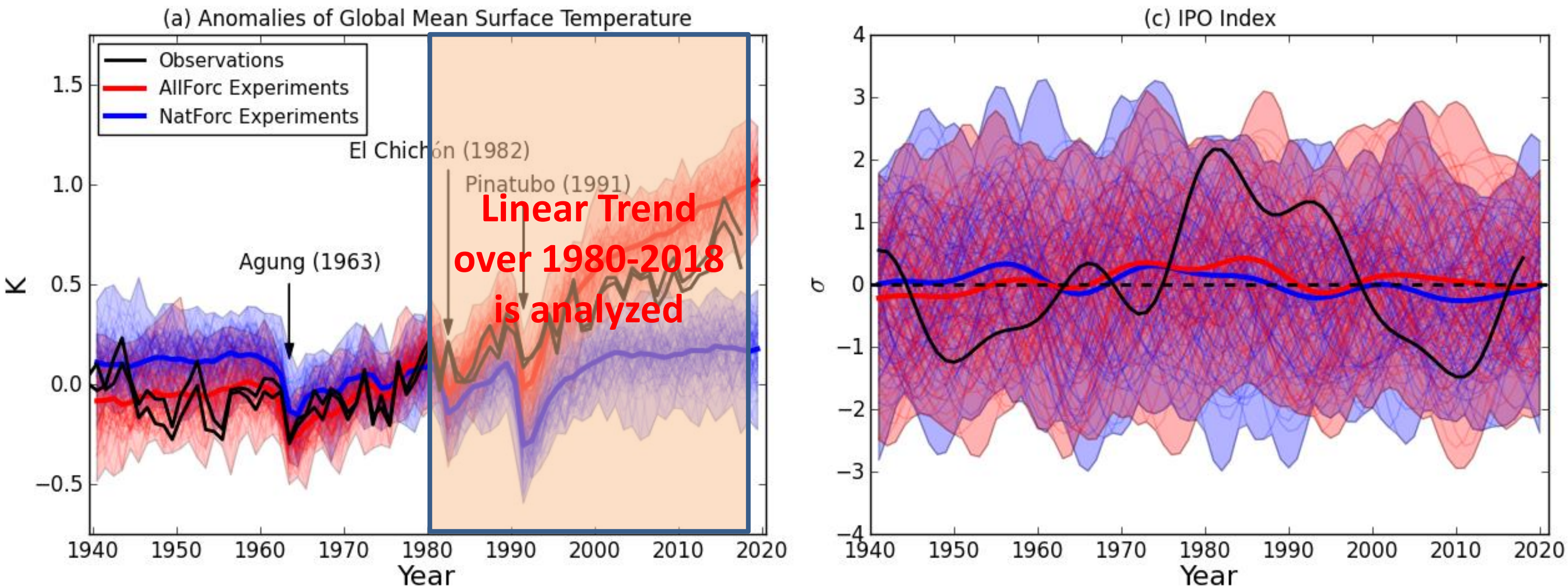
Large-Ensemble Simulations by SPEAR, FLOR, and FLOR-FA

AllForc: Historical simulations by prescribing time-varying external forcing (greenhouse gases, aerosols, volcanic forcing, and solar constant)

95 ensemble members: SPEAR (30 members), FLOR (30 members), and FLOR-FA (35 members)

NatForc: As in AllForc, but only with time-varying volcanic forcing and solar constant.

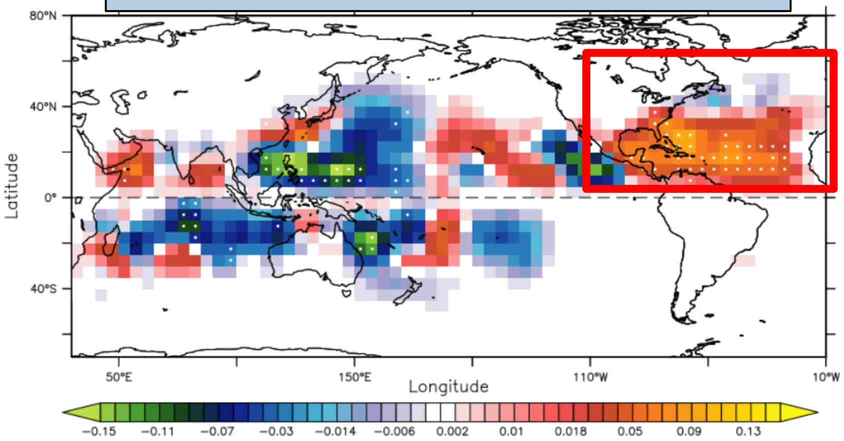
90 ensemble members = SPEAR (30 members), FLOR (30 members), and FLOR-FA (30 members)



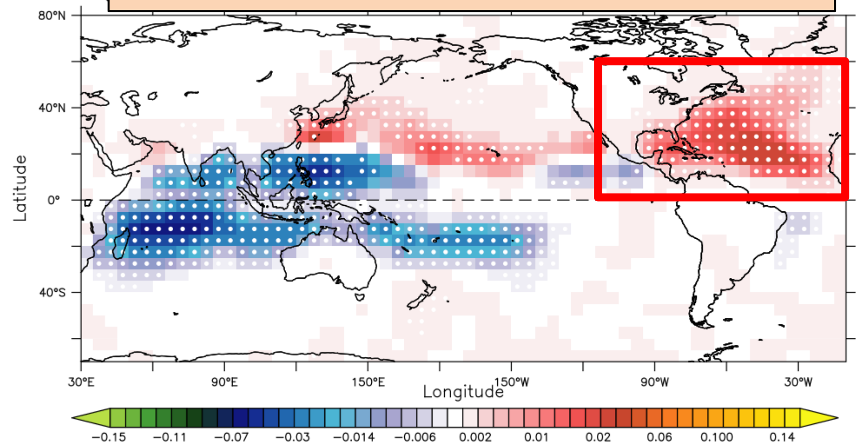
Because of the different initial states, each ensemble member shows a different phase of internal variability. Internal variability can be canceled out by averaging the members.

Effect of External Forcing on the TCF Trend

Observed Trend in TCF (1980-2018)

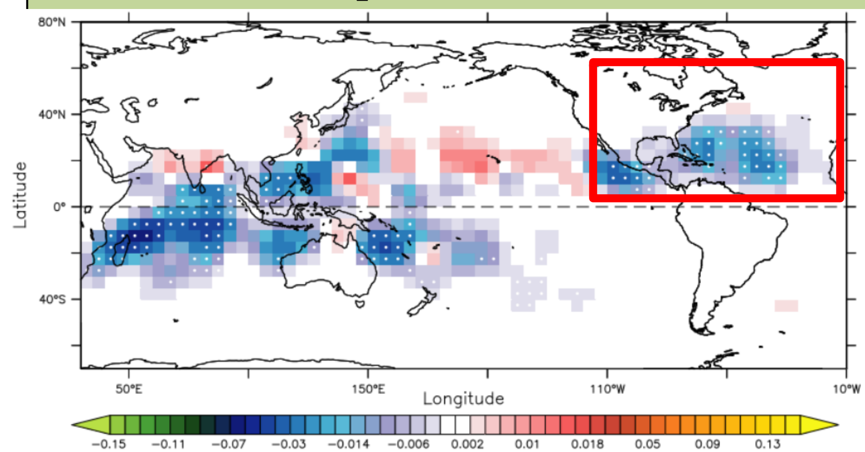


AllForc (95-member mean, 1980-2018)



All forcing includes greenhouse gases, anthropogenic aerosols, ozone.

Transient $2xCO_2$ (3-member mean, 70 yrs)



Transient +1%/yr CO_2 Experiment

- Fully Coupled
- +1% CO_2 increase up to $2xCO_2$ (at year 171) then fixed

Hypothesis:

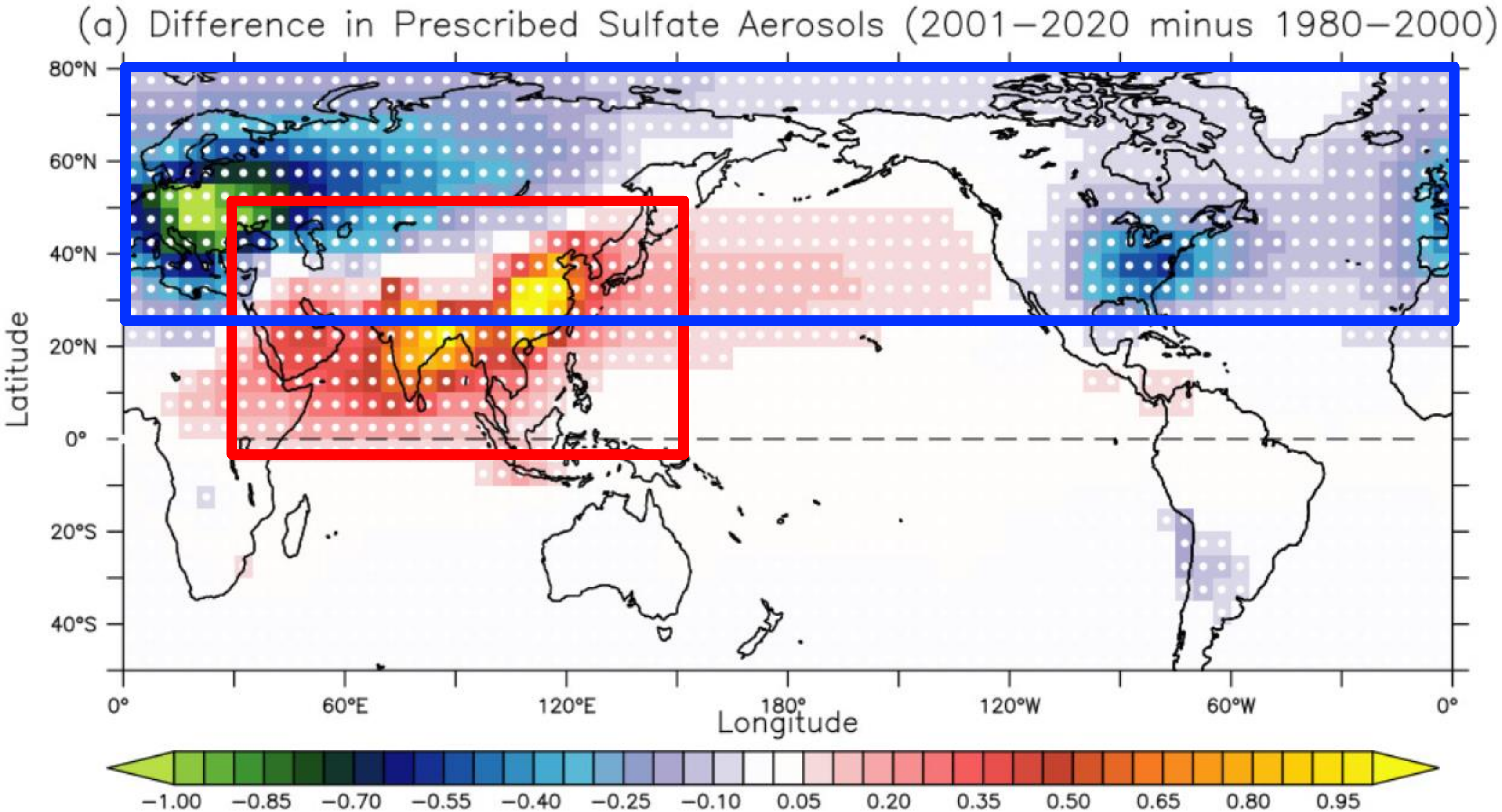
External forcings other than greenhouse gases are responsible for the increased hurricanes in the North Atlantic.

Anthropogenic aerosols may be the key.

Murakami et al. (2020, *PNAS*)

Changes in anthropogenic aerosols in the past 40 years

Sulfate changes (2001-2020 minus 1980-2000)



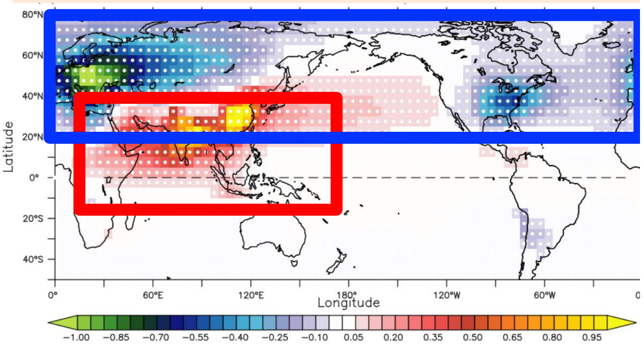
Decreased aerosols from Europe and the United States

Increased aerosols from China and India

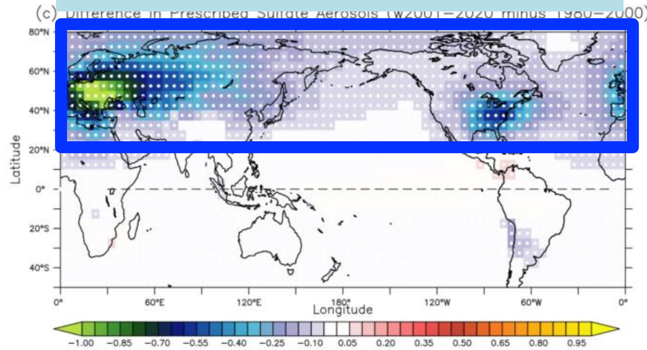
How have these regional changes in aerosols exerted changes in global TC frequency?

Experimental Setting

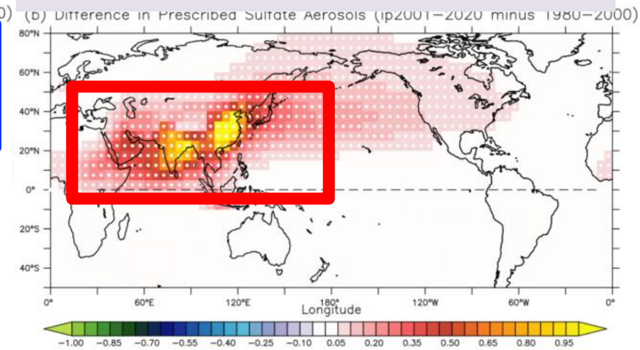
ΔALL21, Sulfate



ΔW21, Sulfate



ΔIP21, Sulfate

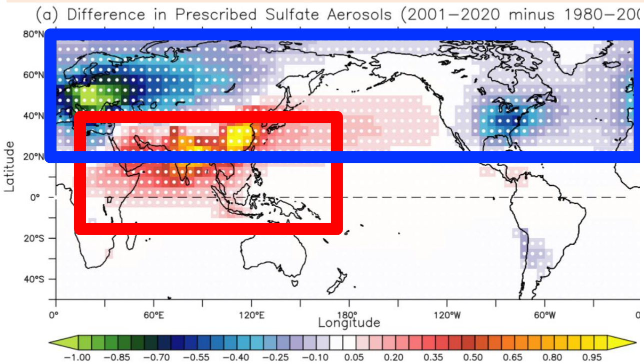


We conducted idealized model experiments using GFDL-SPEAR by imposing different aerosol emissions.

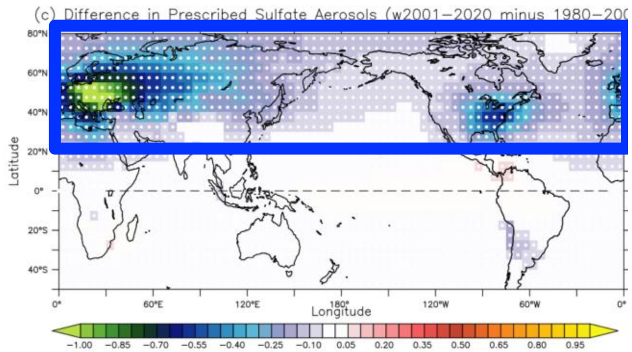
Exp name	Specified emission of anthropogenic aerosols (sulfates, black carbon, organic carbon etc.)	Other external forcings (e.g., CO_2)	Simulation years	Difference from CNTL
CNTL	Mean of 1980-2000	Fixed level at 2000	200 years	—
ALL21	Mean of 2001-2020			ΔALL21
W21	Mean of 2001-2020 for Europe and the US, mean of 1980-2000 for the rest of the world			ΔW21
IP21	Mean of 2001-2020 for China and India, mean of 1980-2000 for the rest of the world			ΔIP21

Effect of anthropogenic aerosols on global tropical cyclones

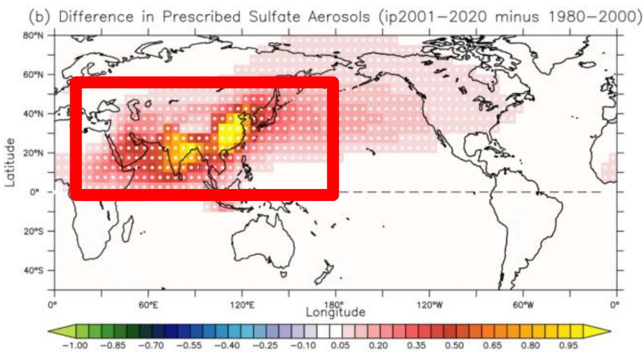
ΔALL21, Sulfate



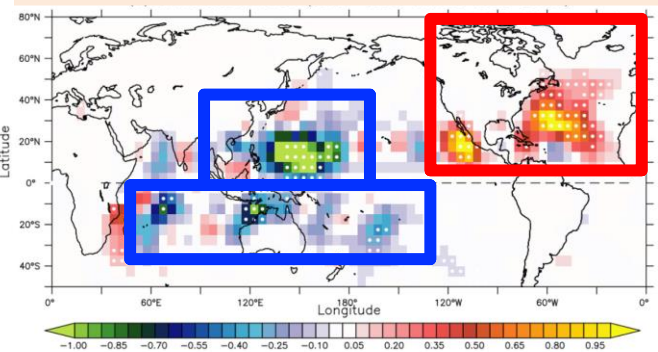
ΔW21, Sulfate



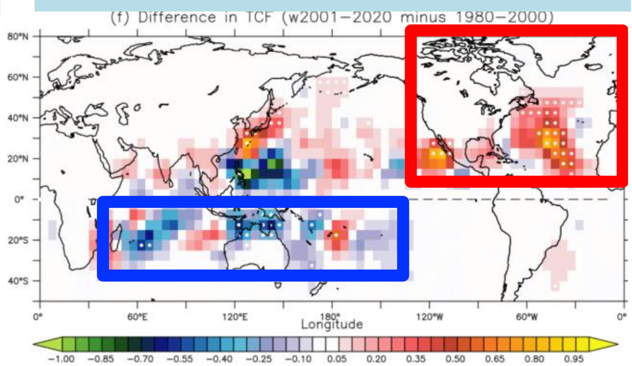
ΔIP21, Sulfate



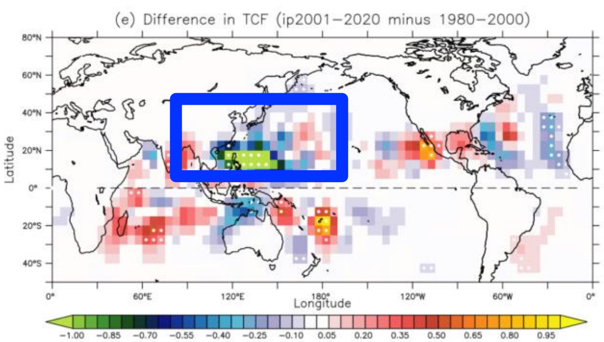
ΔALL21, TCF



ΔW21, TCF



ΔIP21, TCF



Decreased aerosols from Europe and the United States =>

Increased TCF in the North Atlantic

Decreased TCF in the Southern Hemisphere

Increased aerosols from China and India =>

Decreased TCF in the western North Pacific

Observed and simulated changes in TCF

TCF

	Period or Difference	Fractional Difference (p-value) WNP	NA	SH
Observations	2001-2020 minus 1980-2000	− **22.3%** (0.03)	**30.6%** (0.01)	−**34.5%** (0.00)
δALL21	ALL21 minus CNTL	−**4.8%** (0.01)	**8.7%** (0.00)	−**6.4%** (0.01)
δW21	W21 minus CNTL	−1.4% (0.46)	**6.5%** (0.03)	−**4.8%** (0.03)
δIP21	IP21 minusCNTL	−**4.1%** (0.04)	−1.8% (0.60)	1.9% (0.36)

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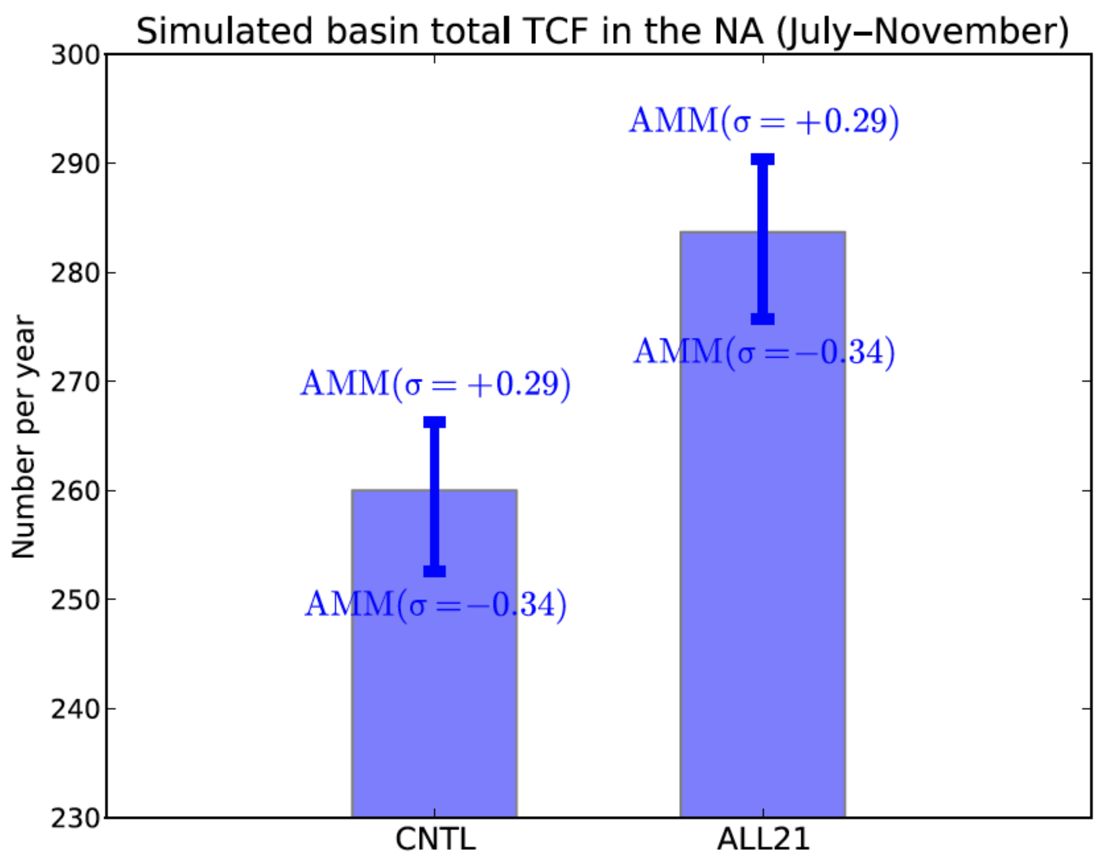
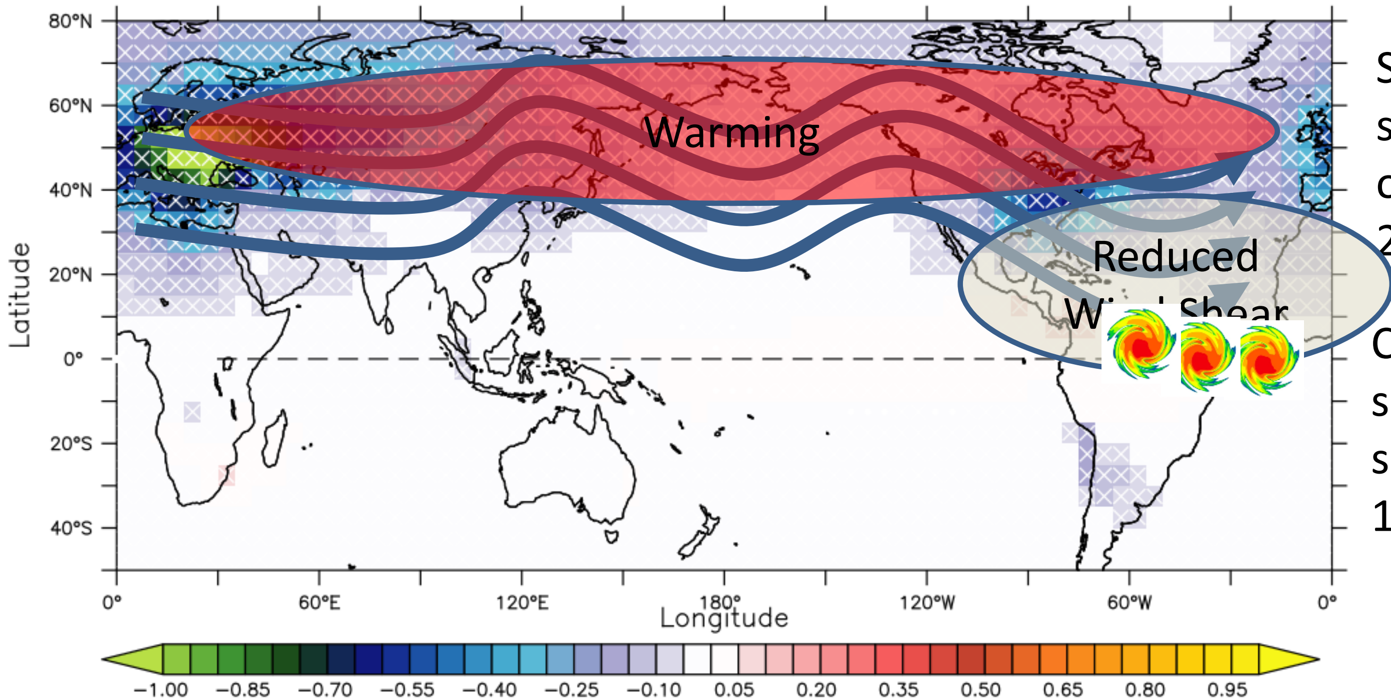


Physical Mechanisms behind the TCF change



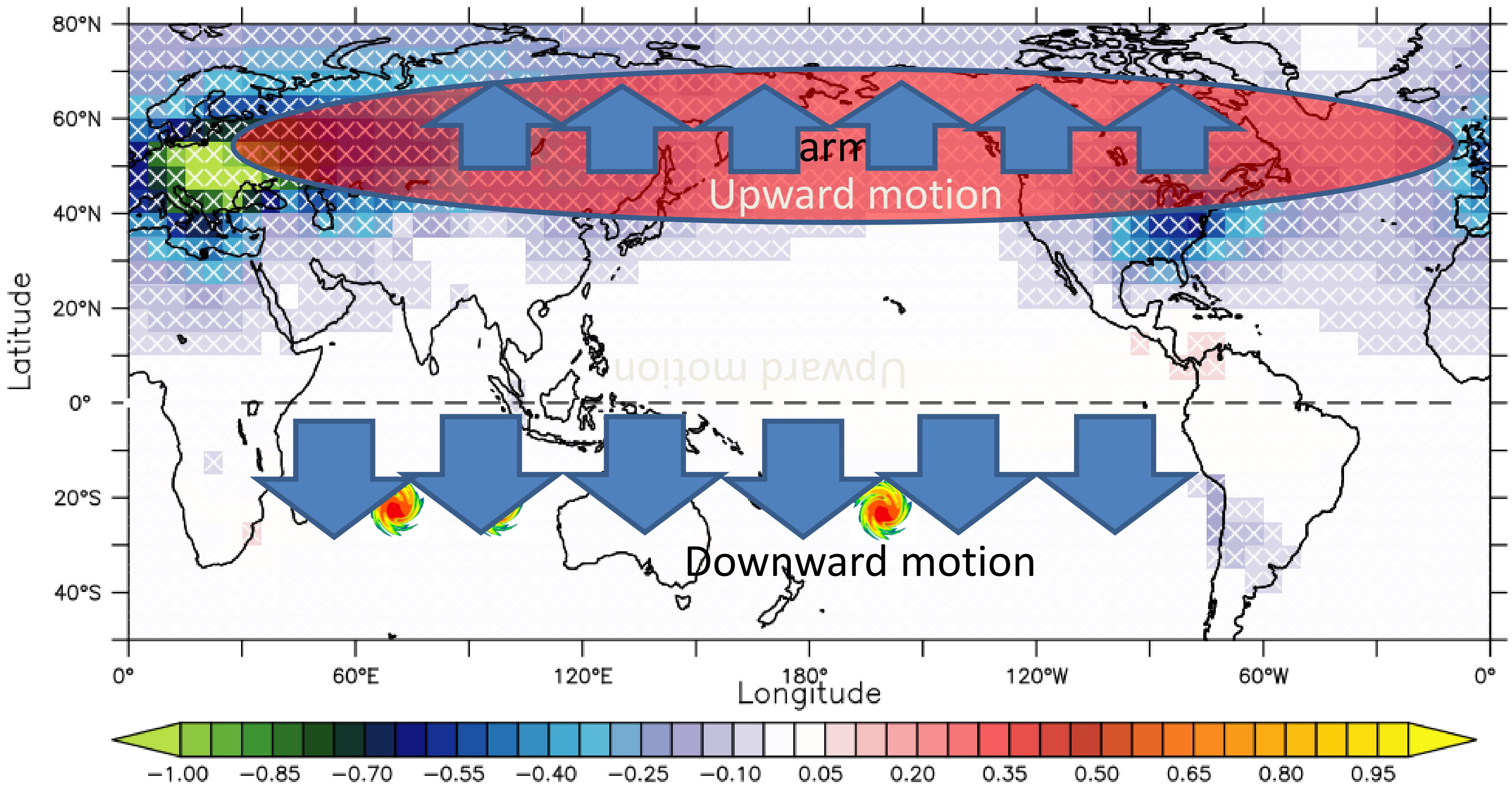
Shading: Linear trend in sulfate concentration over the period 1980-2020

Cross mark: Statistically significant decrease in sulfate over the period 1980-2020

The tropospheric warming in the mid-latitudes by reduced aerosols causes a weakening of the subtropical jet.

This leads to reduced vertical wind shear (reduced difference in wind speeds between lower and upper troposphere), which is favorable for tropical cyclone activity in the North Atlantic (indirect effect).

Physical Mechanisms behind the TCF change

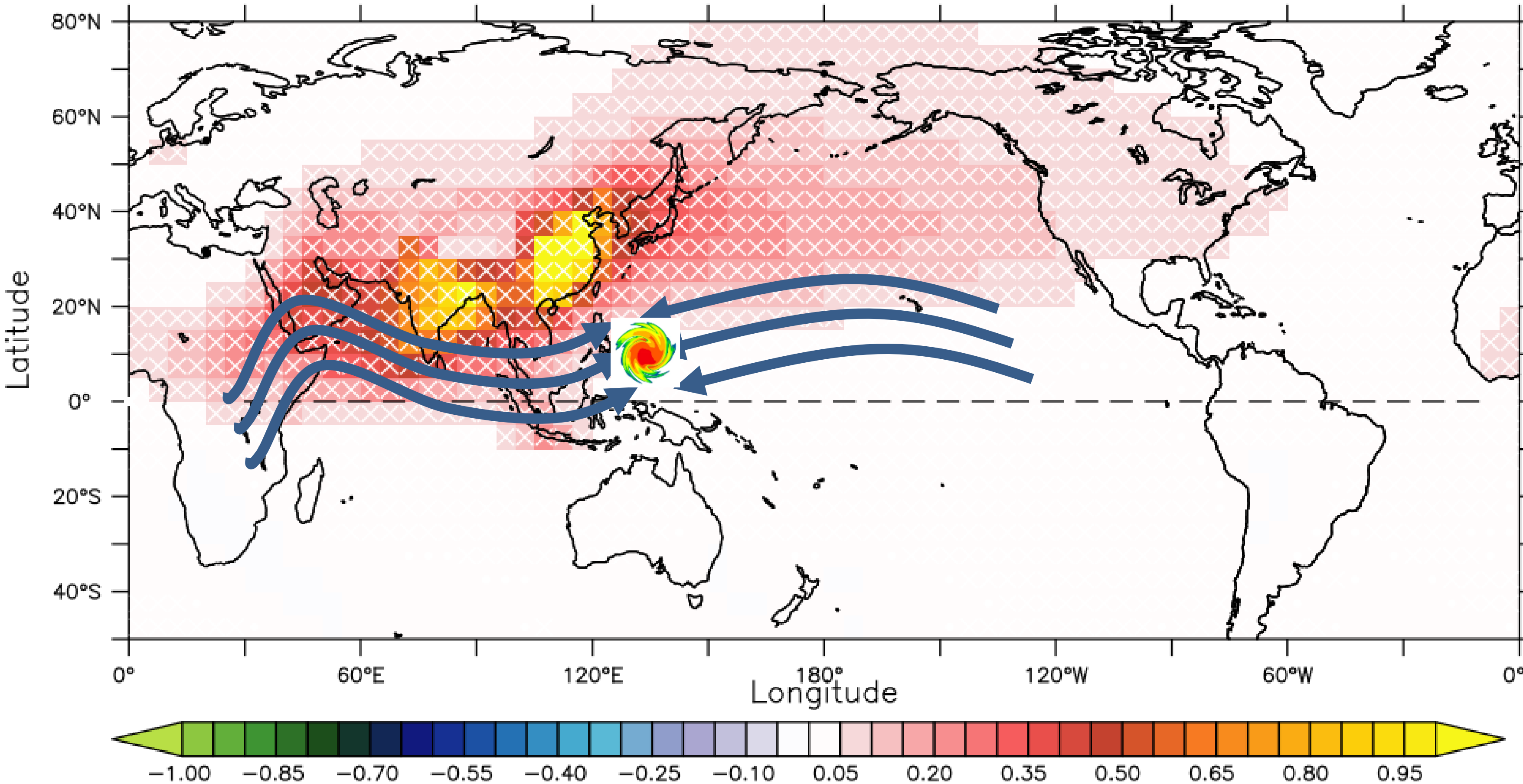


The warming in the mid-and high-latitudes in the Northern Hemisphere also caused Hemispheric circulation anomaly.

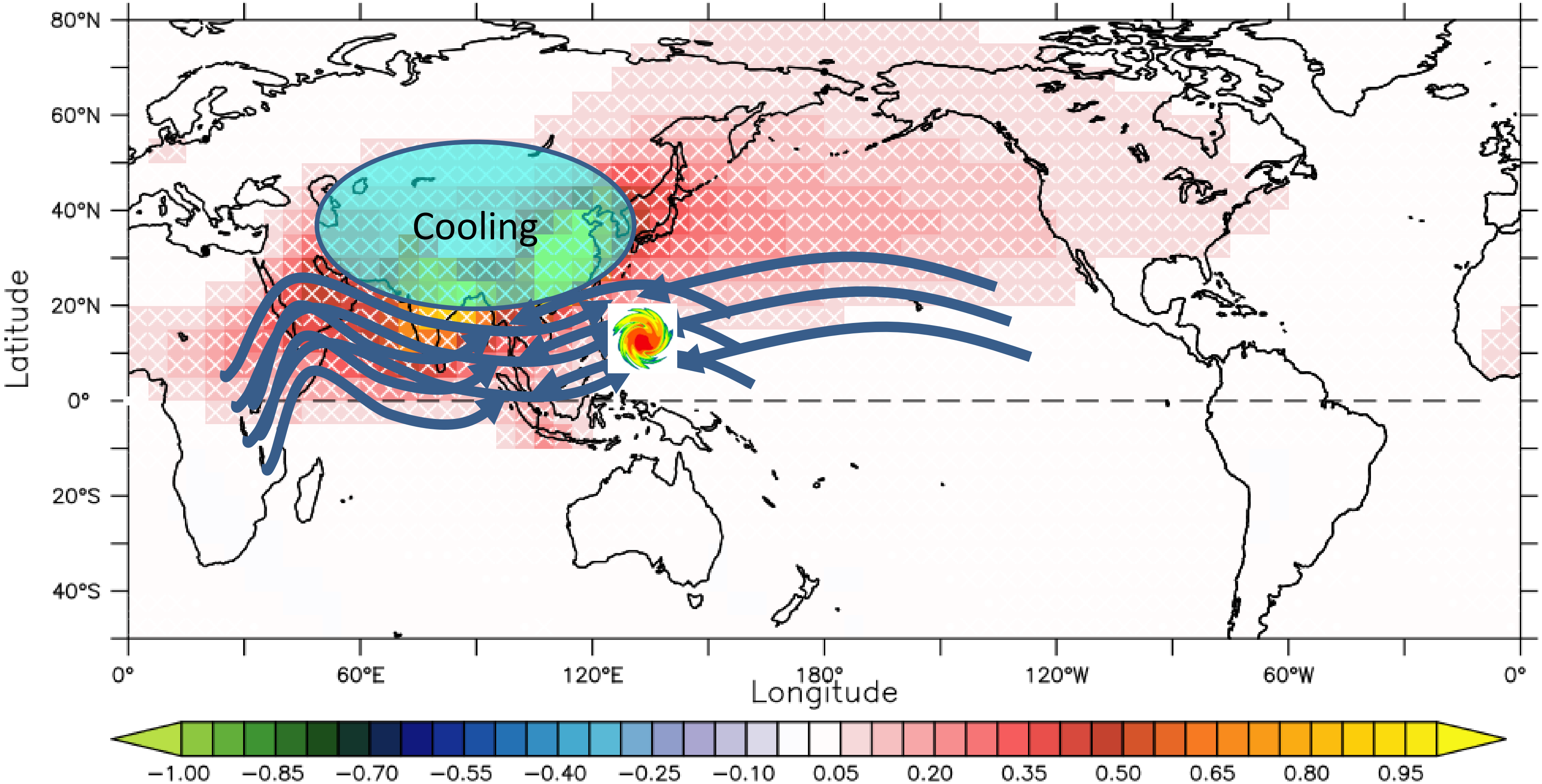
The warming causes anomalous upward motions by the enhanced convective activity.

The anomalous upward motion leads to downward motion in the Southern Hemisphere, in turn reducing tropical cyclones

Physical Mechanisms behind the TCF change



Tropical cyclones in the western North Pacific generally develop around the monsoon trough in the boreal summer.



The cooling over the land surface caused a weakened Indian monsoon, resulting in a weakened monsoon trough.

This in turn led to decreased tropical cyclones over the western North Pacific over the period 1980-2020.

Increased aerosols from China and India helped to reduce tropical cyclones.

Takeaway Message

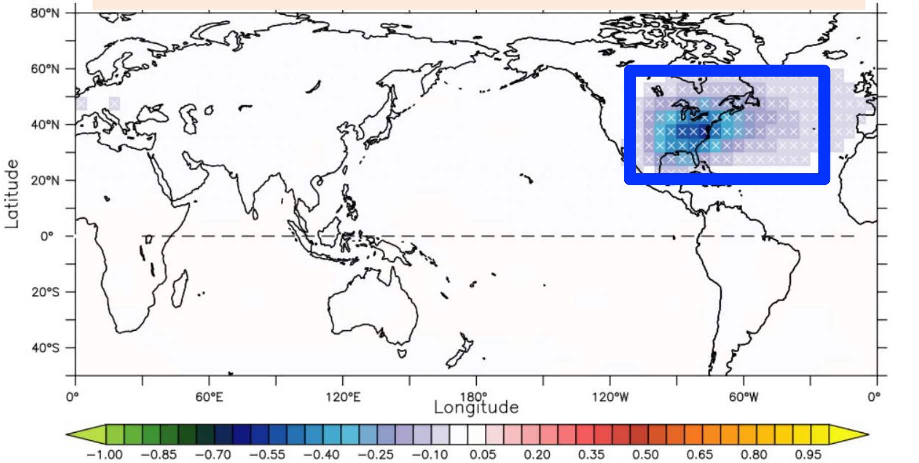
- A substantial influence of anthropogenic aerosols on the changes in global TC frequency of occurrence over 1980–2020.

- The decreased aerosols emission from Europe and the United States might have led to increased hurricanes in the North Atlantic and decreased tropical cyclones in the Southern Hemisphere.

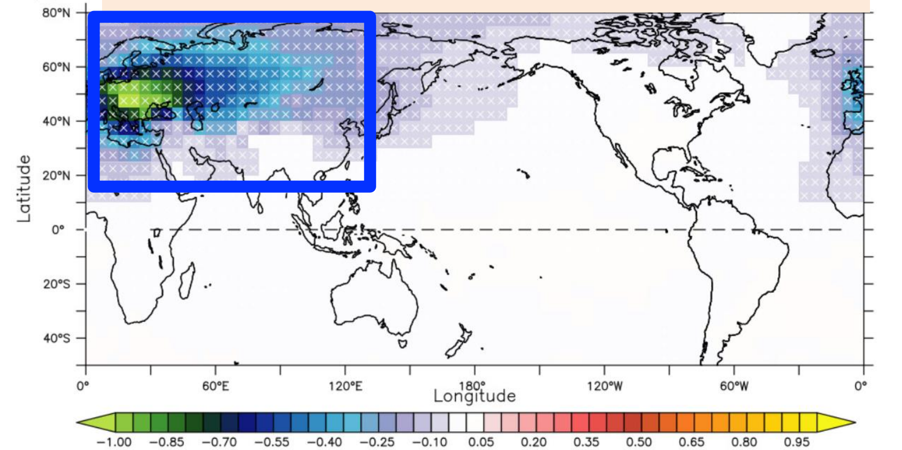
- The increased aerosols emission from China and India might have led to decreased typhoons in the western North Pacific.

Additional Aerosol Experiments (US and EURO)

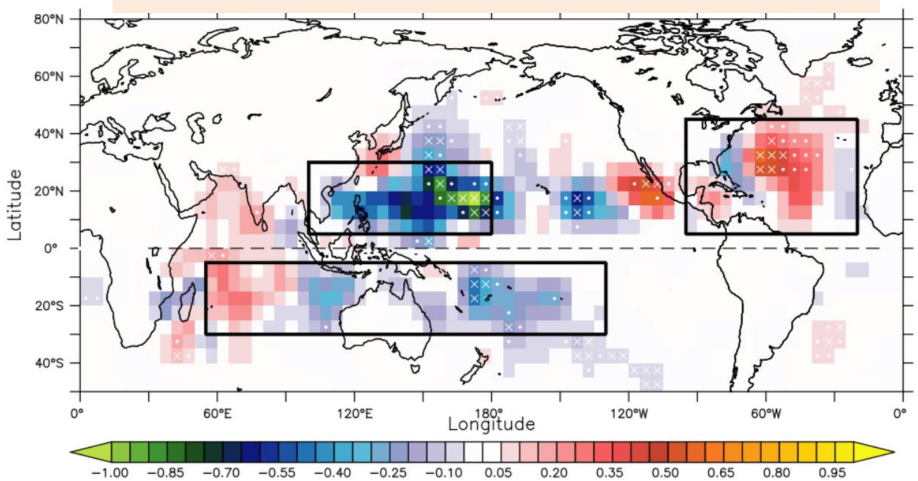
ΔUS, Sulfate



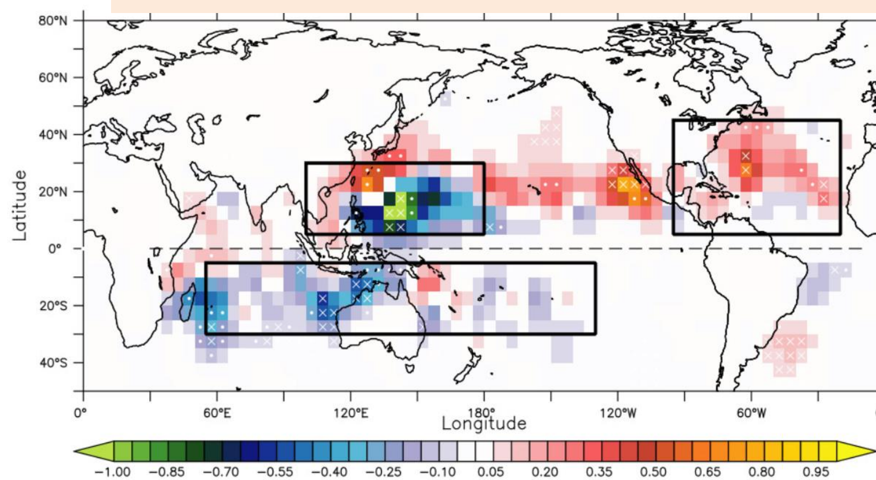
ΔEURO, Sulfate



ΔUS, TCF



ΔEURO, TCF



Additional Aerosol Experiments (China and India)