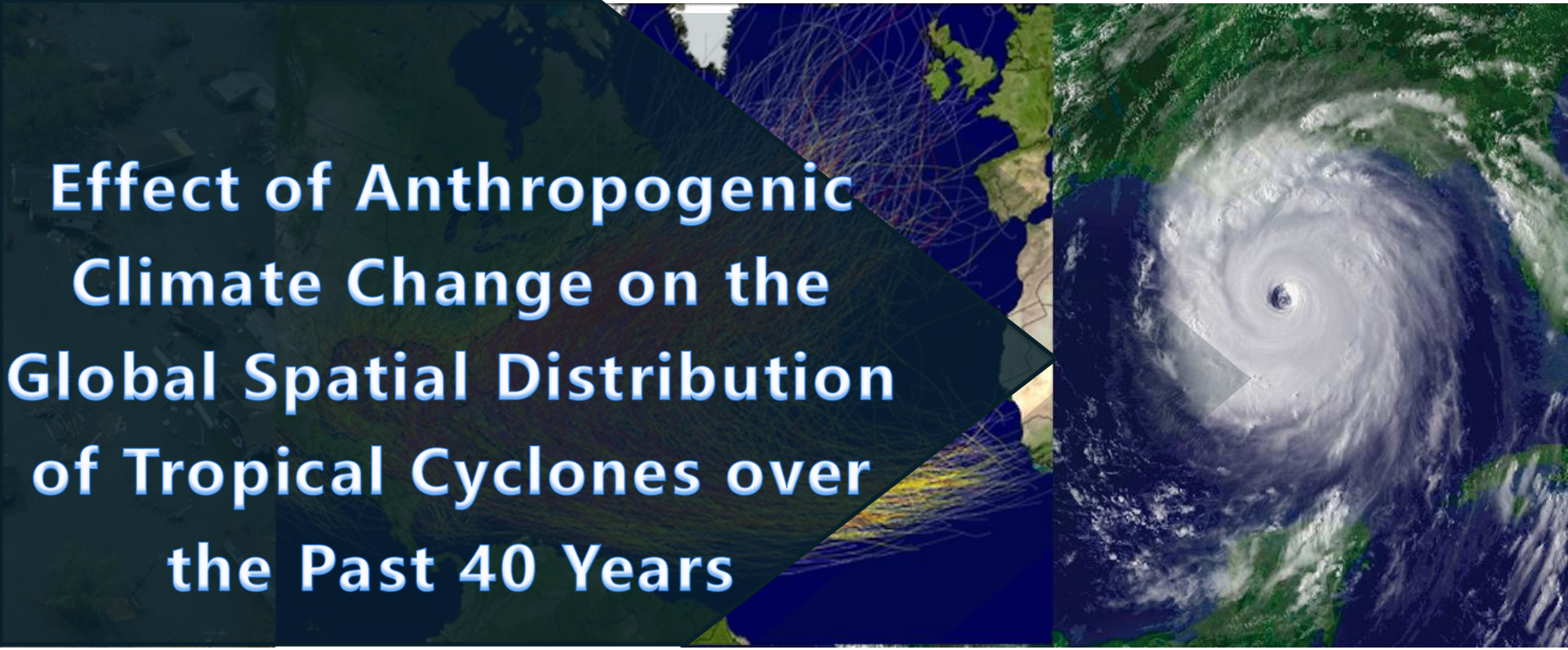


Hiro Murakami

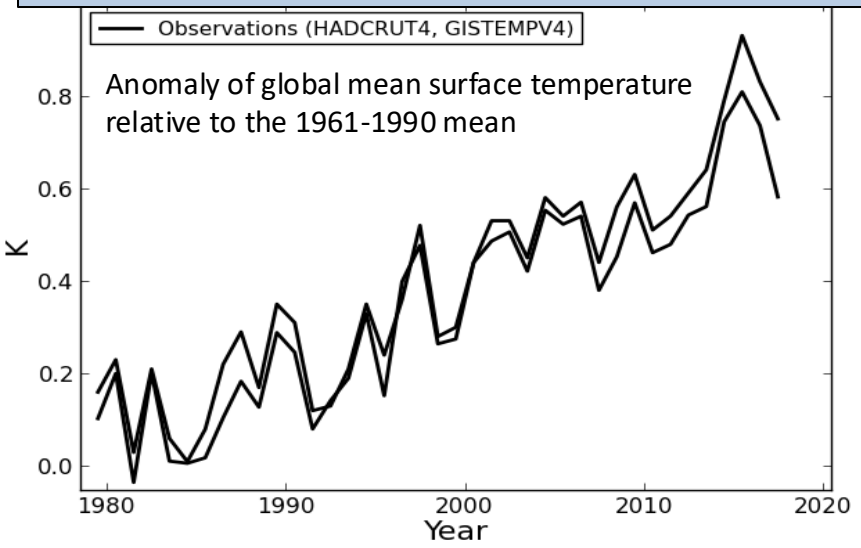
NOAA-GFDL

Murakami, H., T. L. Delworth, W. F. Cooke, M. Zhao, B. Xiang, and P. -C. Hsu, 2020: Detected climatic change in global distribution of tropical cyclones. *PNAS.*, **117(20)**, 10706-10714.

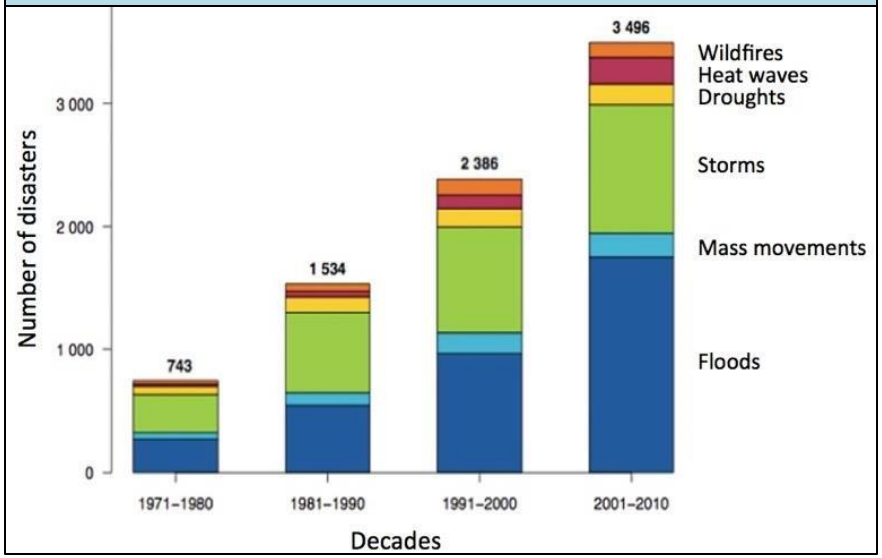
Murakami, H., 2022: Substantial global influence of anthropogenic aerosols on tropical cyclones over the past 40 years. *Sci. Adv.*, **8**, eabn9493.

Observed Trends in Global Mean Surface Temperature and Number of Global Tropical Cyclones (1980-2018)

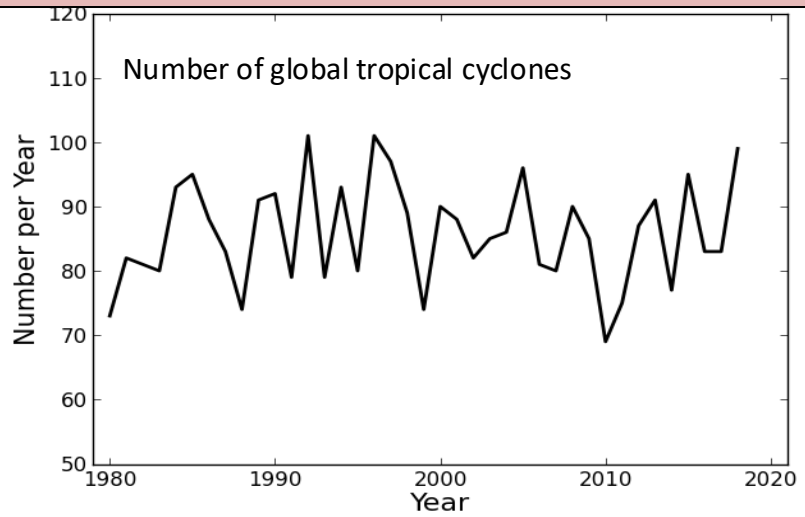
Observed global mean surface temperature shows an increase since 1980.



Global Frequency of Natural Disasters (1971–2010)

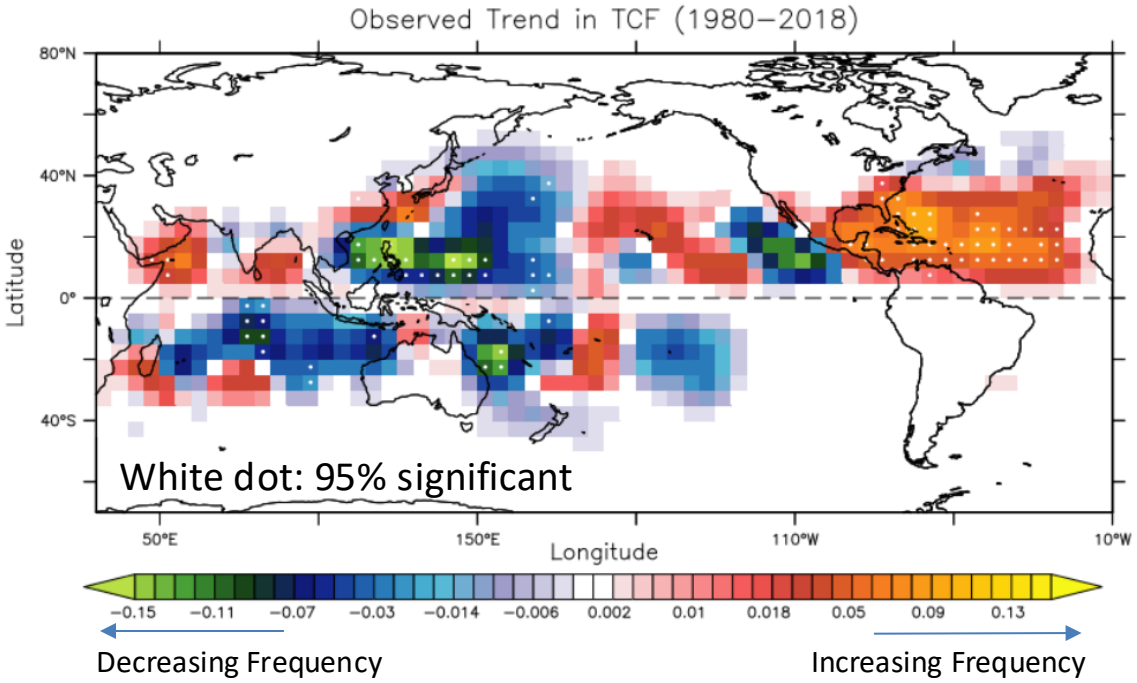


There is no significant trend in global TC number, indicating no impact of global warming on global TC.



Are there really no climatic change emerged in the global tropical cyclone activity?

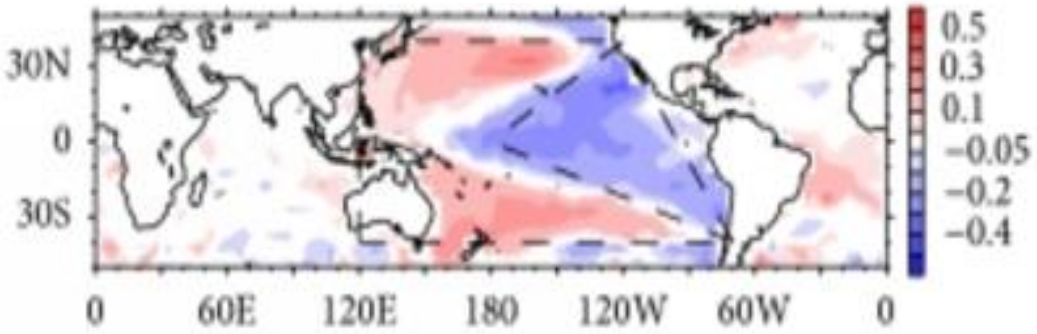
Observed Trend in Global TC Activity (1980-2018)



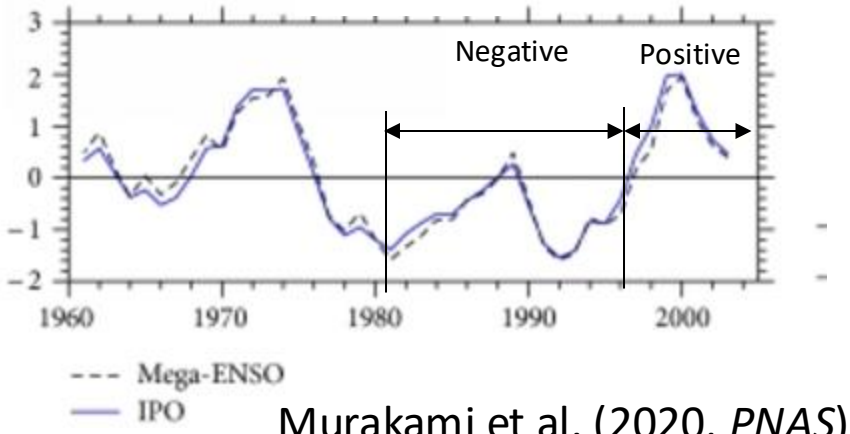
- TCF (or TC density) is defined as total TC frequency of occurrence for every 5x5 degree grid cell.
- TCF shows significant negative and positive trends depending on region over 1980-2018.
- **Is this spatial pattern of the trends due to the external forcing or internal variability?**

Inter-decadal Pacific Oscillation (IPO)

Observed SST regressed on IPO index



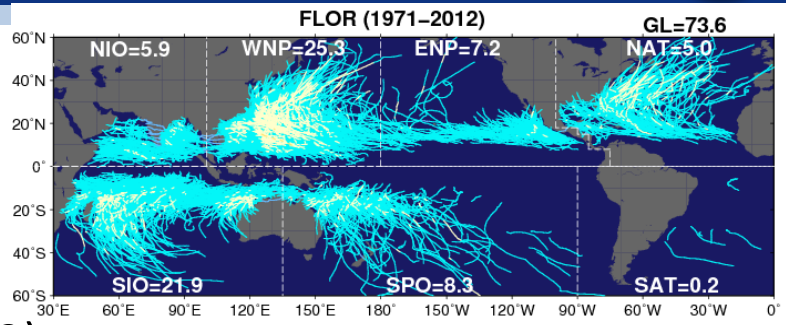
IPO index



Murakami et al. (2020, *PNAS*)

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

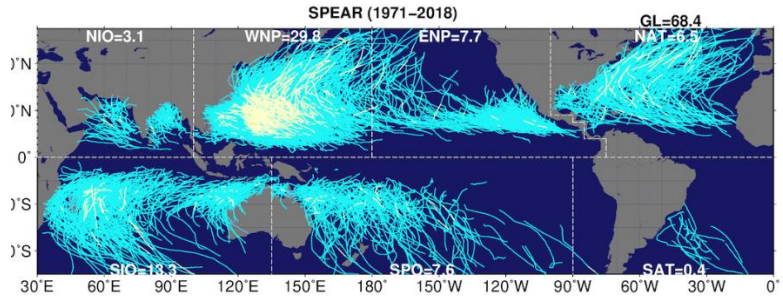
GFDL-FLOR
Vecchi et al. (2014)



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).

Impact of IPO on TCF (Long-term Control Experiments)

PiControl: Free running coupled-model simulations forced with the fixed anthropogenic forcing at the 1860 level.

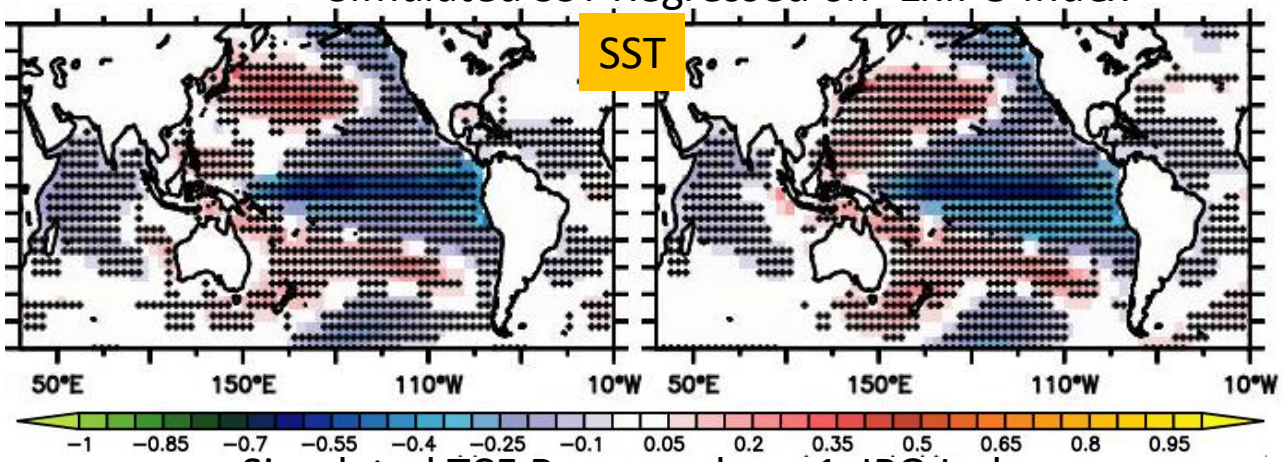
FLOR (1000-years)

SPEAR (1000-years)

FLOR (50-km, Coupled model)
SPEAR (50-km, Coupled model)

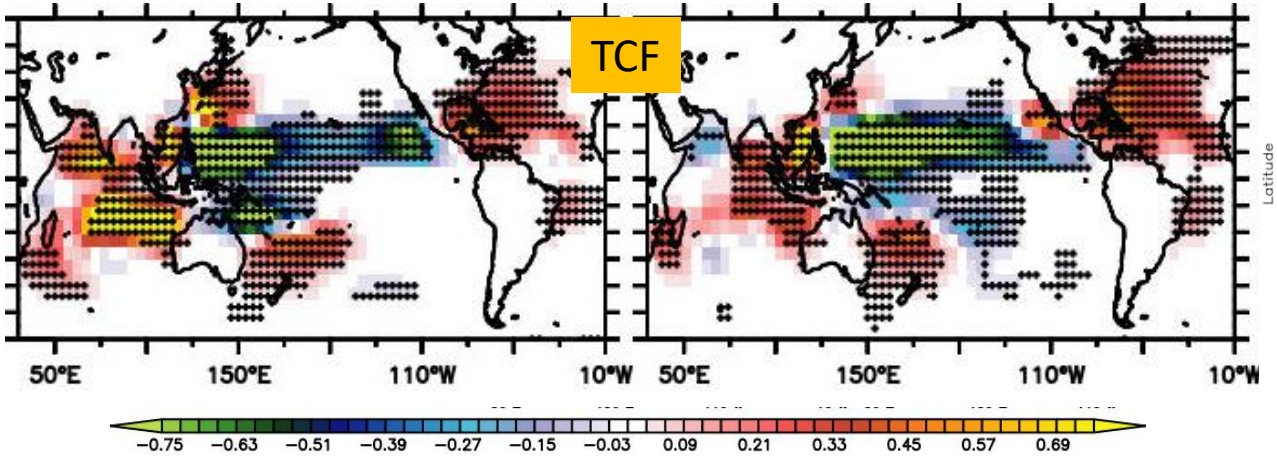
Simulated SST Regressed on -1xIPO Index

SST



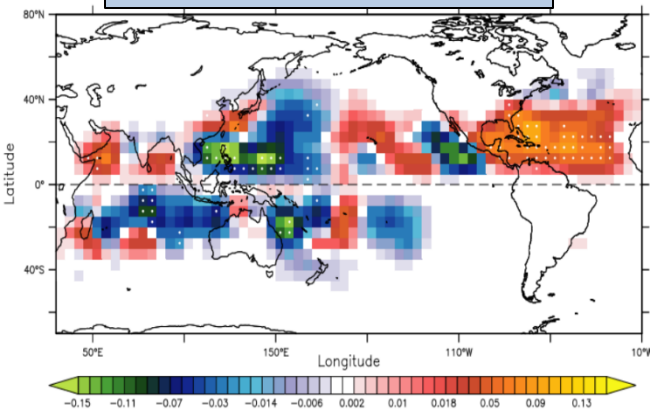
Simulated TCF Regressed on -1xIPO Index

TCF



We hypothesized that the observed TCF trend is **not only caused by the multidecadal internal variability** like IPO, but other external forcing may be related.

Observed Trend in TCF (1980-2018)

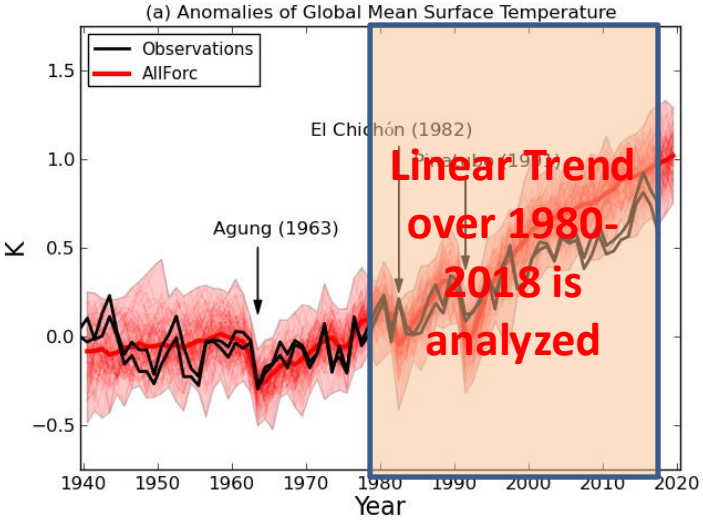


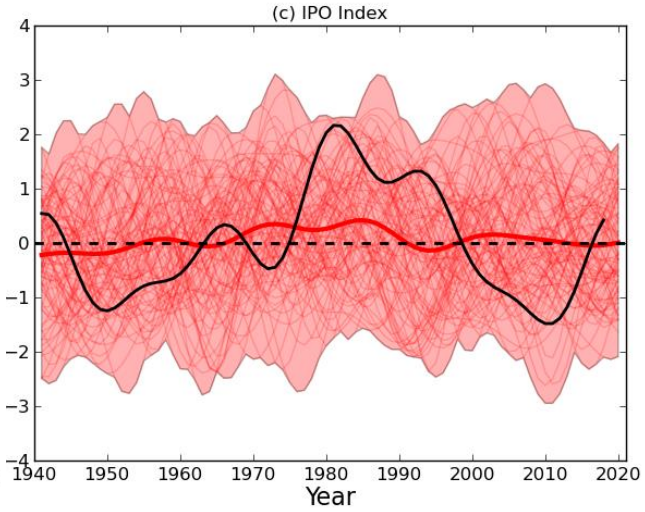
Murakami et al. (2020, *PNAS*)

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

AllForc: 1921-2018: Historical simulations by prescribing time-varying external forcing (green-house gases, aerosols, ozone, and volcanic forcing)

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





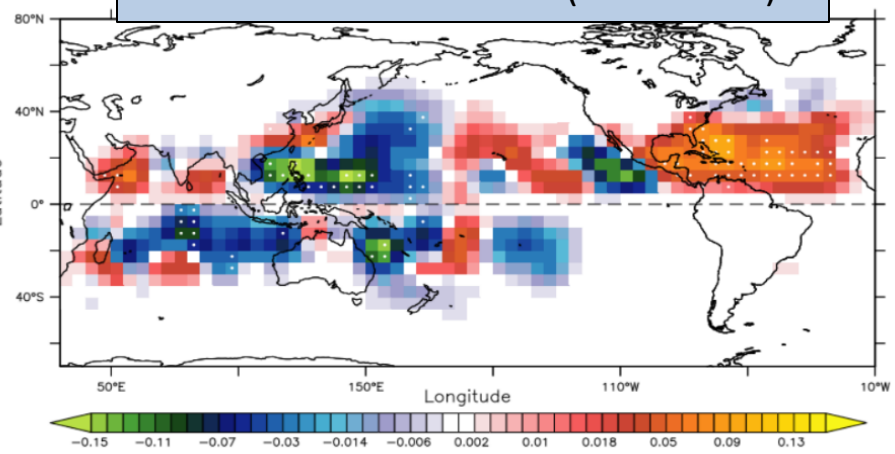
Each ensemble member shows different phase of internal variability.

Internal variability can be canceled out by averaging the members.

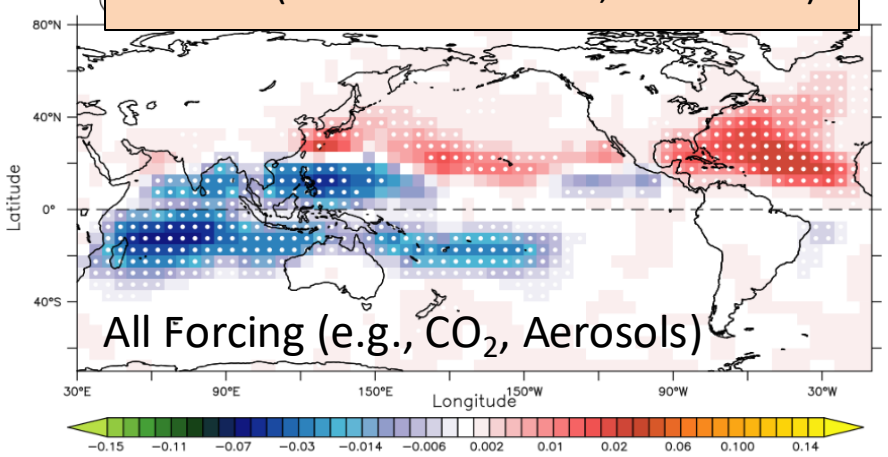
Murakami et al. (2020, *PNAS*)

Effect of External Forcing on the TCF Trend

Observed Trend in TCF (1980-2018)

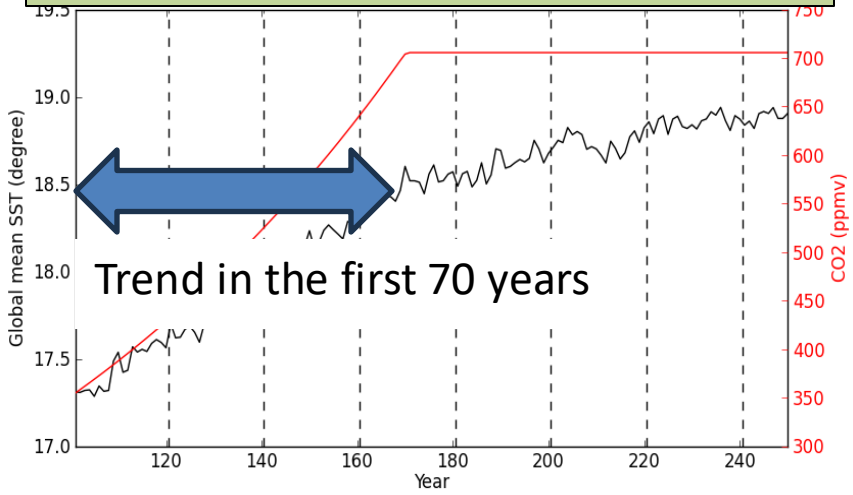


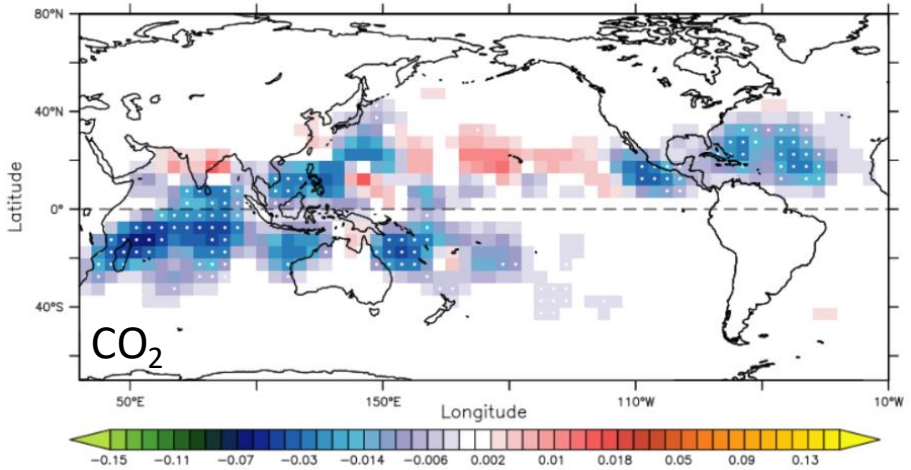
AllForc (95-member mean, 1980-2018)



A similar spatial pattern with observations indicates marked influence of external forcing on global TCF.

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





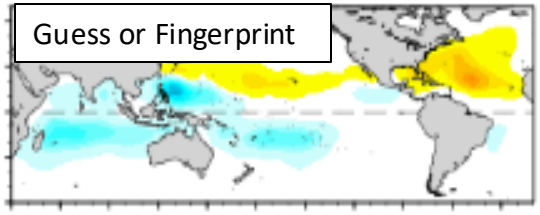
Transient +1%/yr CO_2 Experiment

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

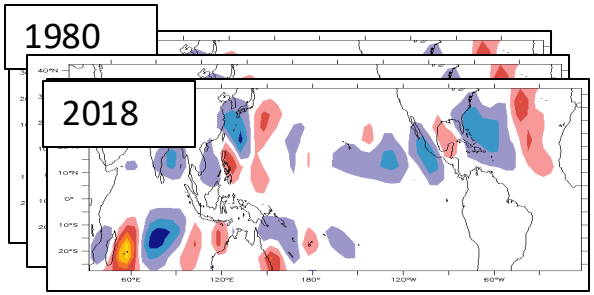
Optimal Fingerprint Analysis

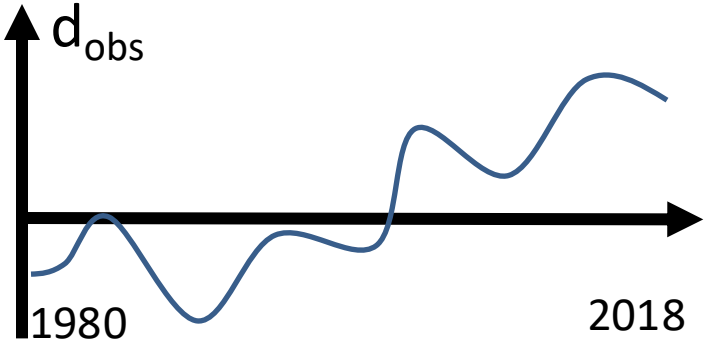
Question: How much of the observed TCF trends over 1980–2018 can be statistically distinguishable from internally generated noise? If they can be distinguished from noise, by what year did this occur?

An Expected Climate Signal Pattern (Guess, or Fingerprint)



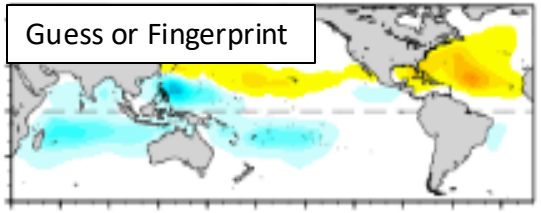
Observed Annual TCF Anomaly (1980-2018)



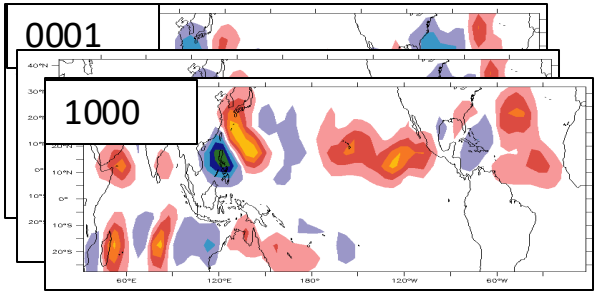


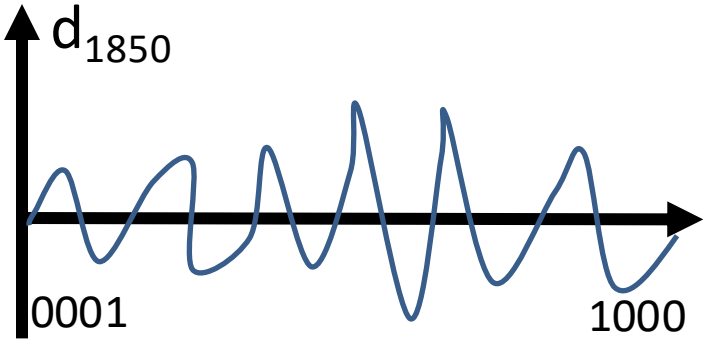
$G(x,y)$ x $TCF_{obs}(x,y,t)$

An Expected Climate Signal Pattern (Guess, or Fingerprint)



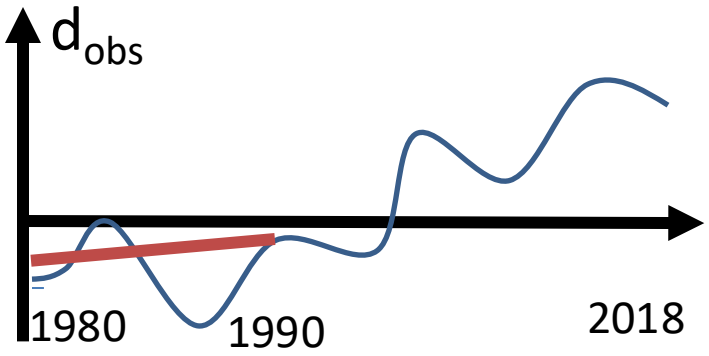
1850Cntl (1000 years)

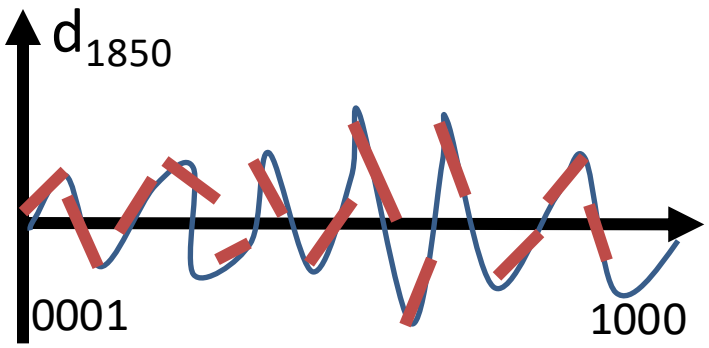




$G(x,y)$ x $TCF_{1860}(x,y,t)$

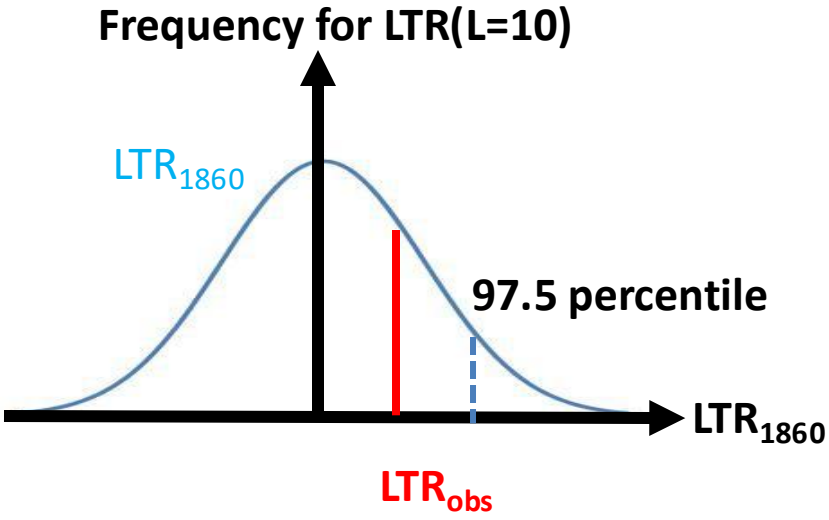
Optimal Fingerprint Analysis (Concept)





Observed linear trend between 1980 – 1990: $LTR_{obs}(L=10)$

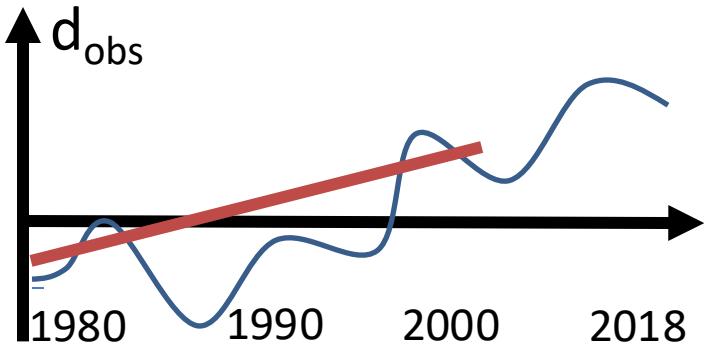
Many $LTR_{1860}(L=10)$ samples can be obtained from 1850Cntl (i.e.,piCntl).

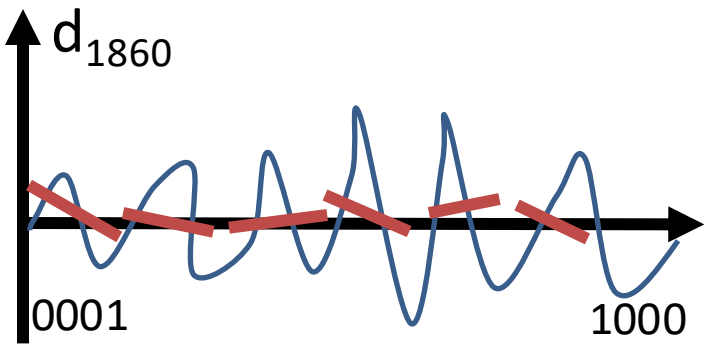


LTR_{obs} is not distinguishable from noise (not detected)

Murakami et al. (2020, PNAS)

Optimal Fingerprint Analysis (Concept)

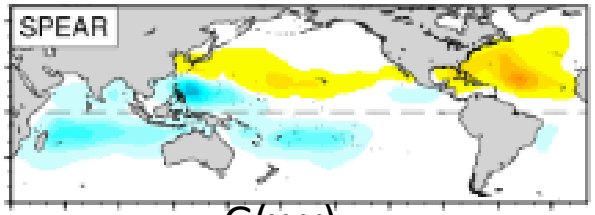




Observed linear trend between 1980 – 2000: $LTR_{obs}(L=20)$

Many $LTR_{1860}(L=20)$ samples can be obtained from 1860Cntl.

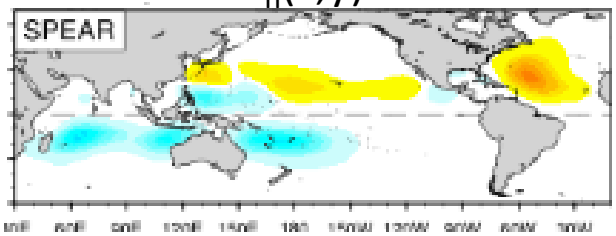
An Expected Climate Signal Pattern (Guess)



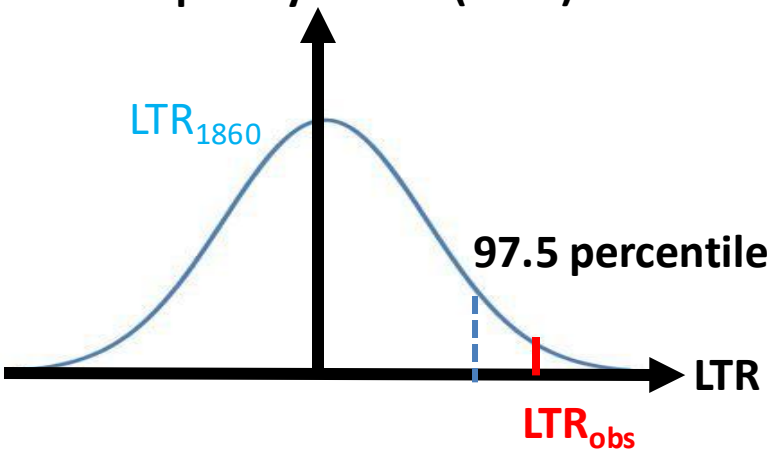
G(x,y)

Optimizing using the first *n*-th EOF modes.

$F_n(x,y)$

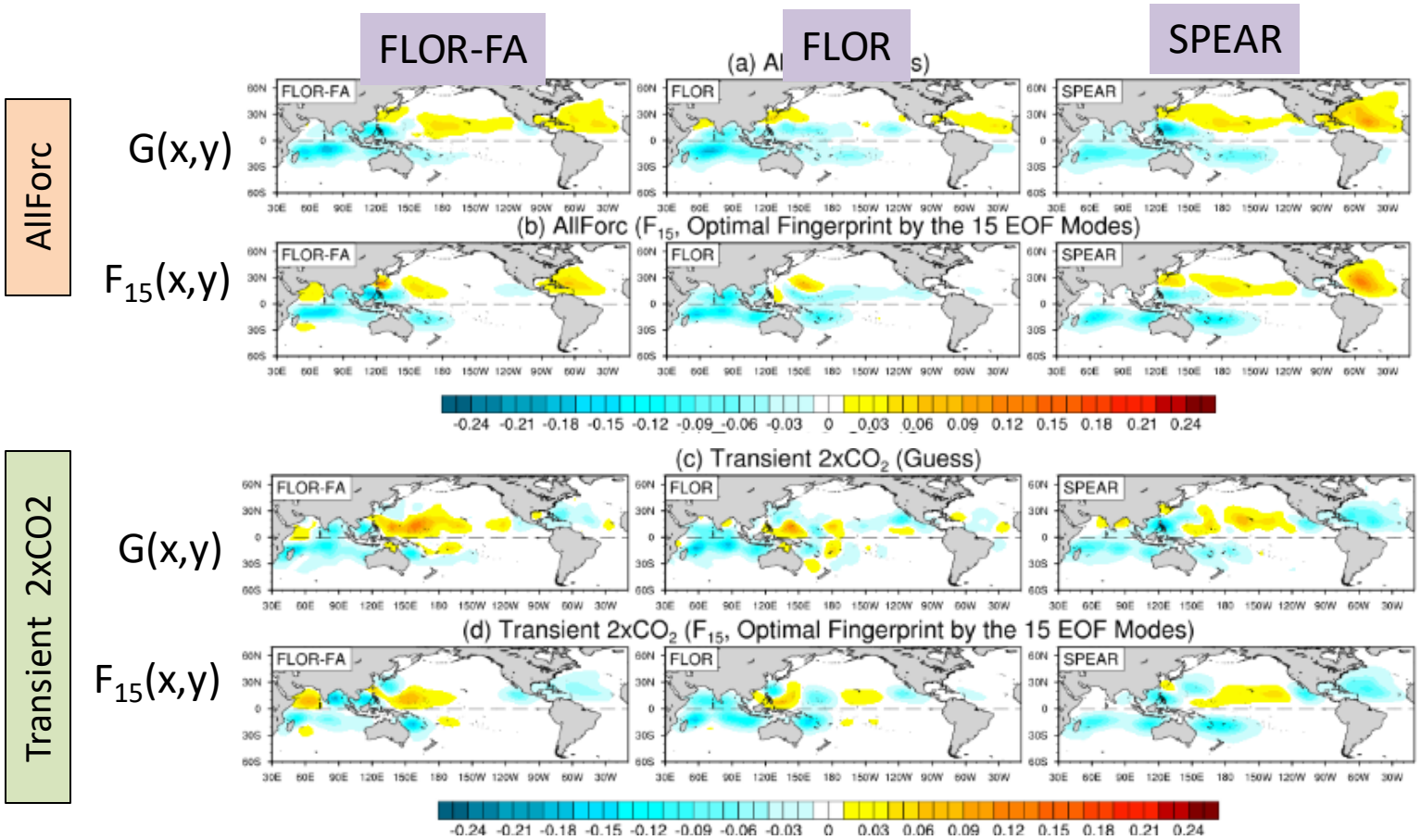


Frequency for LTR(L=20)



LTR_{obs} is distinguishable from noise (detected)

Optimal Fingerprint Analysis (Guess or Fingerprint Spatial Pattern)



Murakami et al. (2020, PNAS)

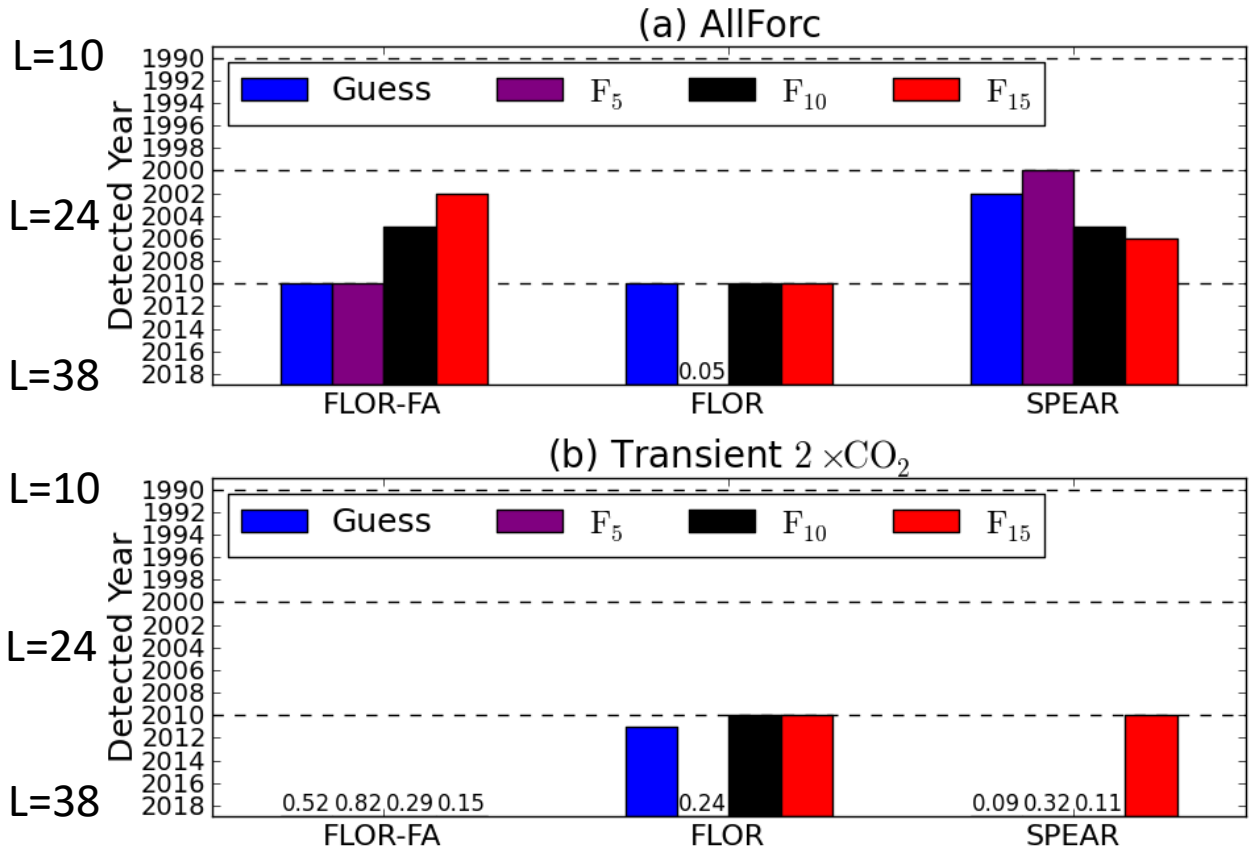
Optimal Fingerprint Analysis (Guess or Fingerprint)

Fingerprints			1850Cntl
AllForc	FLOR-FA	G, F_5, F_{10}, F_{15}	SPEAR
	FLOR		SPEAR
	SPEAR		FLOR-FA
Transient $2xCO_2$	FLOR-FA		SPEAR
	FLOR		SPEAR
	SPEAR		FLOR-FA

- There are 24 fingerprints prepared (2 x 3x 4).
- To avoid artificial skill, independent models should be used for fingerprint and 1850Cntl.

- The detection time is referenced to 1980.
- We begin with L10 (a linear trend from 1980 to 1990) to see if it is detected. So that the earliest detection year is 1990.
- In case of no detection, we repeat the analysis by increasing the length by one year (e.g., L11, L12,…, L38) until it shows a detection.

Optimal Fingerprint Analysis (results)



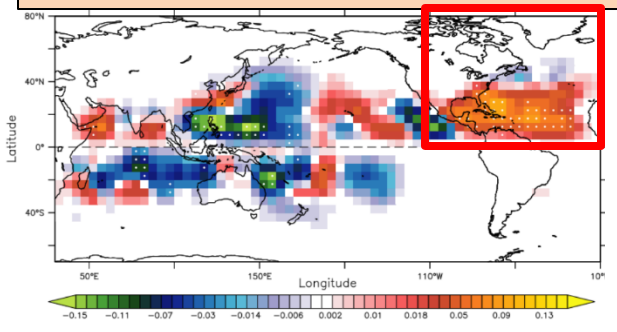
Detected around 2000-2010
⇒ External forcing plays an important role for the observed trend.

Detected around 2010
⇒ Increase in green-house gasses (CO_2) partially contributes to the observed trend.

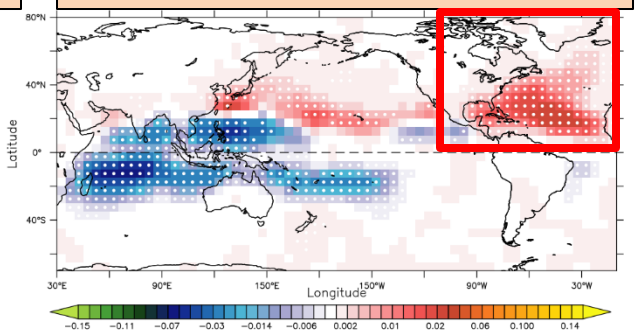
Murakami et al. (2020, *PNAS*)

Effect of Aerosols on Atlantic TCs

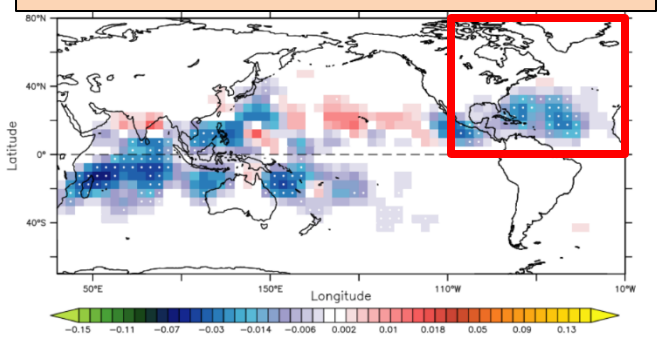
TCF Trend (Observed, 1980-2018)



TCF Trend (AllForc, 1980-2018)

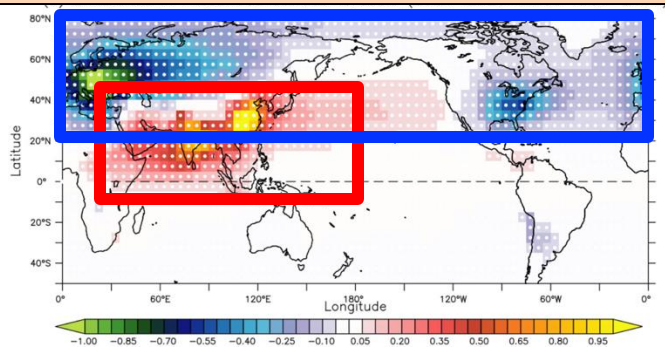


TCF Trend (Transient 2xCO_2 70-yrs)



We hypothesize the increase in tropical cyclones in the North Atlantic is partially attributable to the changes in **anthropogenic aerosols**

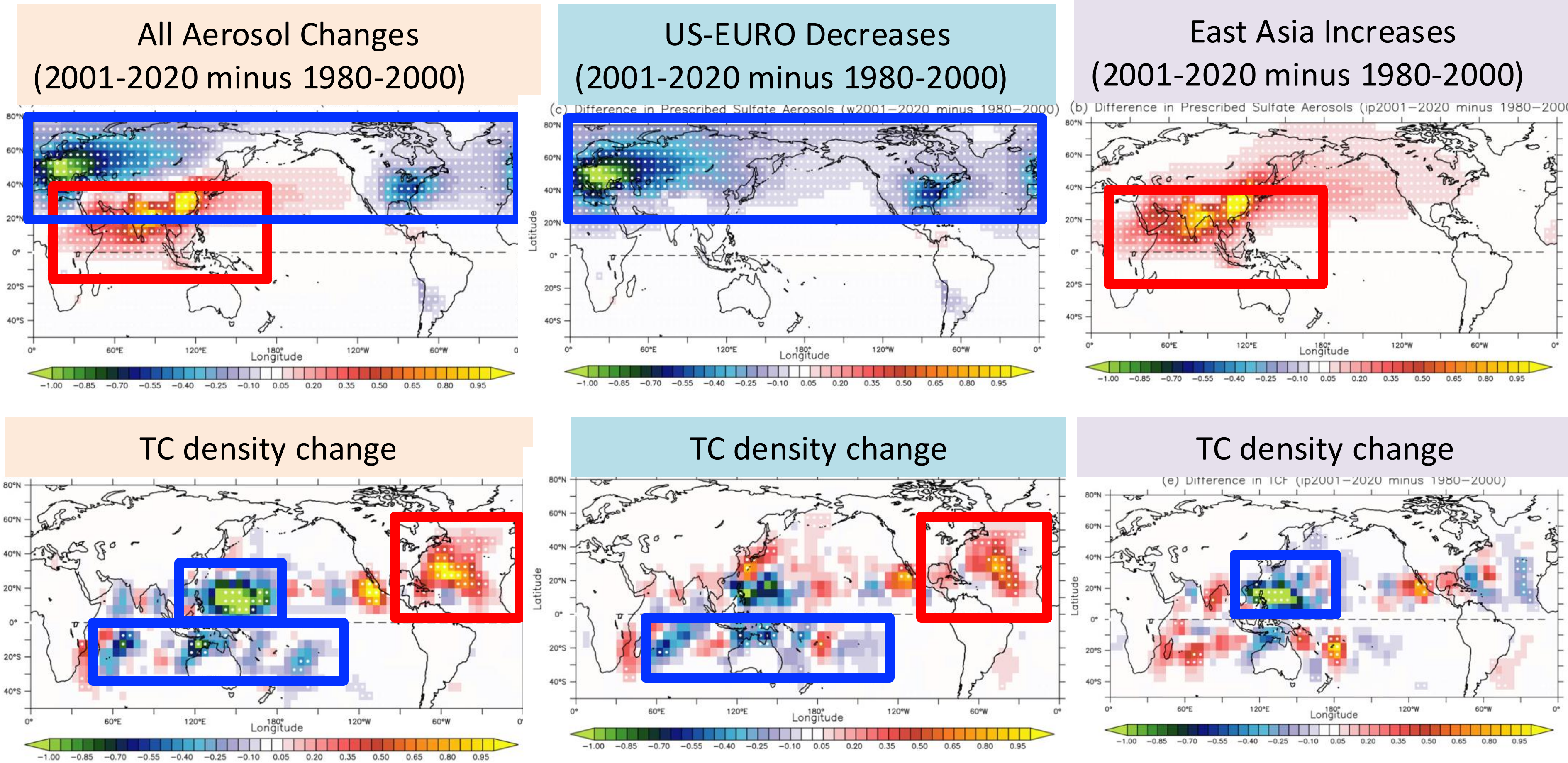
Simulated changes in anthropogenic aerosols (2001-2020 minus 1980-2000)



To investigate the regional impacts of anthropogenic aerosols on tropical cyclones, we conducted long-term simulations using SPEAR, modifying anthropogenic aerosol emissions (i.e., sulfur dioxide, sulfate, black carbon, and organic carbon).

Murakami et al. (2020, *PNAS*), Murakami (2022, *Science Advances*)

Effect of Aerosol Changes on global TCs



Decreased Aerosols in US & Europe => **Increased TCs in the North Atlantic**

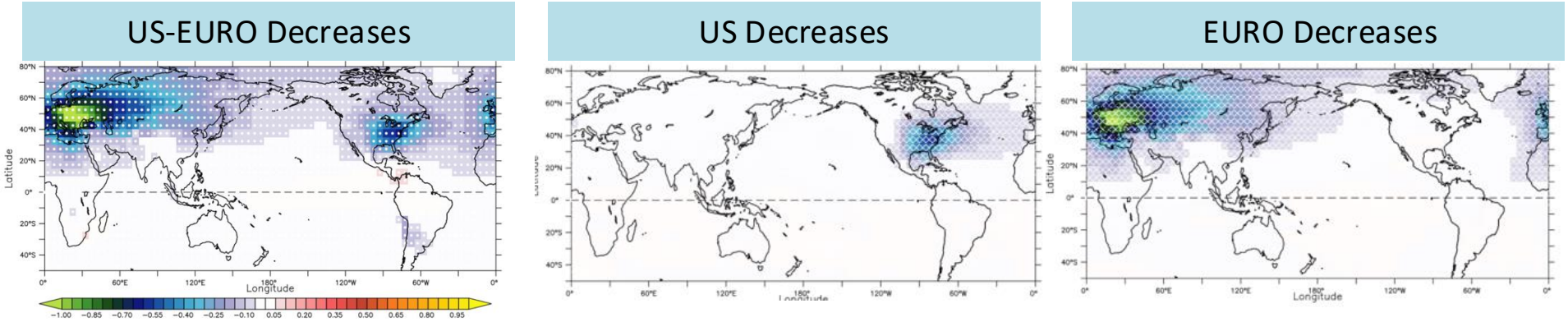
Decreased TCs in the Southern Hemisphere

Increased Aerosols in China & India => **Decreased TCs in the Western North Pacific**

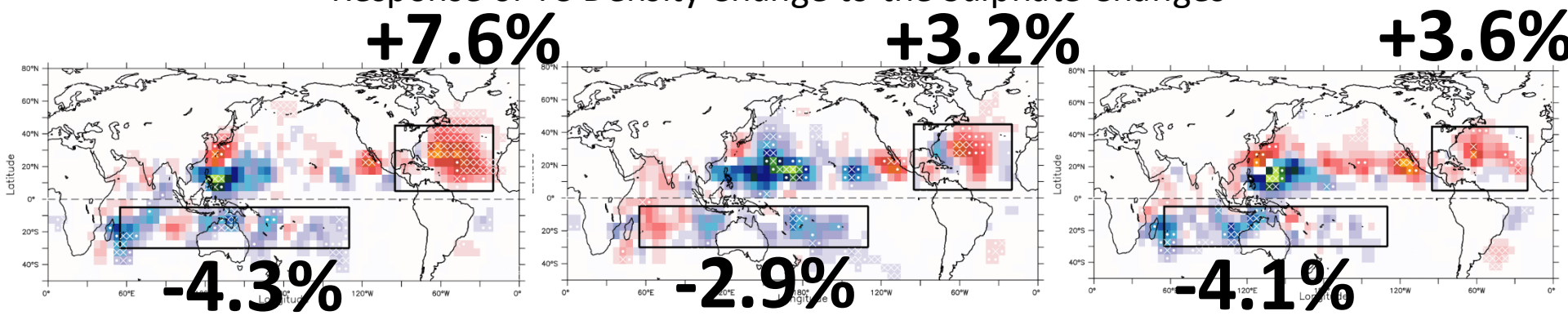
Murakami (2022, *Science Advances*)

Effect of Reduced Aerosol from US and Europe on global TCs

Sulphate Changes Forced in SPEAR



Response of TC Density Change to the Sulphate Changes



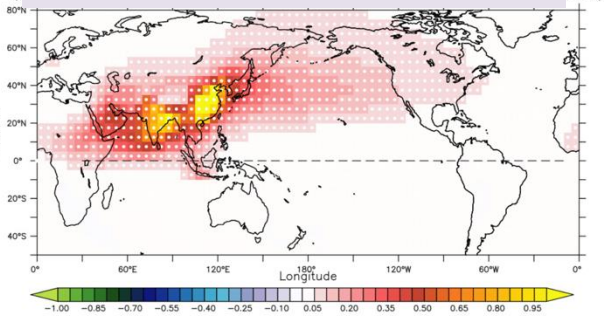
- Reduced aerosols from Europe and the U.S. increased tropical cyclones in the North Atlantic to a similar extent.
- Reduced aerosols from Europe and the U.S. decreased cyclones in the South Indian Ocean and South Pacific, respectively.

Murakami (2024, *GRL*)

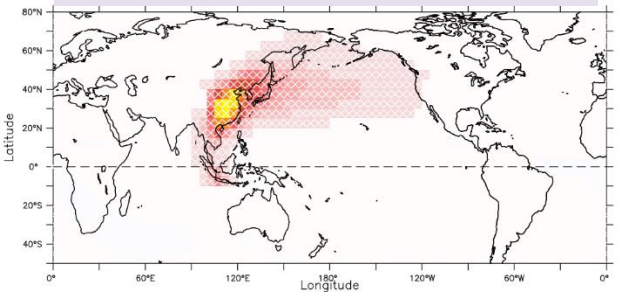
Effect of Increased Aerosol from China and India on WNP TCs

Sulphate Changes Forced in SPEAR

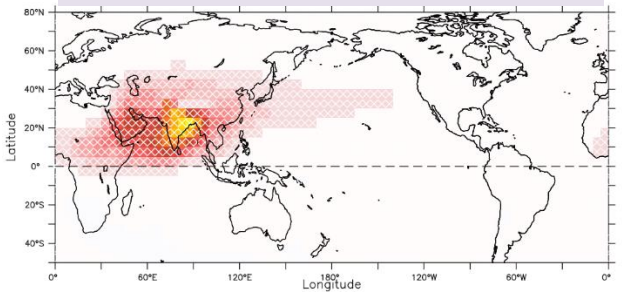
East Asia Increases



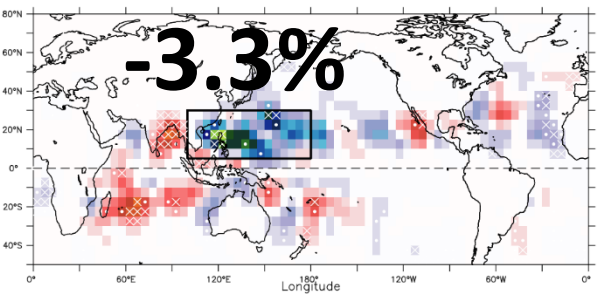
China Increases

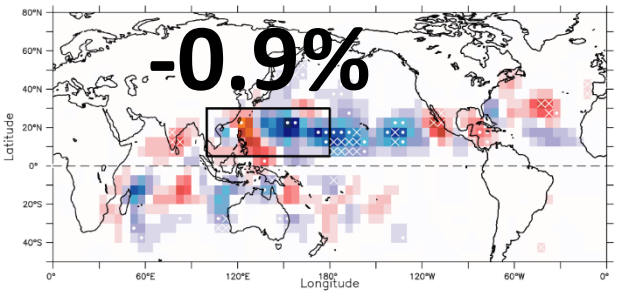


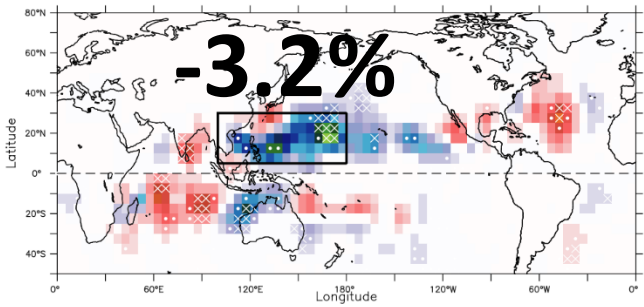
India Increases



Response of TC Density Change to the Sulphate Changes



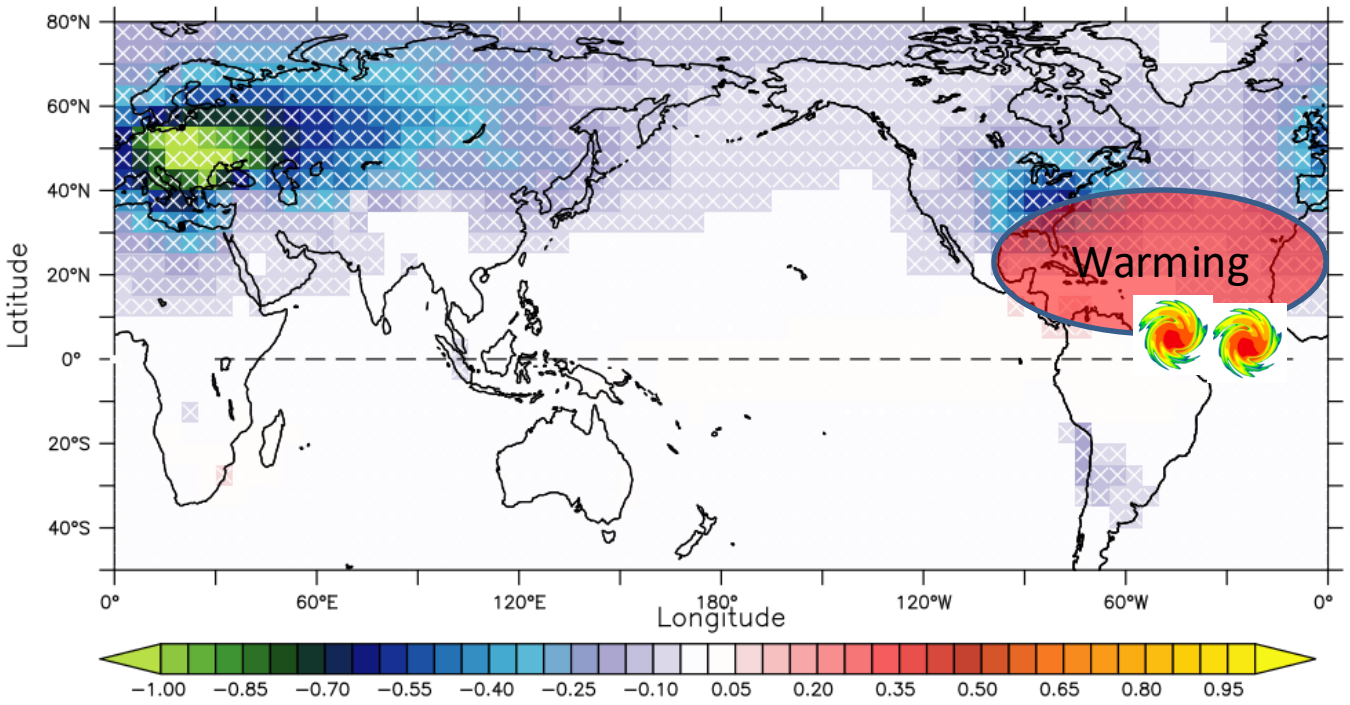




- Increased aerosols from India decreased tropical cyclones in the western North Pacific more significantly compared to increased aerosols from China.

Murakami (2024, *GRL*)

Physical Mechanisms behind the TCF change



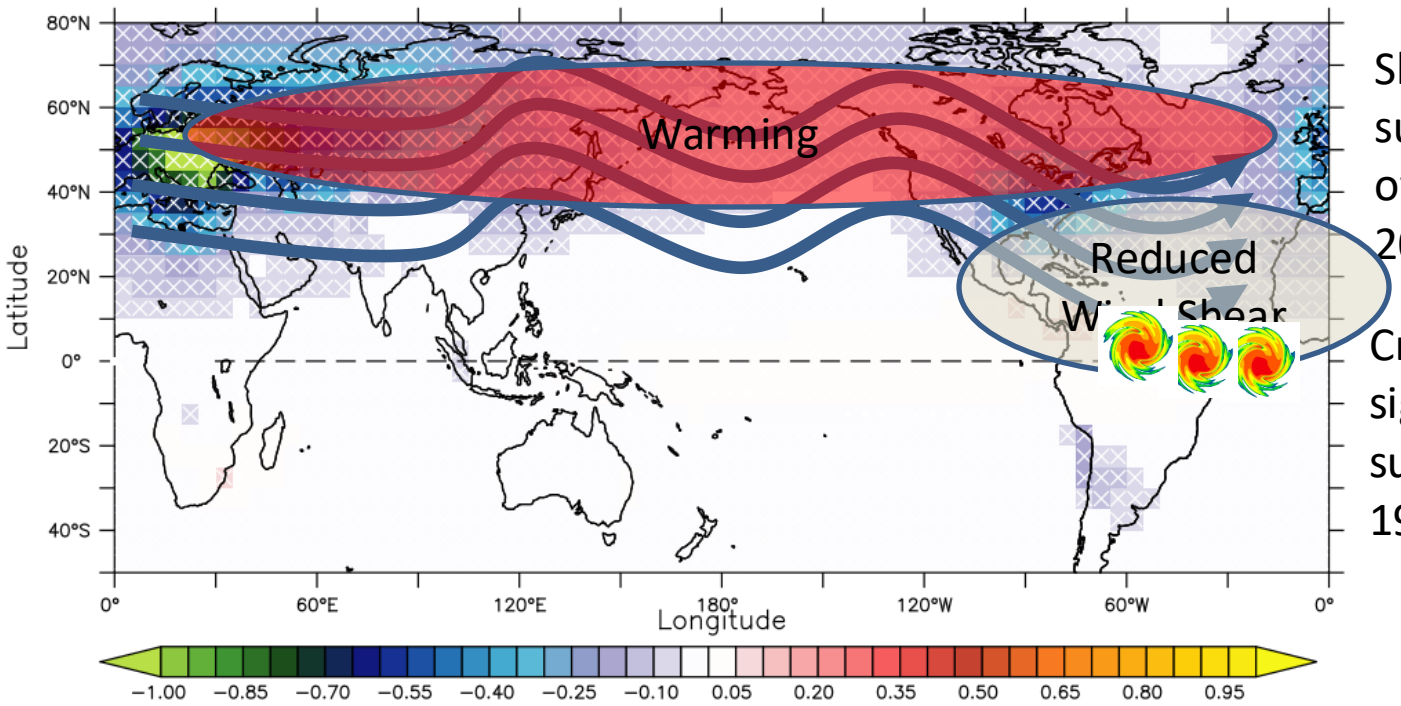
Shading: Linear trend in sulfate concentration over the period 1980-2020

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

- Over the past 40 years, anthropogenic aerosols have significantly decreased in Europe and the United States because of pollution control measures.
- The decrease in aerosols led to a surface warming over the tropical Atlantic by which the frequency of tropical cyclones increased in the North Atlantic (direct effect).

Murakami (2022, *Science Advances*)

Physical Mechanisms behind the TCF change



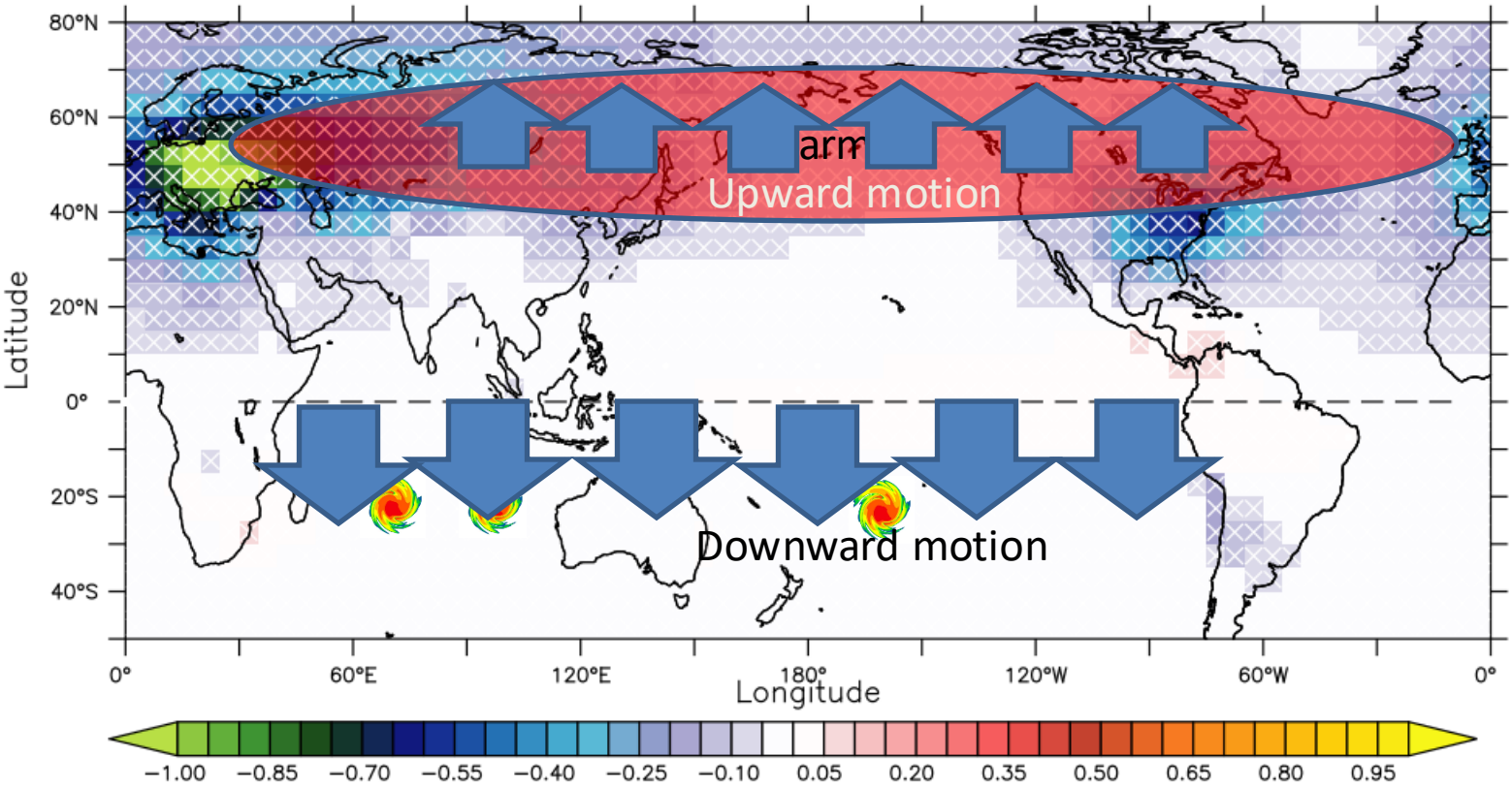
Shading: Linear trend in sulfate concentration over the period 1980-2020

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).

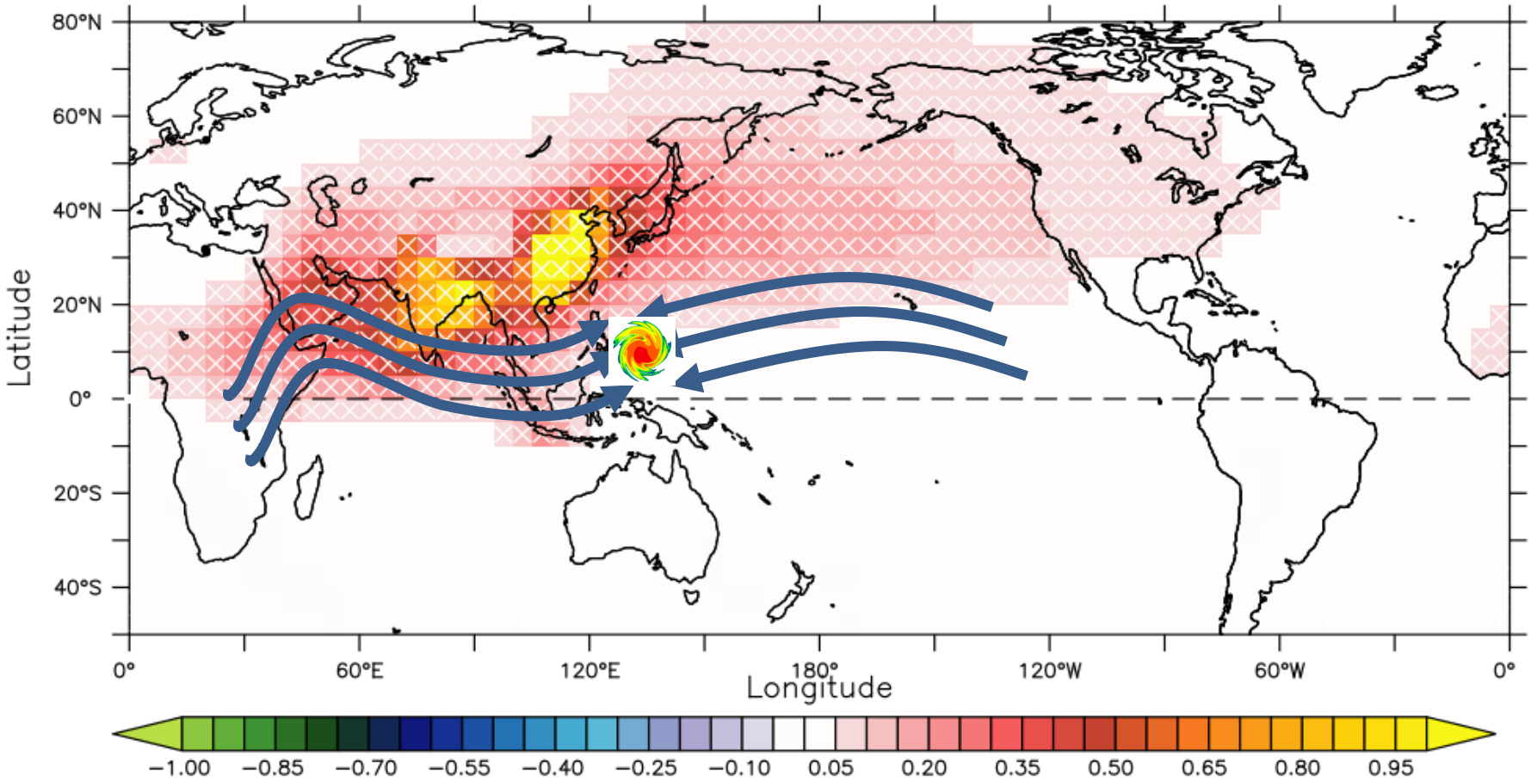
Murakami (2022, *Science Advances*)

Physical Mechanisms behind the TCF change



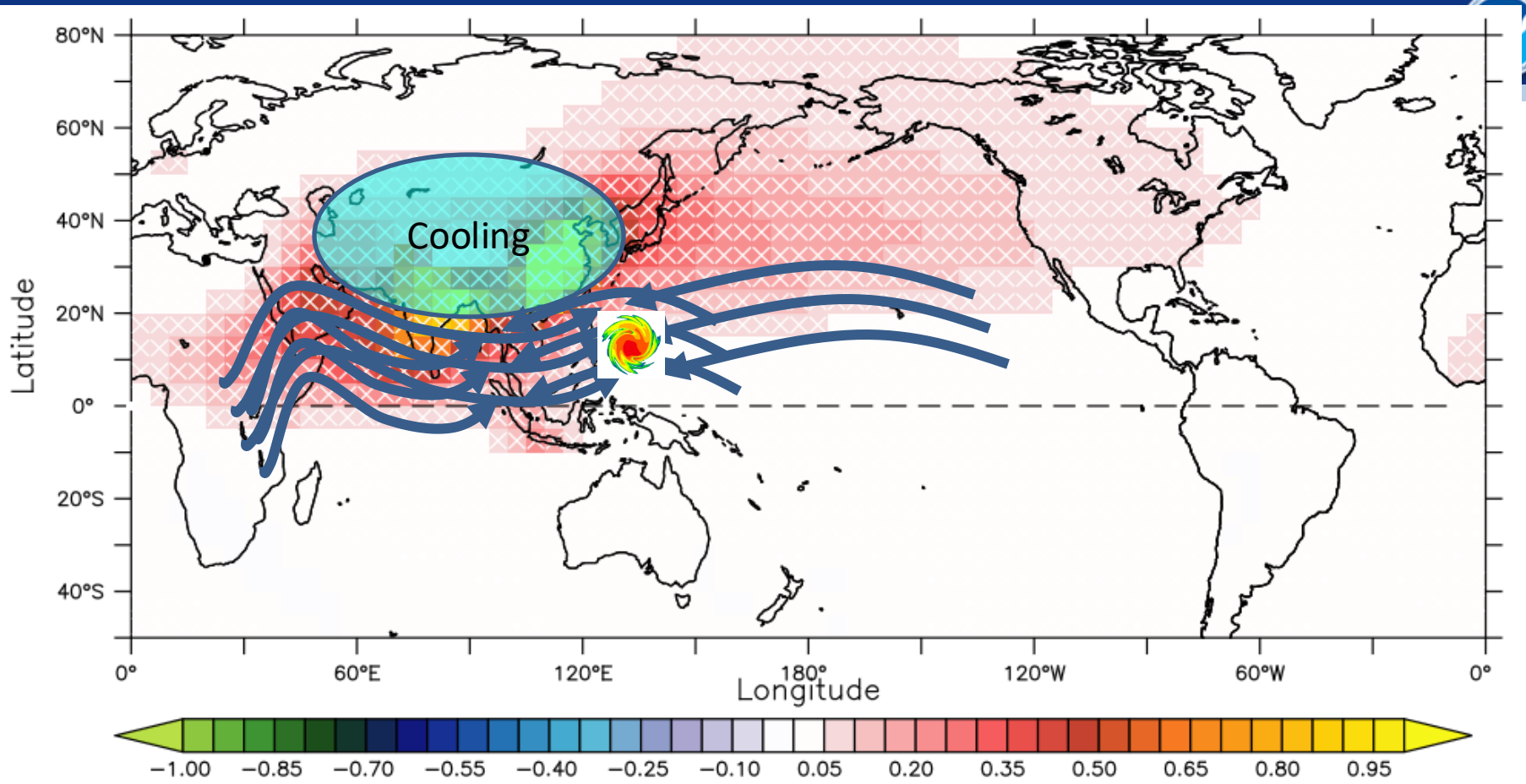
- The warming in the mid-and high-latitudes in the Northern Hemisphere also caused Hemispheric circulation anomaly.
- The warming causes anomalous upward motions by the enhanced convective activity.
- The anomalous upward motion leads to downward motion in the Southern Hemisphere, in turn reducing tropical cyclones

Physical Mechanisms behind the TCF change



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

Murakami (2022, *Science Advances*)



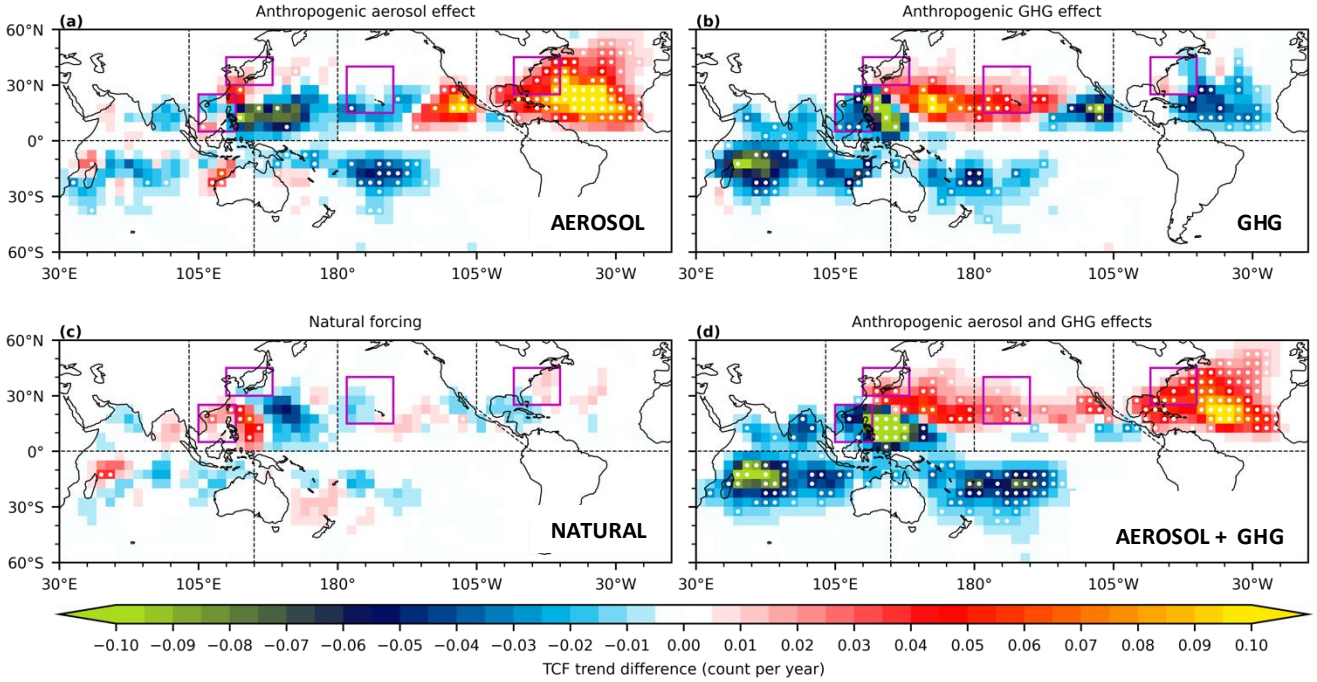
- The cooling over the land surface caused a weakened Indian monsoon, resulting in a weakened monsoon trough.
- This in turn led to decreased tropical cyclones over the western North Pacific over the period 1980-2020.

Increased aerosols from India helped to reduce tropical cyclones.

Murakami (2022, *Science Advances*)

Anthropogenic Forcing Changes Coastal Tropical Cyclone Activity

Modeled ensemble mean TC density trend



SPEAR simulations suggest that:

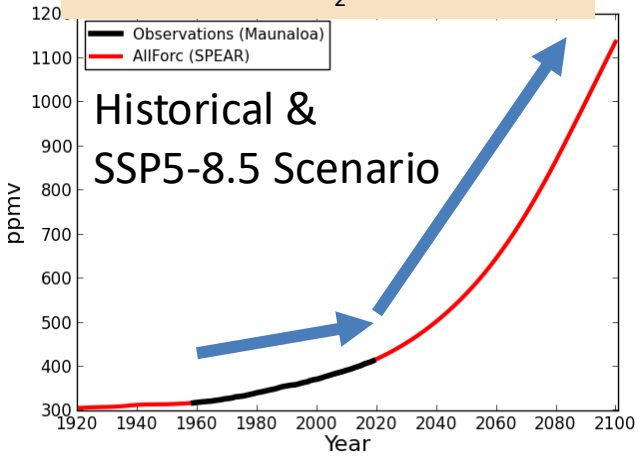
US east coast	Aerosol ☞ TCF ⇧
Hawaii	GHG ☞ TCF ⇧
South China Sea	GHG ☞ TCF ⇩
Japan-Korea	GHG + Aerosol ☞ TCF ⇧

The observed increases in TC density near the **US Atlantic coast** and **Hawaii** are likely related to the **aerosol and GHG effects, respectively**. The observed decrease in the **South China Sea** could be associated with **GHG** emissions alone, whereas the observed increase near **Japan and Korea** would be related to the **aerosol and GHG** combined effects.

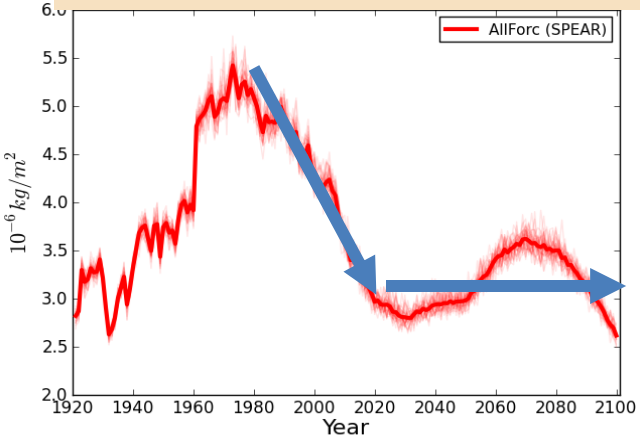
Wang, S., H. Murakami, and W. F. Cooke (2023, *npj Clim. Atmos. Sci.*)

Future Projections for Global and North Atlantic TCs

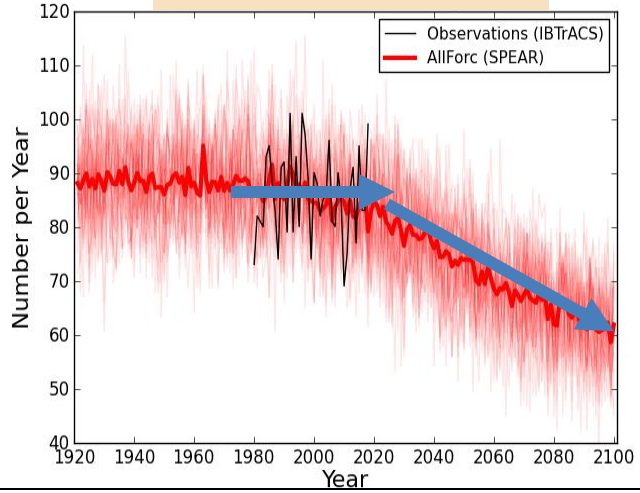
Global Mean CO_2 Concentration



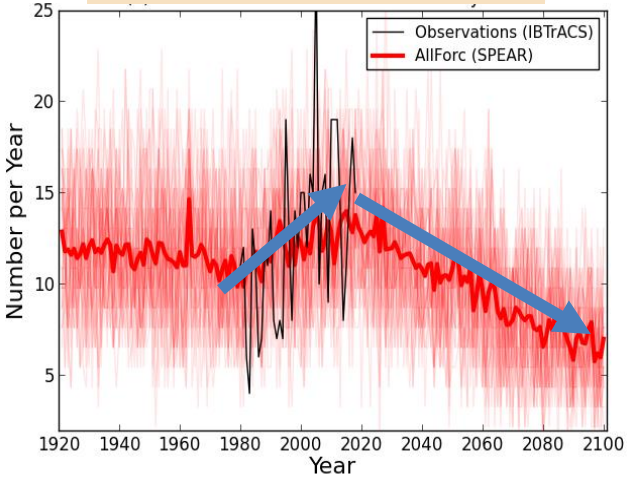
Sulfate Aerosols over North Atlantic



TC Number (Global)



TC Number (North Atlantic)



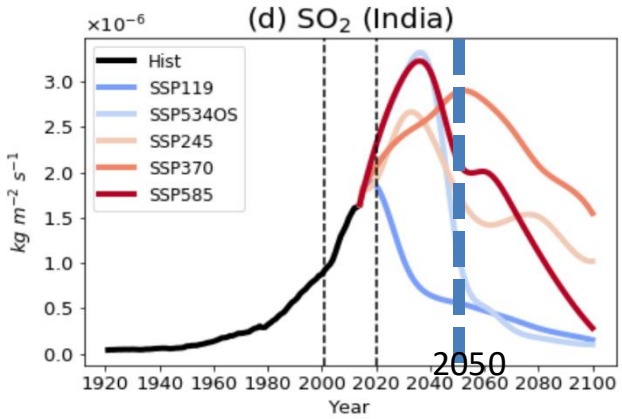
The decreased aerosols may be the important factor for the increased TCs over the North Atlantic over 1980-2020.

The 30-member SPEAR projects decreased global TC number toward the end of this century due to increased CO_2.

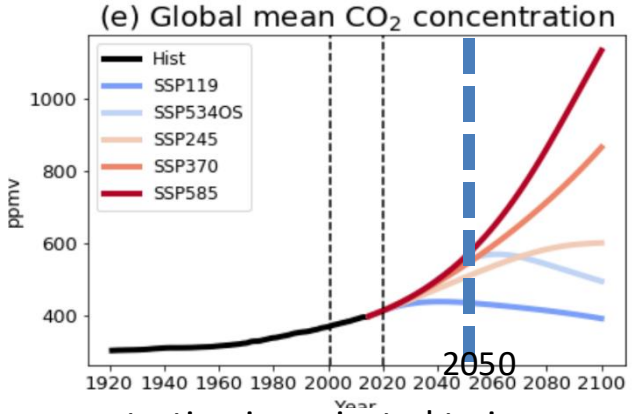
TC number of North Atlantic is also projected to decrease in the future due to the dominant effect of increased CO_2.

Murakami et al. (2020, *PNAS*)

Future Projections for Western North Pacific TCs

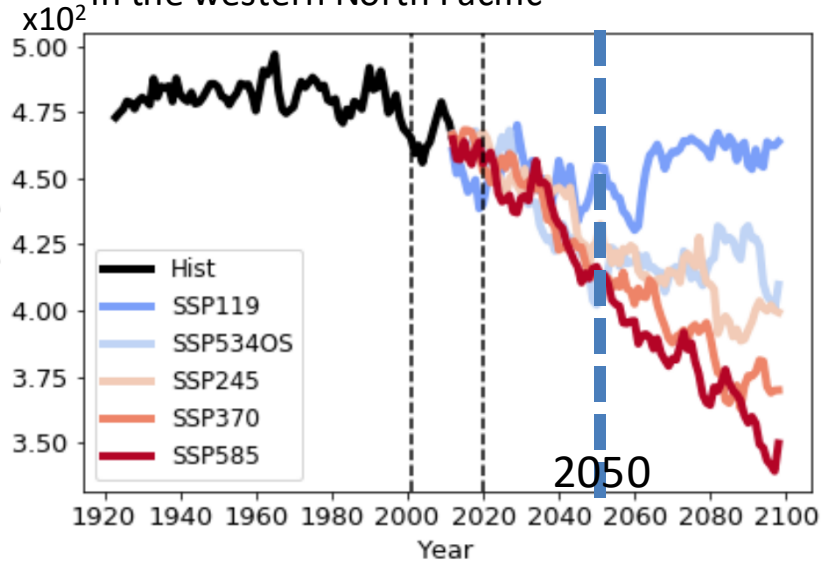


Aerosol emission is projected to increase from India up to 2050



CO2 concentration is projected to increase in the future

Total frequency of occurrence of Typhoons in the western North Pacific



Typhoon occurrence in western North Pacific is projected to decrease in the future

Murakami (2025, *GRL*)

Summary

- A climate change in global TC activity over 1980–2018 has been more evident in the spatial pattern of TC occurrence, rather than the overall number of global TCs.
- The observed spatial pattern of trends is very unlikely to be explained entirely by underlying multi-decadal internal variability; rather, external forcing, such as greenhouse gases and aerosols, likely played an important role.
- The decreased anthropogenic aerosols in the US and Europe may play an important role in the increased TCs over the North Atlantic and decreased TCs over the Southern Hemisphere since 1980, whereas the increased aerosols in China & India may play an important role in the decreased TCs over western North Pacific.
- The models project decreasing trends in global (including North Atlantic and western North Pacific) TCs toward the end of this century owing to the dominant effect of CO_2 increases.

SVD Analysis

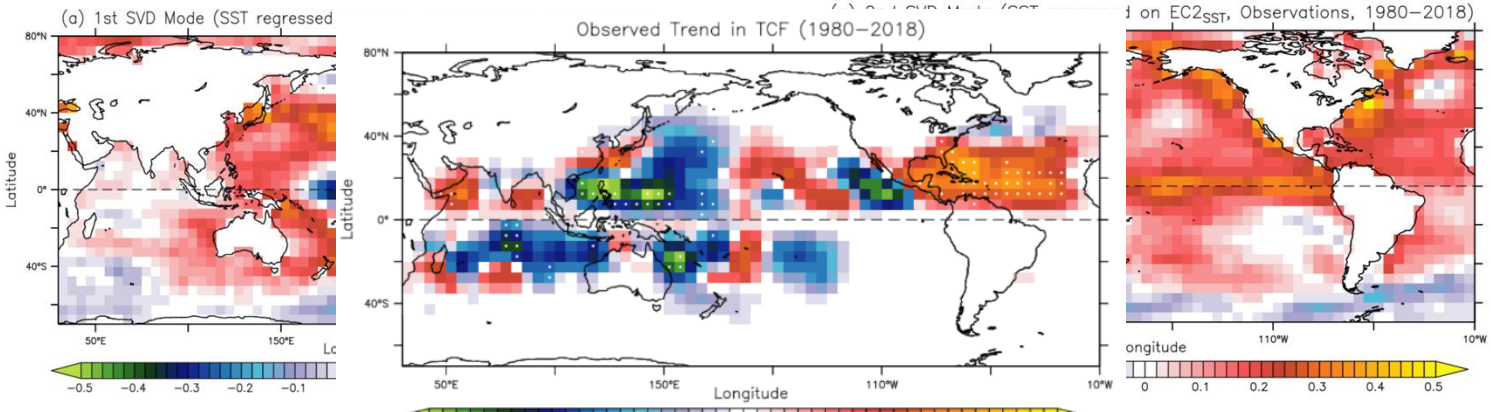
1st SVD Mode (61%, IPO mode)

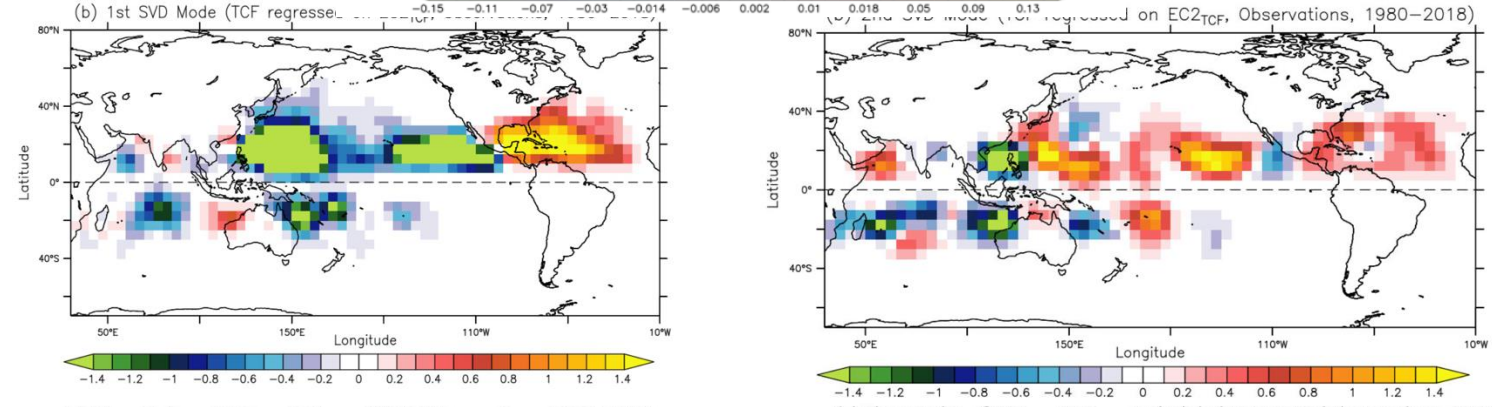
2nd SVD Mode (12%, Global Warming Mode)

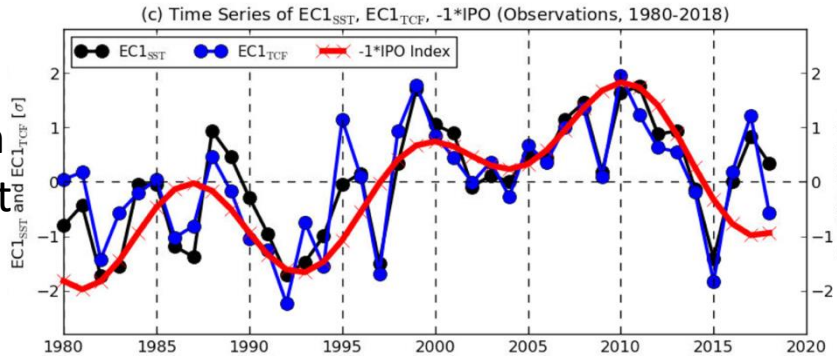
SST

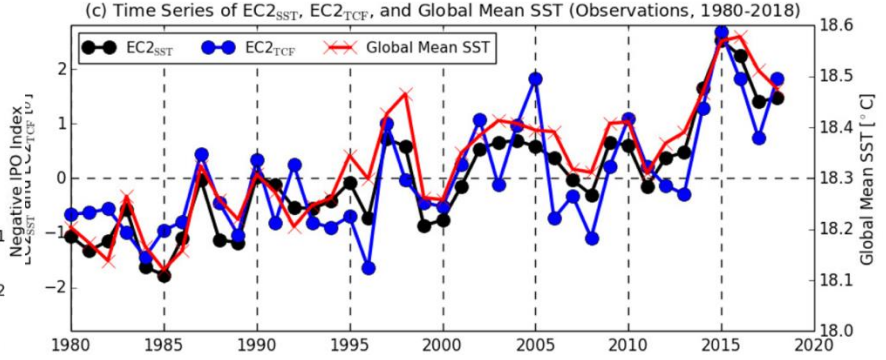
TCF

Expansion coefficient



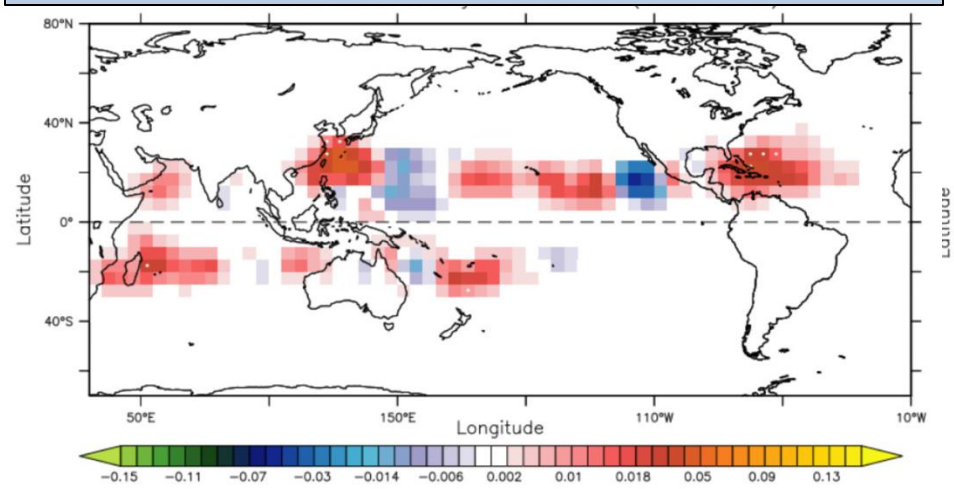




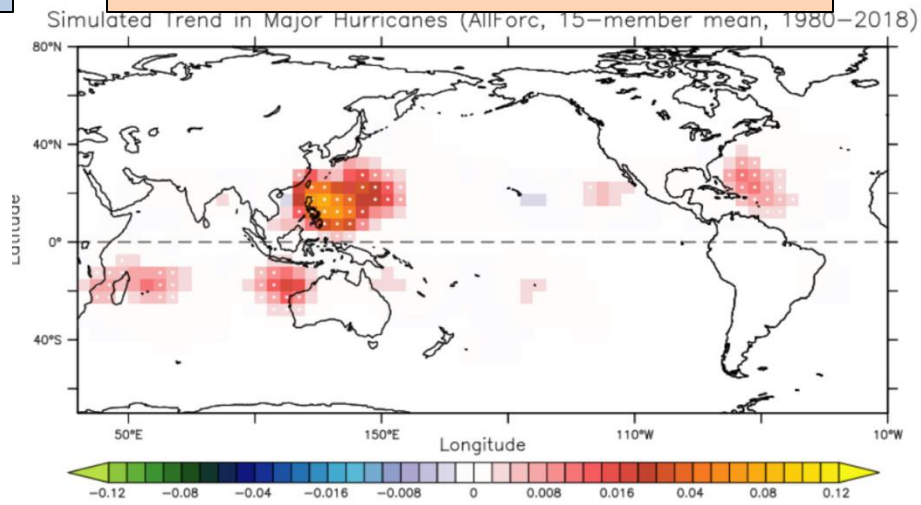


Intense Storms (Major Hurricanes)

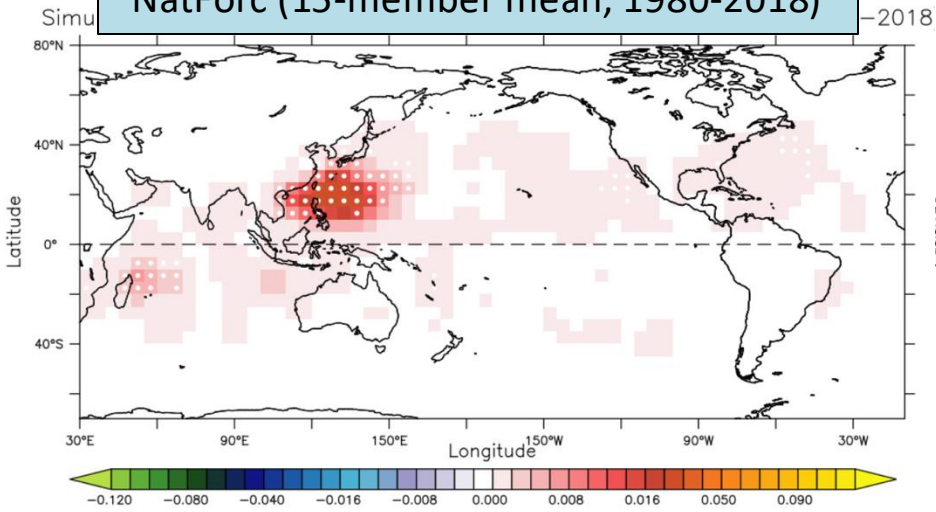
Observed Trend in Major Hurricanes (1980-2018)



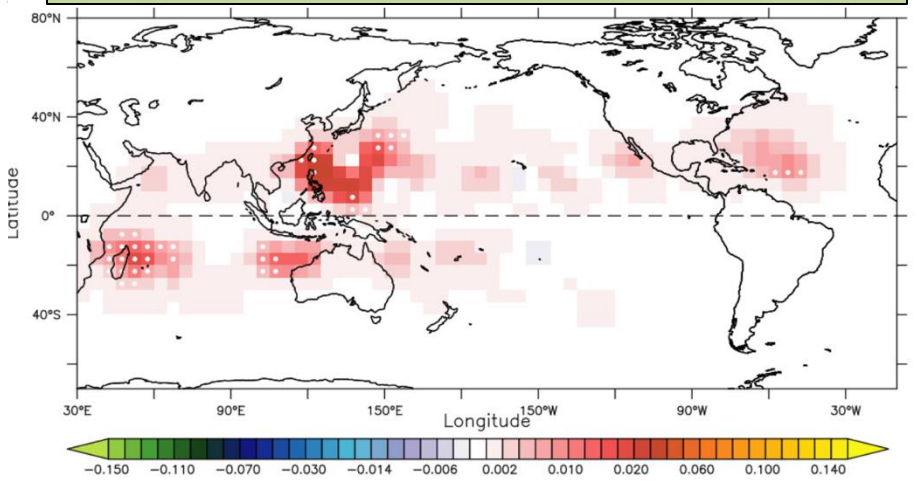
AllForc (15-member mean, 1980-2018)



NatForc (15-member mean, 1980-2018)



Transient 2xCO_2 (one member , 70 yrs)



Effect of volcanic events on intense storms?

Difference between SPEAR(50km) and HiFLOR(25-km)

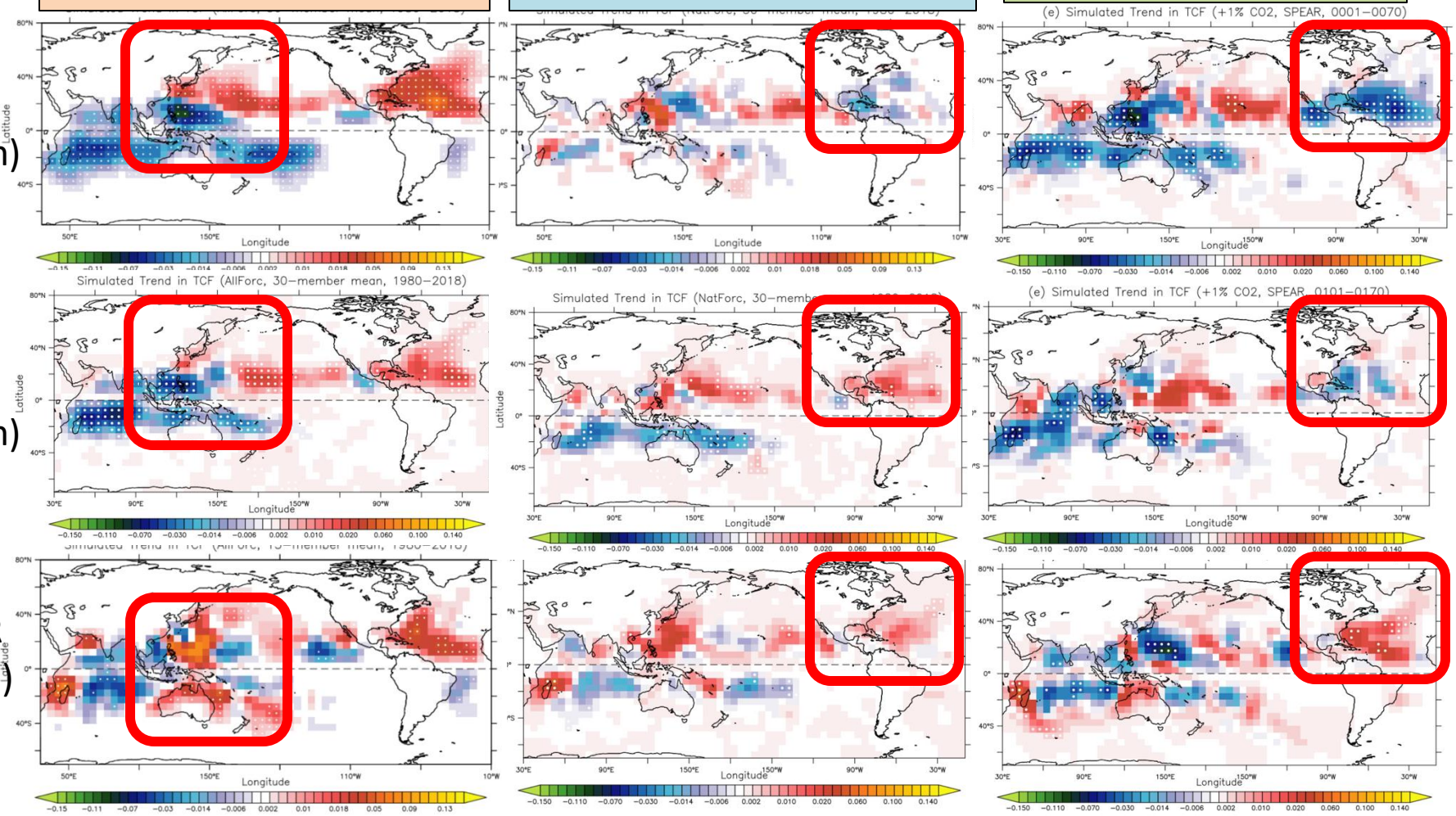
Linear Trend in TCF

AllForc (1980-2018) | NatForc, (1980-2018) | Transient 2xCO_2 (70-yrs)

SPEAR (50-km)

FLOR (50-km)

HiFLOR (25-km)

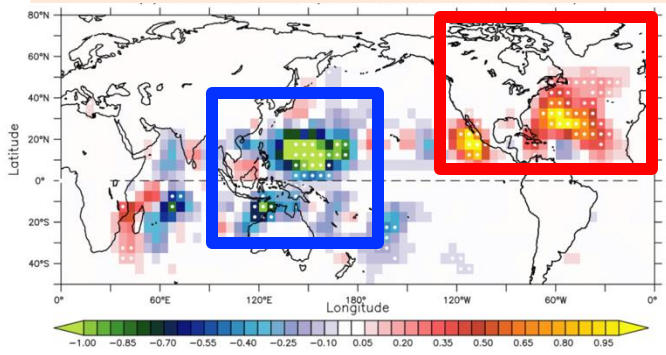


Consistent except for West Pacific

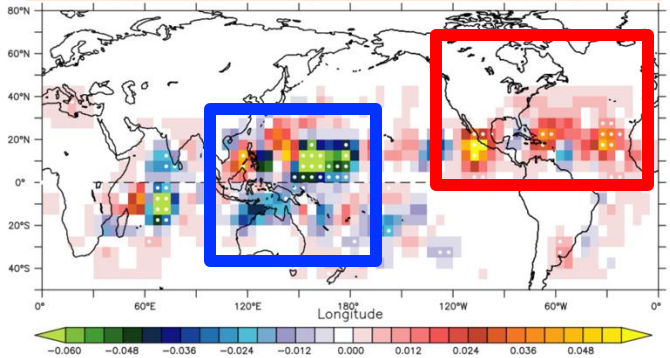
Different in the North Atlantic

Effect of Aerosols on Regional TCs

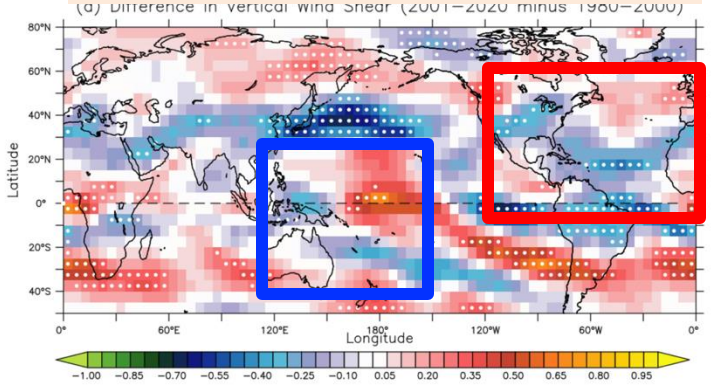
TCF
(2001-2020 minus 1980-2000)



TGF
(2001-2020 minus 1980-2000)



Vertical Wind Shear
(2001-2020 minus 1980-2000)



Winds at 200 hPa
(2001-2020 minus 1980-2000)