Detected Climate Change in Global Distribution of Tropical Cyclones

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Outline

In this presentation, I would like to clarify the following open questions.

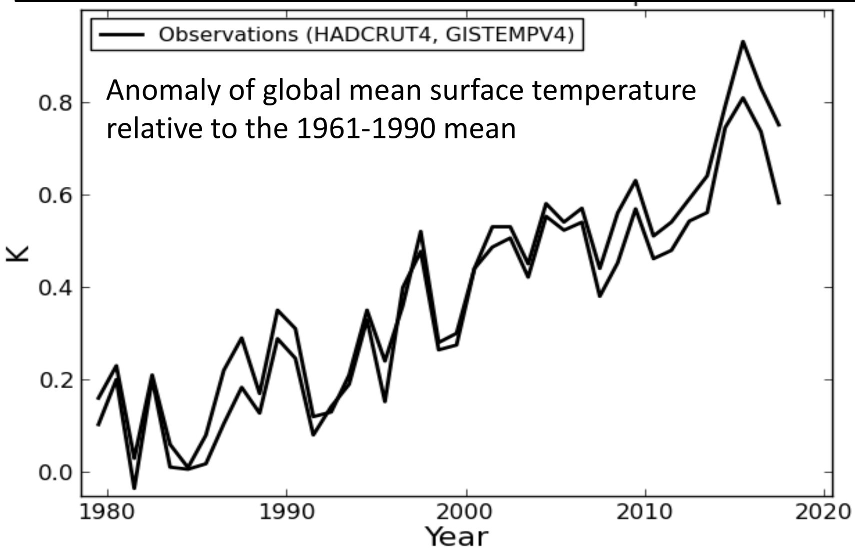
1. Are there any significant changes in global tropical cyclone activity over the past 40 years?
2. If so, were they affected by external forcing and distinguishable from internally generated noise?
3. If they can be distinguished from noise, by what year did they occur?
4. How did anthropogenic aerosols change global tropical cyclones over the past 40 years?

Keywords: Large-Ensemble Simulations, Fingerprint Analysis, SVD analysis

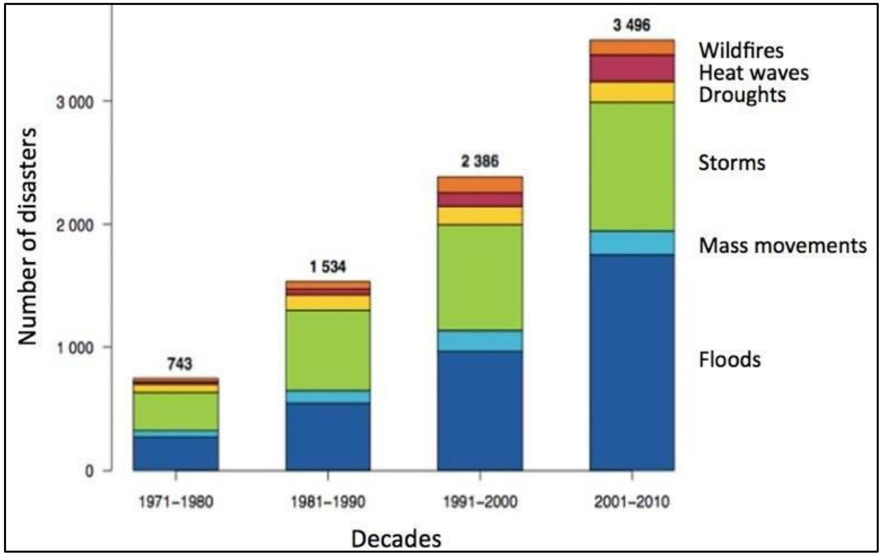
Reference: Murakami et al. (2020, PNAS), Murakami (2022, Science Advances)

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

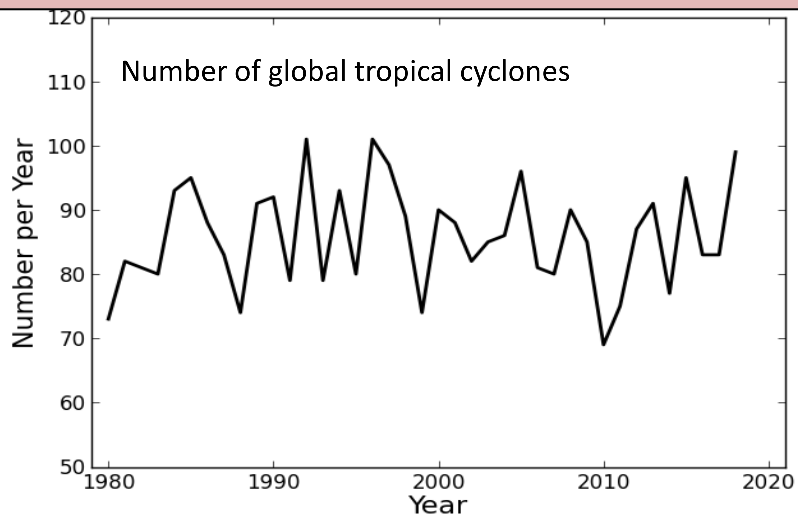
The observed global mean surface temperature shows an increase between 1980 and 2018.



Global Frequency of Natural Disasters (1971–2010)



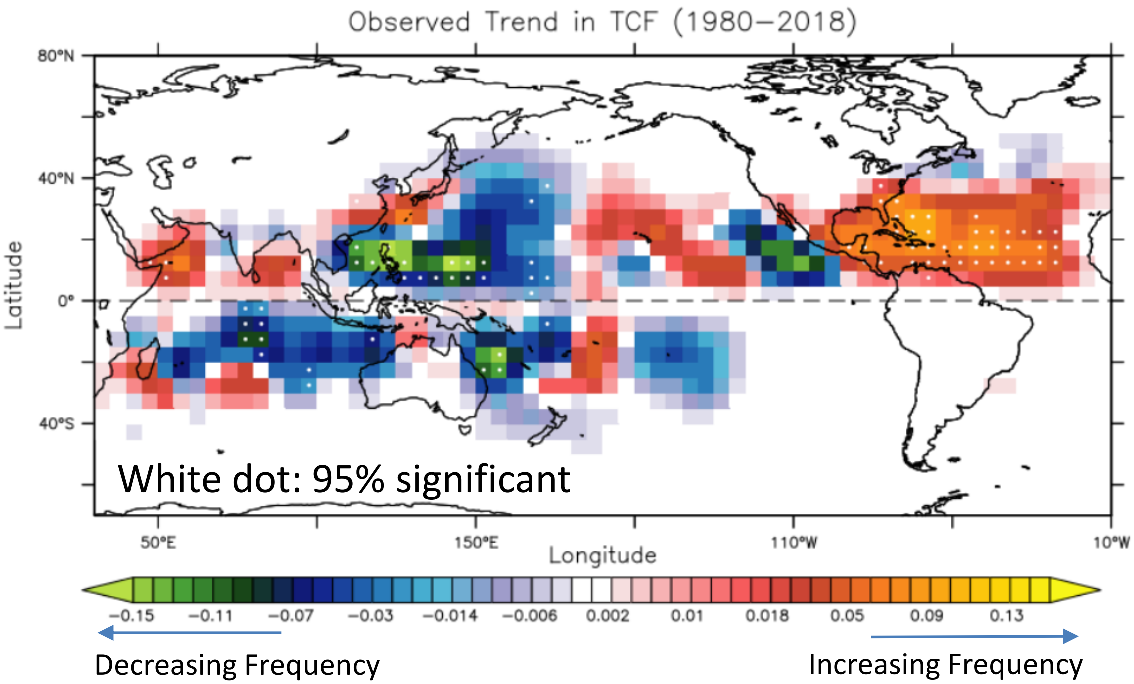
There is no significant trend in global TC number, indicating no impact of global warming on global TC.



An open question:

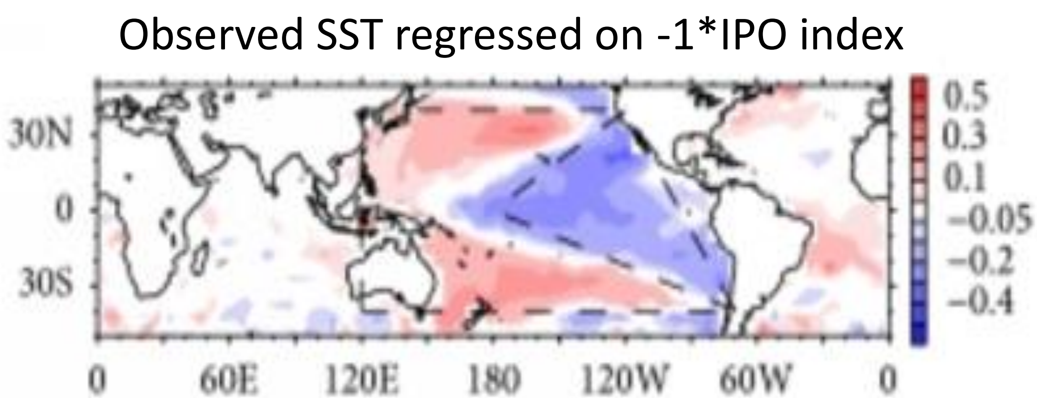
Are there indeed no climatic changes emerged in the global tropical cyclone activity?

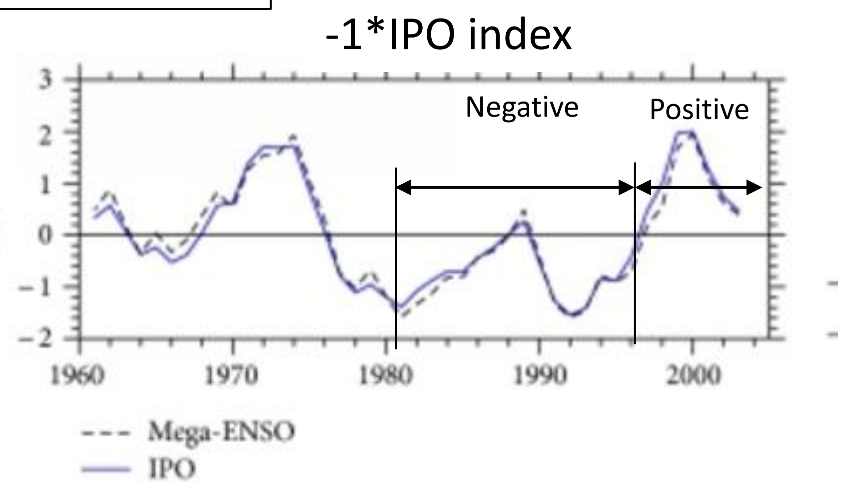
Observed Trend in Global TC Activity (1980-2018)



- 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)





SVD Analysis

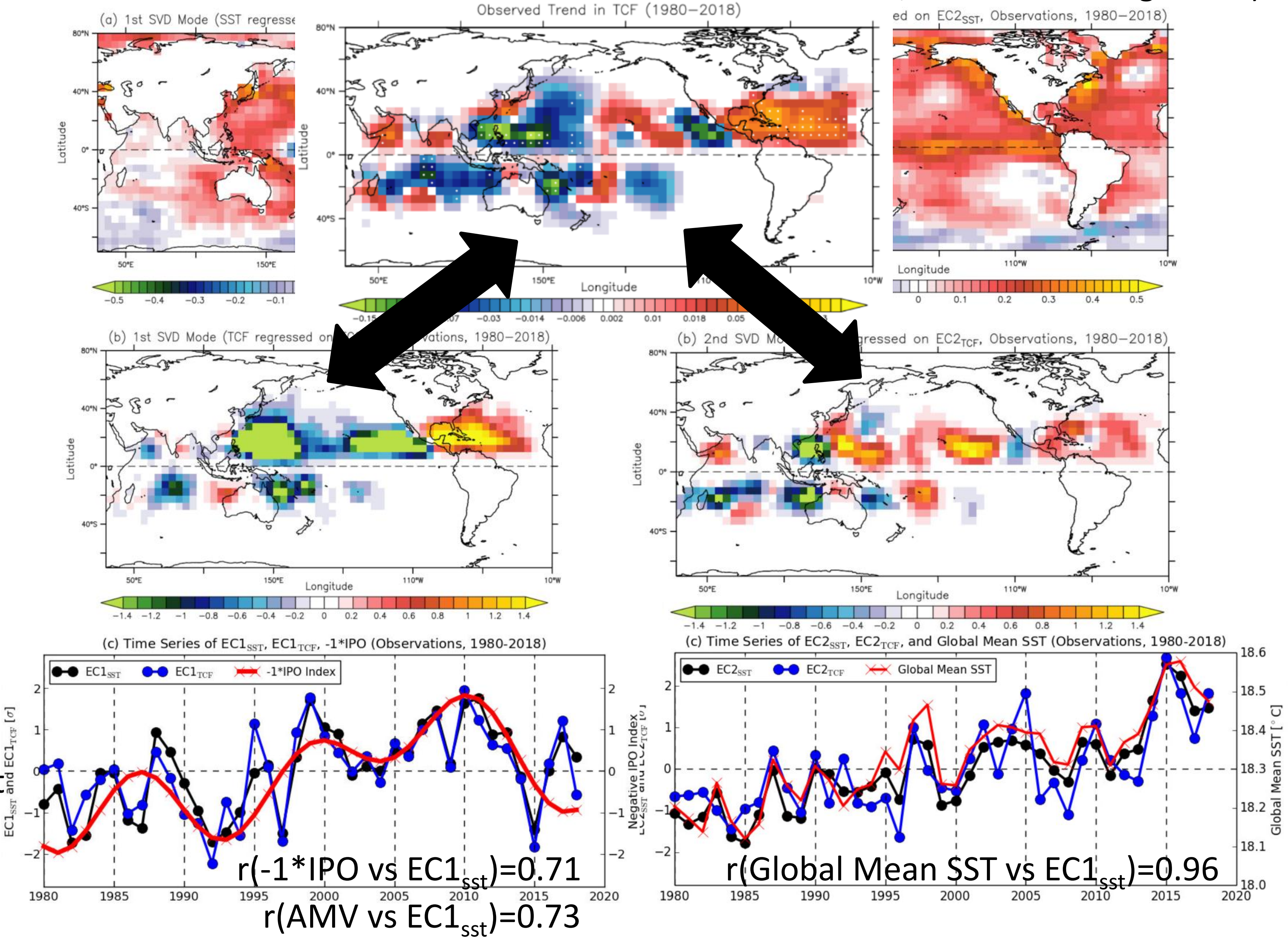
1st SVD Mode (61%, IPO mode)

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

SST

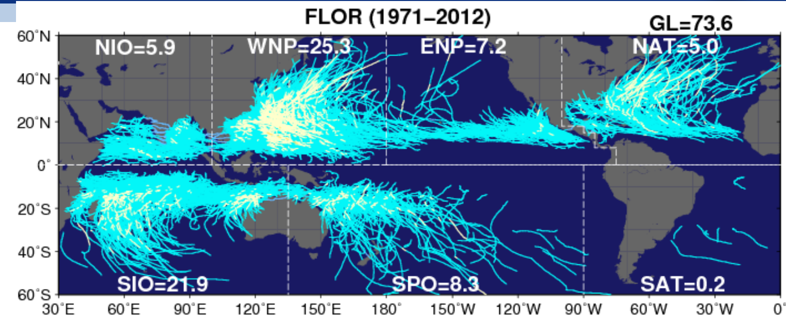
TCF

Expansion coefficient



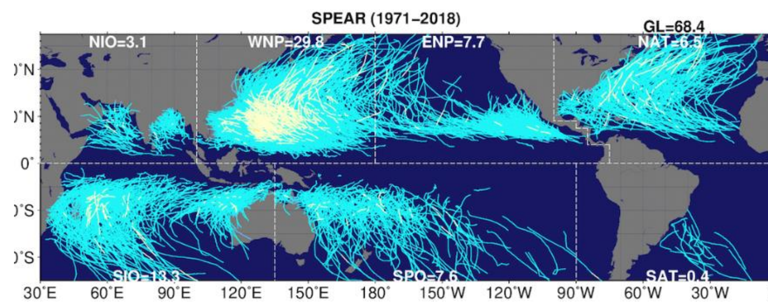
GFDL-FLOR & SPEAR –High-Resolution Climate Model–

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).

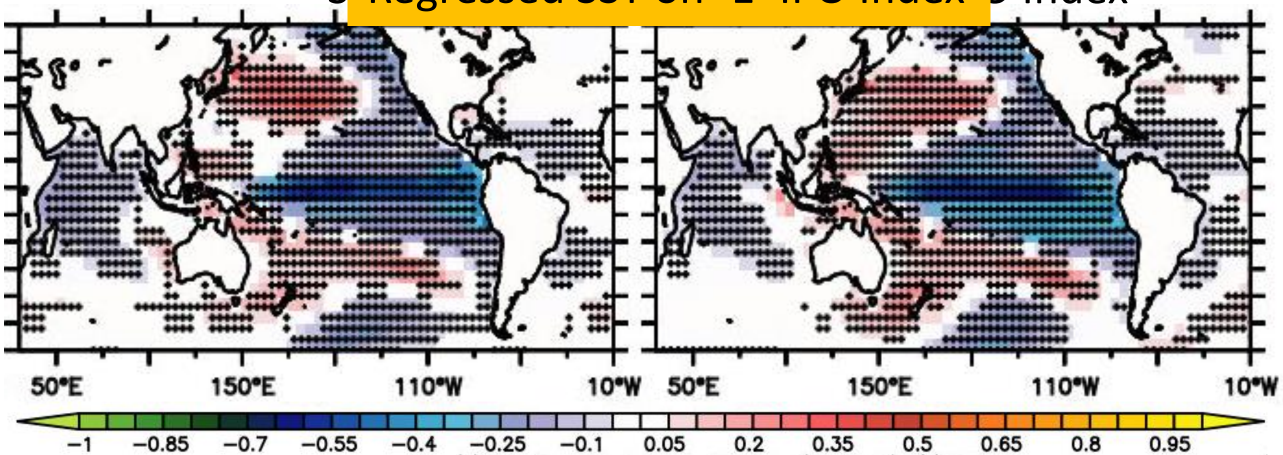
Impact of IPO on TCF (Long-term Control Experiments)

1850Cntl: Free running coupled-model simulations forced with the fixed anthropogenic forcing at the 1850 level (or say PiControl).

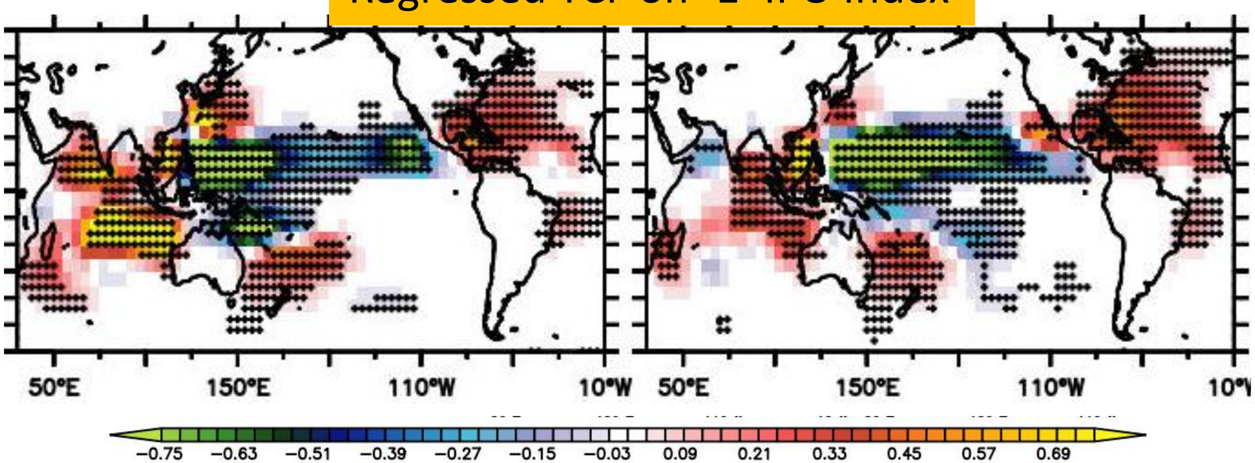
FLOR (1000-years)

SPEAR (1000-years)

Regressed SST on -1*IPO Index

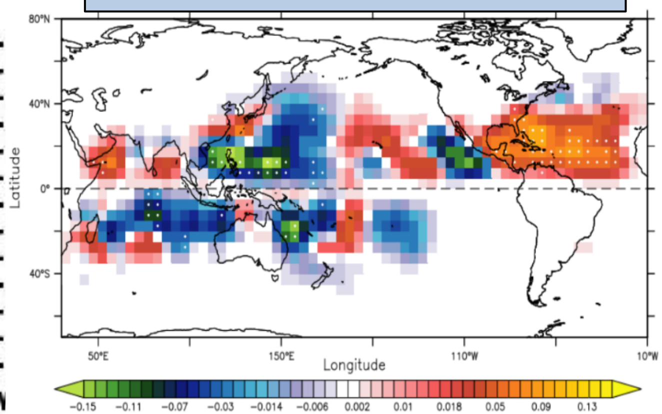


Regressed TCF on -1*IPO Index



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)



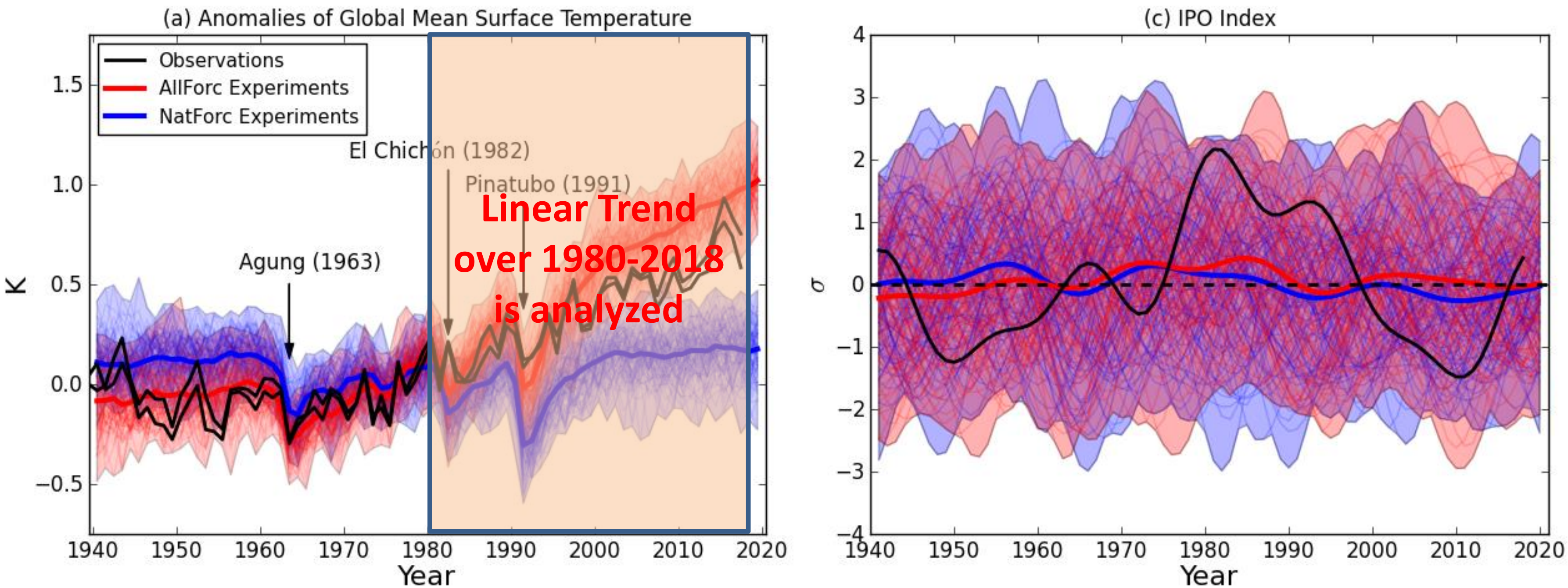
Large-Ensemble Simulations by SPEAR, FLOR, and FLOR-FA

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.

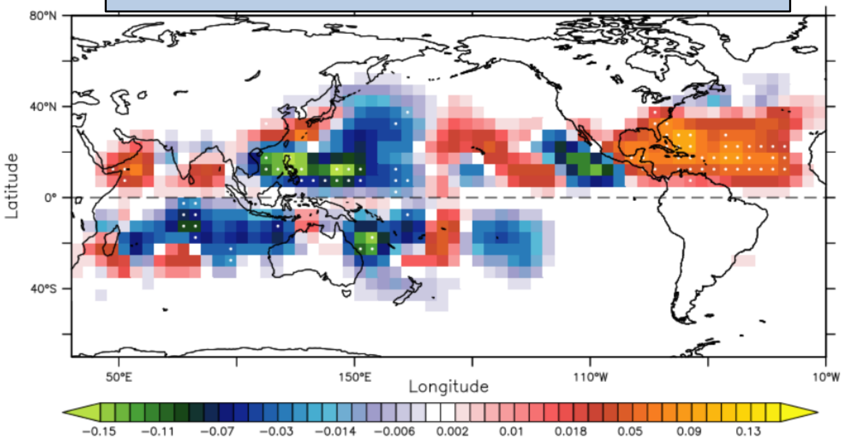
90 ensemble members = SPEAR (30 members), FLOR (30 members), and FLOR-FA (30 members)



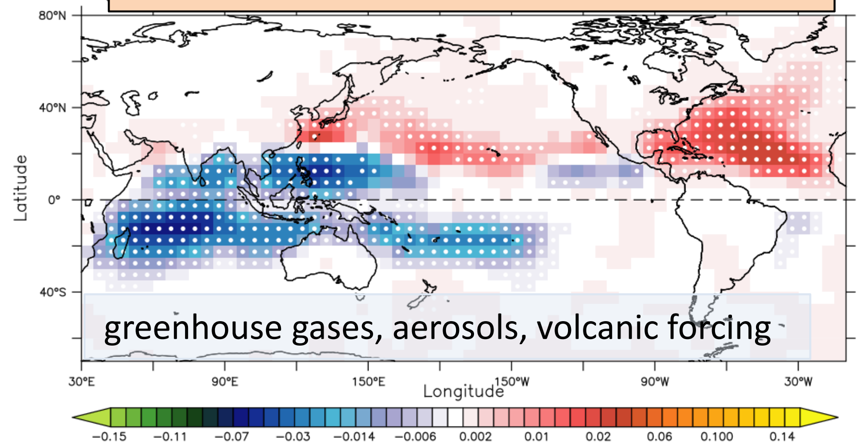
Because of the different initial states, each ensemble member shows a different phase of internal variability. Internal variability can be canceled out by averaging the members.

Effect of External Forcing on the TCF Trend

Observed Trend in TCF (1980-2018)

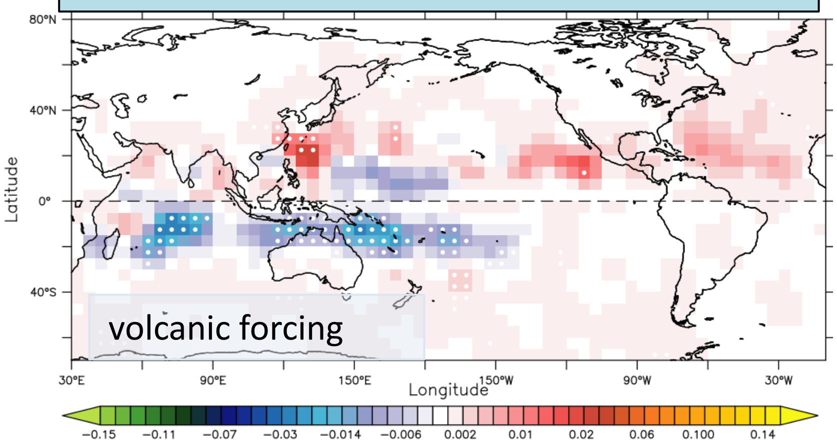


AllForc (95-member mean, 1980-2018)



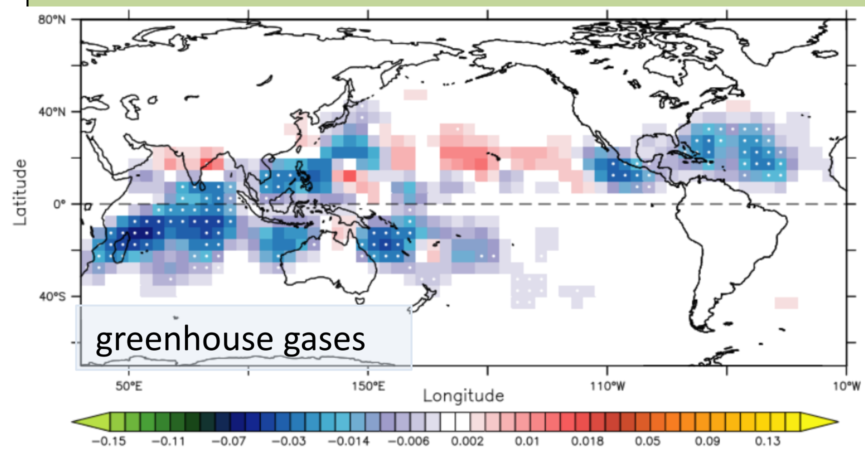
A similar spatial pattern with observations indicates marked influence of external forcing on global TCF.

NatForc (90-member mean, 1980-2018)



Volcanic forcing causes a northward shift in TCF, which is also similar to the observed TCF trend.

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

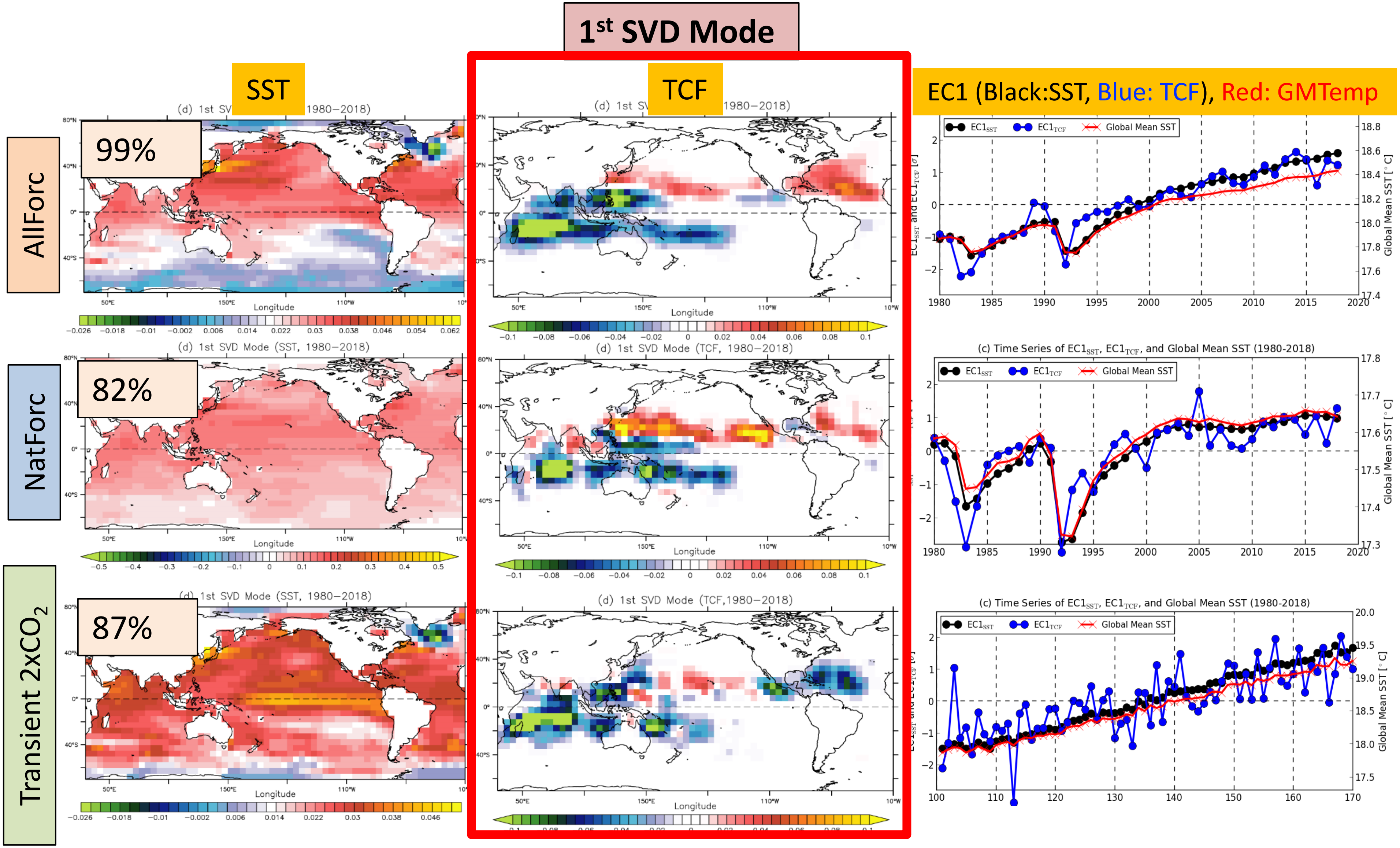


Transient +1%/yr CO_2 Experiment

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

Effect of External Forcing on the TCF Trend

SVD analysis is applied to the ensemble mean for each experiment.

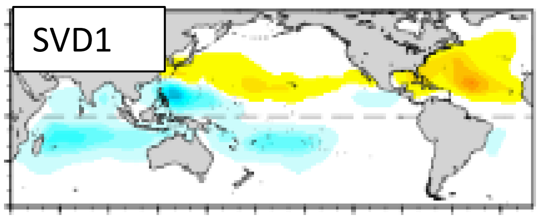


The 1st SVD mode of TCF is assumed to be the expected climate signal of TCF

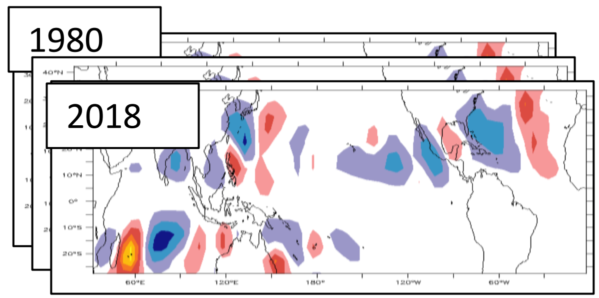
Optimal Fingerprint Analysis

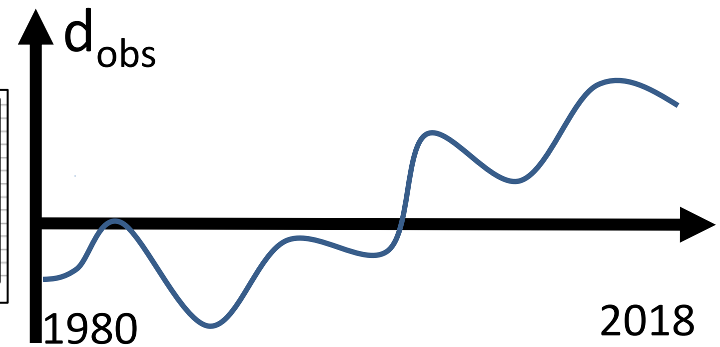
Question: How much of the observed TCF trends over 1980–2018 can be statistically distinguishable from internally generated noise? If they can be distinguished from noise, by what year did this occur?

An Expected Climate Signal Pattern (Guess, or Fingerprint)



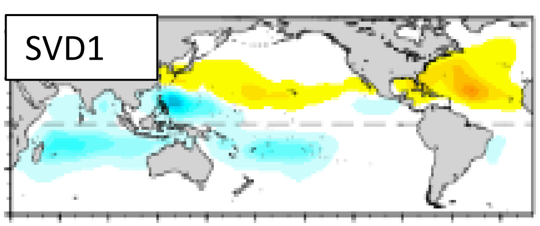
Observed Annual TCF Anomaly (1980-2018)



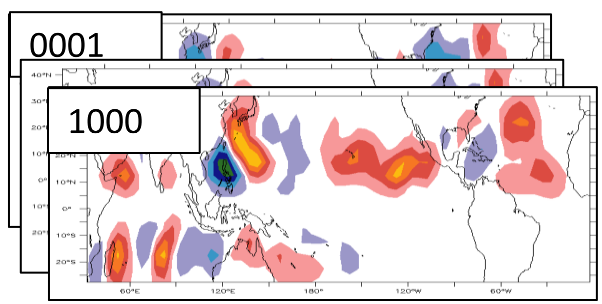


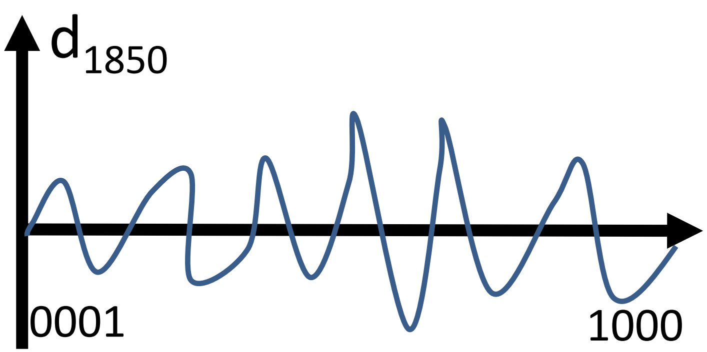
G(x,y) x $TCF_{obs}(x,y,t)$

An Expected Climate Signal Pattern (Guess, or Fingerprint)



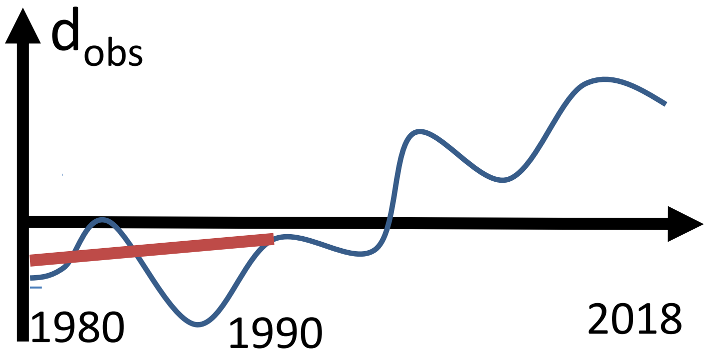
1850Cntl (1000 years)

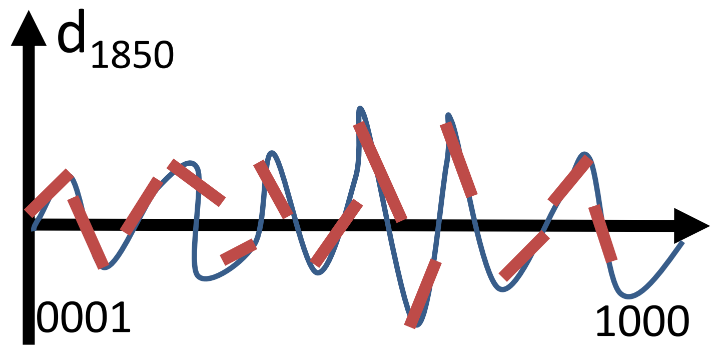




G(x,y) x $TCF_{1860}(x,y,t)$

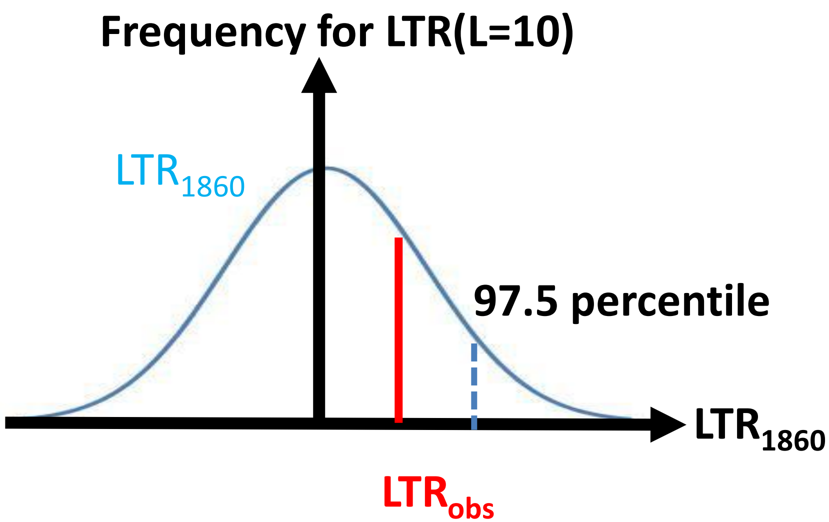
Optimal Fingerprint Analysis (Concept)





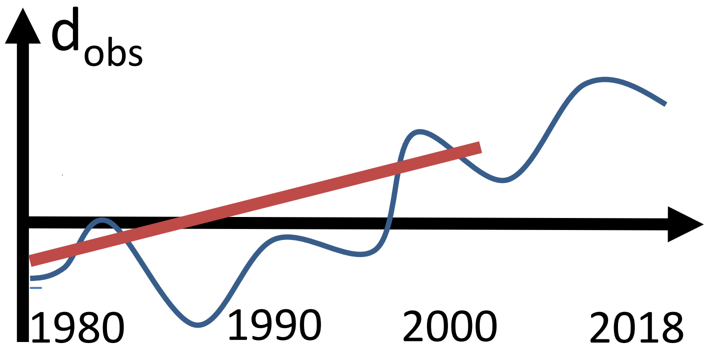
Observed linear trend between 1980 – 1990: $LTR_{obs}(L=10)$

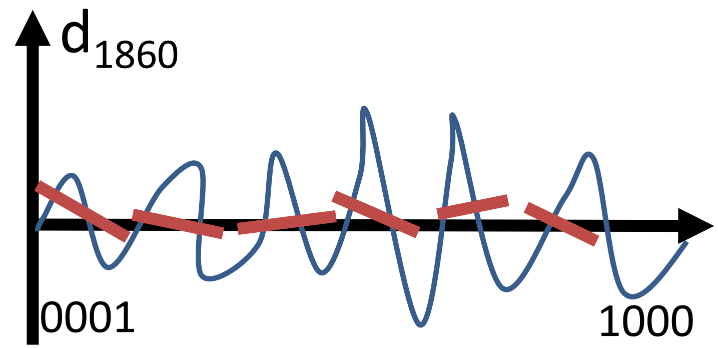
Many $LTR_{1860}(L=10)$ samples can be obtained from 1850Cntl.



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

Optimal Fingerprint Analysis (Concept)

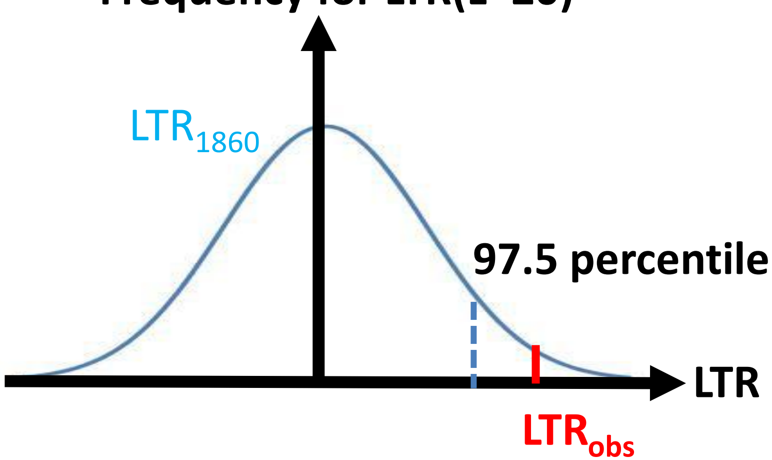




Observed linear trend between 1980 – 2000: $LTR_{obs}(L=20)$

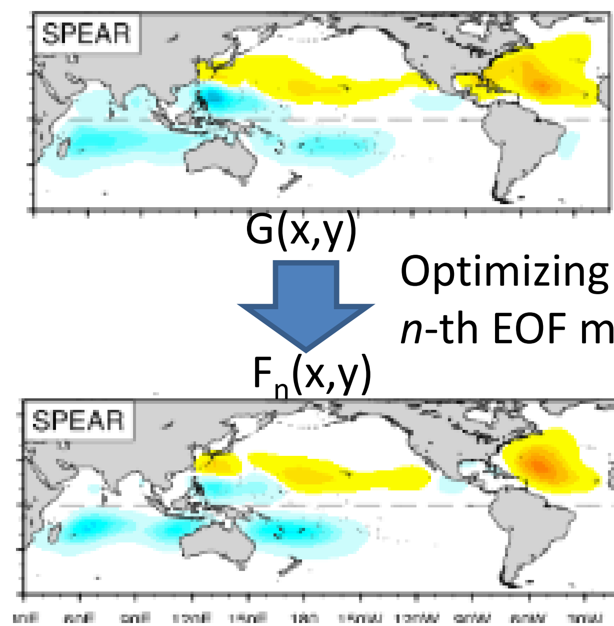
Many $LTR_{1860}(L=20)$ samples can be obtained from 1860Cntl.

Frequency for LTR(L=20)



LTR_{obs} is distinguishable from noise (detected)

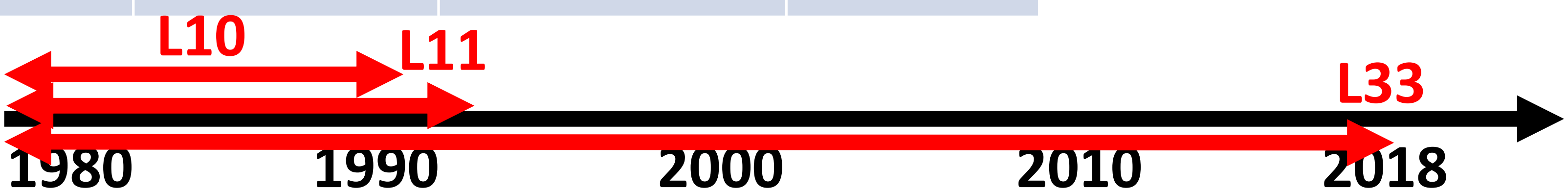
An Expected Climate Signal Pattern (Guess)



Optimal Fingerprint Analysis (Guess or Fingerprint)

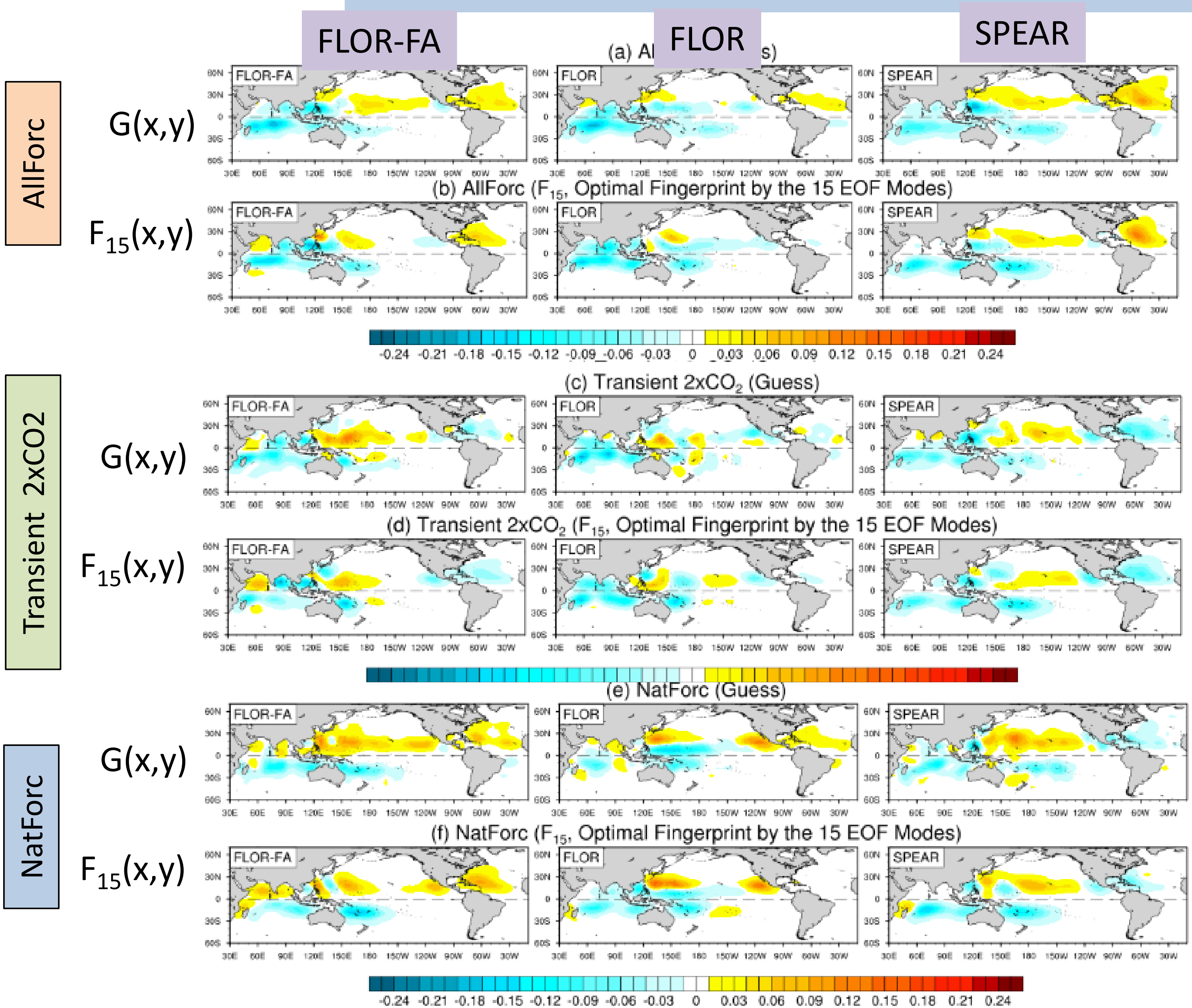
Fingerprints			1850Cntl
AllForc	FLOR-FA	G, F_5, F_{10}, F_{15}	SPEAR
	FLOR		SPEAR
	SPEAR		FLOR-FA
Transient $2xCO_2$	FLOR-FA		SPEAR
	FLOR		SPEAR
	SPEAR		FLOR-FA
NatForc	FLOR-FA		SPEAR
	FLOR		SPEAR
	SPEAR		FLOR-FA

- There are 36 fingerprints prepared (3 x 3x 4).
- To avoid artificial skill, independent models should be used for fingerprint and 1850Cntl.

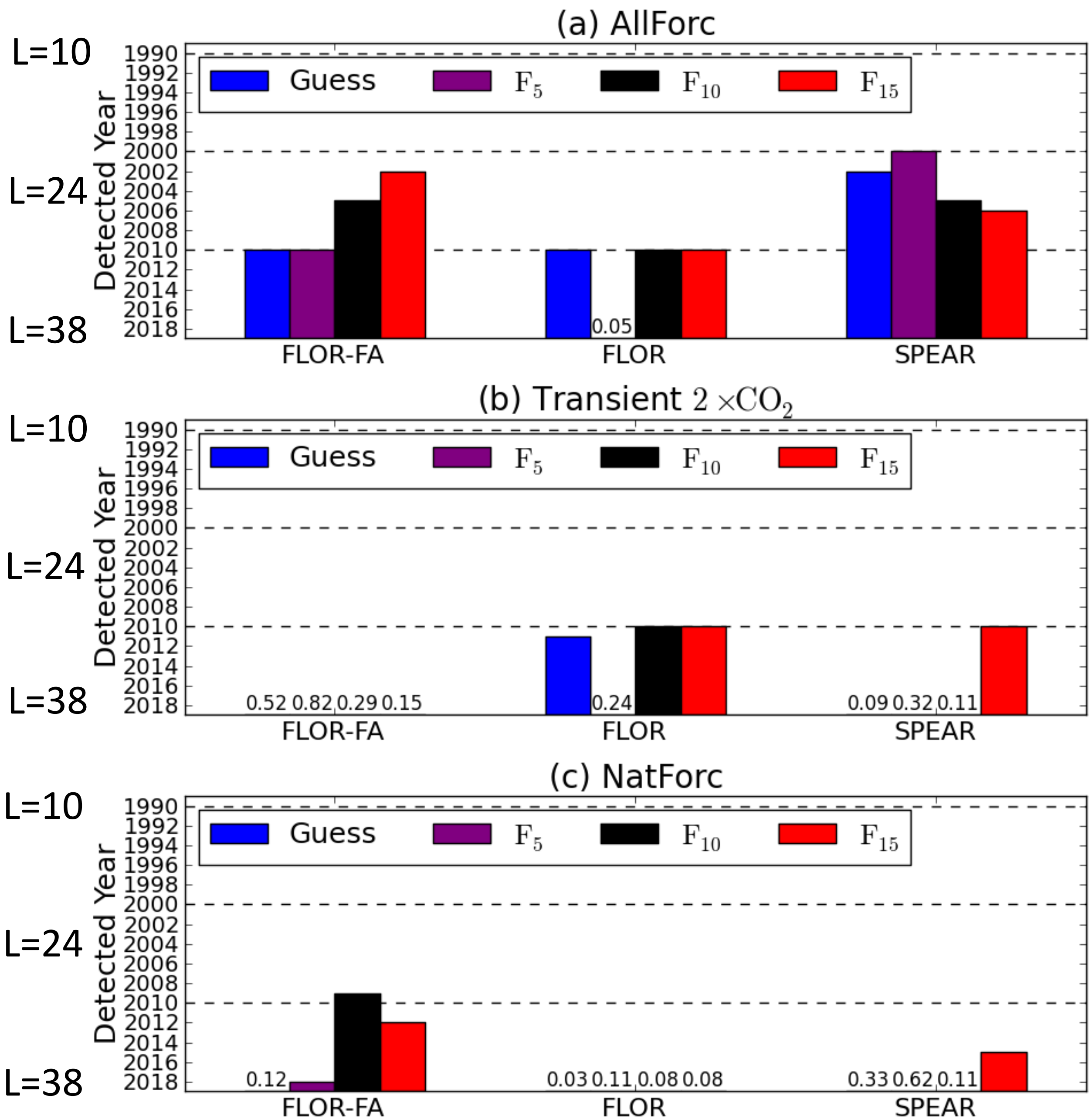


- The detection time is referenced to 1980.
- We begin with L10 (a linear trend from 1980 to 1990) to see if it is detected. So that the earliest detection year is 1990.
- In case of no detection, we repeat the analysis by increasing the length by one year (e.g., L11, L12,…, L38) until it shows a detection.

Optimal Fingerprint Analysis (Guess or Fingerprint)



Optimal Fingerprint Analysis



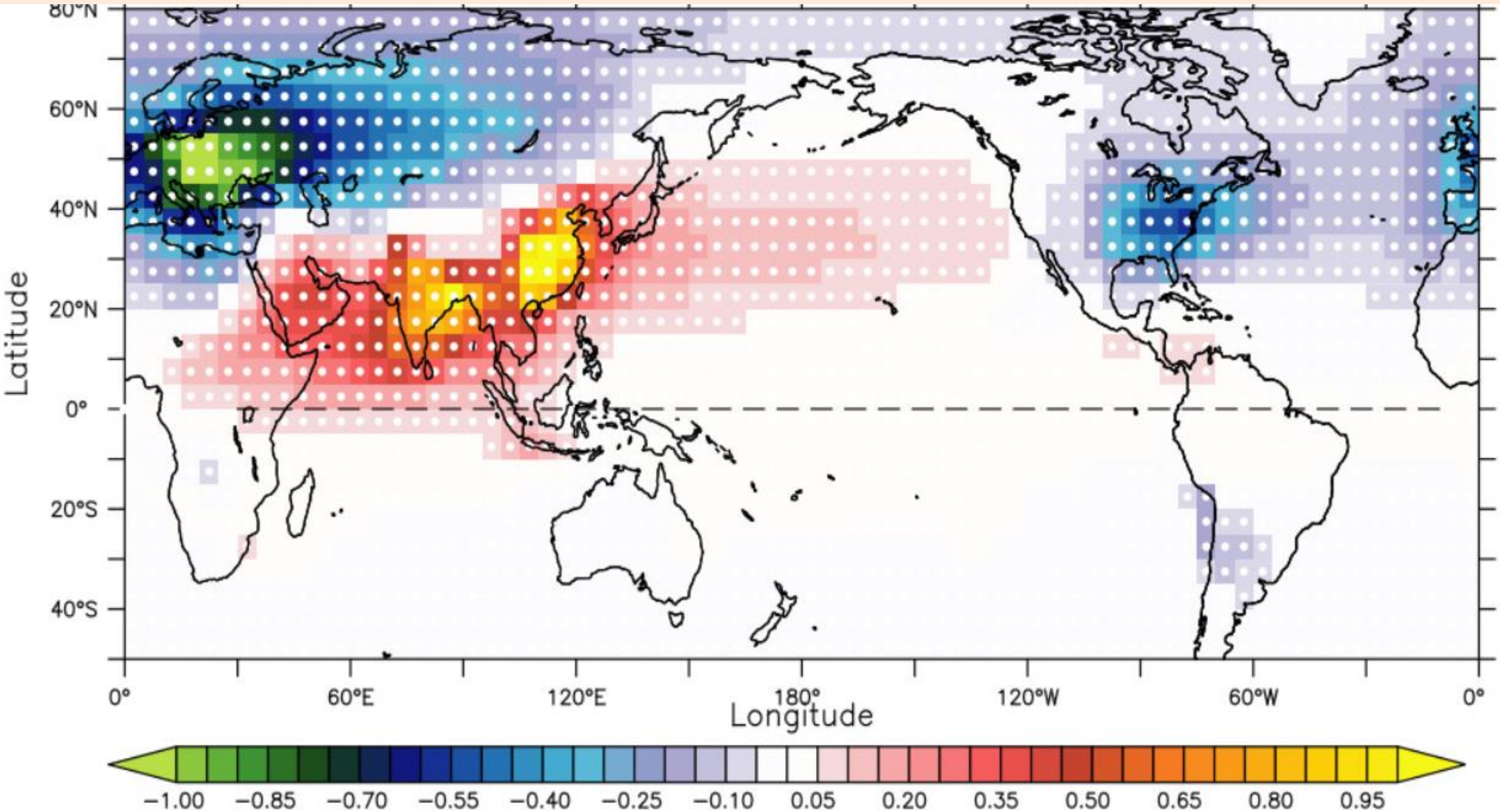
Detected around 2010
⇒ External forcing play an important role for the observed trend.

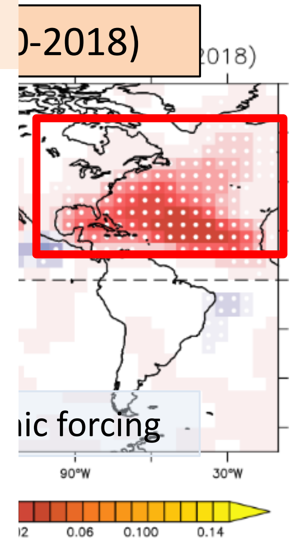
Detected around 2010
⇒ Increase in greenhouse gases (CO_2) partially contributes to the observed trend.

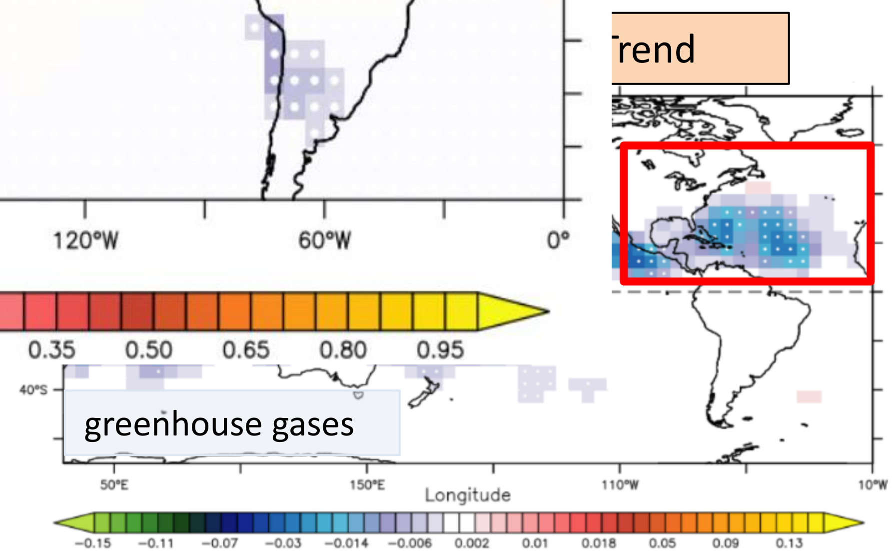
Volcanic forcing also plays a minor role.

Effect of Aerosols on Atlantic TCs

Sulfate Change (2001-2020 minus 1980-2000)







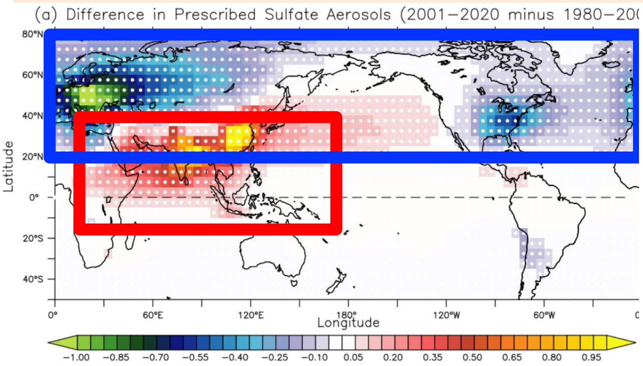
Open questions:

- Anthropogenic aerosols might have also exerted a substantial impact on TCs not only in the North Atlantic but in the global ocean.
- Regional changes in aerosols may differently influence global TCs.

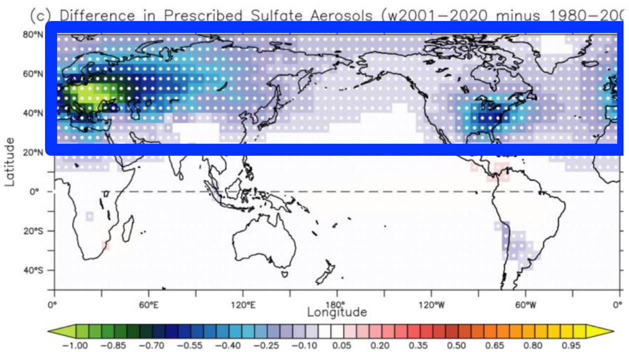
There is a marked difference in the North Atlantic.

Idealized Model Experiments

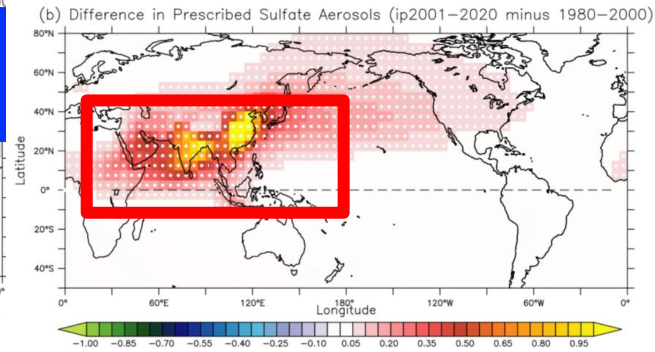
ΔALL21, Sulfate



ΔW21, Sulfate



ΔIP21, Sulfate

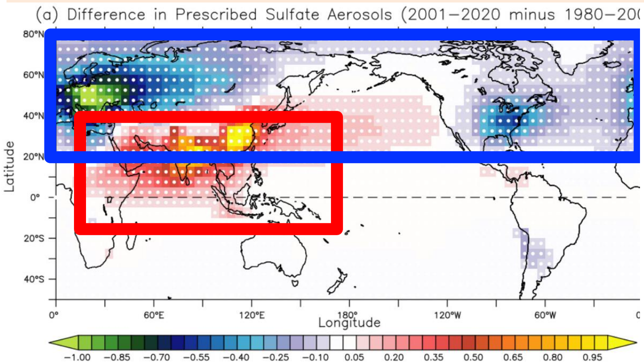


Using SPEAR, additional idealized experiments were conducted by specifying different aerosol emissions.

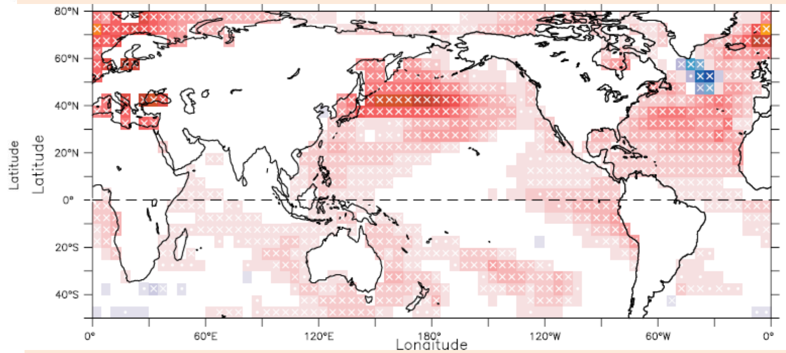
Exp Name	Level of Anthropogenic Aerosols	Other external forcing	Simulation length	Difference from CNTL
CNTL	Mean of 1980-2000			—
ALL21	Mean of 2001-2020			ΔALL21
W21	Same as CNTL, but 2001-2020 mean for Europe and the US.	Fixed at 2000 level	200 years	ΔW21
IP21	Same as CNTL, but 2001-2020 mean for China and India.			ΔIP21

Simulated Changes in TCF by the Idealized Experiments

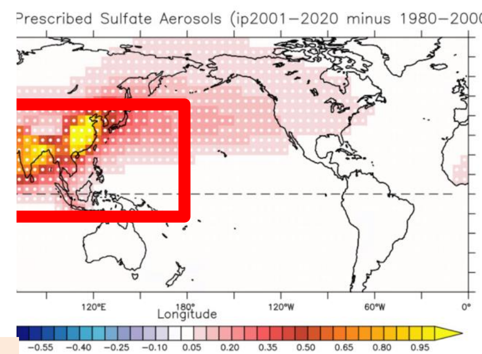
ΔALL21, Sulfate



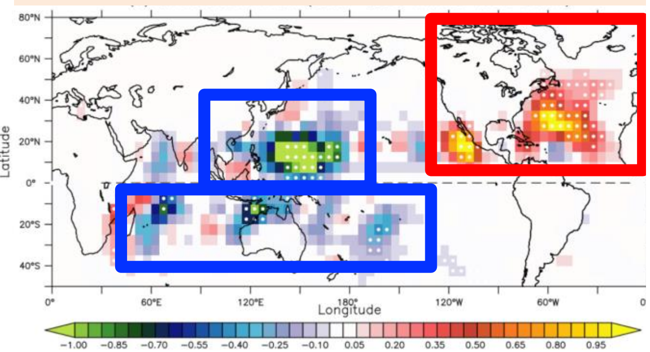
ΔALL21, SST



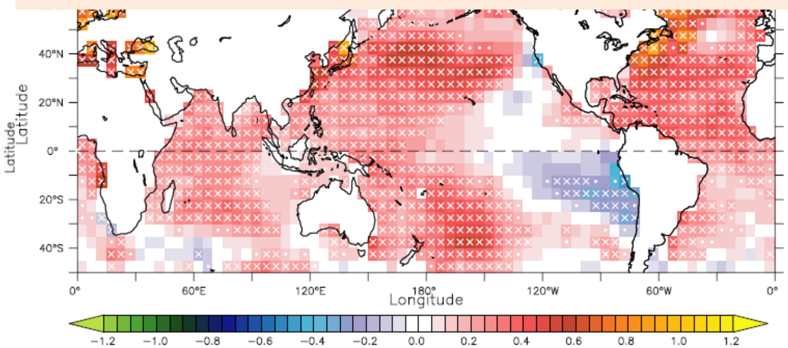
ΔIP21, Sulfate



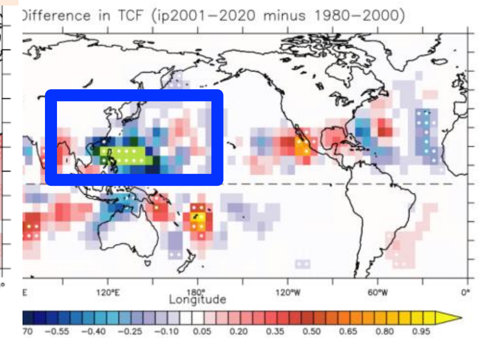
ΔALL21, TCF



Observed SST Change (2001-2020 minus 1980-2000)



ΔIP21, Sulfate



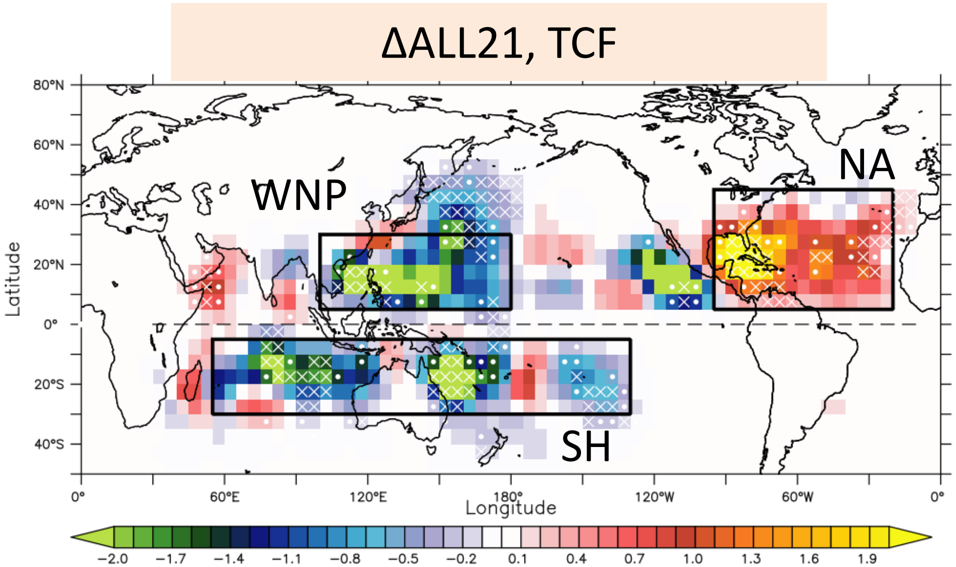
Decreased Aerosols in US & Europe => **Increased TCs in the North Atlantic**

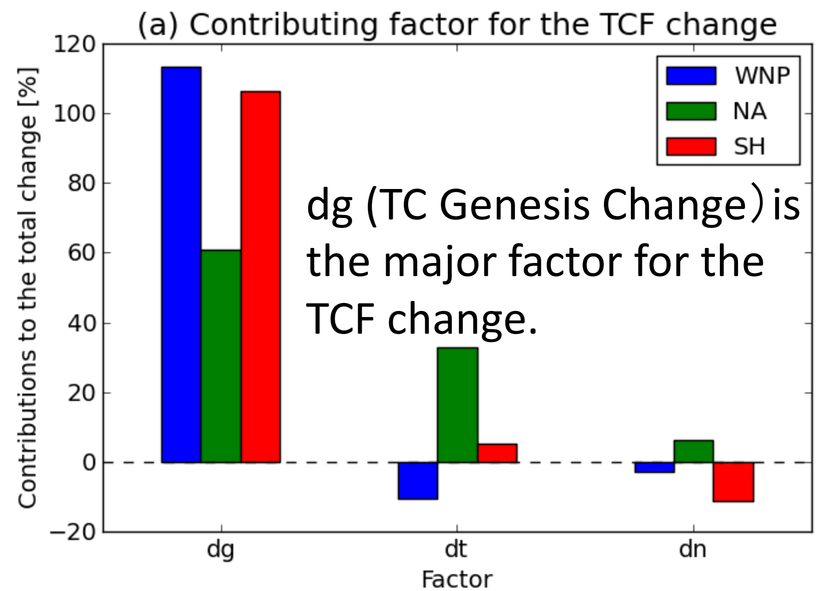
Decreased TCs in the Southern Hemisphere

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

The potential effect of aerosols on the La Nina-like SST decadal change

Empirical Analysis of TCF Change

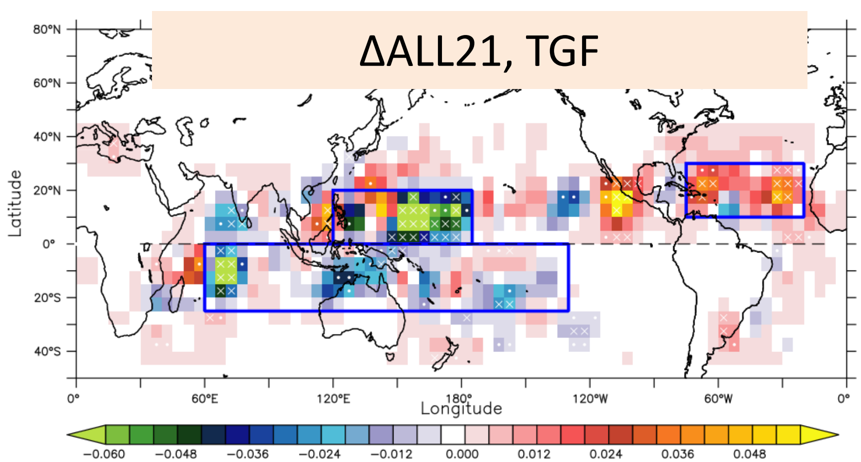




An empirical TCF analysis (Murakami et al. 2013)

$$\delta f(A) = \underbrace{\iint_C \delta g(A_0) \times \overline{t(A, A_0)} dA_0}_{dg} + \underbrace{\iint_C \overline{g(A_0)} \times \delta t(A, A_0) dA_0}_{dt} + \underbrace{\iint_C \delta g(A_0) \times \delta t(A, A_0) dA_0}_{dn}$$

TCF Change = TC Genesis Change (dg) + TC Track Change (dt) + Non-Linear Effect (dn)

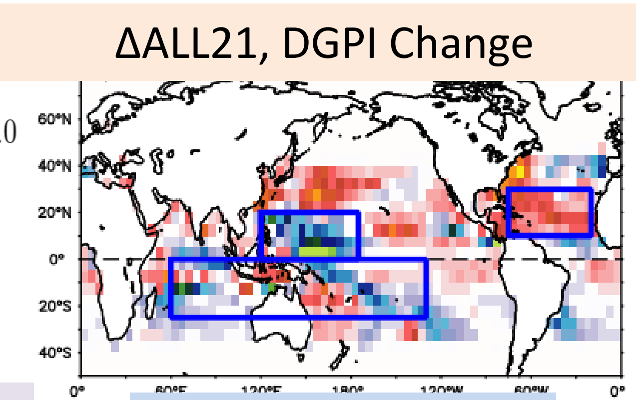


Analysis of TC Genesis Change via Genesis Potential Index

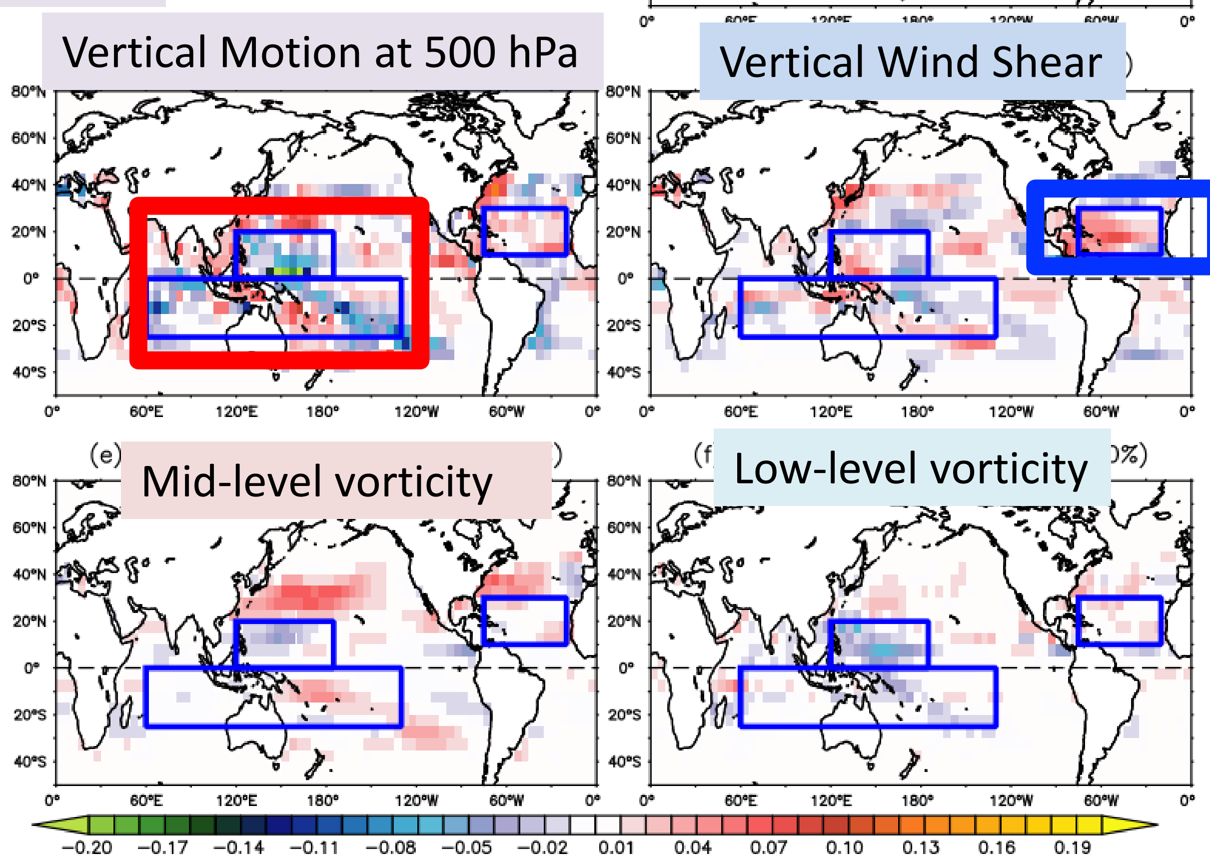
A new Dynamic GPI (Wang and Murakami 2020, Murakami and Wang 2022)

$$DGPI = (2.0 + 0.1 \times V_s)^{-1.7}\left(5.5 - \frac{du_{500}}{dy} \times 10^5\right)^{2.3}(5.0 - 20 \times \omega_{500})^{3.4}(5.5 + |\zeta_{a500} \times 10^5|)^{2.4}e^{-11.8} - 1.0$$

Vertical Wind Shear	Mid-level vorticity	Vertical Motion at 500 hPa	Low-level vorticity

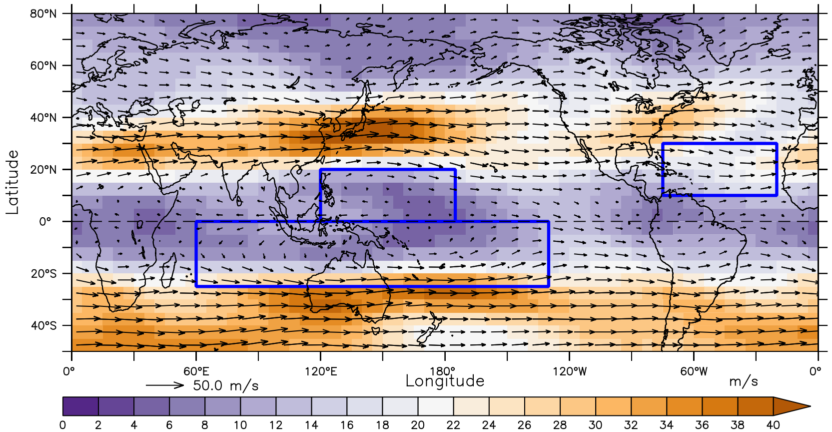


Region	The Critical Element for the GPI Change
North Atlantic	Vertical Wind Shear
Western North Pacific	Vertical Motion at 500 hPa
Southern Hemisphere	Vertical Motion at 500 hPa

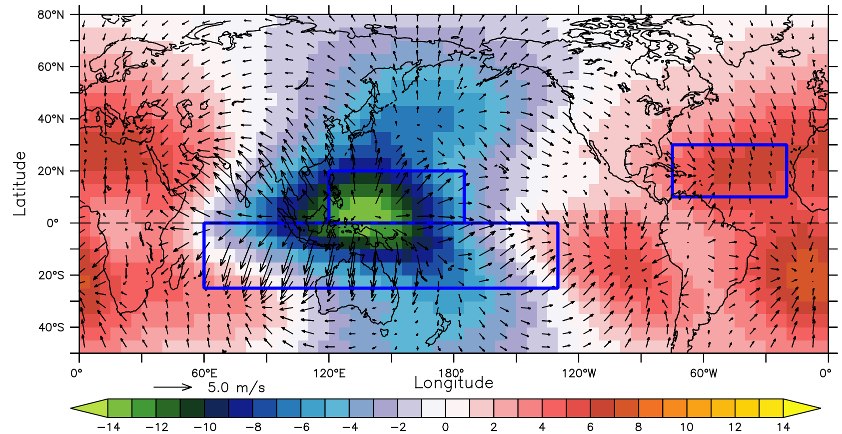


Large-scale Flow Changes (ΔALL21)

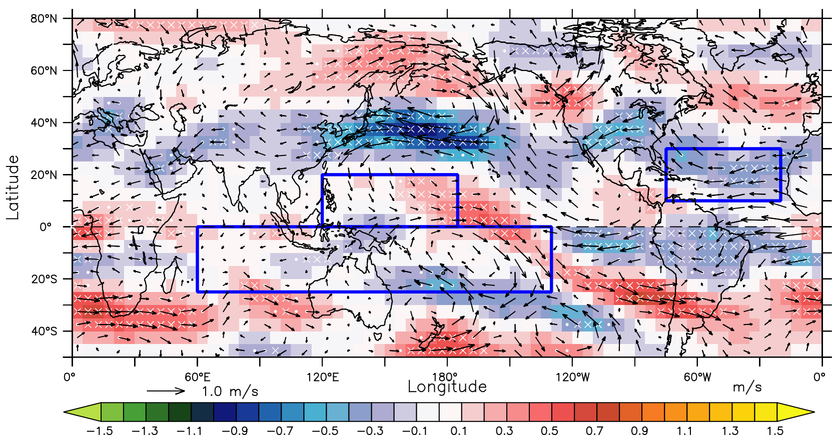
(a) Winds at 200 hPa (CNTL)



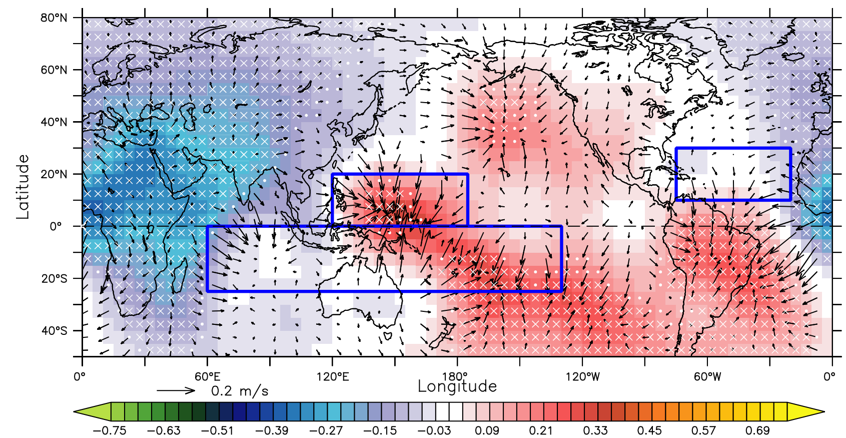
(b) X_{200} and Divergence Winds (CNTL)



(c) Winds at 200 hPa (δALL21)



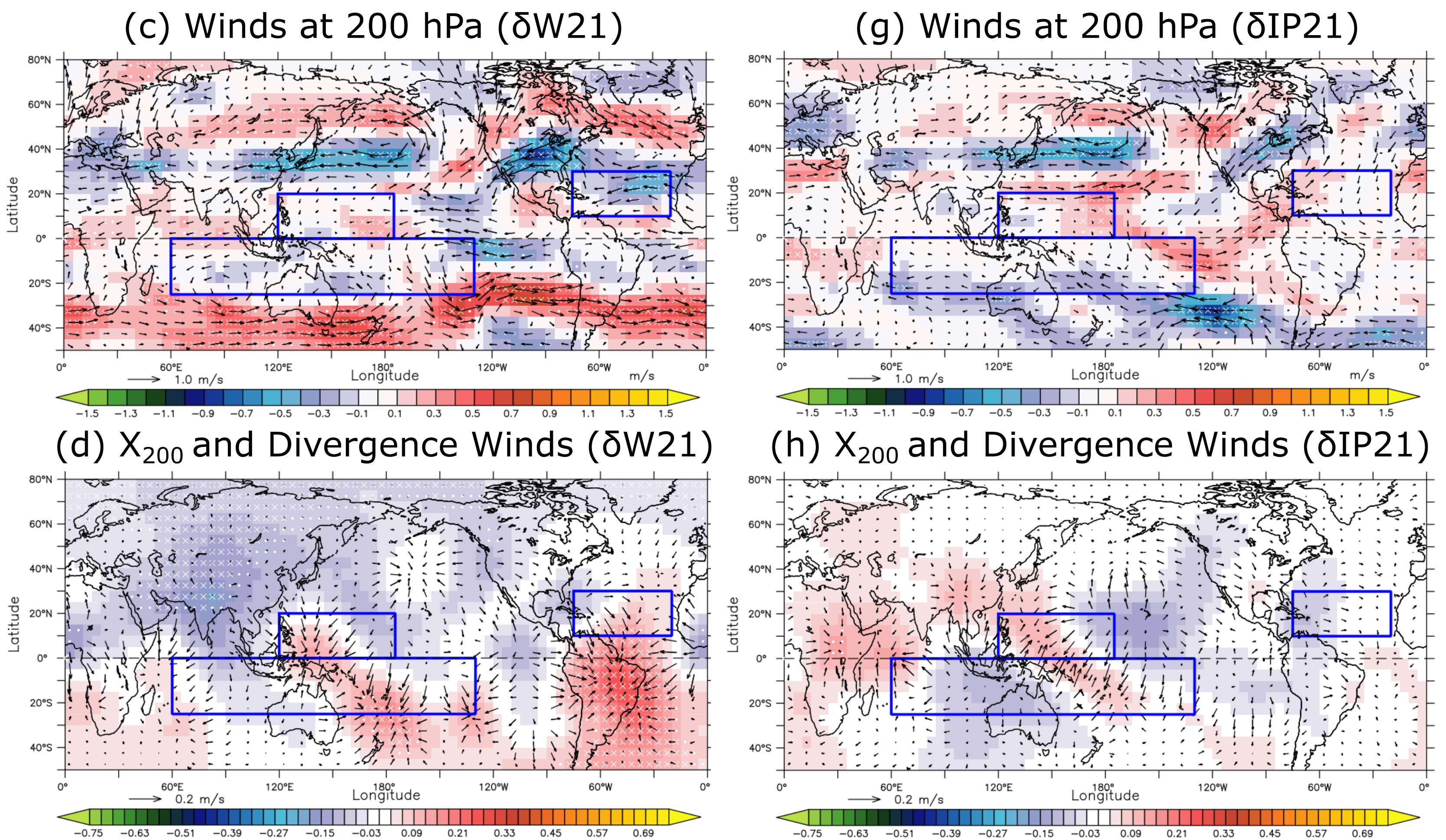
(d) X_{200} and Divergence Winds (δALL21)



A northward shift in subtropical jet caused decreased wind shear in the North Atlantic
->Increased TCs in North Atlantic

Decreased divergence at the upper-level troposphere in W. Pacific and S. Hemisphere
->Weakened convections
->Decreased TCs in W. Pacific and S. Hemisphere

Large-scale Flow Changes（ΔW21 and ΔIP21)

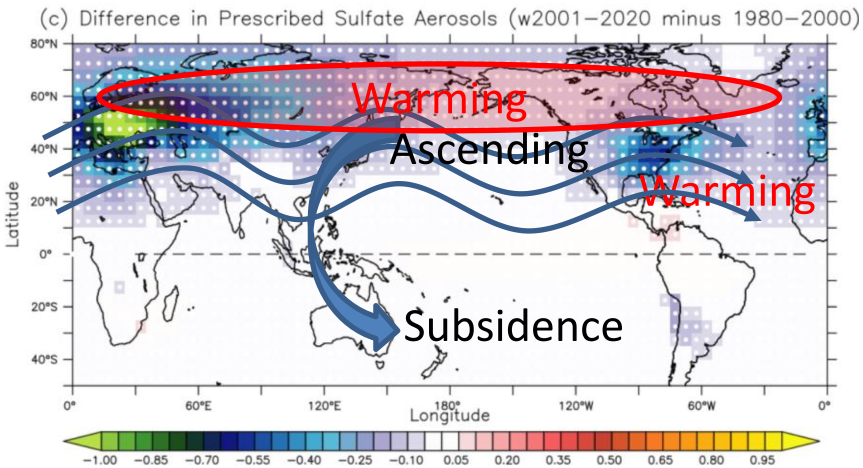


A northward shift in jet is seen in ΔIP21, but not extended to the North Atlantic.

The convergence changes are larger in ΔW21 than in ΔIP21 in the Southern Hemisphere.

Schematic Diagram for the Effect of Aerosols on Global TCs

ΔW21



Decreased Aerosols -> Warming Local Ocean

-> Increased TCs in the North Atlantic

Decreased Aerosols -> Decreased meridional gradient of atmospheric temperature

-> Poleward shift in subtropical jet

-> Decreased wind shear

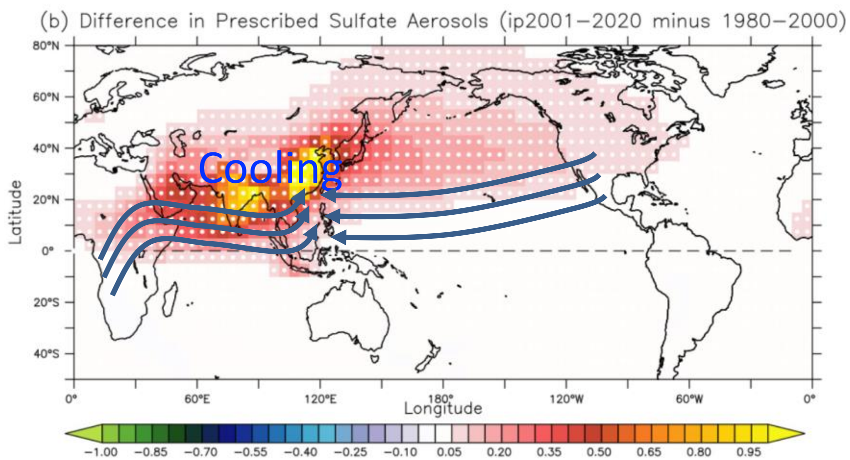
-> Increased TCs in the North Atlantic

Warming North Hemisphere -> Hadley Circulation Anomaly

-> Subsidence anomaly in the Southern Hemisphere

-> Decreased TCs in the Southern Hemisphere

ΔIP21



Increased Aerosols -> Cooling South-East Asian Continent

-> Weakening of Indian Monsoon

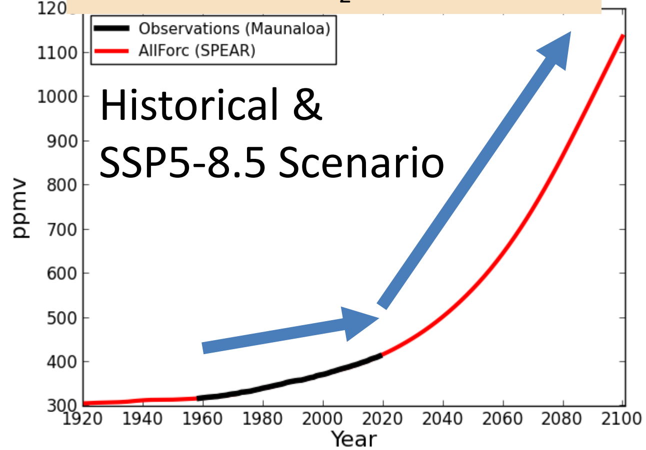
-> Weakening of Monsoon Trough in the western North Pacific

-> Decreased TCs in the Western North Pacific

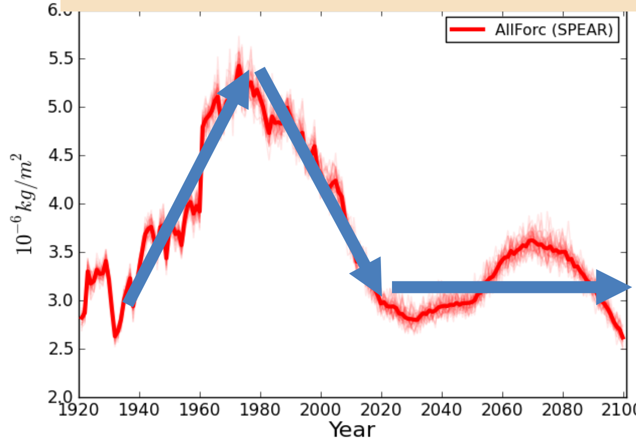
Consistent with Ramasamy and Chen (1997), Ming and Ramaswamy (2009), Bollasina et al. (2011)

Future Projections

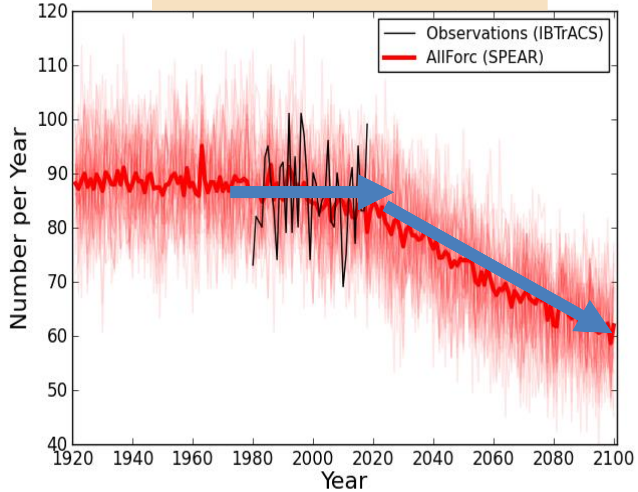
Global Mean CO_2 Concentration



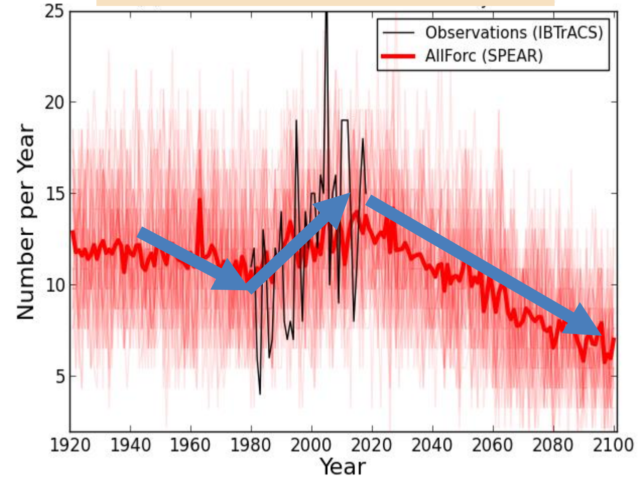
Sulfate Aerosols over North Atlantic



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.

Summary

- A climate change in global TC activity over the period 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, aerosols, and volcanic eruptions 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 since 1980, whereas the increased aerosols in China & India may play an important role in the decreased TCs over WNP.

- The models project decreasing trends in global (including North Atlantic) TCs toward the end of this century owing to the dominant effect of CO_2 increases.

Reference

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. *Proc. Natl. Acad. Sci.* U.S.A., **117(20)**, 10706-10714.

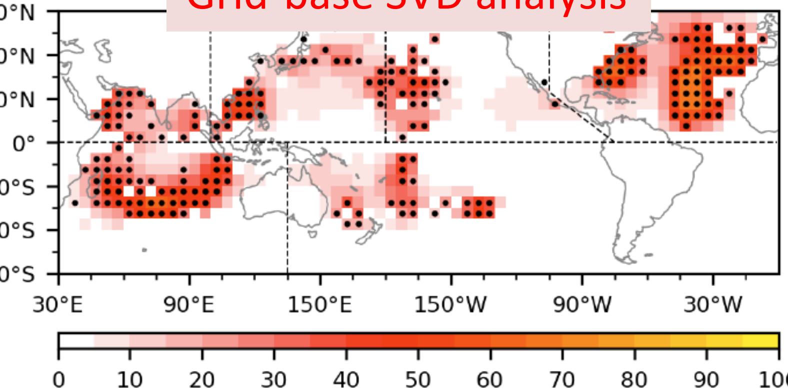
Murakami, H., 2022: Substantial global influence of anthropogenic aerosols on tropical cyclones over the past 40 years. *Sci. Adv.,* **8,** eabn9493.

Murakami, H. and B. Wang, 2022: Patterns and frequency of projected future tropical cyclone genesis are governed by dynamic effects. *Nature Commun. Earth Environ.*, **3,** 77.

Ongoing Research (Part I)

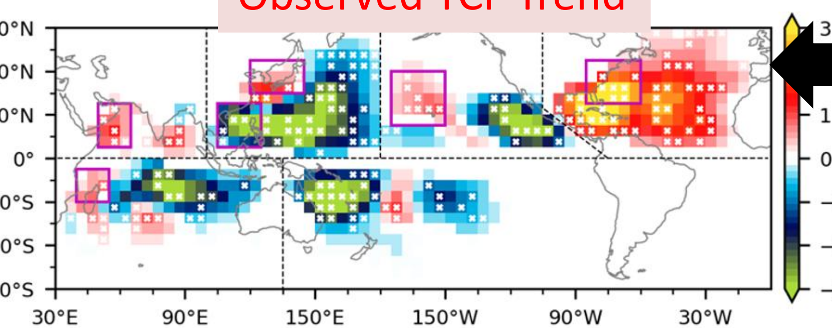
Goal: To identify the regions where anthropogenic climate changes may play a dominant role in the past 40-yr observed TCF trends relative to the internal variability.

Grid-base SVD analysis



Black dots indicate TCF changes that are highly correlated with the global warming mode than the internal mode based on a “grid-base SVD analysis”.

Observed TCF Trend



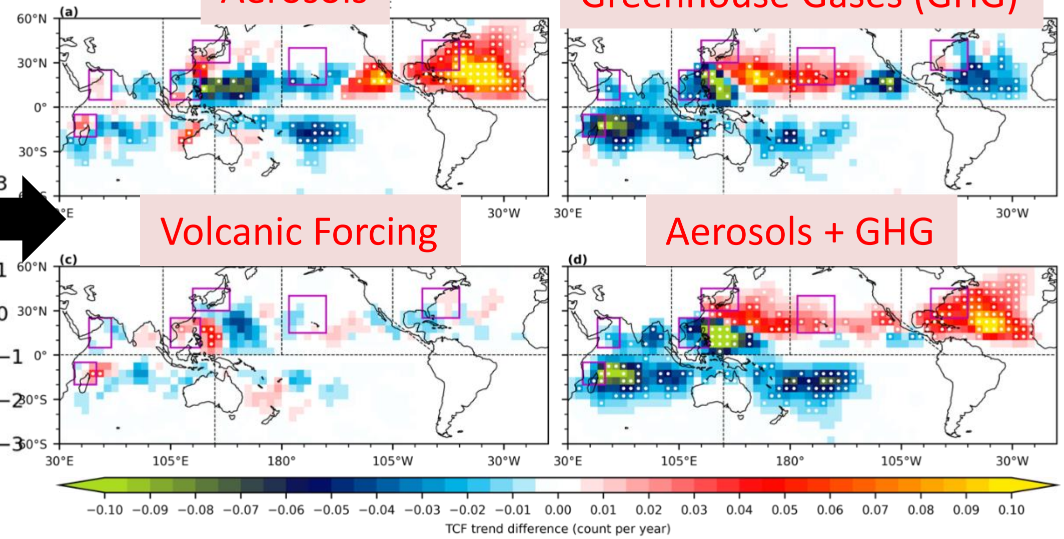
We focus on the 6 coastal regions where global warming mode is dominant for the TCF trend.

Aerosols

Greenhouse Gases (GHG)

Volcanic Forcing

Aerosols + GHG



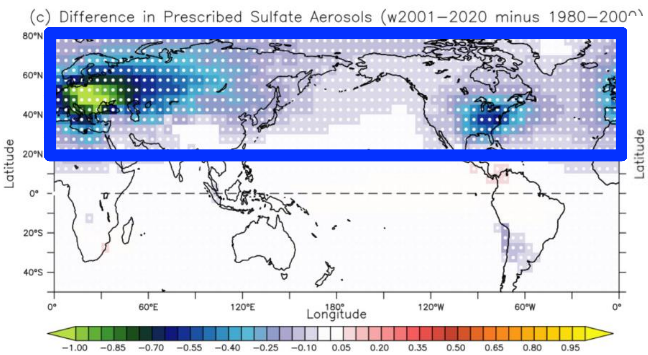
The trends of ensemble mean by the large-ensemble experiments that consider the single or multiple external forcing.

Shuai Wang and Hiro Murakami (in preparation)

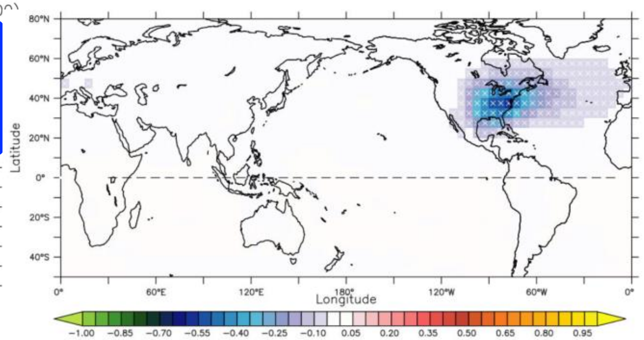
Ongoing Research (Part II)

Goal: To identify which of the aerosols decreases in Europe or the U.S. played important role in the global TCF.

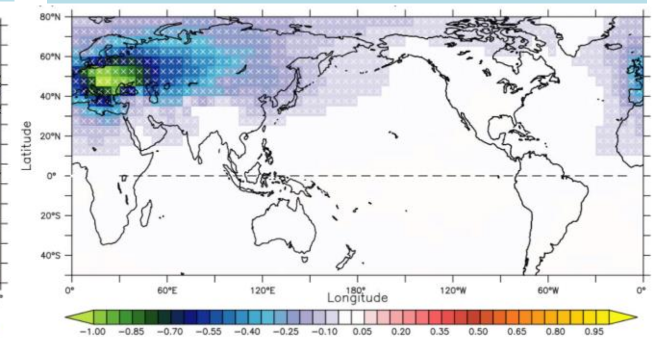
ΔW21, Sulfate



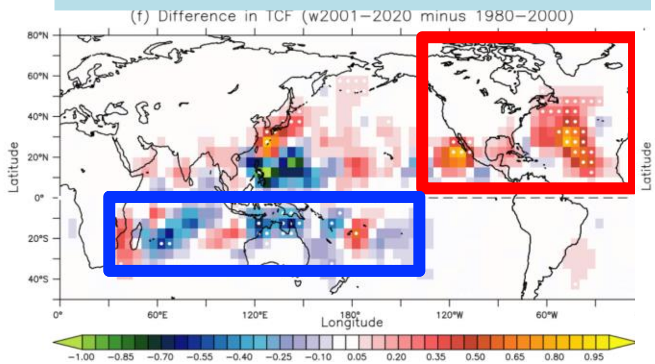
ΔUS21, Sulfate



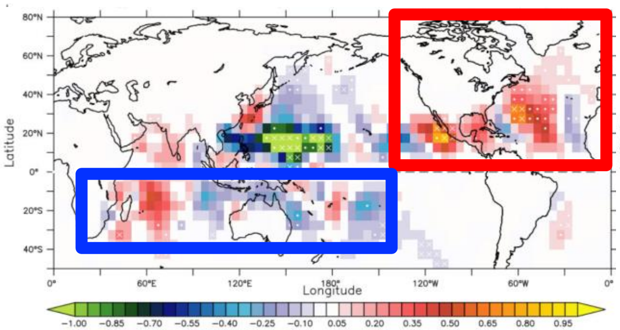
ΔEURO21, Sulfate



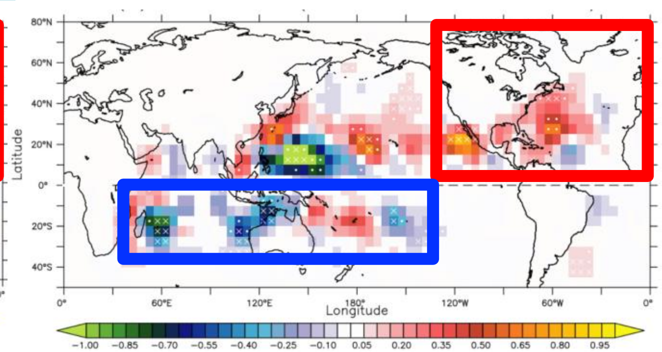
ΔW21, TCF



ΔUS21, TCF



ΔEURO21, TCF



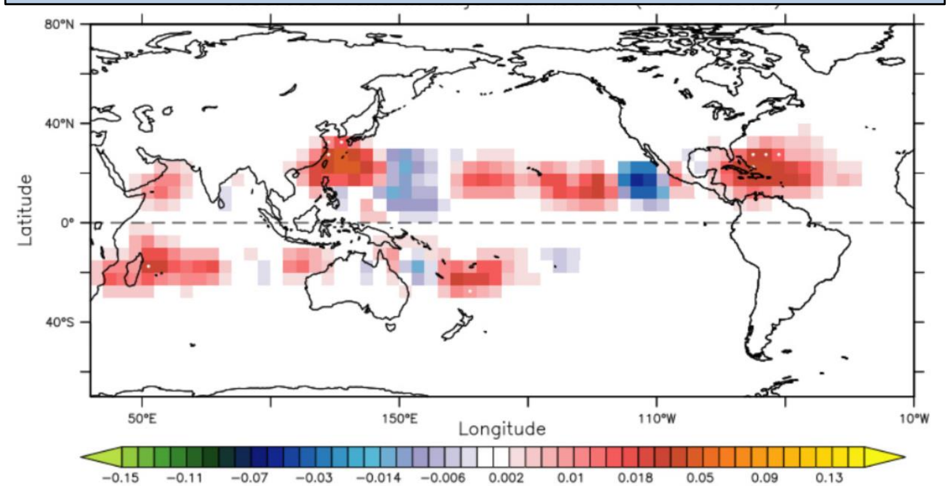
Decreased Aerosols in **both** US & Europe => **Increased TCs in the North Atlantic**

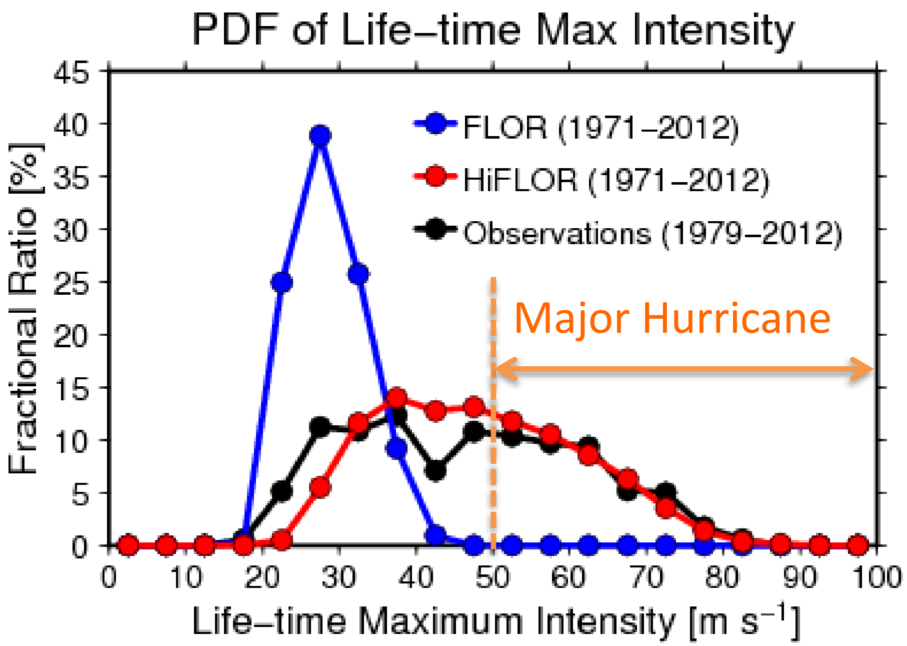
Decreased Aerosols in Europe => **Decreased TCs in the Southern Hemisphere**

Future Research

Goal: To identify the cause for the observed trends in major hurricane density

Observed Trend in Major Hurricanes (1980-2018)



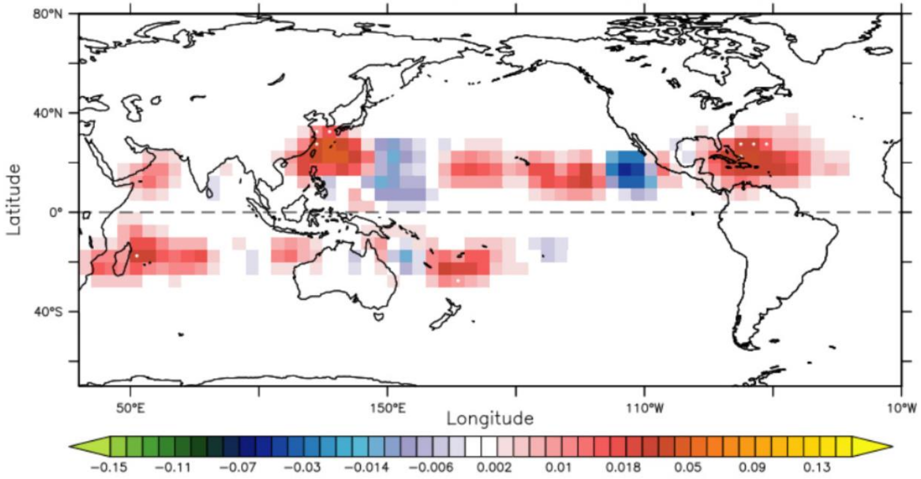


	FLOR	HiFLOR
Base Model	AM2.5 (Atmosphere model of CM2.5), MOM4 (Ocean model of CM2.1)	
Resolution	Atmosphere : **50 km**, L32 Ocean: 100 km, L50	Atmosphere : **25 km**, L32 Ocean: 100 km, L50

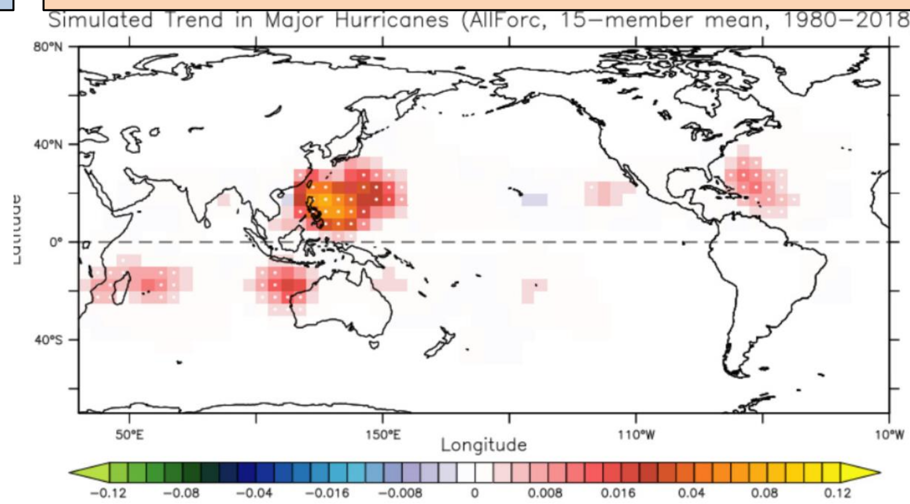
We also plan to use SPEAR-Hi (25-km-mesh SPEAR) in the future.

Linear Trend ion Major Hurricanes

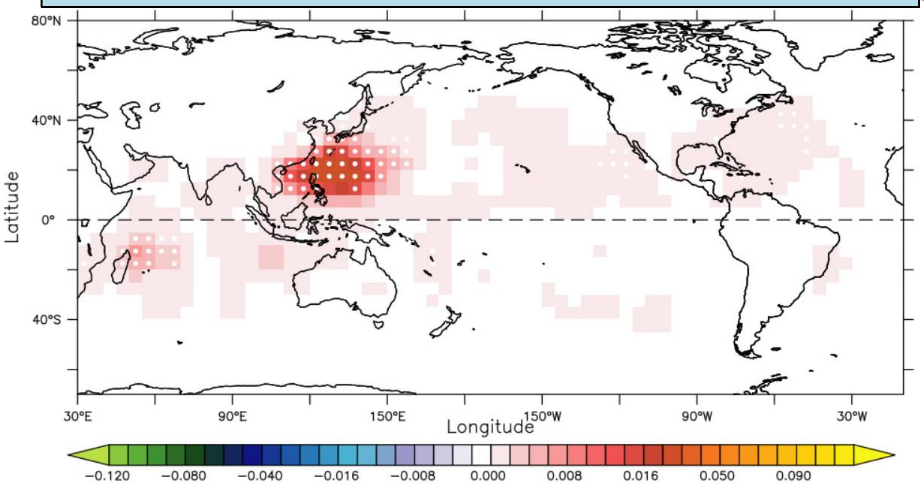
Observed Trend in Major Hurricanes (1980-2018)



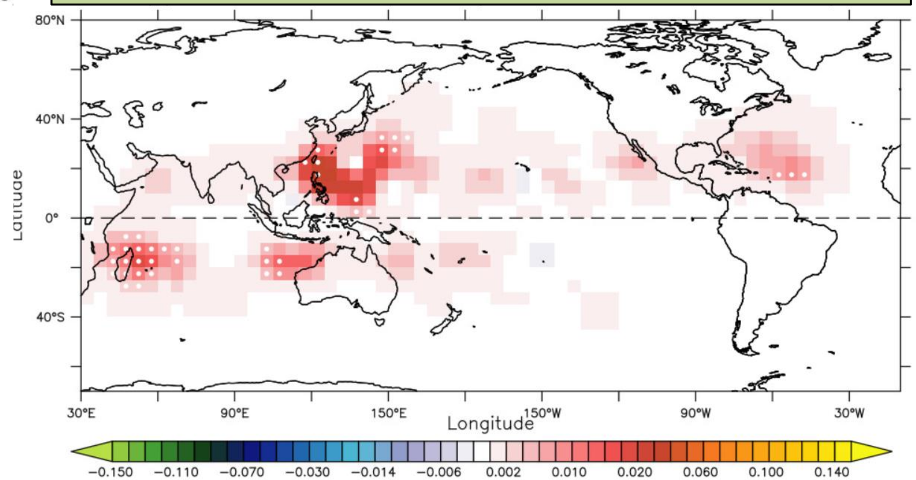
AllForc (15-member mean, HiFLOR, 1980-2018)



NatForc (15-member mean, HiFLOR, 1980-2018)



Transient 2xCO_2 (one member , HiFLOR, 70 yrs)



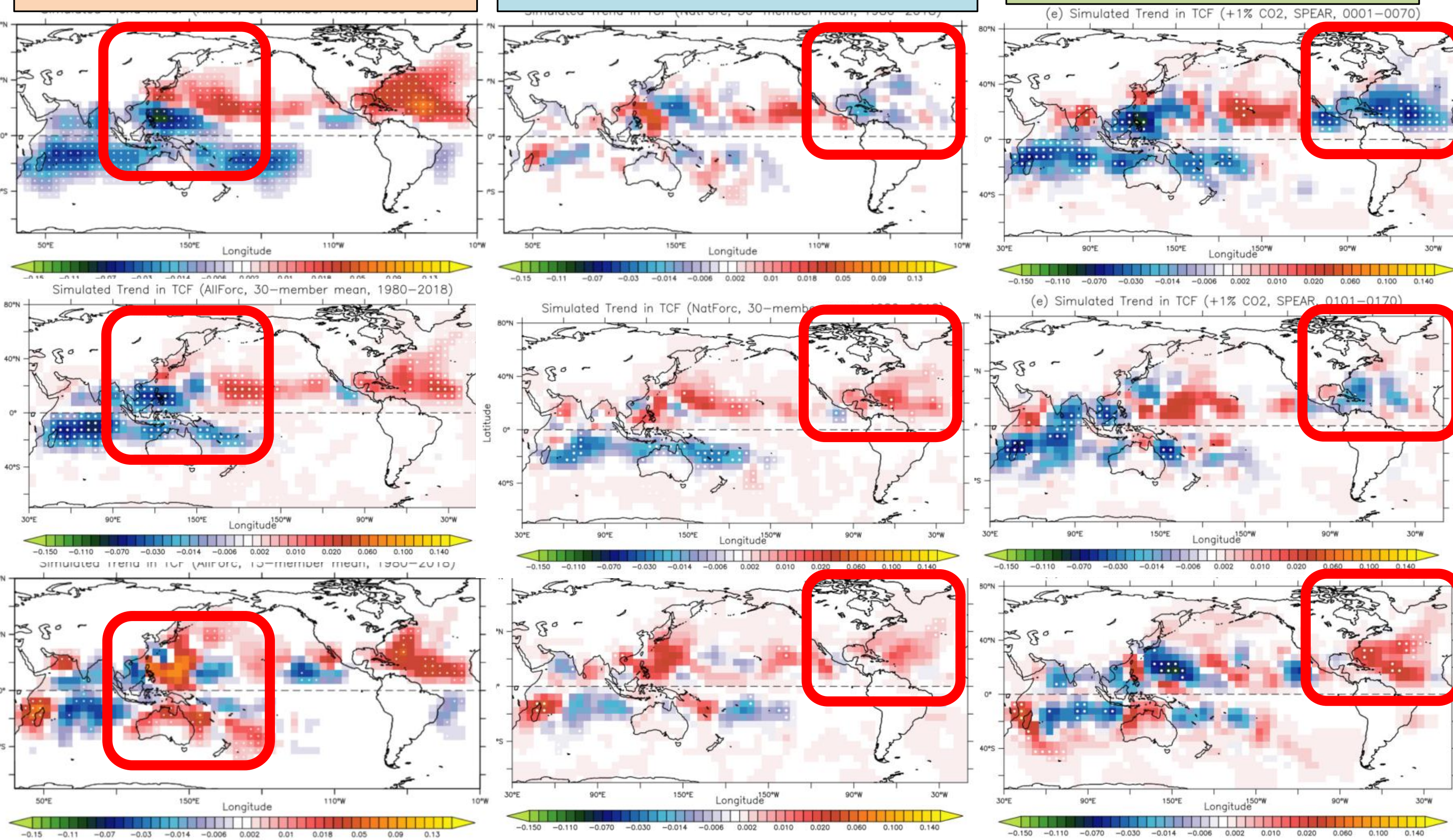
Effect of volcanic events on major hurricanes?

End

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