Part II. Projected future changes in tropical cyclones - Recent Studies -

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Typhoon Meeting in Japan

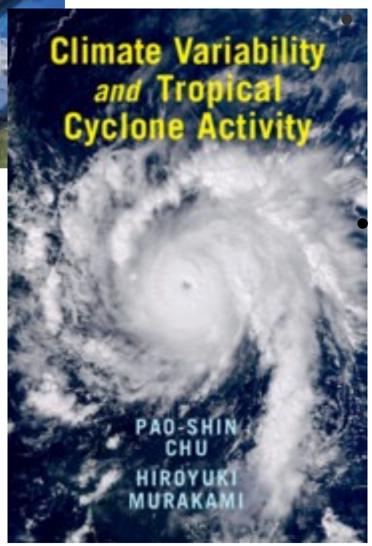
Topics

Projected future changes in tropical cyclones
- Recent Studies -

1. A brief review of the history of Future Projections for TCs
2. Recent studies on future changes
   Global TC frequency, TC intensity, TC size, TC precipitation
3. Projected changes in regional TC activity
   Western North Pacific
   Central Pacific
   North Indian Ocean
   Medicanes
   Extra-tropical transition storms in the North Atlantic
4. A short summary

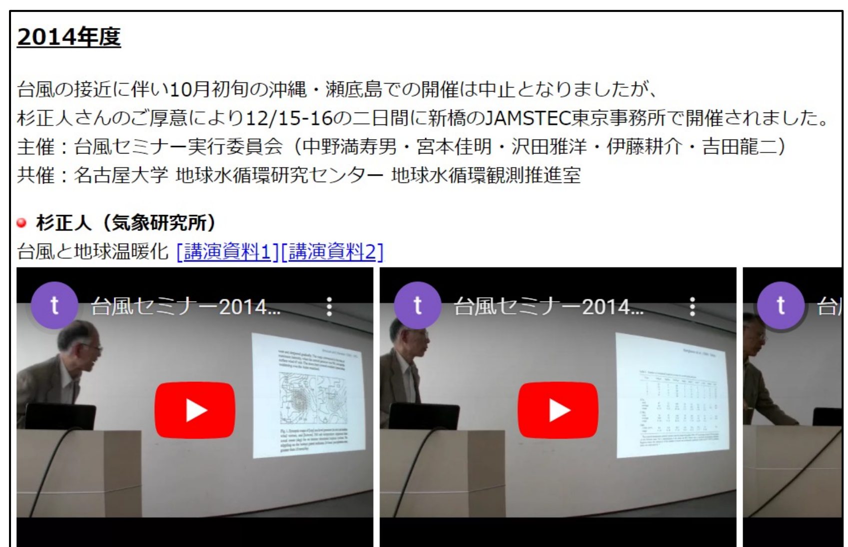
Reference

- 気象研究ノート第 226 号、第 227 号
  台風研究の最前線（下）
  第 11 章 台風と地球温暖化(吉村 純・杉 正人・村上裕之)



- Chu, P. and H. Murakami, 2022: “Climate variability and tropical cyclone activity.” Cambridge University Press.

- 日本気象学会台風研究連絡会のホームページ
  (https://itonwp.skr.uryukyu.ac.jp/Typhoon_Research_Group/)
  2014年度の杉さん講演資料



2014年度

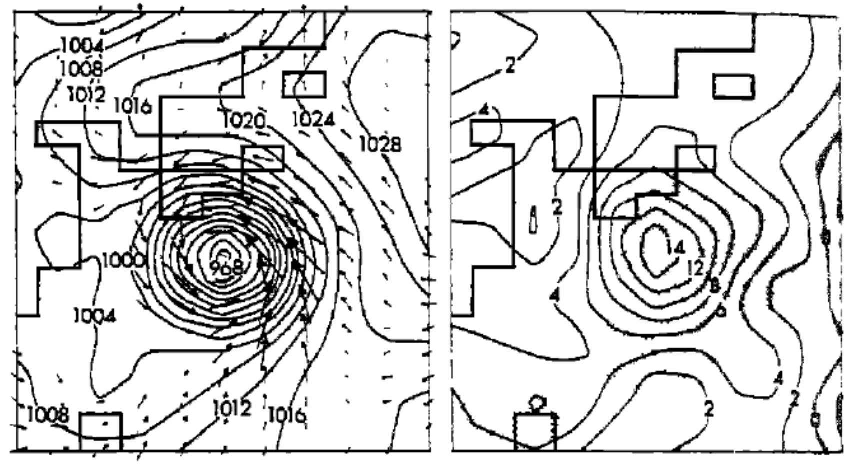
台風の接近に伴い10月初旬の沖縄・瀬底島での開催は中止となりましたが、
杉正人さんのご厚意により12/15-16の二日間に新橋のJAMSTEC東京事務所で開催されました。
主催：台風セミナー実行委員会（中野満寿男・宮本佳明・沢田雅洋・伊藤耕介・吉田龍二）
共催：名古屋大学 地球水循環研究センター 地球水循環観測推進室

- **杉正人（気象研究所）**

台風と地球温暖化 [講演資料1][講演資料2]

A brief review of the history of Future Projections for TCs

1990 Broccoli and Manabe (1990, *GRL*)



Simulated TC by the R30 model

- Model s
  R15 (500-km) Atmosphere-mixed layer ocean
  R30 (300-km) Atmosphere-mixed layer ocean
- Cloud treatment
  FC: Fixed cloud
  (cloud distribution is prescribed based on climatological data))
  VC: Variable cloud
  (cloud is predicted)
- Experiments
  1X: CO_2 = 300 ppmv
  2X: CO_2 = 600 ppmv

Simulated global TC metrics

Experiment	Integration Segment	Number of Storms	Storm-Days	Average Duration
	R15FC-1X	68.3	117.2	1.72
	R15FC-2X	72.3	139.4	1.93
FC	% diff. (2X-1X)	+5.9	+18.9*	+12.2
Increased	R30FC-1X	55.0	100.2	1.82
	R30FC-2X	56.6	116.2	2.05
	% diff. (2X-1X)	+2.9	+16.0	+12.6
	R15VC-1X	81.0	171.4	2.12
	R15VC-2X	75.8	148.9	1.96
VC	% diff. (2X-1X)	-6.4	-13.1*	-7.5
Decreased	R30VC-1X	101.8	245.3	2.41
	R30VC-2X	95.3	217.5	2.28
	% diff. (2X-1X)	-6.4	-11.3*	-5.7

A brief review of the history of Future Projections for TCs (1996-2006)

1990 Broccoli and Manabe (1990) 300 and 600 km, Increase or decrease

Haarsma et al. (1993) 300km, increase

1993 IWTC III "Projected future changes are uncertain because of low resolution in models"

Bengtsson (1996) 120km ECHAM3, 5-yr time slice, decrease (NH:27%, SH:57%)

May (2000) 120km ECHAM3, 30-yr time slice, decrease (NH:23%, SH:22%)

2000

Tsutsui (2002) 300km NCAR model, no change

Bengtsson (2007) 200km ECHAM5, no change

Sugi et al. (2002) 120km JMA-GSM89, 10-yr time slice, decrease (NH:28%, SH:39%)

McDonald et al. (2005) 100km HadAM3, 10-yr time slice, decrease (6%)

Hasegawa and Emori (2005) 100km former MIROC, 10-yr time slice, decrease (4%)

Yoshimura et al (2006) 120km JMA-GCM89 with different convection, decrease (9-18%)

Oouchi et al. (2006) 20km MRI-AGCM, decrease (30%), but increase in intense storms

2006 IWTC VI "Projected future decrease in global TCs is still uncertain"

A brief review of the history of Future Projections for TCs (2006-2014)

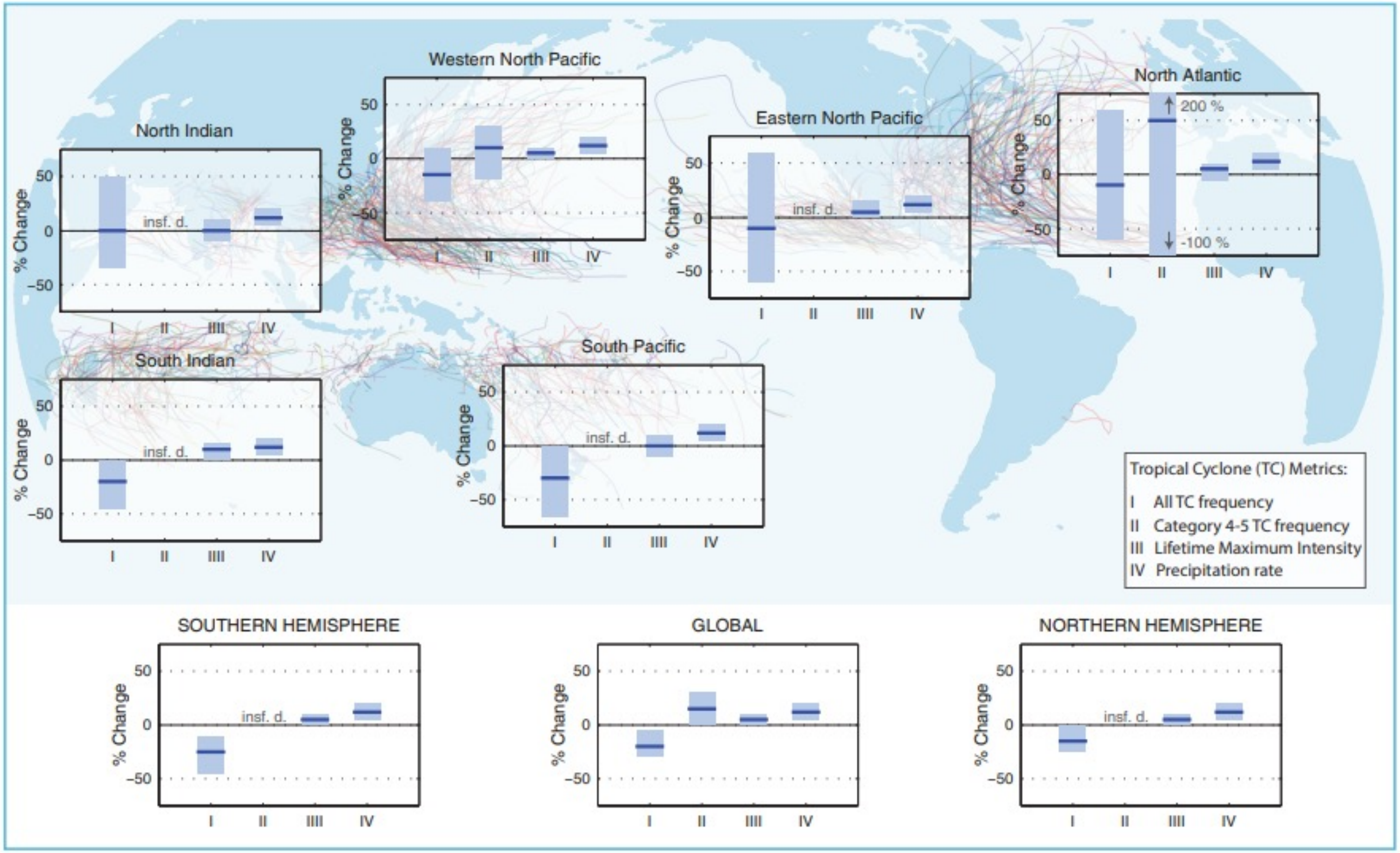
2006 IWTC VI, IPCC AR4 "Projected future decrease in global TCs is still uncertain."

Many modeling studies have been published since 2006.

2010 Knutson et al. (2010, Nature Geoscience)

They commonly project the decreased number of total global storms, but the increased number in the intense category.

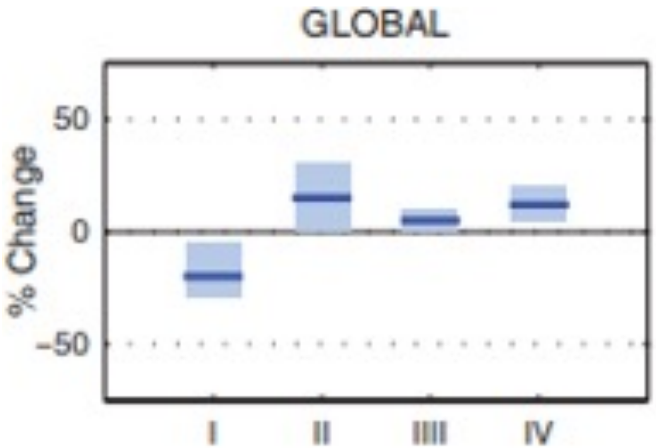
2014 IPCC AR5



A brief review of the history of Future Projections for TCs (2006-2014)

2014 IPCC AR5

- The average intensity of tropical cyclones, the proportion of Category 4 and 5 tropical cyclones and the associated average precipitation rates are projected to increase for a 2°C global temperature rise above any baseline period (**medium confidence**).
- Rising mean sea levels will contribute to higher extreme sea levels associated with tropical cyclones (**very high confidence**).
- Coastal hazards will be exacerbated by an increase in the average intensity, magnitude of storm surge and precipitation rates of tropical cyclones. There are greater increases projected under RCP8.5 than under RCP2.6 from around mid-century to 2100 (**medium confidence**).
- There is **low confidence** in changes in the future frequency of tropical cyclones at the global scale



Tropical Cyclone (TC) Metrics:

I All TC frequency
II Category 4-5 TC frequency
III Lifetime Maximum Intensity
IV Precipitation rate

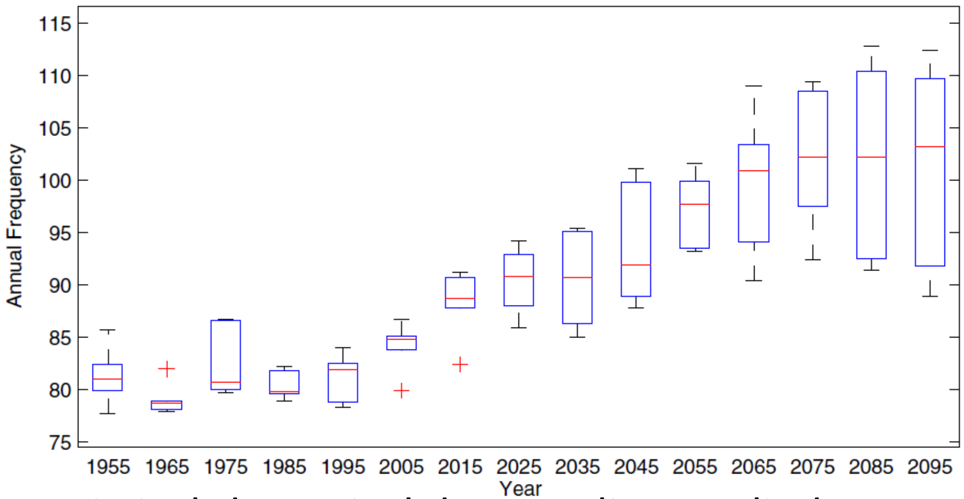
After IPCC AR5 (2014-): Statistical-Dynamical Downscaling by Emanuel (2013)

Downscaling CMIP5 climate models shows increased tropical cyclone activity over the 21st century

Emanuel (2013, PNAS)

Kerry A. Emanuel[1]

Number of global TCs



Statistical-dynamical downscaling applied to CMIP5 Historical and RCP8.5

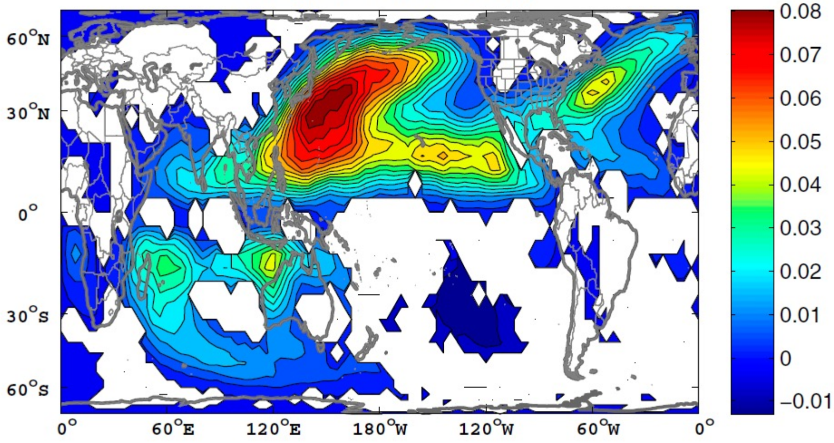


Fig. 2. Change in track density, measured in number of events per 4° × 4° grid box per year, averaged over the six models. The change is the average over the period 2006–2100 minus the average over 1950–2005. The white regions are where fewer than five of the six models agree on the sign of the change.

Table 2. Comparison between CMIP3 and CMIP5 changes in downscaled tropical cyclone frequency and power dissipation

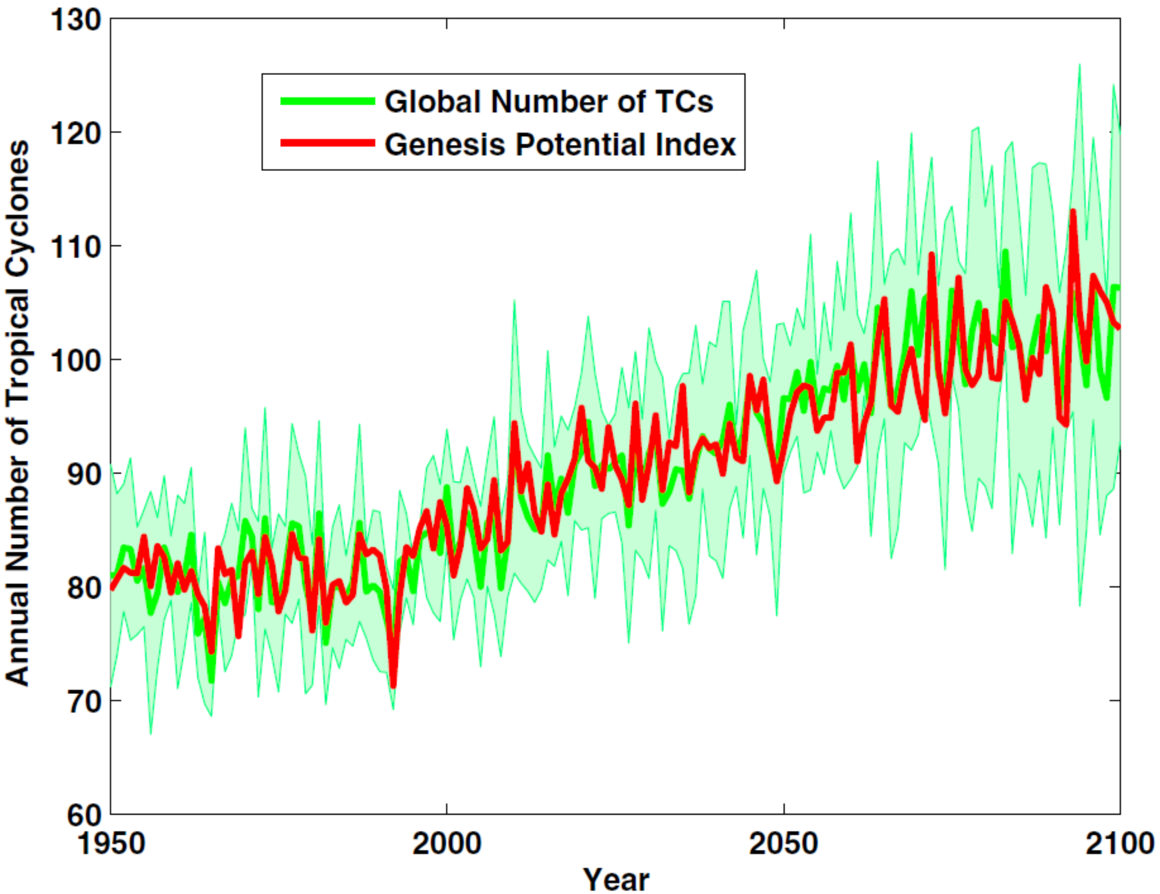
Institute ID	CMIP3 model	CMIP5 model	CMIP3 change in global frequency, %	CMIP5 change in global frequency, %	CMIP3 change in global power dissipation, %	CMIP5 change in global power dissipation, %
NCAR	CCSM3	CCSM4	−3	+11	+5	+8
GFDL	CM2.0	CM3	−13	+41	+2	+72
MOHC		HADGEM2-ES		+22		+31
MPI	ECHAM5	MPI-ESM-MR	−11	+29	+4	+57
MIROC	MIROC3.2	MIROC5	−12	+38	+8	+80
MRI	MRI-CGCM2.3.2a	MRI-CGCM3	+2	+13	+22	+26

For CMIP3 models, the listed numbers are percentage changes from the 20-y period 1981–2000 to the 20-y period 2181–2200 under emissions scenario A1b. For the CMIP5 models, the listed numbers represent percentage changes from 1981–2000 to 2081–2100 under radiative forcing scenario RCP8.5.

Statistical-Dynamical Downscaling by Emanuel (2013)

Emanuel (2013, *PNAS*)

$$GPI \equiv |\eta|^3 \chi^{-4/3} MAX\left(\left(V_{pot} - 35\,\mathrm{m\cdot s^{-1}}\right), 0\right)^2 \left(25\,\mathrm{m\cdot s^{-1}} + V_{shear}\right)^{-4}$$



GPI is increased in the future as the increase in TC number.

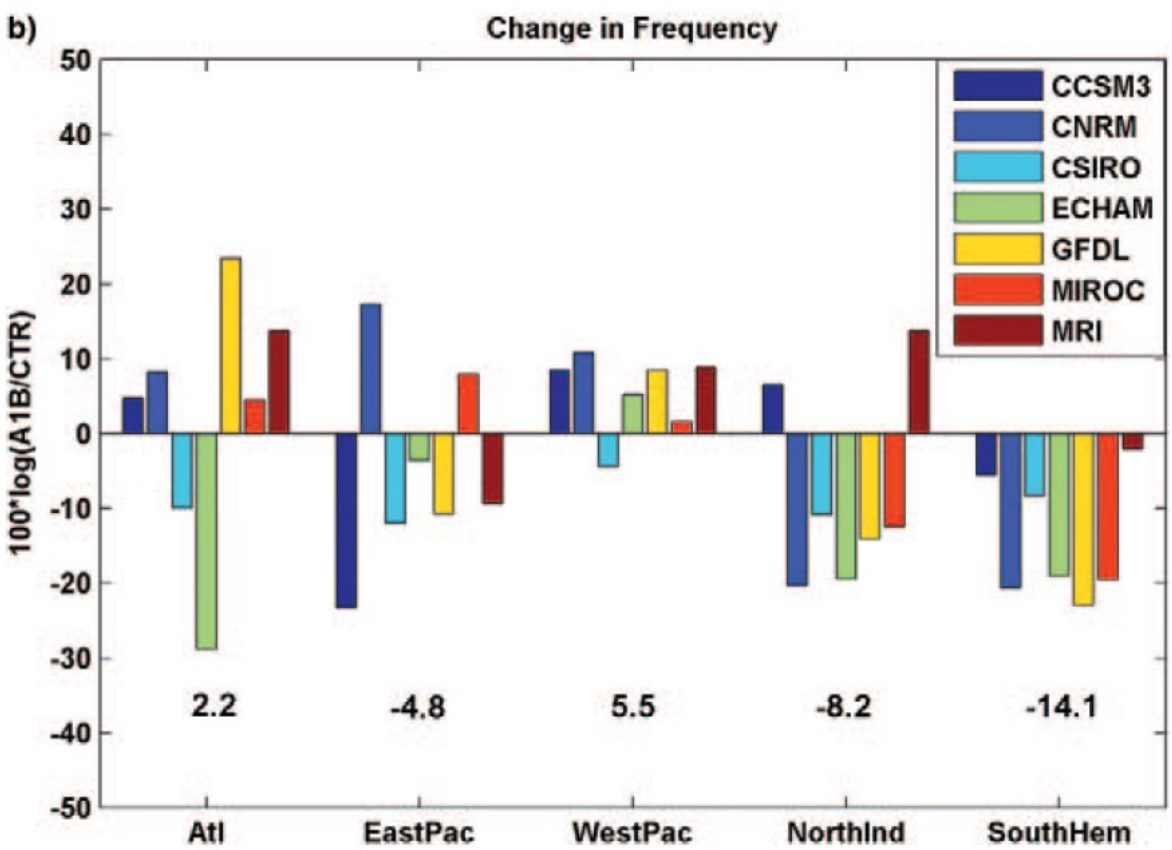
Emanuel (2013) indicates that background environmental conditions are important to determine future changes in TCs.

Statistical-Dynamical Downscaling by Emanuel (2013)

But, 5 years ago, Emanuel (2008, *BAMS*) concluded:

A new technique for deriving hurricane climatologies from global data, applied to climate models, indicates that global warming should reduce the global frequency of hurricanes, though their intensity may increase in some locations.

Downscaled from CMIP3 models (A1B minus historical)



Increase in entropy deficit
May be the reason for the
Decreased TCs under warming
climates

$$\chi_m \equiv \frac{s_b - s_m}{s_0^* - s_b},$$

Projected future changes in TCs directly computed from CMIP5 model outputs

TC detection method by Camarogo and Zebiak (2002).

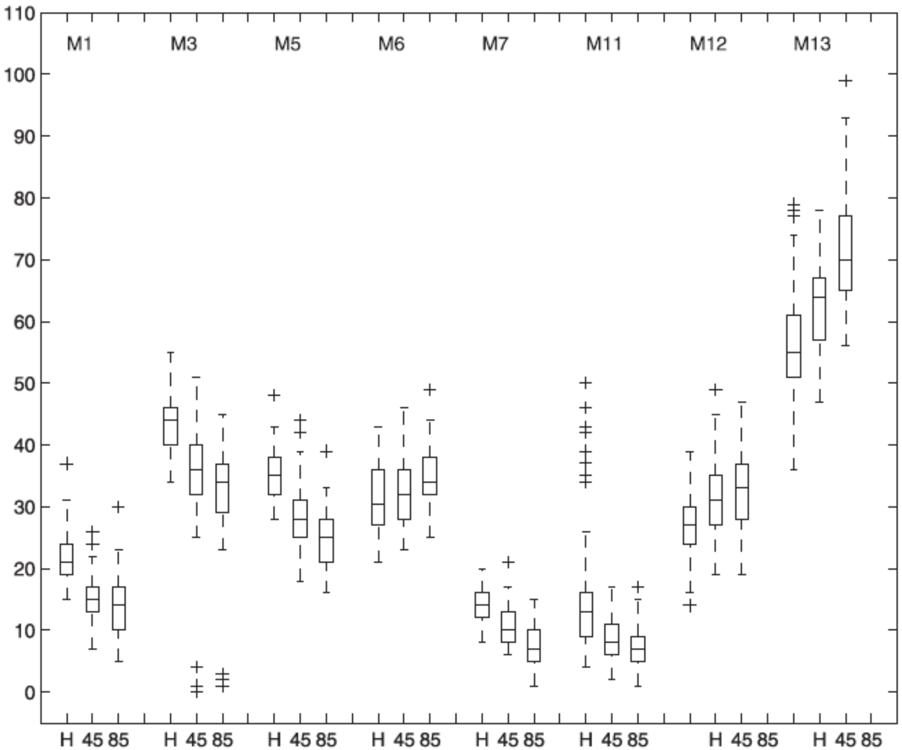


FIG. 7. Global number of TCs per year in models for the historical (H) run for the period 1951–2000 and in the future scenarios RCP4.5 (45) and RCP8.5 (85) in 2051–2100. Range boxes as in Fig. 3.

Some models (M6, M12, and M13) shows Projected increase in the number of global TCs.

Canargo (2013, *J. Climate*)

TC detection method by Murakami et al. (2012).

CMIP5 RCP4.5		CMIP5 RCP8.5	
Model ID	GL %	Model ID	GL %
1	−7.0[b]	1	+7.8[b]
2	−5.0[c]	2	+33.5[a]
3	−10.1[a]	3	−19.7[a]
4	−15.8[a]	4	−21.6[a]
5	−16.0[a]	5	−35.5[a]
6	−15.6[a]	6	−40.4[a]
7	−23.3[a]	7	−32.3[a]
8	−6.6[b]	8	−14.9[a]
9	−3.4	9	−13.2[a]
10	−2.0	10	−2.4
11	−0.5	11	+5.6[b]

All of the models under the RCP4.5 show decreases in global TCs, whereas a few models under RCP8.5 show increases.

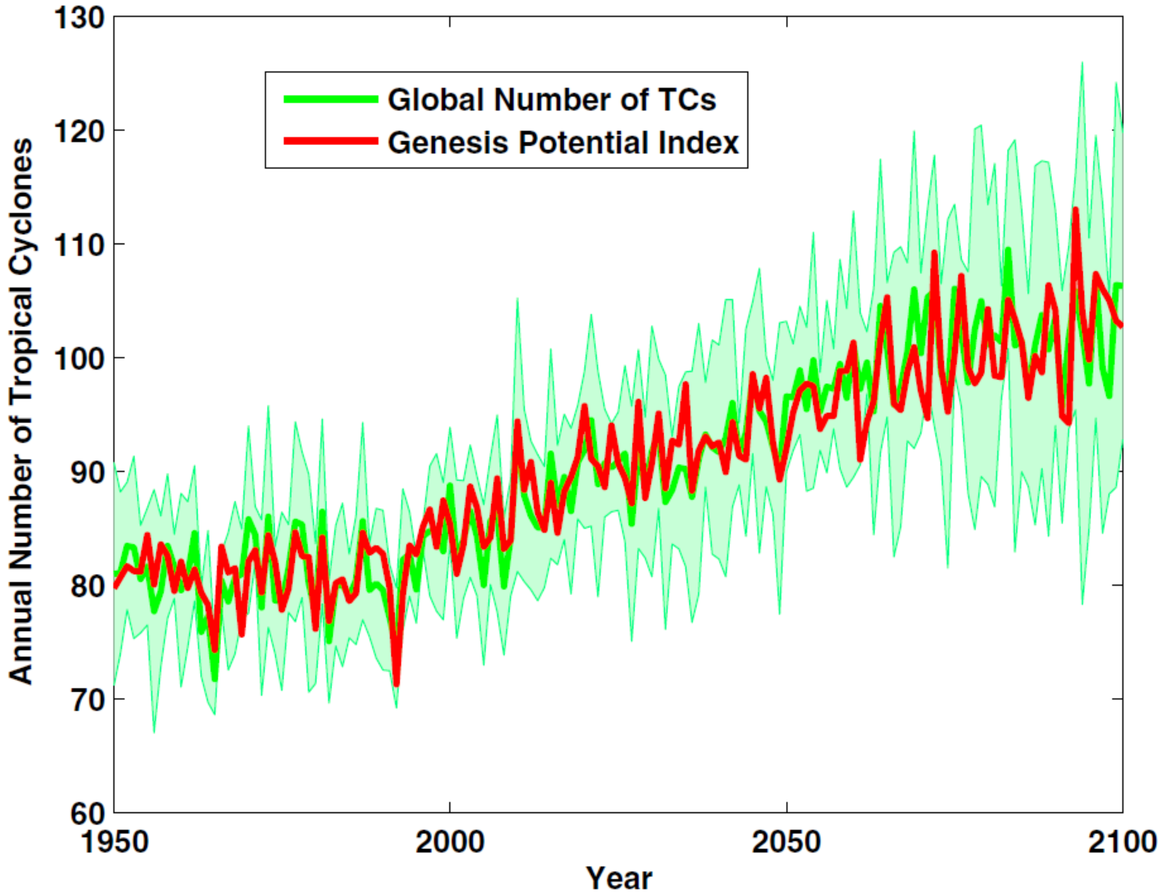
Murakami et al. (2014, *J. Climate*)

The difference in TC detection methods may also affect results.

Statistical-Dynamical Downscaling by Emanuel (2013)

Emanuel (2013, *PNAS*)

$$GPI \equiv |\eta|^3 \chi^{-4/3} MAX\left(\left(V_{pot} - 35\,\mathrm{m}\cdot\mathrm{s}^{-1}\right), 0\right)^2 \left(25\,\mathrm{m}\cdot\mathrm{s}^{-1} + V_{shear}\right)^{-4}$$



Which large-scale environment Is responsible for the changes in TC genesis?

Environmental factor that leads to increase in GPI

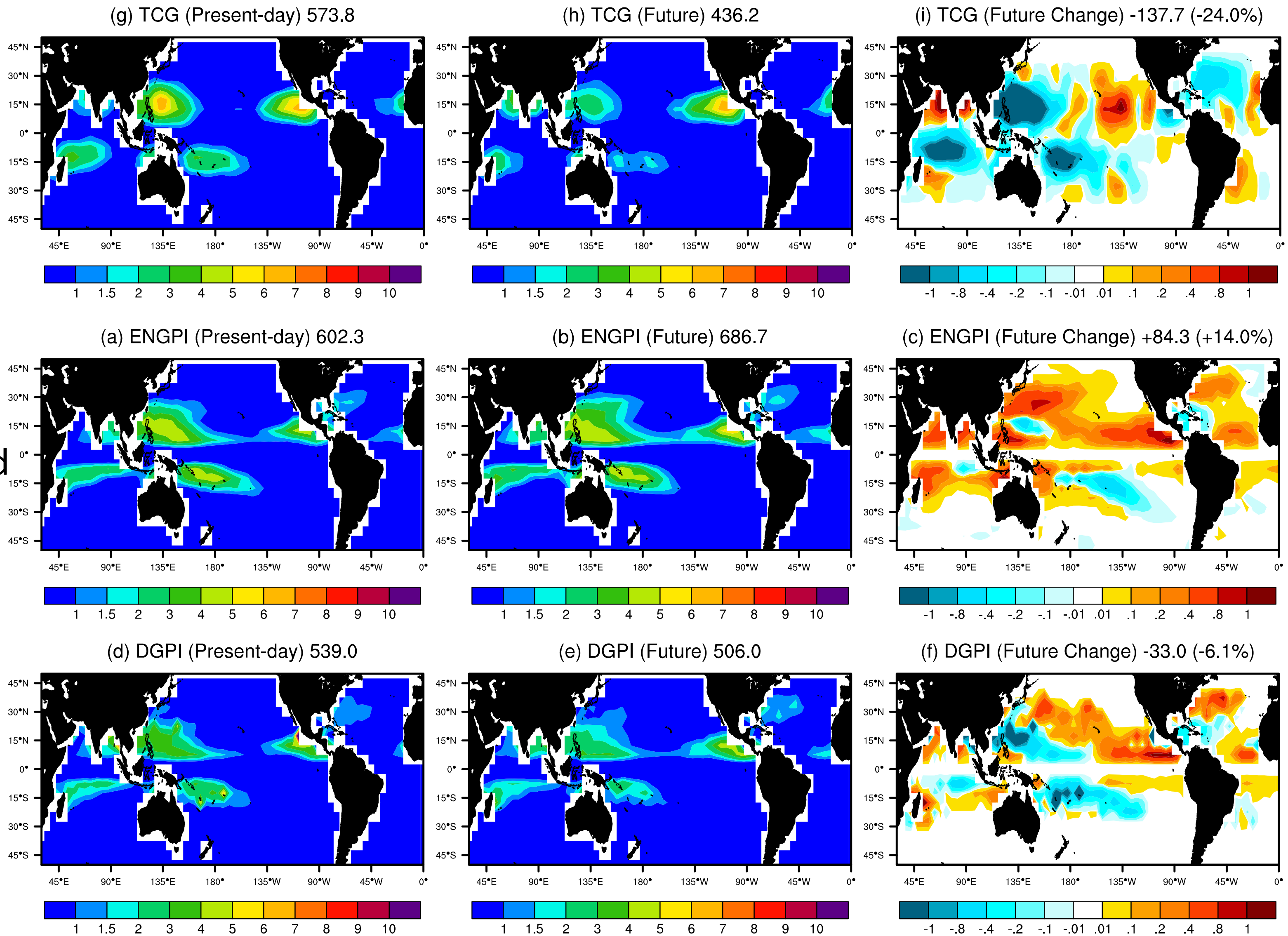
Murakami and Wang
(2022, *Commun. Earth Environ.*)

20-km mesh MRI-AGCM (Future (RCP8.5) minus Present-day)

Directly detected TC genesis

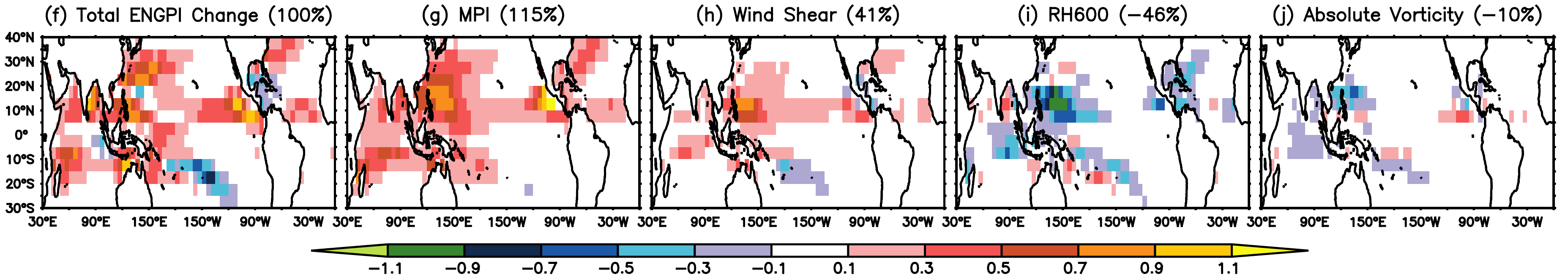
GPI (Emanuel and Nolan, 2004)

DGPI (Wang and Murakami, 2020)



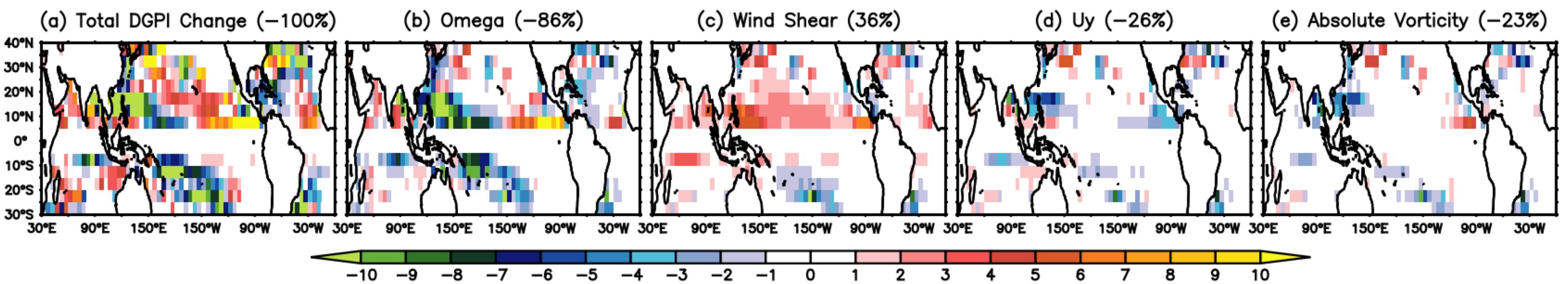
Environmental factors responsible for the GPI changes

$$\mathrm{GPI} = (1.0 + 0.1\times V_s)^{-2.0}\left(\frac{\mathrm{dRH}_{600}}{50}\right)^{3}\left(\frac{\mathrm{MPI}}{70}\right)^{3}|\zeta_{a850}\times 10^{5}|^{1.5}$$



PI largely (erroneously) contributes to positive changes in GPI.

$$\mathrm{DGPI} = (2.0 + 0.1\times V_s)^{-1.7}\left(5.5 - \frac{du_{500}}{dy}\times 10^{5}\right)^{2.3}(5.0 - 20\times\omega_{500})^{3.4}(5.5 + |\zeta_{a850}\times 10^{5}|)^{2.4}e^{-11.8} - 1.0$$



ω_{500} largely (correctly) contributes to negative changes in GPI.

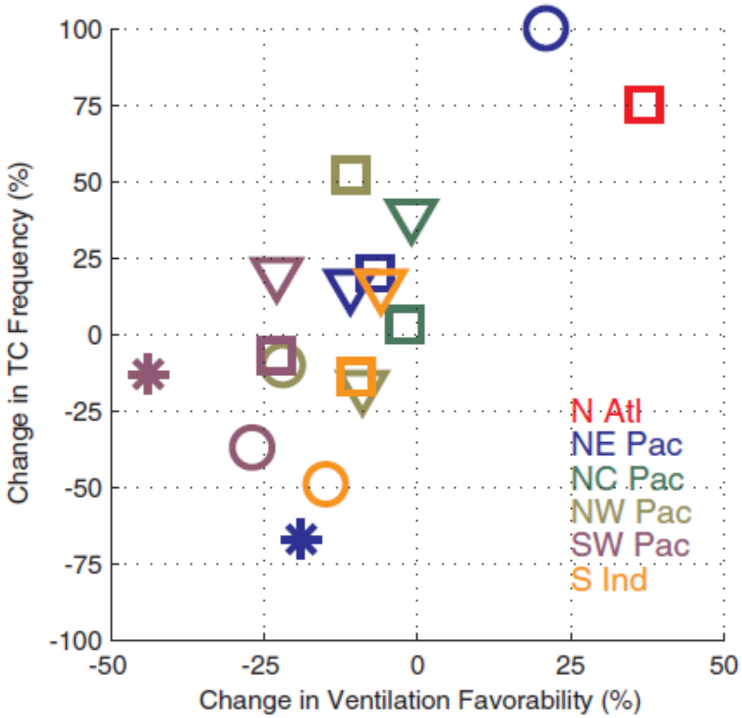
Murakami and Wang (2022, *Commun. Earth Environ.*)

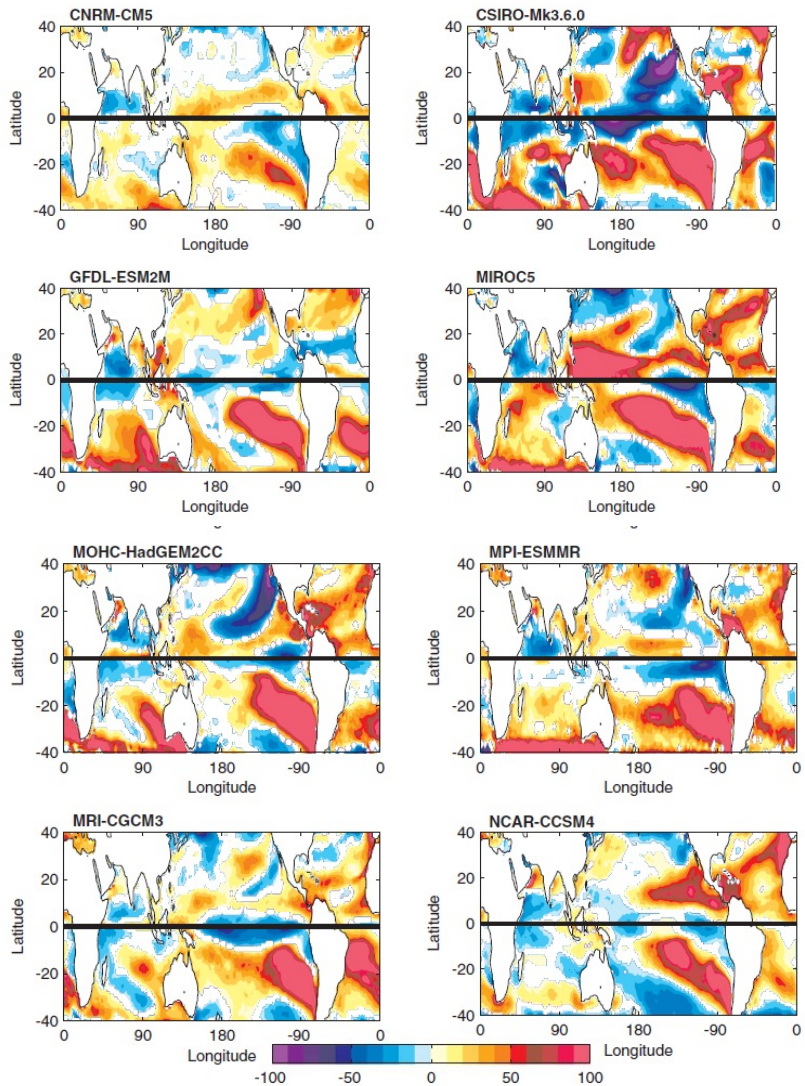
Ventilation Index (importance of vertical wind shear)

Ventilation Index

$$\Lambda \equiv \frac{u_s \chi_m}{u_{pi}}$$

where Λ is the non-dimension ventilation index; u_s vertical wind shear; χ_m is the entropy deficit, u_{pi} is potential intensity.

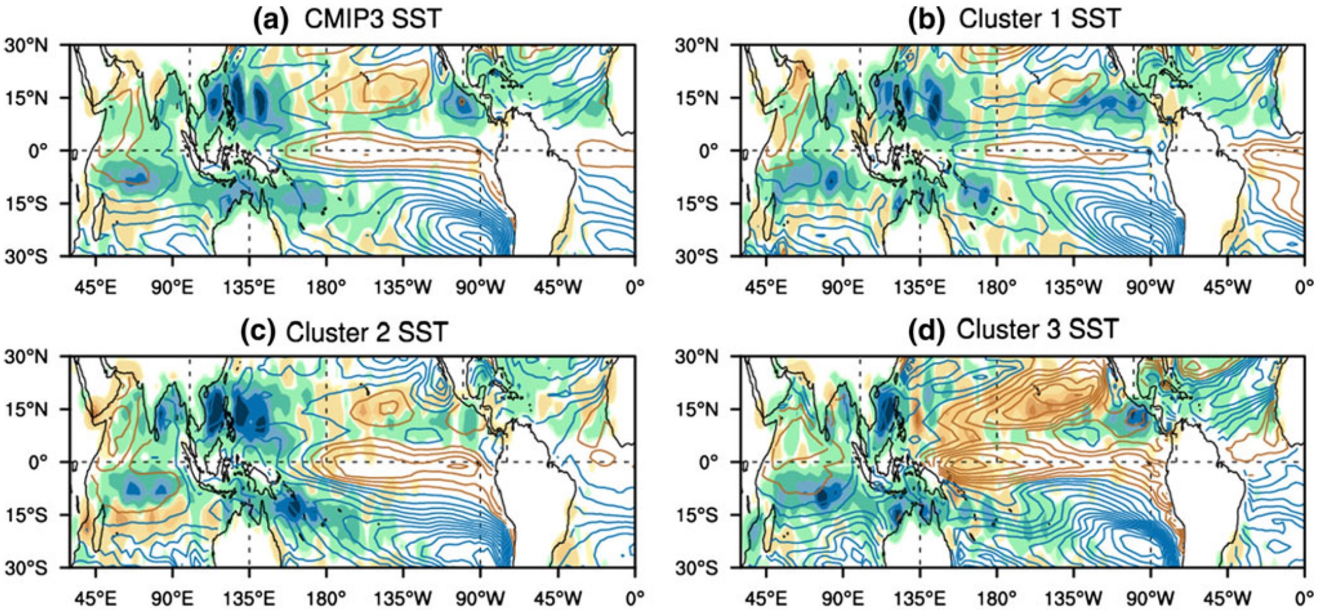




Projected future changes in the ventilation index by the 8 CMIP5 models

Tang and Camargo (2014, *JAMES*)

Relative SSTs

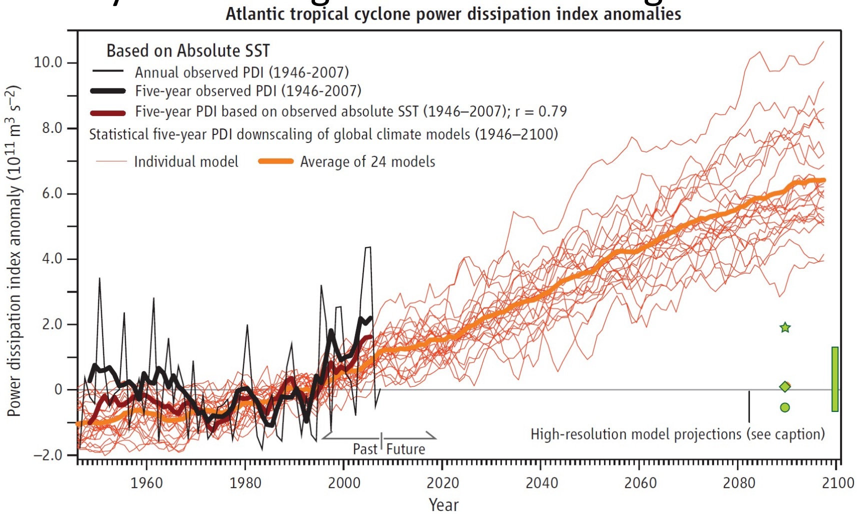


Contour: Projected future changes in SST anomaly (Sa, contours) [K] relative to tropical (30S–30N) mean.

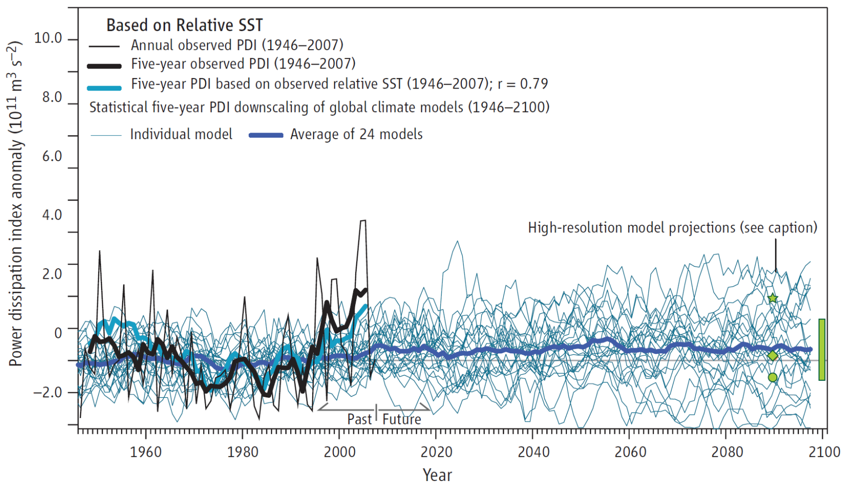
Shading: Future changes in TC genesis frequency

Murakami et al. (2012, *Clim. Dyn.*)

PDI by a linear regressed model using absolute SST



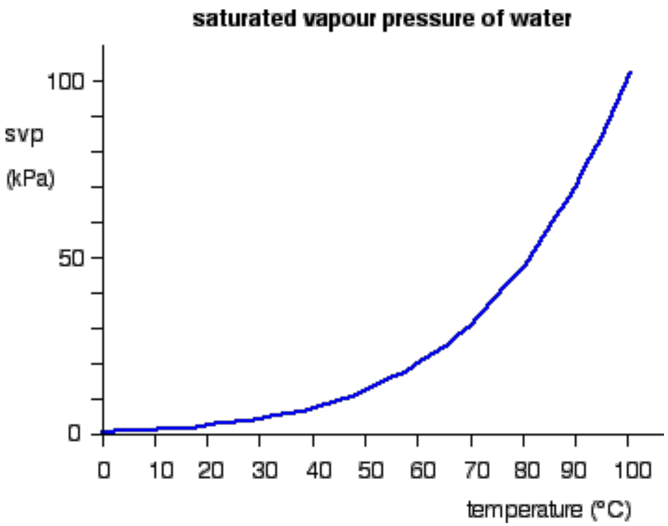
PDI by a linear regressed model using relative SST



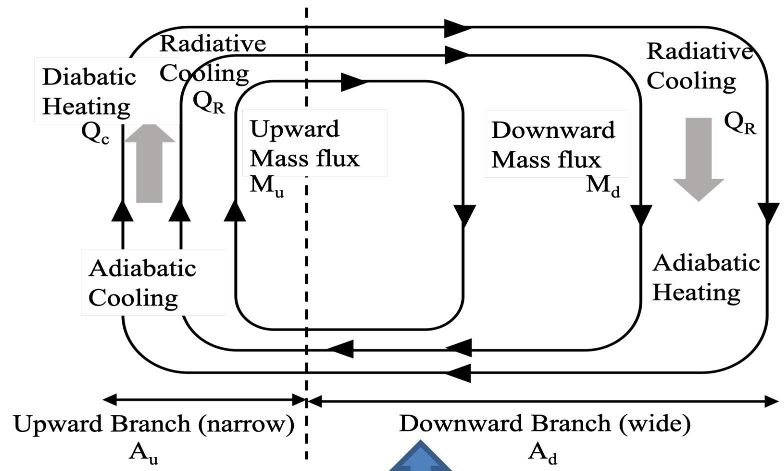
Vecchi et al. (2008, *Science*)

Potential large-scale environment affecting future changes in global TC frequency

1. Entropy Deficit



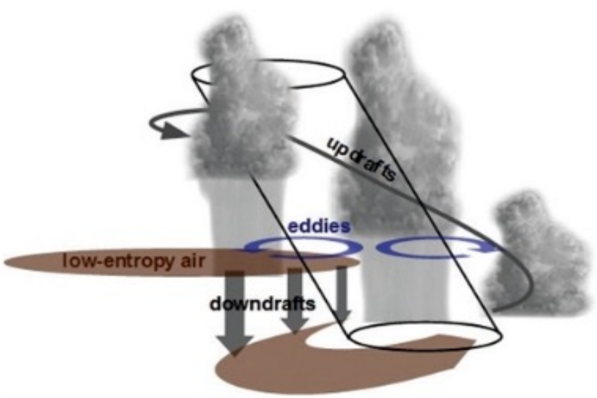
2. Mass Flux (ω_{500})



$$M_u \left| \frac{\partial \theta}{\partial p} \right| \approx \frac{\theta}{T} \frac{1}{C_p} (Q_c - Q_R)$$

Sugi and Noda (2002)

3. Ventilation Index (V_{shear})



4. Potential Intensity (relative SST)

A consensus has not been reached!

Another study showing projected increases in global TC number

Vecchi et al. (2021) conducted some idealized experiments using high-resolution dynamical model.

Models: GFDL-FLOR (coupled, **50**-km Atmosphere/land & 100-km Ocean/Ice)
GFDL-HiFLOR (coupled, **25**-km Atmosphere/land & 100-km Ocean/Ice)

Experiments:

Fully coupled:

1990 Control (free run with fixed anthropogenic forcing level at 1990)

Transient 2xCO2 (doubling CO2 relative to 1990 level)

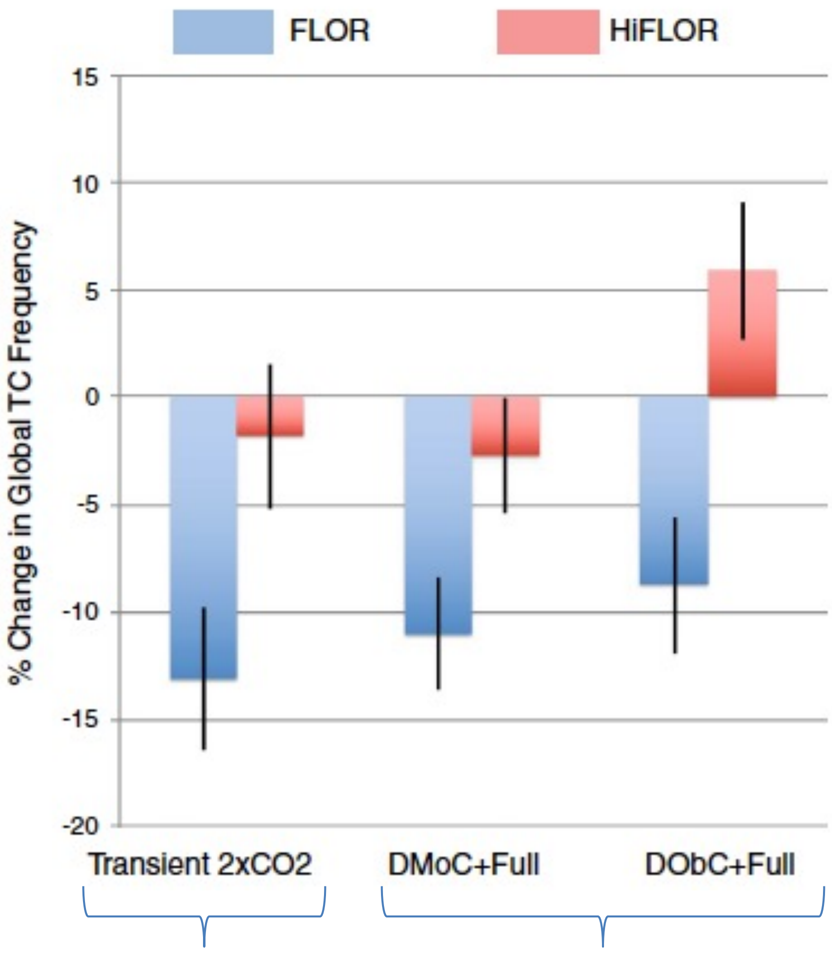
SST nudged: $$\partial SST(x,y,t)/\partial t = \chi(x,y,t) + \frac{1}{\tau}\left(SST_T(x,y,t) - SST(x,y,t)\right)$$

Experiment name	CO_2 forcing	SST nudging target
MoC	352.7 ppm	1990-control coupled model monthly climatology (years 201–250)
MoC + Full	705.4 ppm	Transient 2×CO_2 coupled model climatology (years 201–250)
ObC	352.7 ppm	HadISSTv1.1 monthly SST climatology (1986–2005)
ObC + Full	705.4 ppm	HadISSTv1.1 monthly SST climatology (1986–2005) + transient 2×CO_2 SST response climatology (years 201–250)
ObC + 2 K + 2×CO_2	705.4 ppm	HadISSTv1.1 monthly SST climatology (1986–2005) + 2 K uniform
ObC + 2 K	352.7 ppm	HadISSTv1.1 monthly SST climatology (1986–2005) + 2 K uniform
ObC + 2×CO_2	705.4 ppm	HadISSTv1.1 monthly SST climatology (1986–2005)

Vecchi et al. (2019, *Clim. Dyn.*)

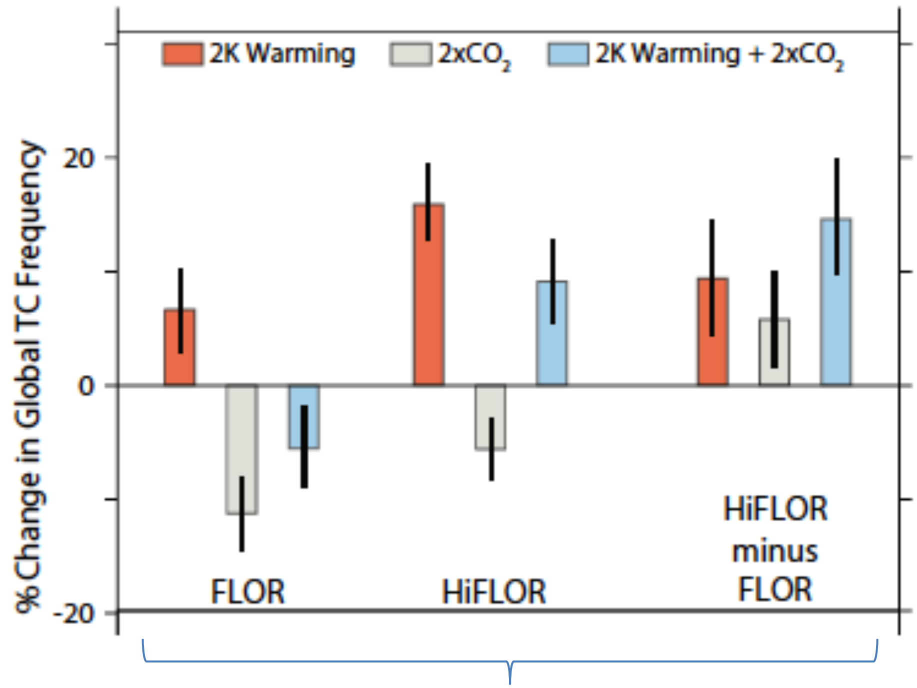
Vecchi et al. (2021, *Clim. Dyn.*) --Increased TCs by HiFLOR--

Simulated Changes in global TC number relative to the 1990 Control.



Fully Coupled

SST-Nudged



SST-Nudged

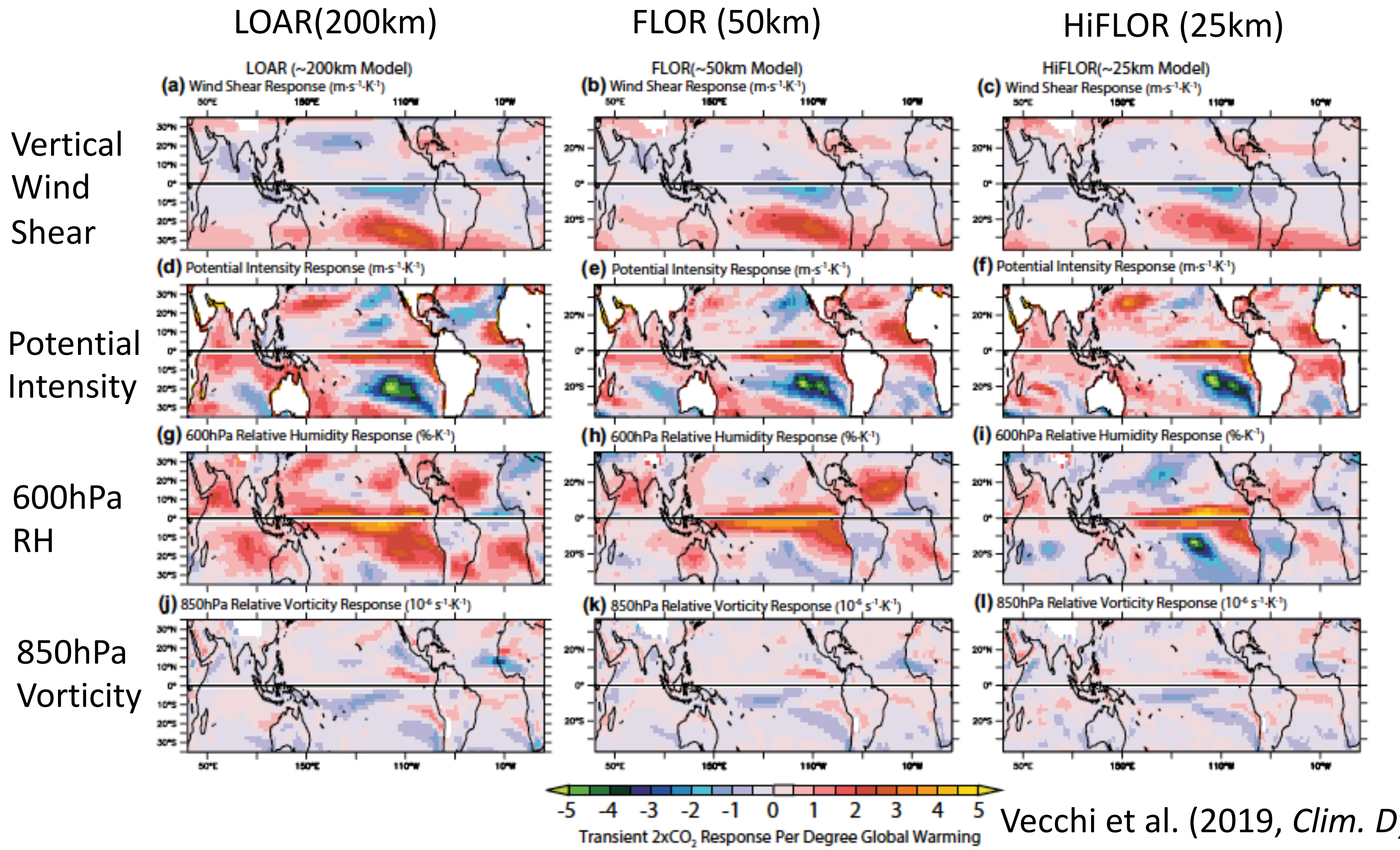
HiFLOR increases TCs more under +2K warming than 2XCO2, leading to increased TCs.

FLOR projects decreased TCs, whereas HiFLOR projects no change or increased TCs

Vecchi et al. (2019, *Clim. Dyn.*)

Vecchi et al. (2021, *Clim. Dyn.*) –Large-scale Parameters--

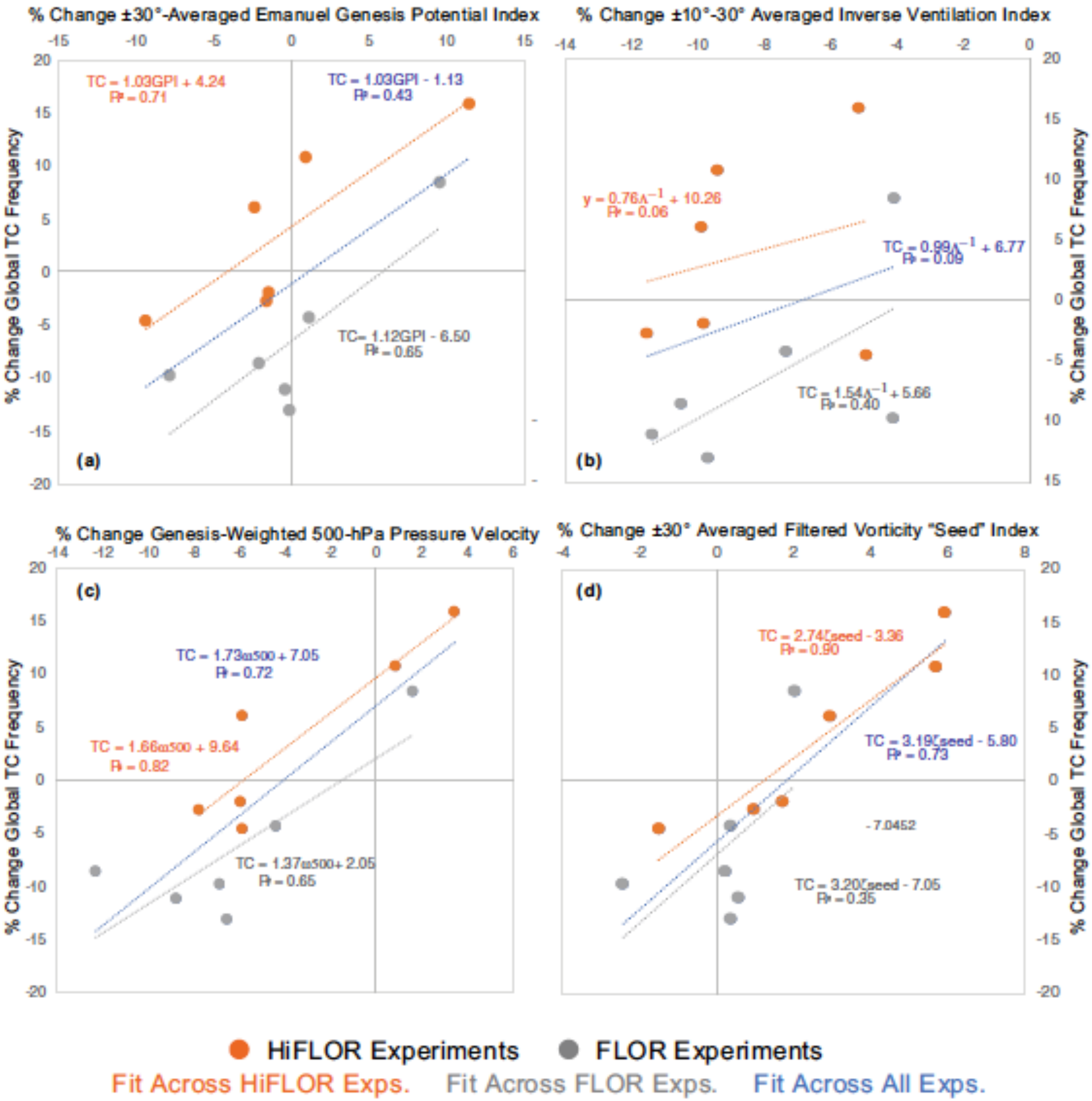
Some key large-scale parameters (Transient CO2 minus 1990 Control)



Vecchi et al. (2019, *Clim. Dyn.*)

None of the parameters explains the model differences in TC genesis frequency.

Vecchi et al. (2021, *Clim. Dyn.*) –Large-scale Parameters--



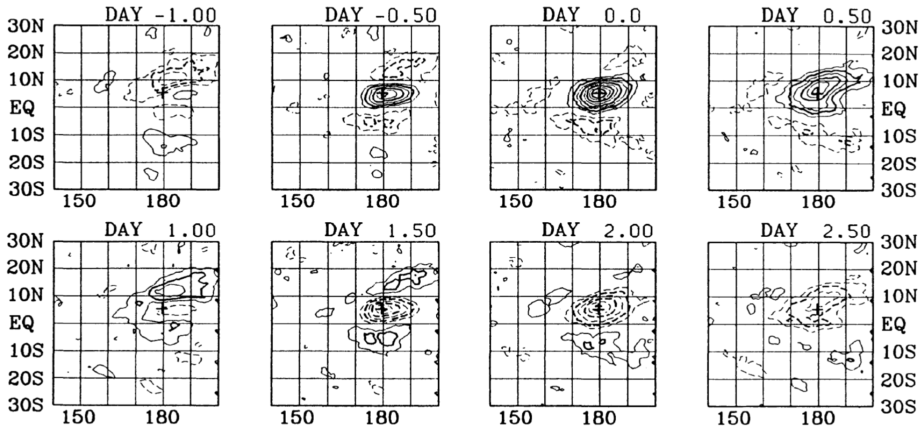
"Seed" index explains well the simulation differences in changes in global TC number

Vecchi et al. (2019, *Clim. Dyn.*)

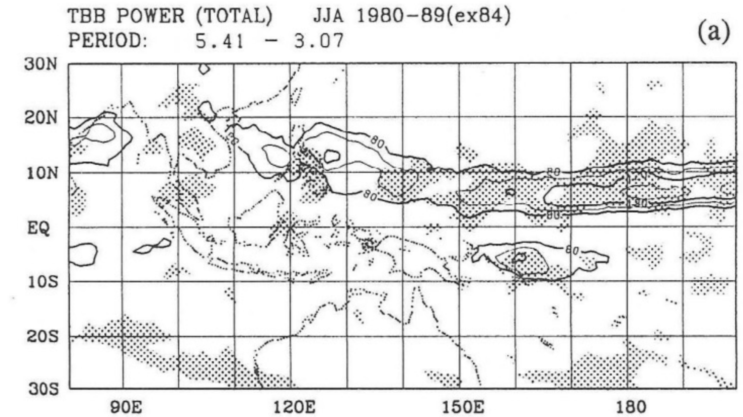
TC Seeds

TC Seeds: Pre-TC synoptic-scale disturbances (e.g., easterly waves, monsoon depressions, TD-type)

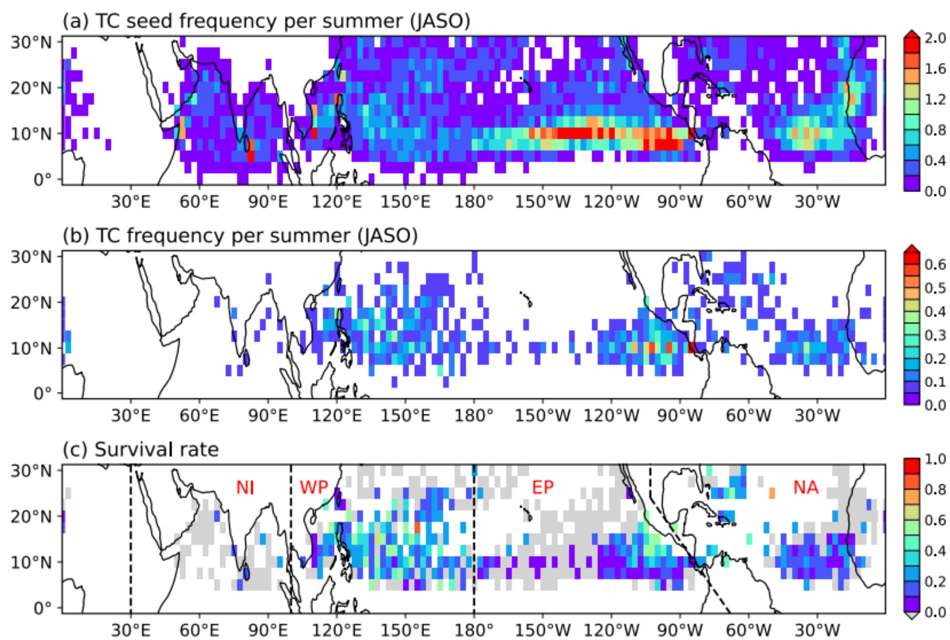
The typical wavelength is 2000 km



3-5 day variance in TBB

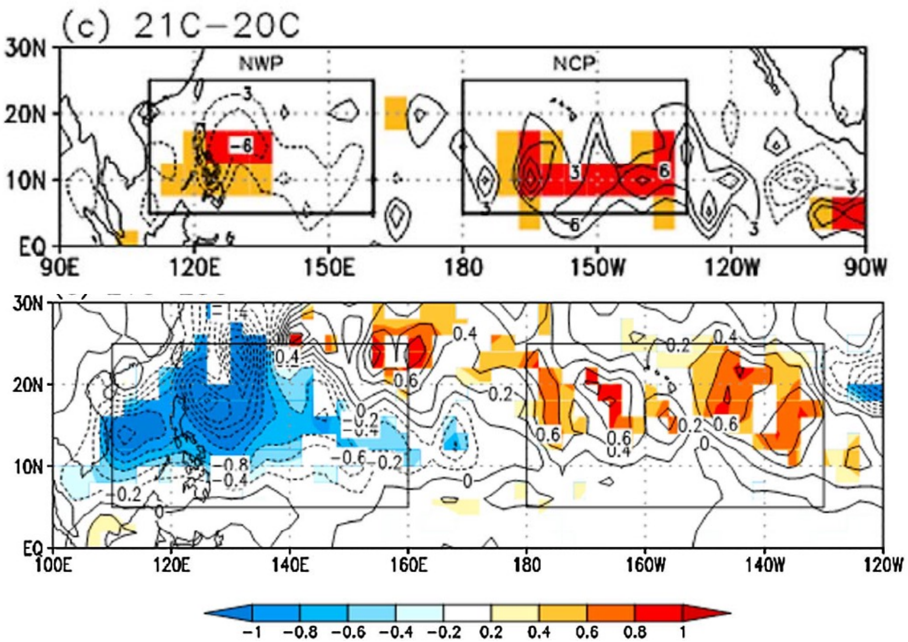


Takayabu and Nitta (1993, *JMSJ*)



Ikehata and Satoh (2021, *GRL*)

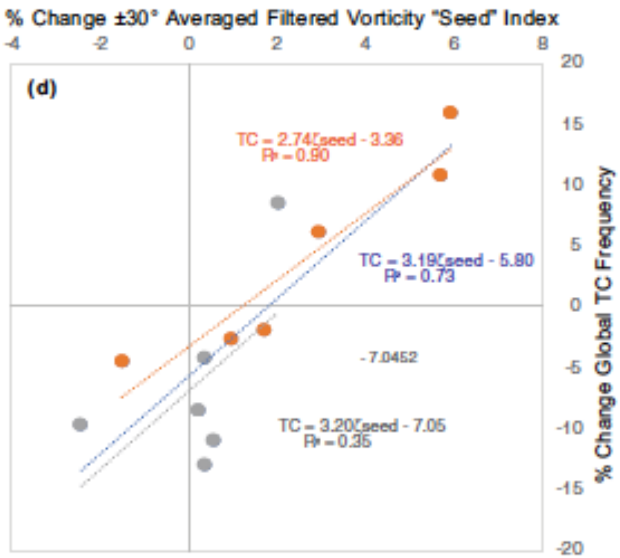
Projected changes in TC genesis associated with TC seeds



Li et al. (2010, *GRL*) showed projected Increase in TC genesis over the central Pacific and decrease over the western North Pacific under the A1B scenario.

Changes in 2-8-day variance in vorticity at 850hPa reproduces well the TC genesis change, indicating the importance of synoptic-scale disturbances.

Vecchi et al. (2021)



"Seed" index explains well the simulation differences in changes in global TC number

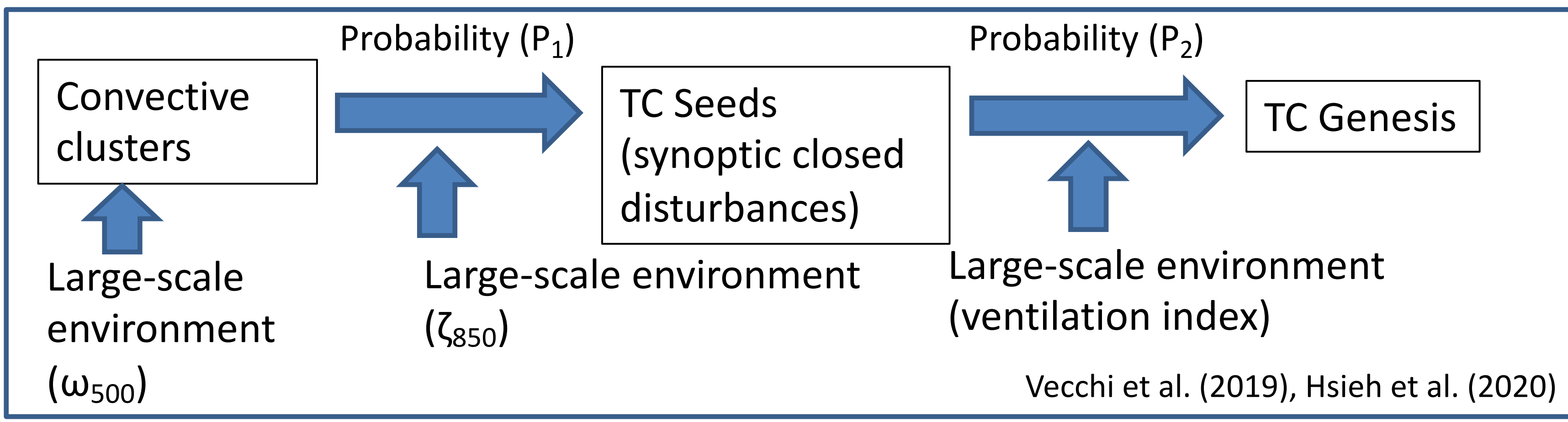
Binomial distribution

$$\frac{\Delta n}{n} = \frac{\Delta N}{N} + \frac{\Delta p}{p}$$

TC genesis number

TC seeds number

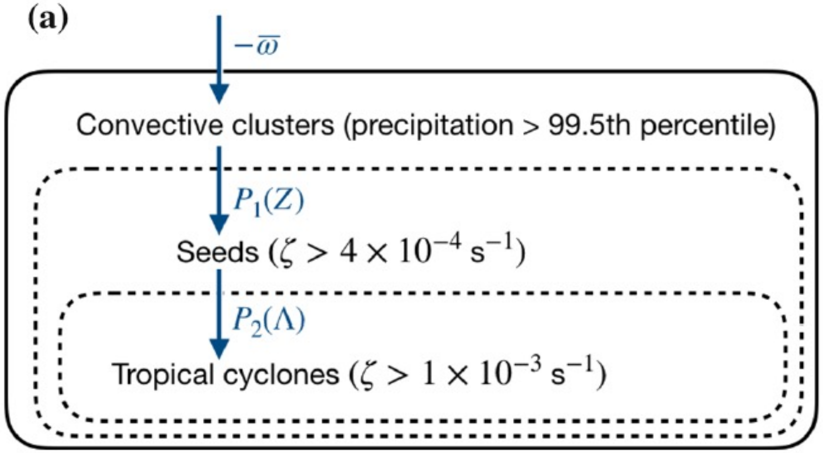
Probability of seed to Develop into TC

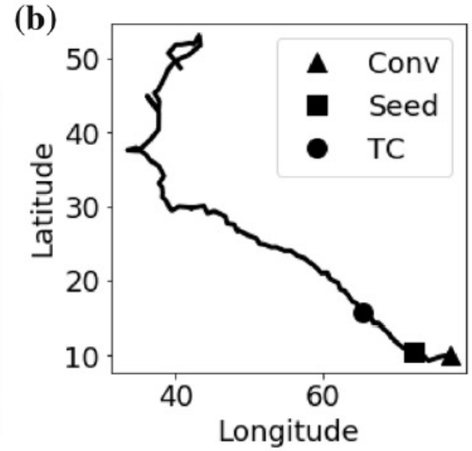


Even though P_2 decreases, the number of TC genesis can increase if P_1 largely increases.

Vecchi et al. (2019, *Clim. Dyn.*)

Hsieh et al. (2020, *Clim. Dyn.*)





$$n_{TC} = n_s P_2 = n_c P_1 P_2,$$

$$n_c = c_0 \cdot (-\overline{\omega})$$ (depends on ω_{500})

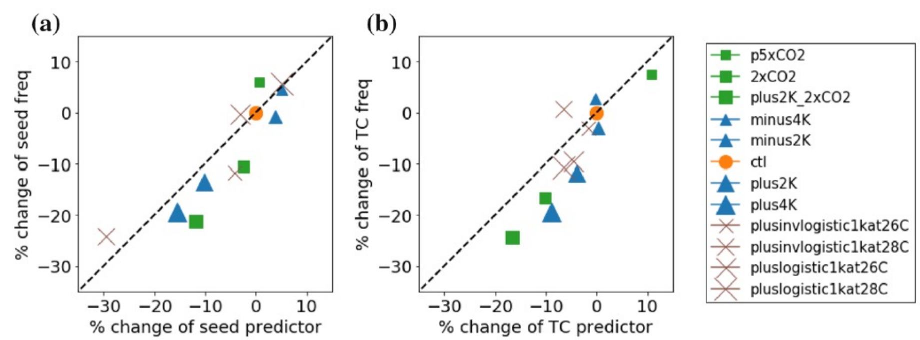
$$P_1 = \frac{1}{1 + Z^{-1/\sigma}} \approx c_1 Z$$

$$Z \equiv \frac{|f + \overline{\zeta}|}{\sqrt{|\beta + \overline{\zeta}_y| U}},$$

(depends on large-scale vorticity

$$P_2 = \frac{1}{1 + (\Lambda_0/\Lambda)^{-1/\sigma'}},$$

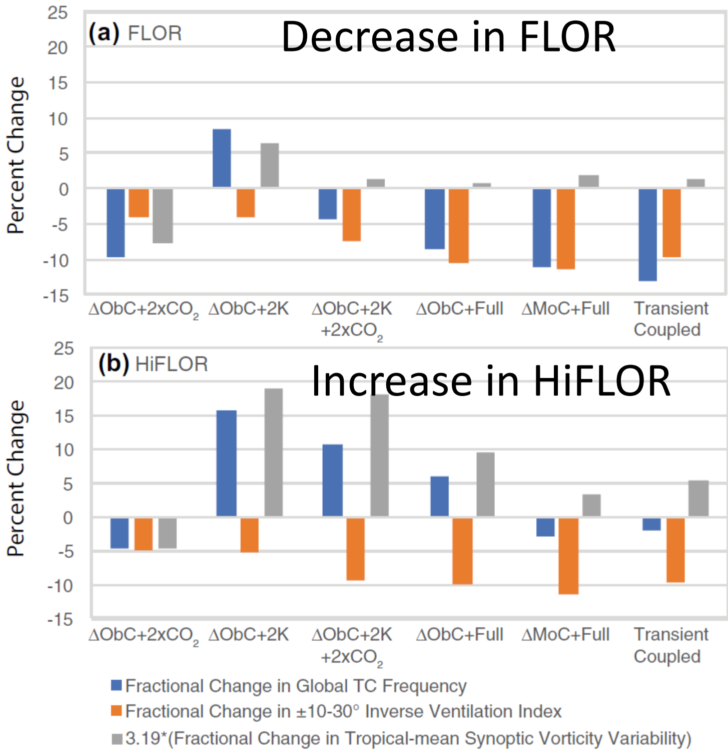
(depends on ventilation index)

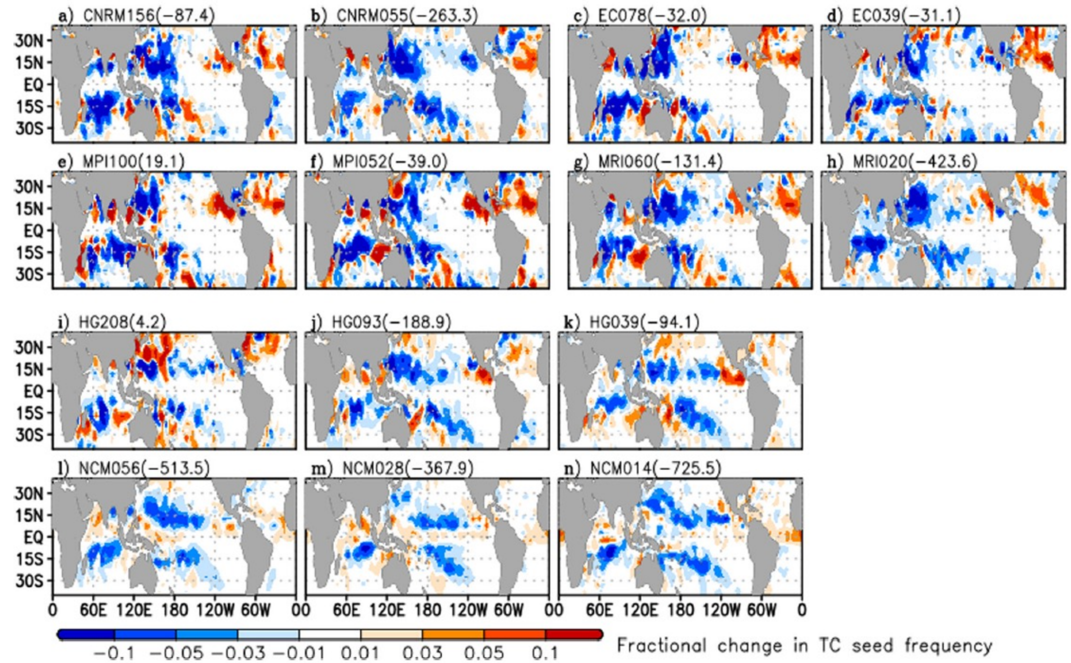


This model reproduced the nTC changes among the different experiments.

Hsieh et al. (2020, *Clim. Dyn.)*

Future changes in TC seeds





TC seeds are projected to decrease by most of CMIP6 models during 1990-2049

Vecchi et al. (2019, *Clim. Dyn.*)

Definition: 2-8-day vorticity variance

Yamada et al. (2021, *Prog. Earth Planet Sci.)*

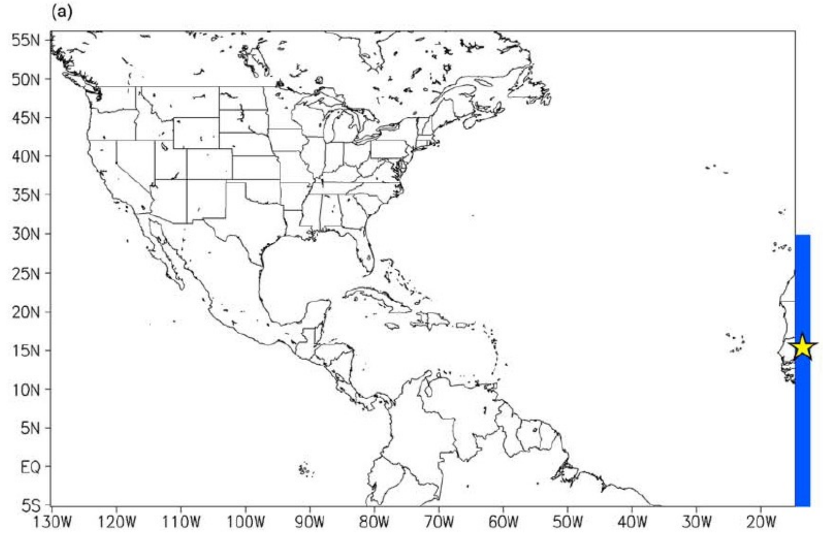
Definition: Candidate of TCs during the TC detection algorithm (weaker storms)

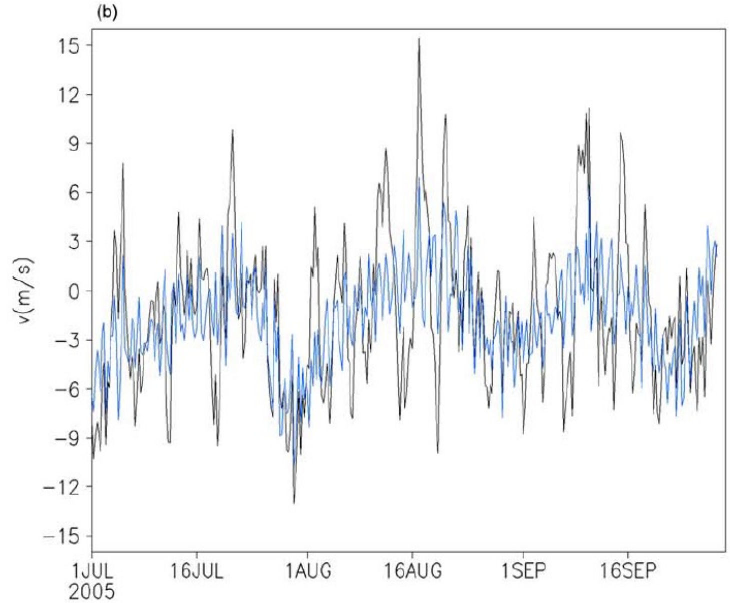
Sugi et al. (2021, *SOLA)*

MRI-AGCM, NICAM showed projected decreases in TC seeds in the future

Definition: Maximum wind speed between 10m s^{-1} and 17m s^{-1}

Less role of TC seeds on the NA TCs





Patricola et al. (2018, *GRL*) did conduct idealized experiments by placing a sponge layer to kill synoptic-scale disturbance from the African continent (AEW).

Table 1

Measures of Atlantic TC Activity From the Ensemble Average of the Control and AEW Suppressed Simulations

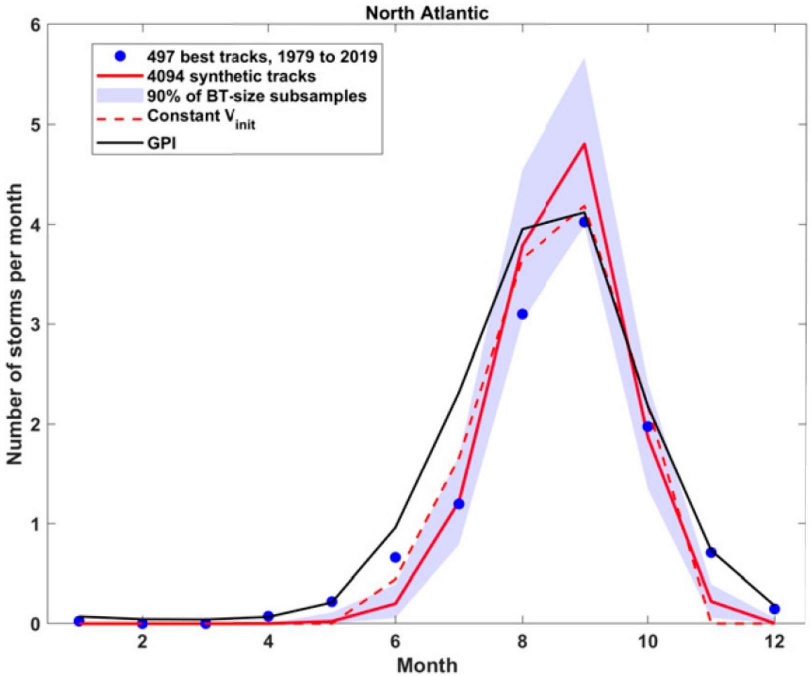
	Control	AEW suppressed	% change	*p* value
Number of TCs/season	19.5	20.2	+4%	0.64
Number of TC days/season	105	117	+11%	0.17
ACE (10^4 kt^2)	168	192	+15%	0.07

Note. This includes the percent change relative to the control simulation and the *p* value corresponding to a *t* test for difference of the means.

No change (or increased) TCs, indicating less role of TC seeds on the climatology of TC number in the North Atlantic.

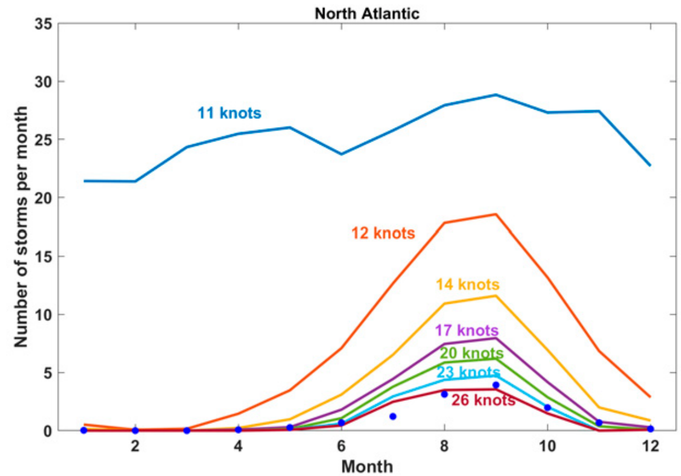
Rebuttal paper by Emanuel (2022, J. Climate)

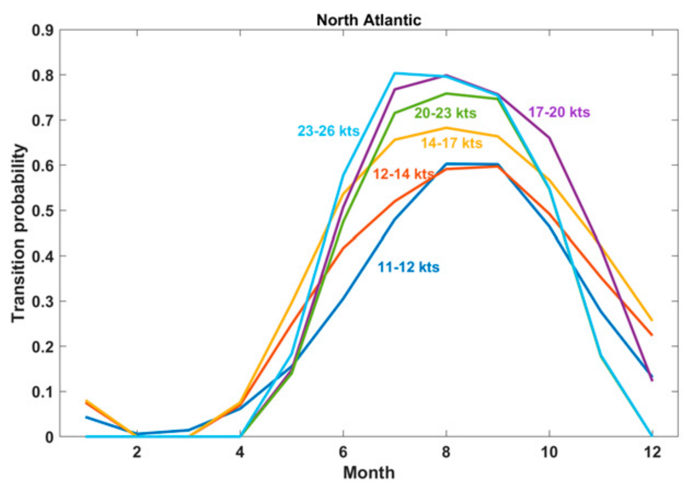
1. Changing the rate of TC seeds does not change the TC genesis number by Emanuel's hybrid model.



Red: Constant Seeding rate
Dashed red: TC seeding rate depending on GPI

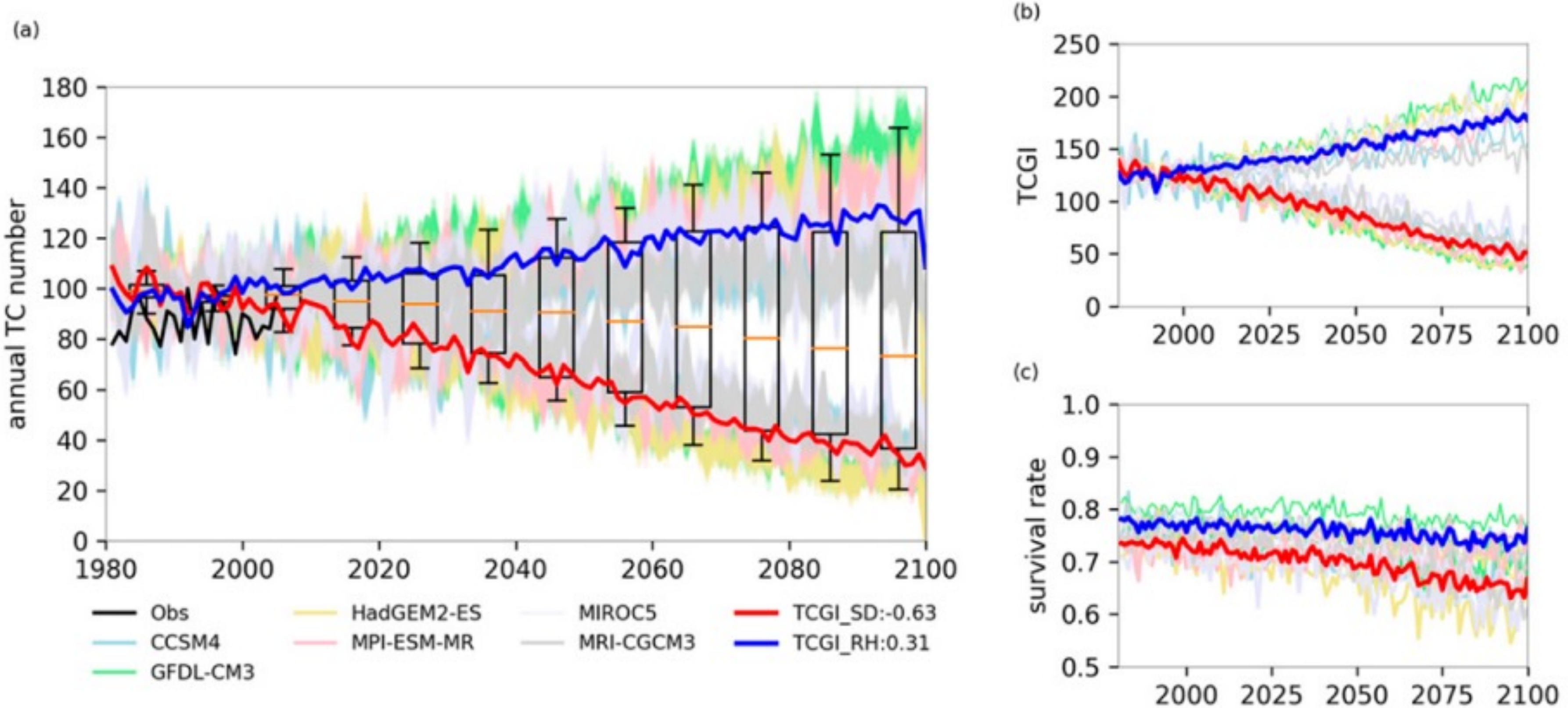
2. TC rate from TC seeds depend on intensity of TC seeds.





3. TC seeds do not determine TC genesis, but large-scale parameters determine TC genesis

Uncertainty in Statistical Dynamical Downscaling

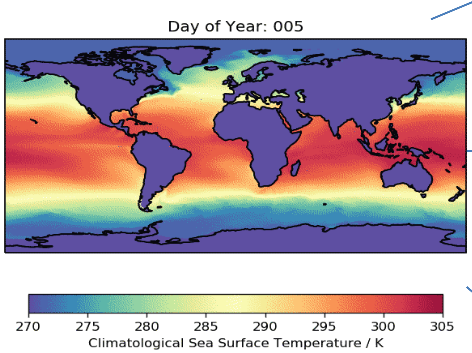


CRH case: $\mu = \exp(b + b_{\eta}\eta_{850,c} + b_{\mathrm{CRH}}\mathrm{CRH} + b_{\mathrm{PI}}\mathrm{PI} + b_{\mathrm{SHR}}\mathrm{SHR}),$

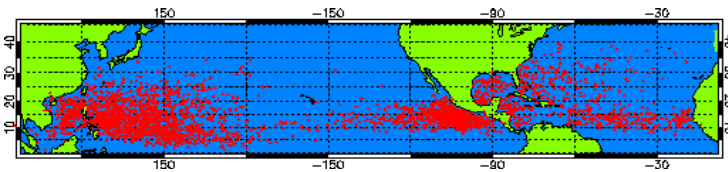
SD case: $\mu = \exp(b + b_{\eta}\eta_{850,c} + b_{\mathrm{SD}}\mathrm{SD} + b_{\mathrm{PI}}\mathrm{PI} + b_{\mathrm{SHR}}\mathrm{SHR}).$

Lee et al. (2020, *J. Climate*)

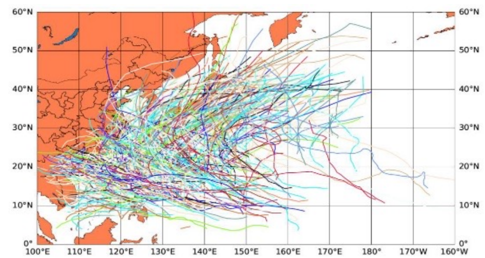
Princeton synthetic storm model (PepC)



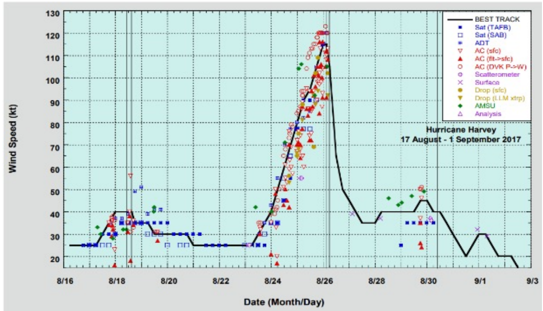
Environmental obtained from reanalysis or climate model outputs



cluster-Poisson regression



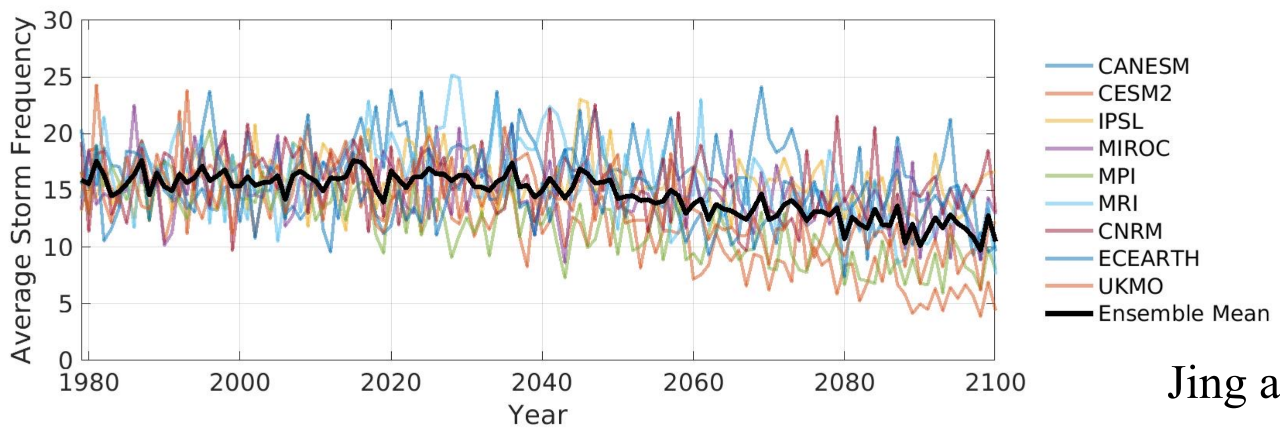
analog-wind track model



Environmental-dependent hidden Markov chain

Jing and Lin (2020)

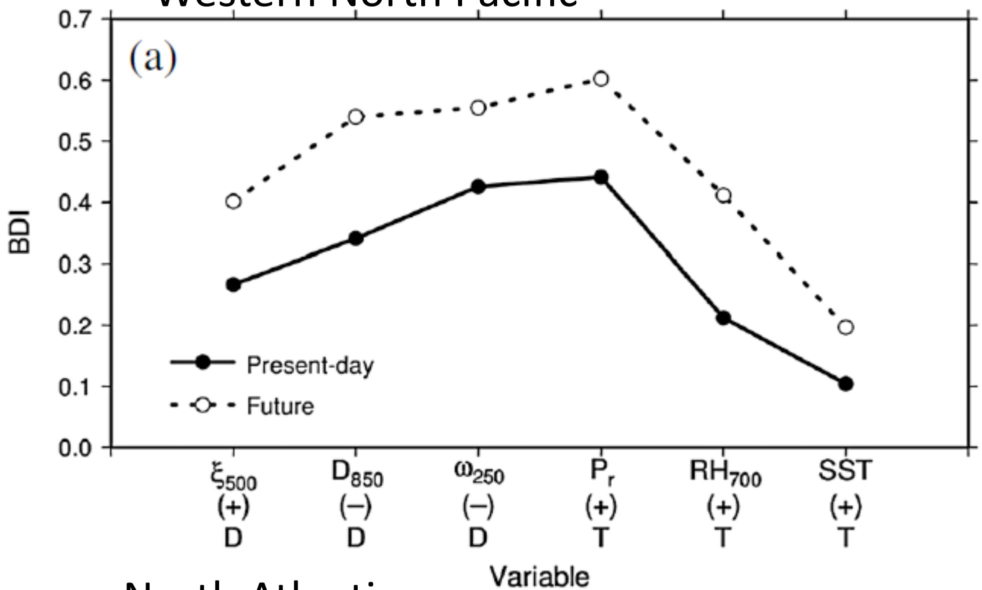
Projection of North Atlantic TCs under historical and SSP5-8.5 scenario



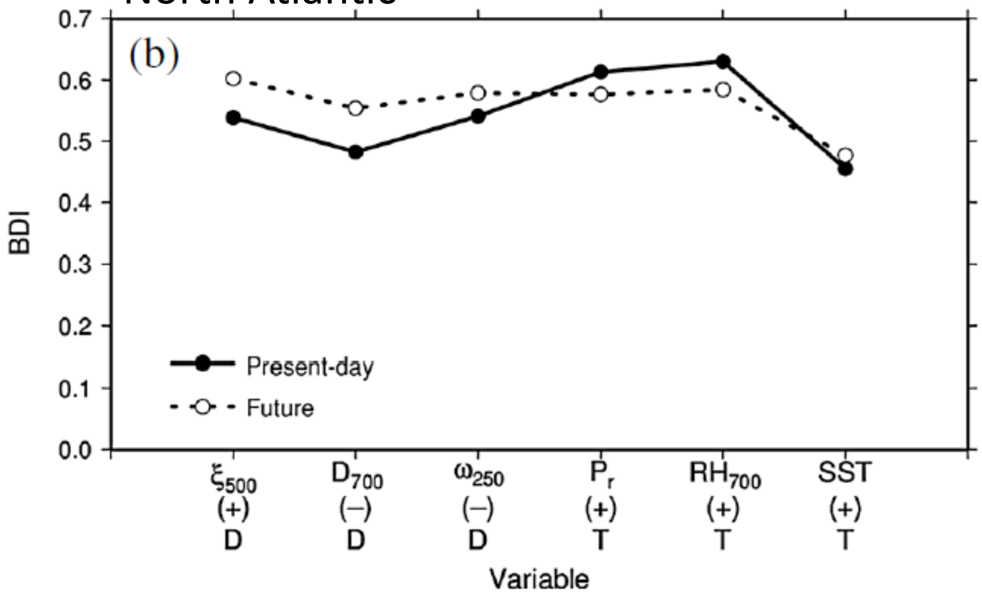
Jing and Lin (2020, *JAMES*)

Changes in the dominant effect of large-scale parameters on TC genesis

Western North Pacific



North Atlantic



$$\mathrm{BDI} = \frac{M_{\mathrm{DEV}} - M_{\mathrm{NONDEV}}}{\sigma_{\mathrm{DEV}} + \sigma_{\mathrm{NONDEV}}},$$

BDI is applied to 20-km MRI-AGCM for both present-day and future simulations.

A large BDI indicates that that variable is critical for separating developing and Non-developing storms.

The most important parameters for TC genesis

	WNP	NA
Present-day	Dynamical	Thermodynamical
Future	Dynamical	Dynamical

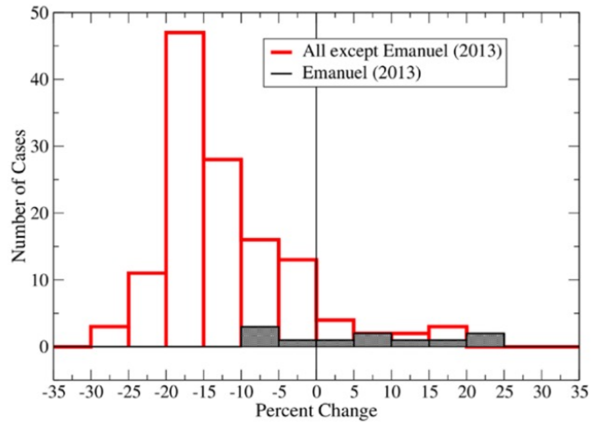
Dynamical parameters are more Important for future in the North Atlantic

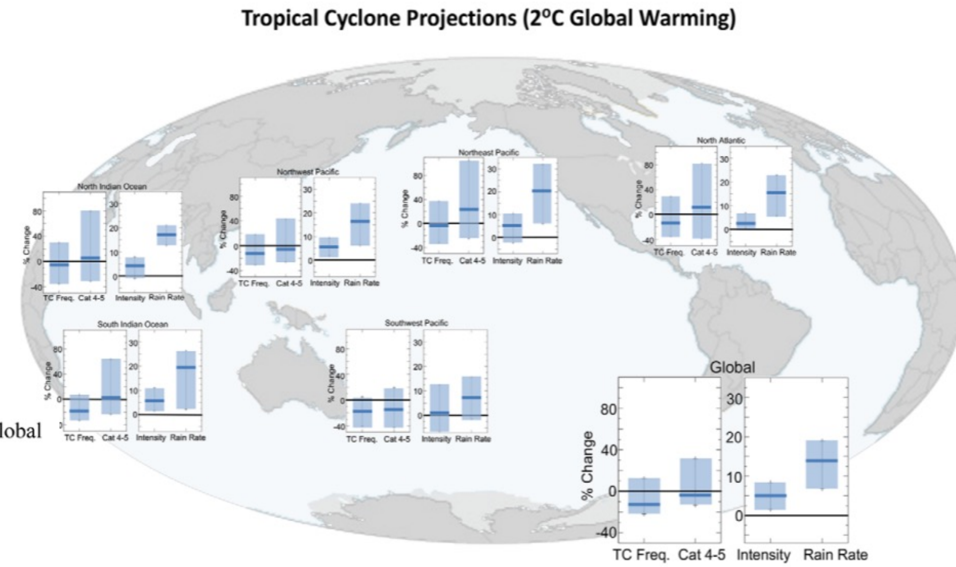
Murakami et al. (2013, *GRL*)

A brief review of the history of Future Projections for TCs (2020-)

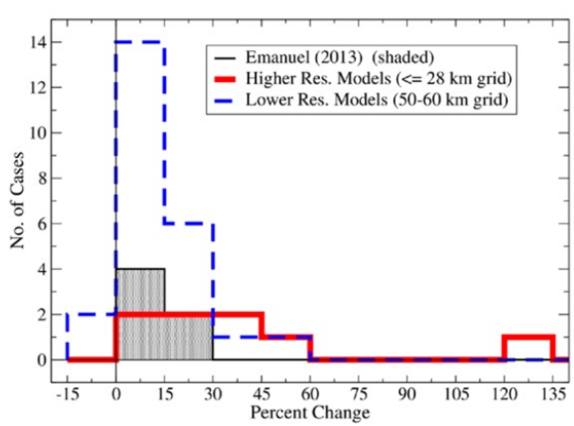
2020 Knutson et al. (2020, *BAMS*)

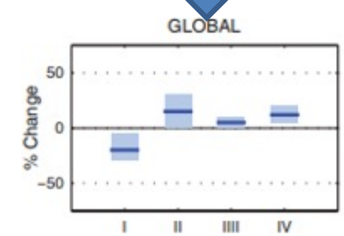
a) Frequency of Tropical Cyclones (Cat. 0-5): Global





c) Percent Change in Proportion of Cat. 4-5 Tropical Cyclones: Global





2022 IWTC-X (Indonesia)

The projected change in the global number of TCs has become **more uncertain** since IWTC-9 due to projected increases in TC frequency by a few climate models.

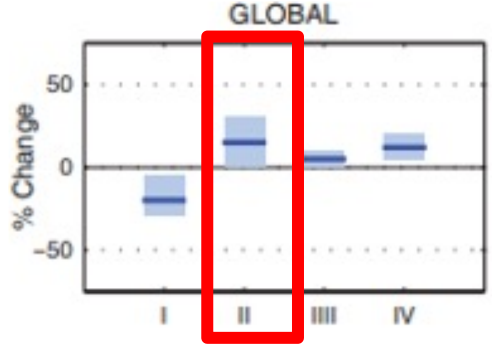
IPCC AR5 (2014)

Projected changes in TC intensity

There is a general consensus from theory and climate modeling that the strongest TCs will get stronger in the future and will at least become a larger fraction of total TC frequency.

Knutson et al. (2020):

There is a ~13% increase in the proportion of intense TCs (Cat. 4–5) under 2˚C warming



Lee et al. (2020):

Statistical-dynamical downscaling led to a relative increase in intense TCs, with an increased fraction undergoing rapid intensification in both genesis scenarios used.

Roberts et al. (2020):

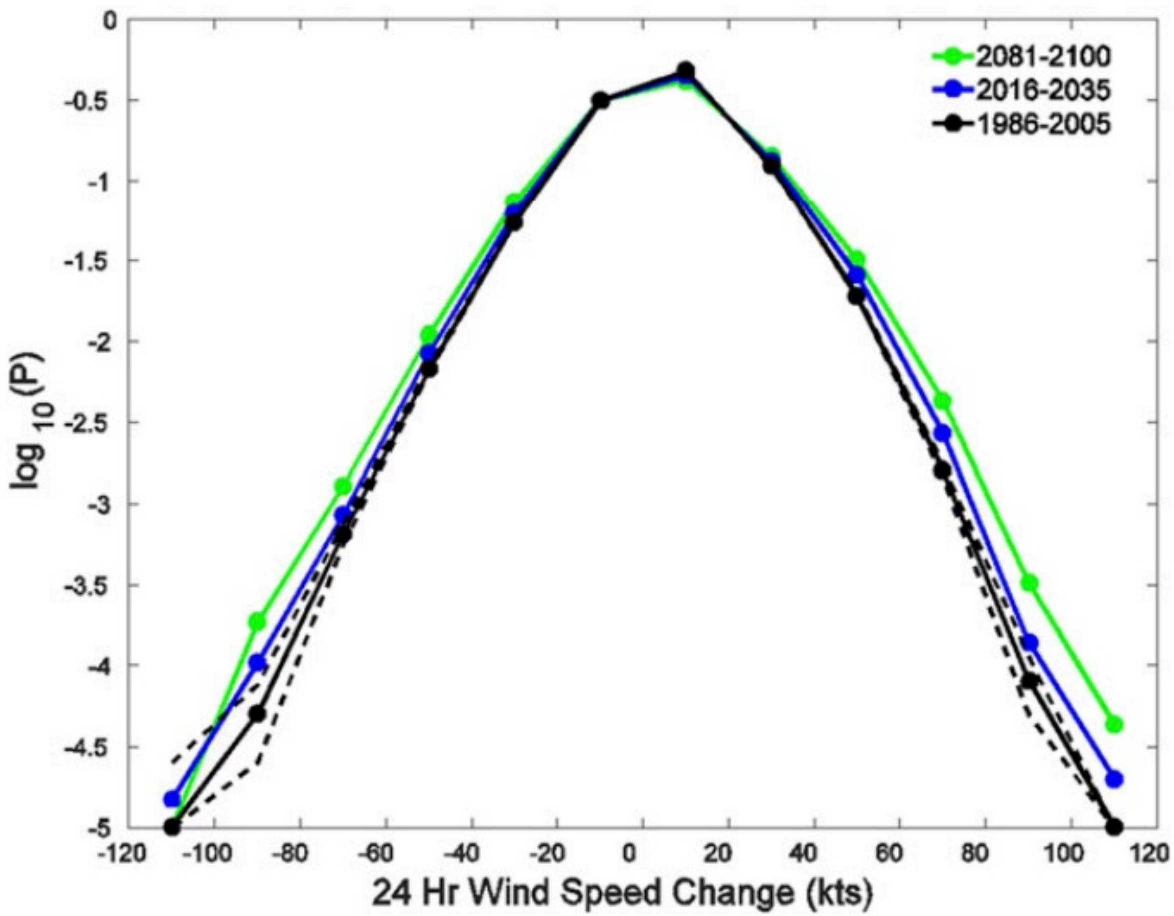
Small increases in intensity in HighResMIP simulations by 2050, but with mixed results across models.

Emanuel (2021):

A large increase in intensification rate in the future, in particular, > 20% increase at higher intensity regimes

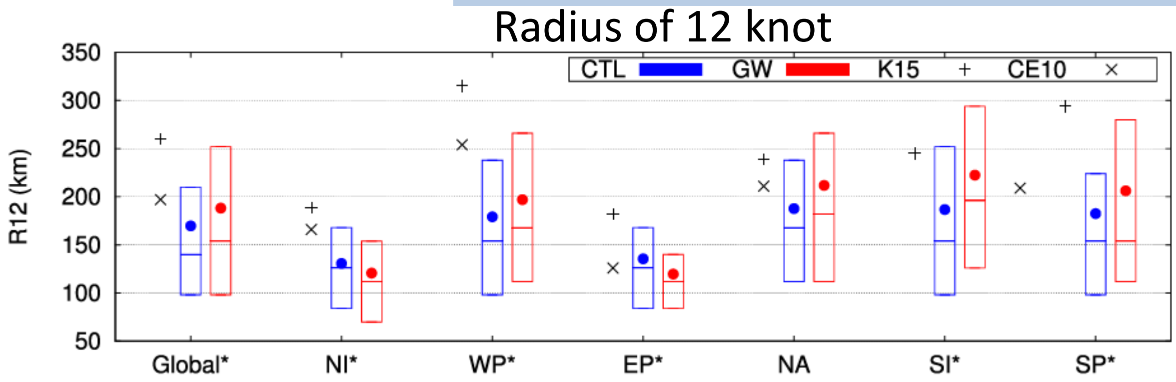
Projected changes in Rapid Intensification

Projected increases in the frequency of Rapid intensification of TCs.



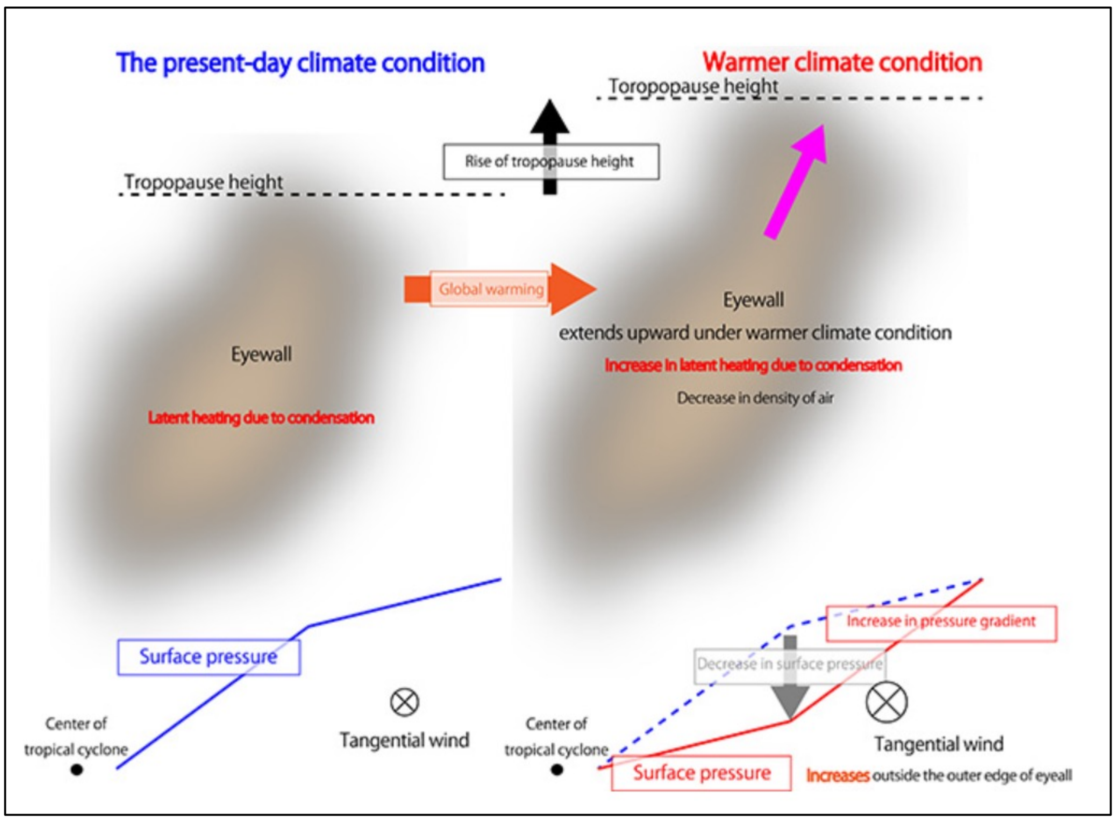
Bhatia et al. (2018, *J. Climate*)

Projected changes in TC size



14-km NICAM

Projected increased mean TC size



Increased height of tropopause

↓

Lower SLP around the eyewall

↓

Increase in pressure gradient

↓

Increased wind speed at the outer region (i.e., increased outer size)

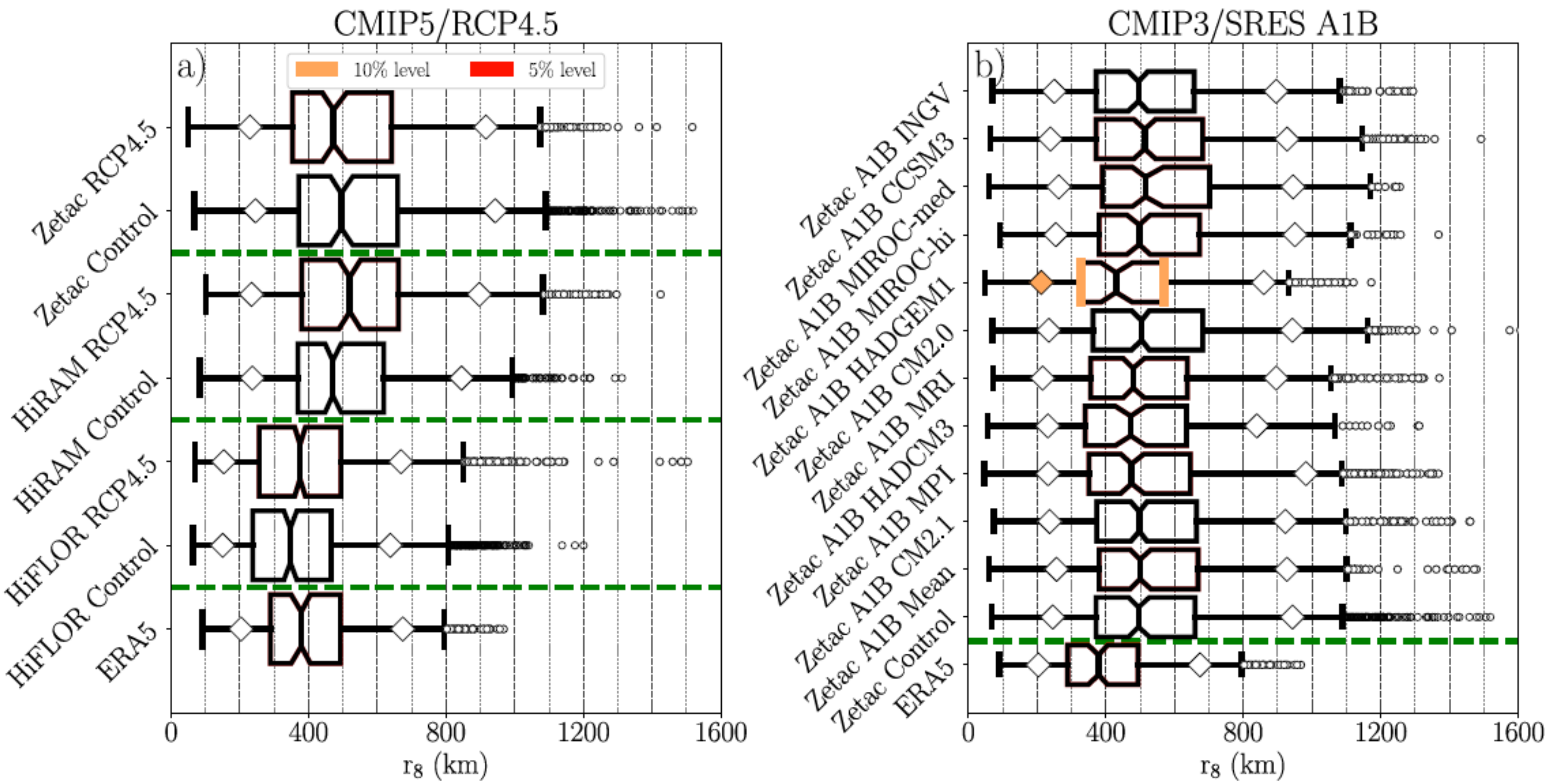
Source: https://www.jamstec.go.jp/e/about/press_release/20170914/

Yamada et al. (2017, *J. Climate*)

Projected changes in TC size

r_s: Azimuthal wind is less than or equal to 8 m s^{-1}

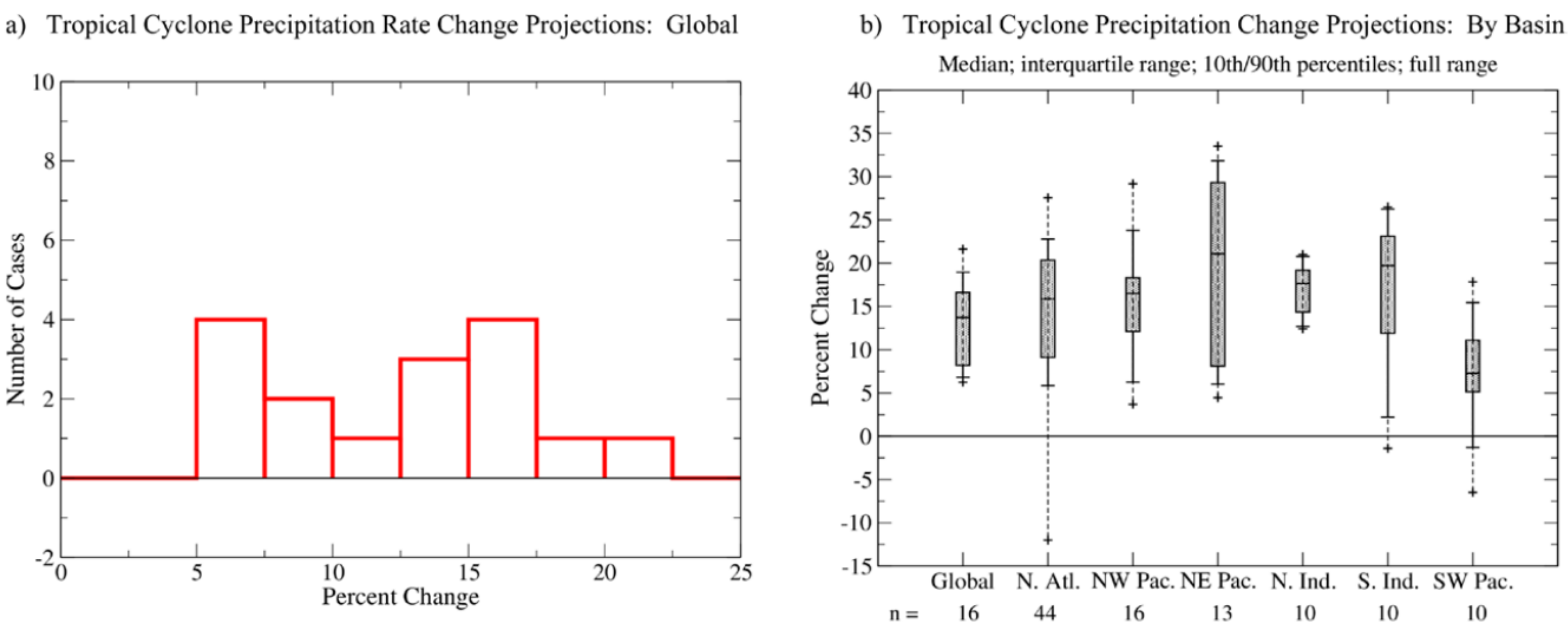
HiFLOR: GFDL 20-km coupled model
HiRAM: GFDL 50-km atmospheric model
Zetac: 9-km GFDL Hurricane model



No significant future change in the outer size of the North Atlantic storms.

Schenkel et al. (2023, *J. Climate*)

Projected changes in TC rainfall



All 16 global projections from eight studies indicate a mean global increase (median: **+14**%; range: +6% to +22%).

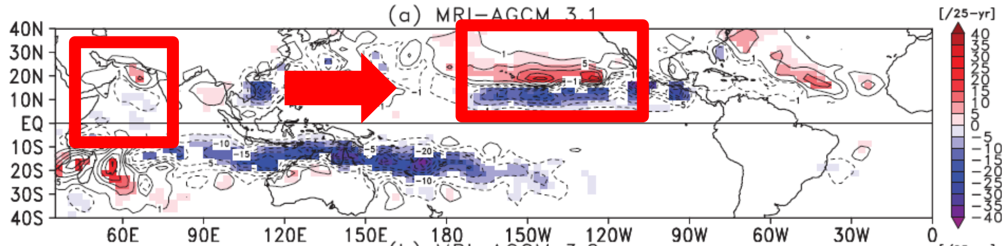
The projected 14% TC rain-rate increase for a 2°C global warming implies a slightly stronger than 7% increase per 1° C of tropical SST warming (Clausius-Clapeyron).

Tropospheric water vapor content will increase in a warmer climate (IPCC 2013).

Knutson et al. (2020, *BAMS*)

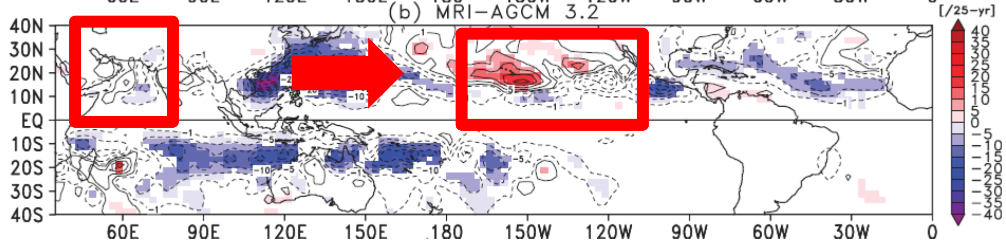
Projected changes in regional TC activity

Projected future changes in TC density



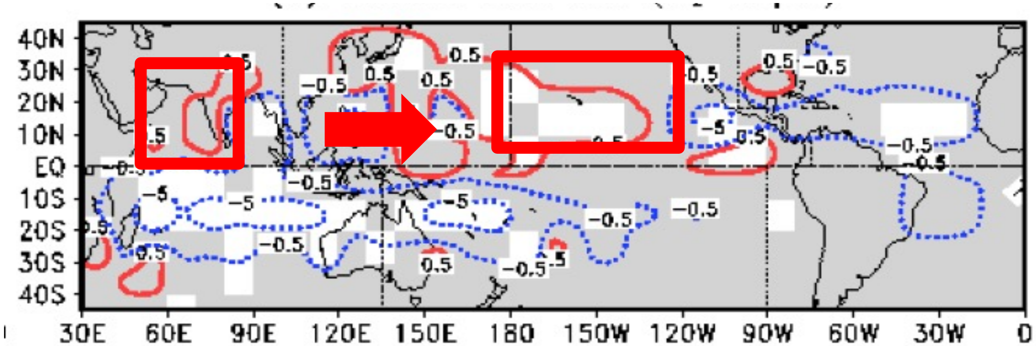
MRI-AGCM3.1S A1B

Murakami et al. (2012, *J. Climate*)



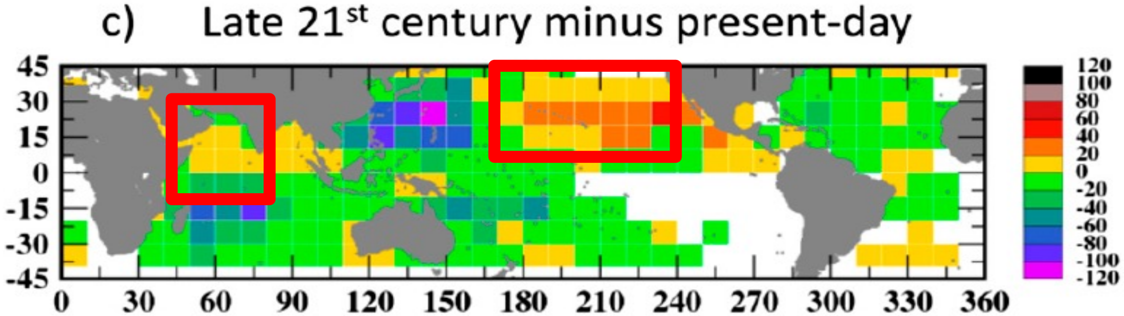
MRI-AGCM3.2S RCP4.5

Murakami et al. (2012, *J. Climate*)



CMIP5 models RCP4.5

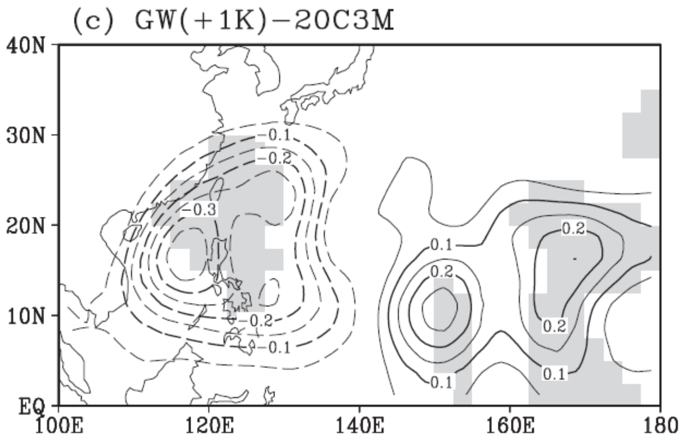
Murakami et al. (2014, *J. Climate*)



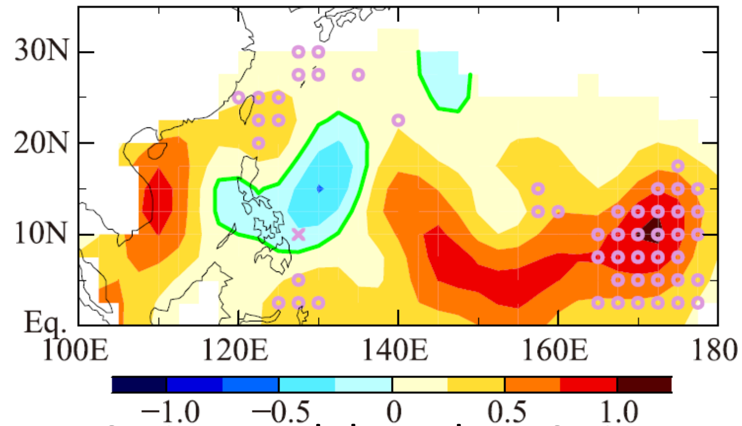
GFDL-HiRAM & ZTAC

Knutson et al. (2015, *J. Climate*)

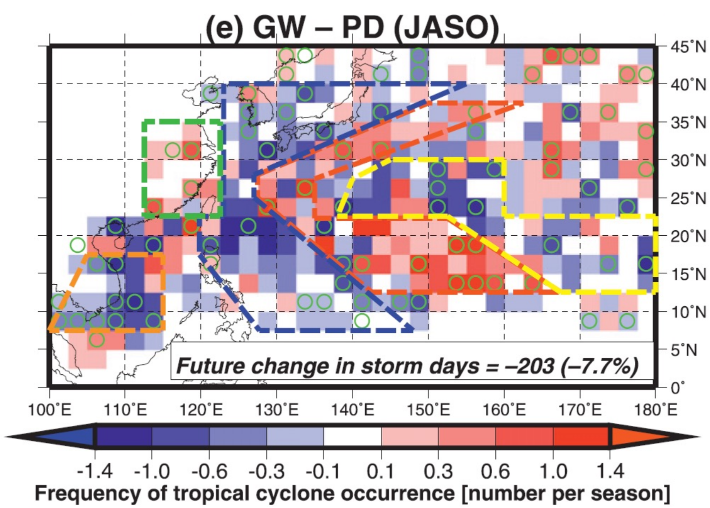
Projected eastward shift of TC tracks in the WNP



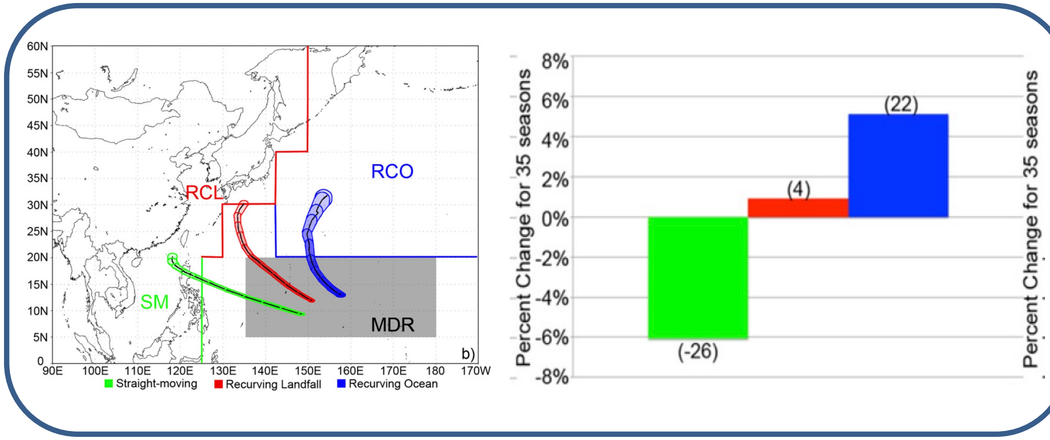
3 CMIP3 models under A1B scenario
Yokoi and Takayabu (2009, *JMSJ*)



7 CMIP5 models under RCP4.5 scenario
Yokoi et al. (2012, *SOLA*)



MRI-AGCM3.1S under A1B scenario
Murakami et al.(2011, *J. Climate*)

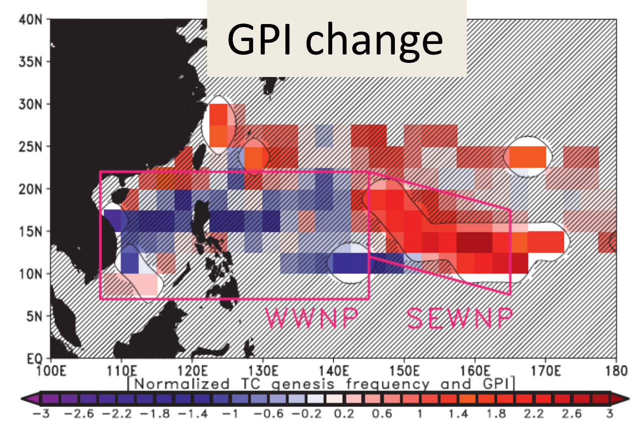


Advection model applied to the CMIP5 model outputs
Colbert et al. (2015, *J. Climate*)

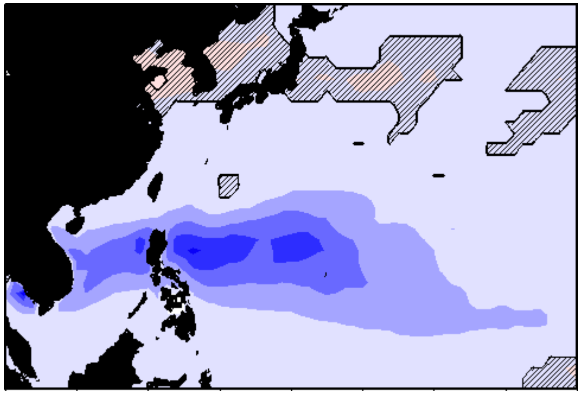
Projected eastward shift of TC tracks in the WNP

Murakami et al. (2011, *J. Climate*)

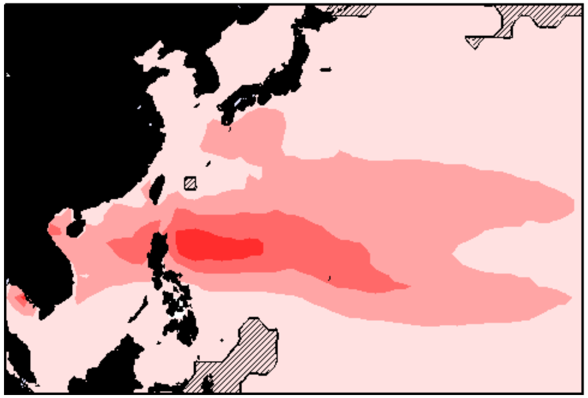
$$GPI' = \left|10^5 \eta\right|^{\frac{3}{2}} \left(\frac{RH}{50}\right)^3 \left(\frac{MPI}{70}\right)^3 (1+0.1V_s)^{-2} \left(\frac{-\omega+0.1}{0.1}\right)$$



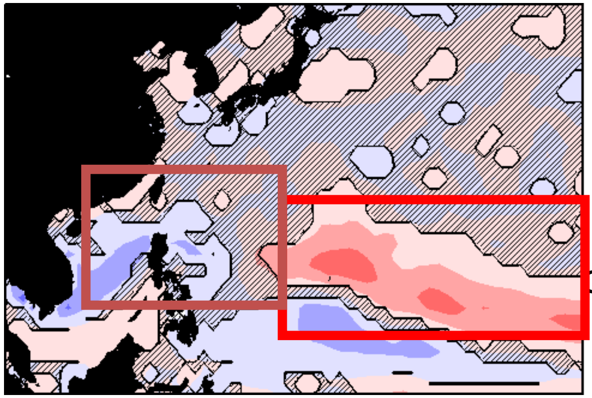
RH



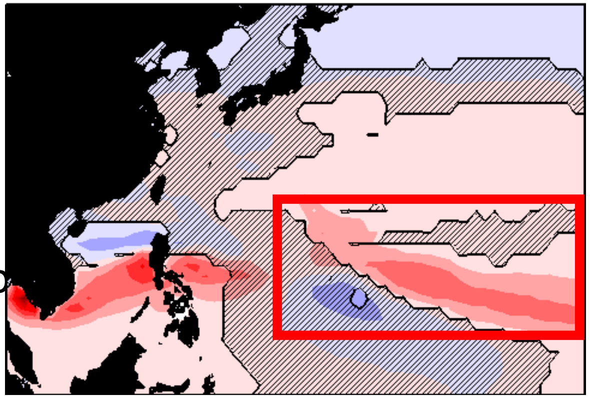
MPI



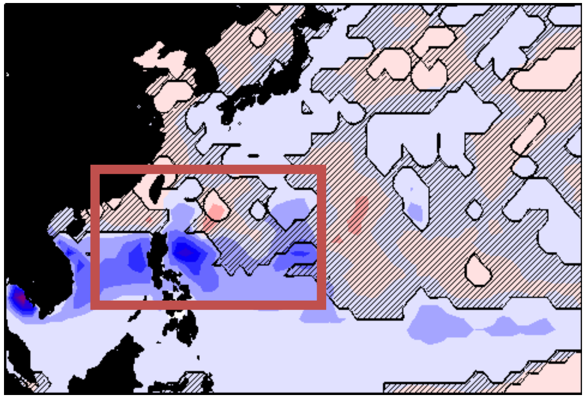
η (low-level vorticity)

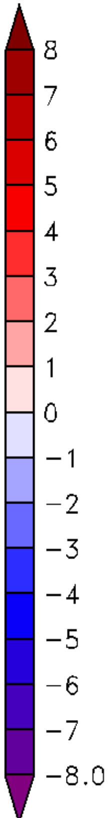


Vs (vertical wind shear)

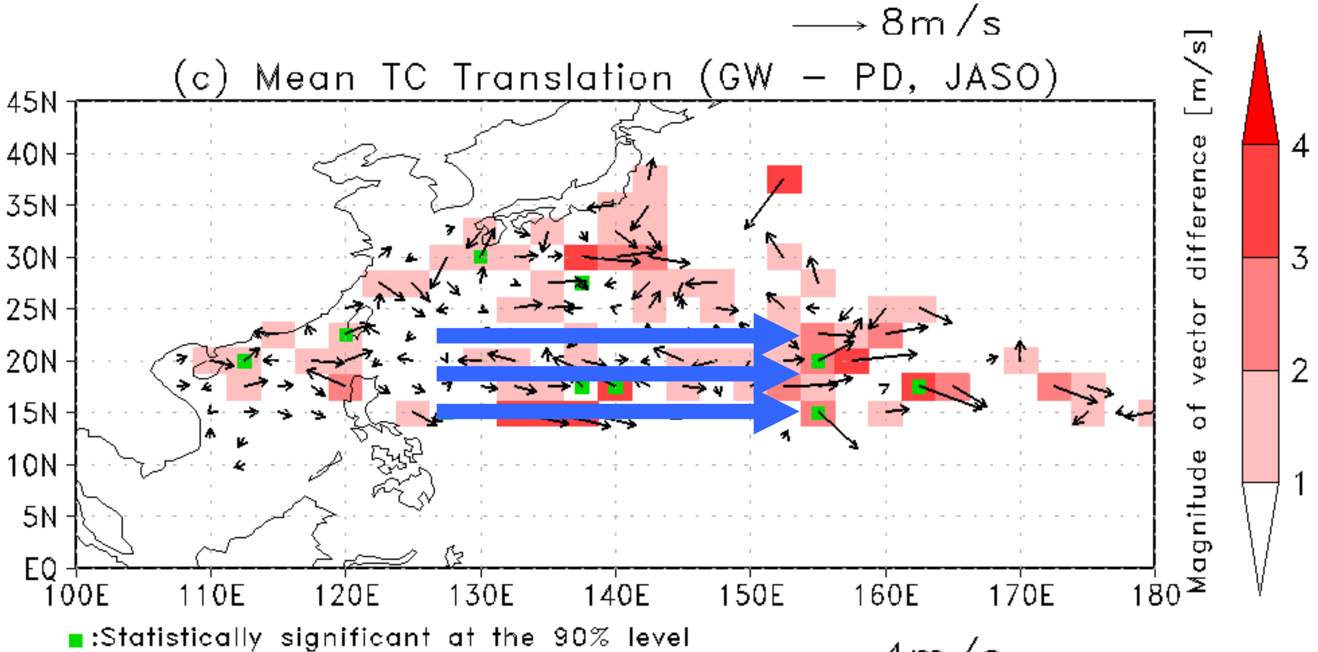


ω (mid-level vertical motion)

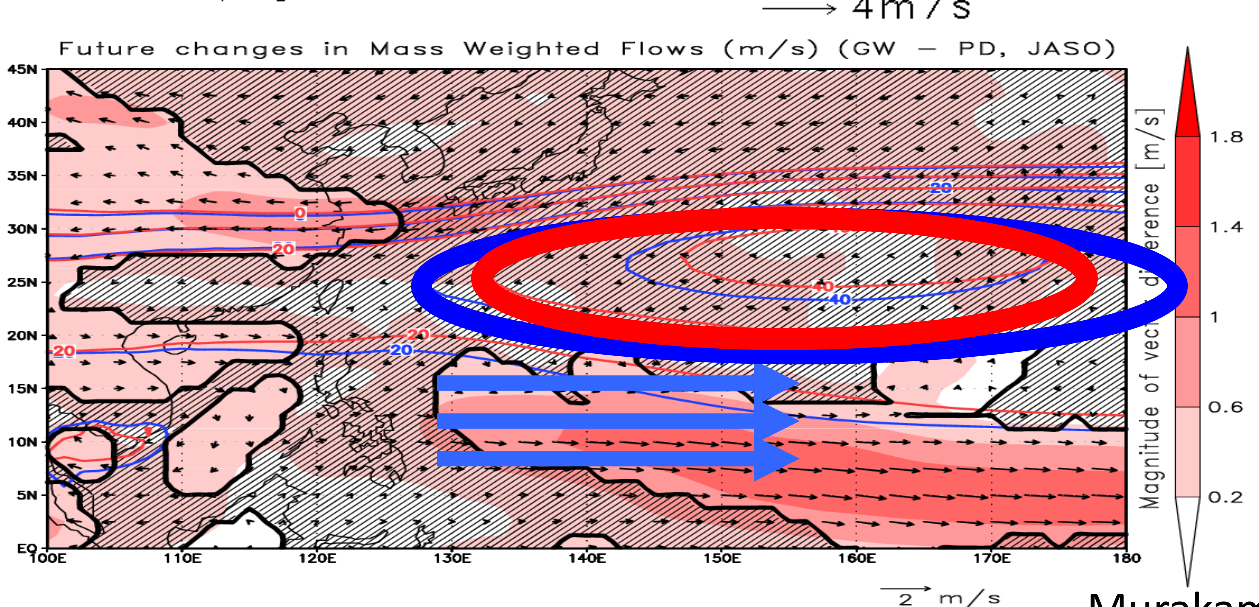




Projected eastward shift of TC tracks in the WNP



Slow down of TC motion
-> early recurve

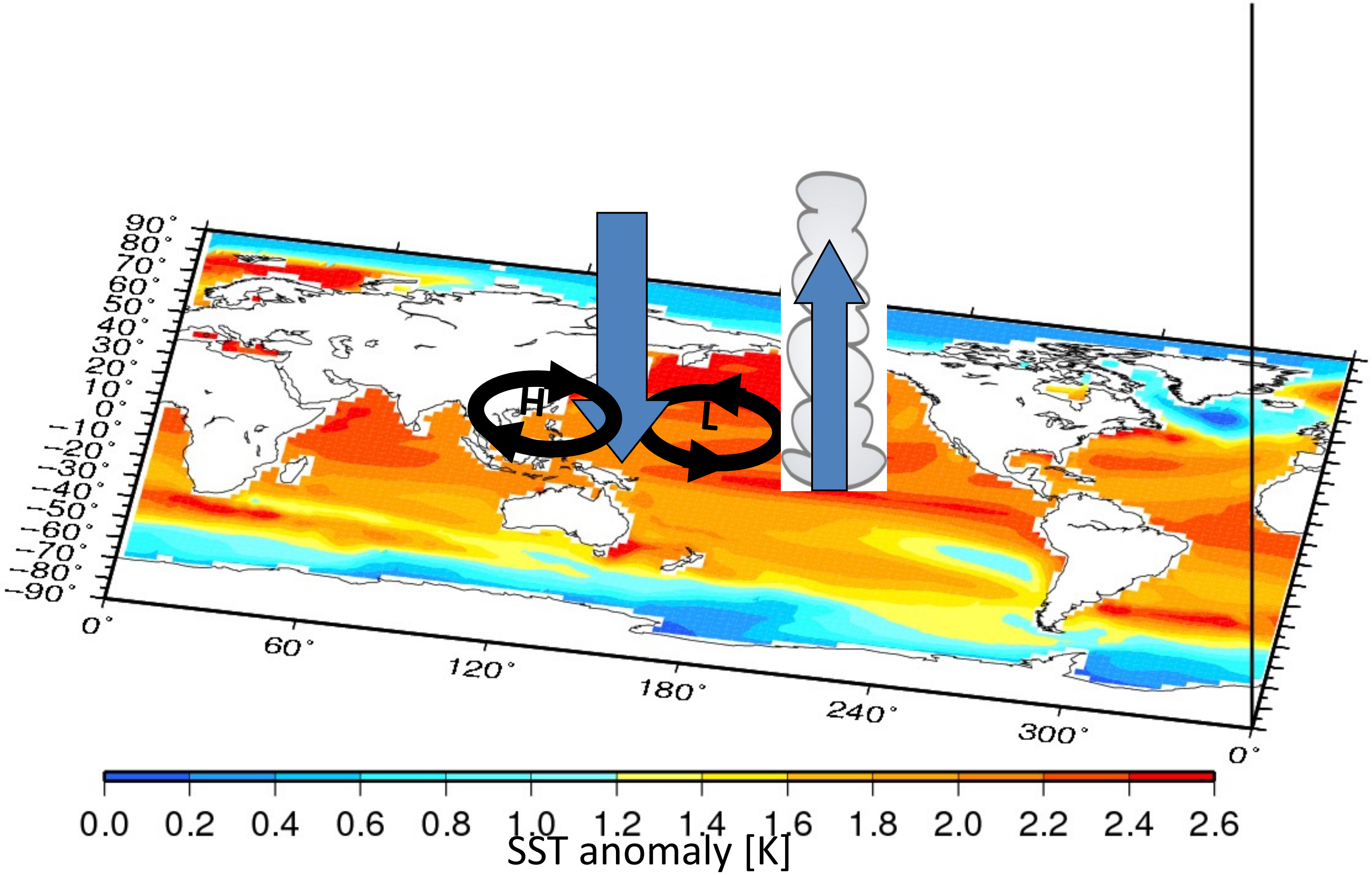


Eastward shift in Subtropical high

Westerly wind change

Murakami et al. (2011, *J. Climate*)

Projected eastward shift of TC tracks in the WNP

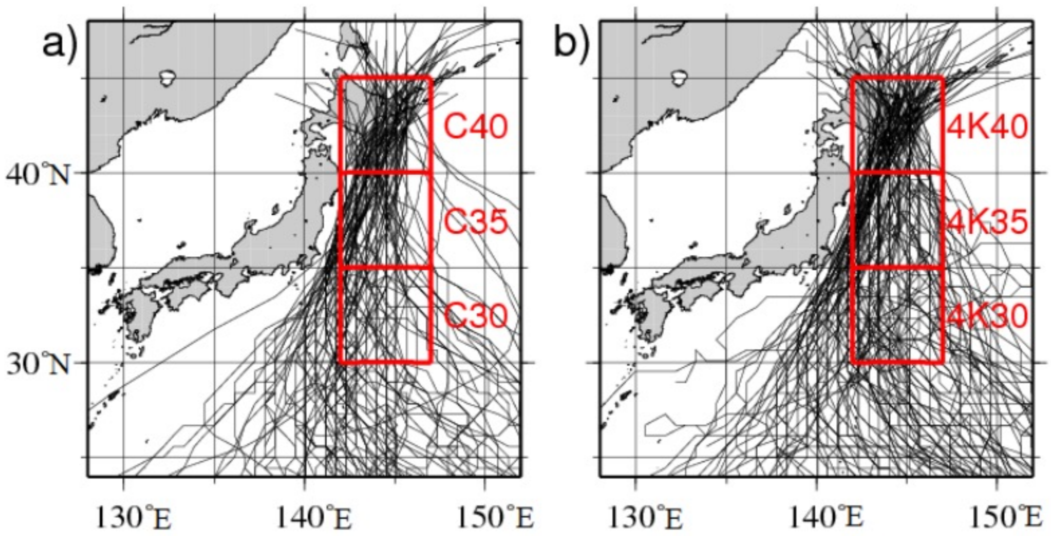


The Rossby-wave response related to the spatial pattern of SST change

Murakami et al. (2011, *J. Climate*)

Projected changes in regional TC activity

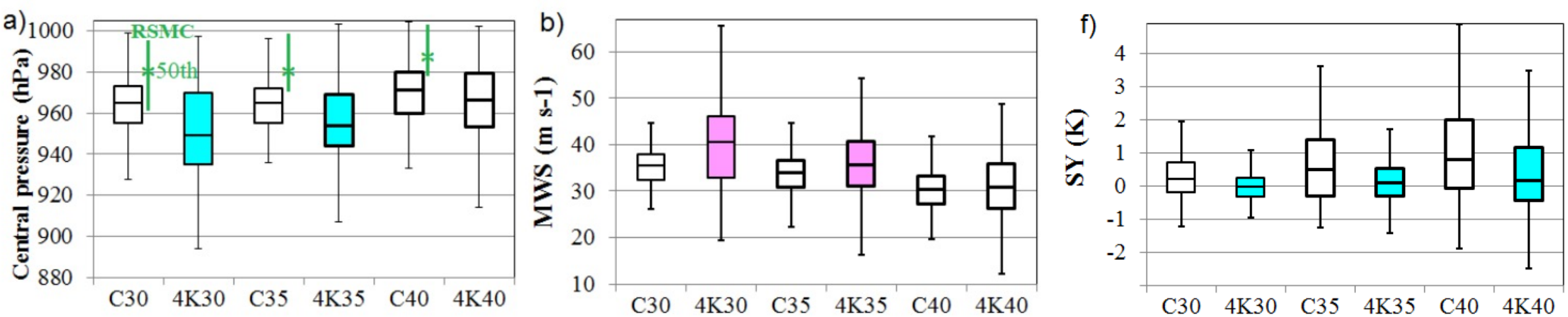
Current Climate (C) Future +4K (4K)



d4PDF (20-km MRI RCM)

downscaling

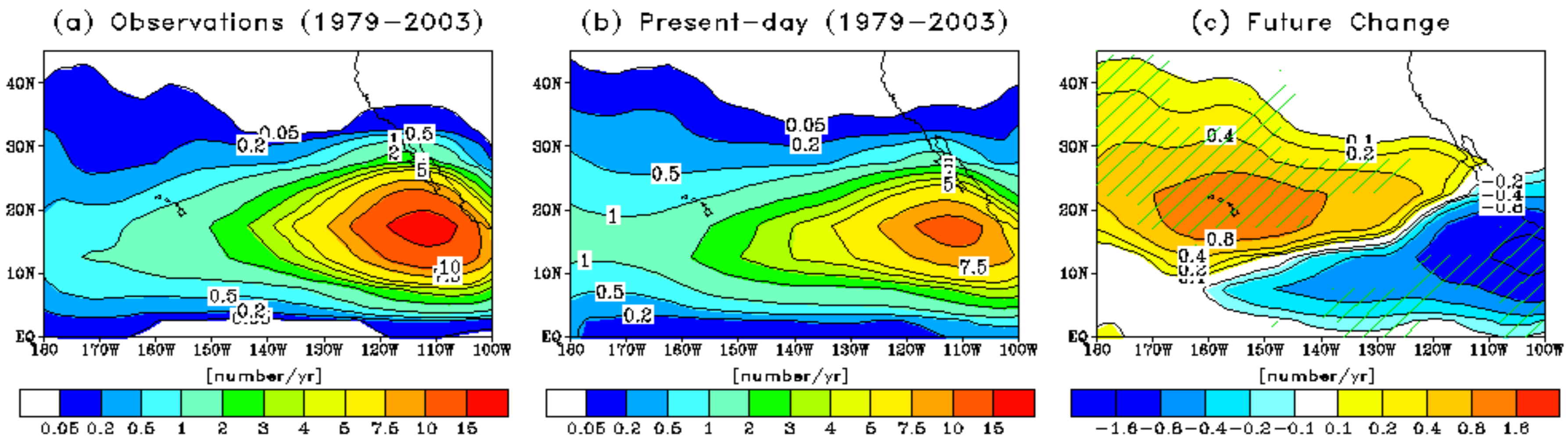
4-km regional model (CReSS)



- More intense storms in 4K
- More axisymmetric structure of TCs (more tropical-type storms than extra-tropical)

Kanada et al (2020, *SOLA*)

Projected increase in TCs near Hawaii



The annual mean of tropical cyclone frequency of occurrence counted at every 5 x 5-degree grid box. The region with green hatching in (c) indicates significance (99% level) and robustness in the change among the experiments.

Fig. C reveals an east-west contrast in projected future changes in TCF: **increase in the subtropical central Pacific** and **reduction in the eastern tropical Pacific**.

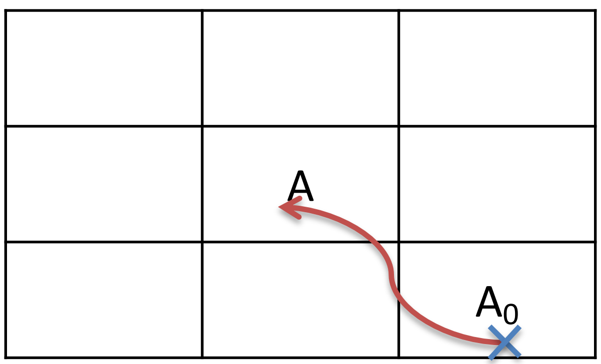
Murakami et al. (2013, *Nat. Clim. Change*)

Empirical Statistical Analysis (Total Analysis)

To assess the relative importance of TC genesis and tracks in terms of future changes in local TCF, a simple empirical statistical analysis is applied.

TCF in a grid cell (*A*) can be written as follows.

$$f(A) = \iint_C g(A_0) \times t(A, A_0) dA_0$$



$g\ (A_0)$: Frequency of TC genesis in a grid cell A_0

$t\ (A, A_0)$: Probability that a TC generated in grid cell A_0 travels to the grid cell A.

C: Entire eastern Pacific domain to be integrated

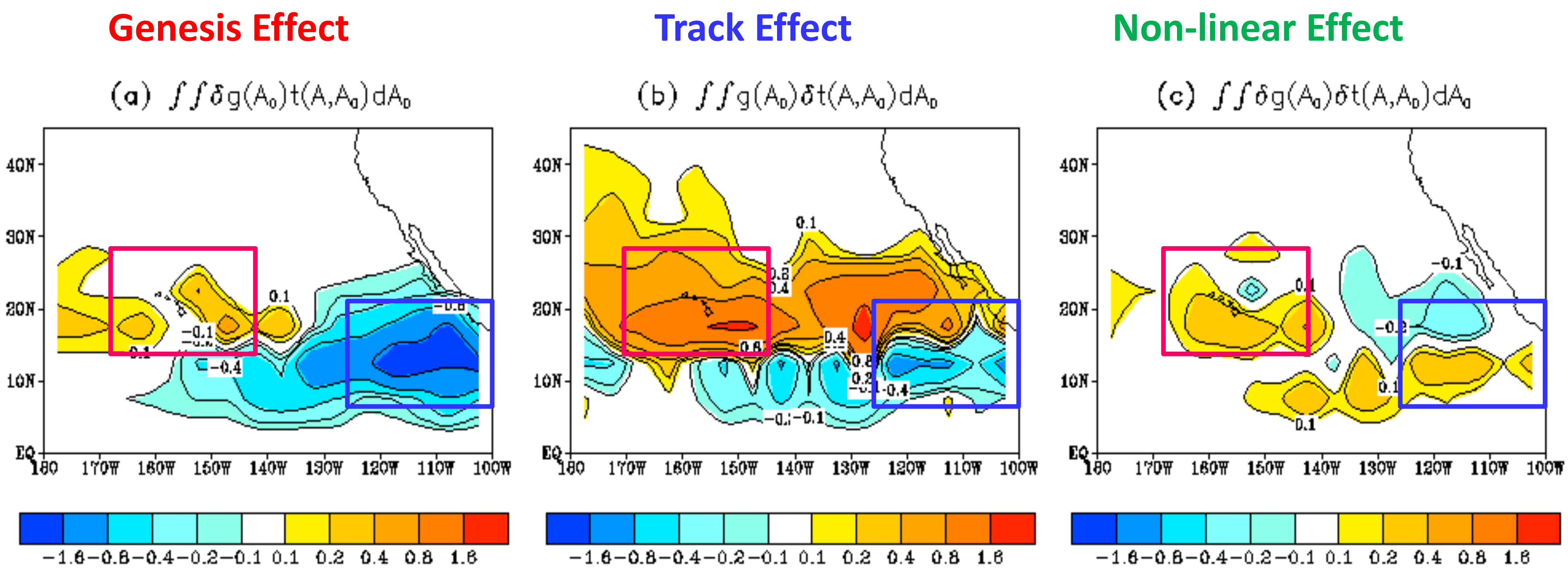
Future change in TCF in the grid cell *A* is computed as follows.

$$\delta f(A) = \underbrace{\iint_C \delta g(A_0) \times \overline{t(A, A_0)} dA_0}_{\text{Genesis Effect}} + \underbrace{\iint_C \overline{g(A_0)} \times \delta t(A, A_0) dA_0}_{\text{Track Effect}} + \underbrace{\iint_C \delta g(A_0) \times \delta t(A, A_0) dA_0}_{\text{Non-linear Effect}}$$

Genesis Effect **Track Effect** **Non-linear Effect**

Murakami et al. (2013, *Nat. Clim. Change*)

Empirical Statistical Analysis (Total Analysis)



▪TC track effect has the largest contribution to the projected increase in TCF around the Hawaiian regions.

▪TC genesis effect has the largest contribution to the projected decrease in TCF in the tropical eastern Pacific.

Murakami et al. (2013, *Nat. Clim. Change*)

Empirical Statistical Analysis (Origin Analysis)

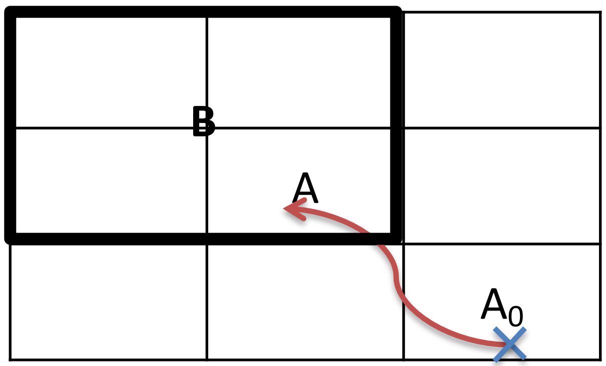
Here, we want to identify the locations associated with a large contribution to the increase in TCF in a specific region near Hawaii.
The effect of remote grid cell A_0 on TCF changes in a specific region B (e.g., Hawaiian region) is described as follows.

$$\delta f(B, A_0) = \iint_B \delta g(A_0) \times \overline{t(A, A_0)} dA + \iint_B \overline{g(A_0)} \times \delta t(A, A_0) dA + \iint_B \delta g(A_0) \times \delta t(A, A_0)\, dA$$

Effect of TC genesis change in A0 on TCF change in region B

Effect of TC track change

Effect of Non-linearity

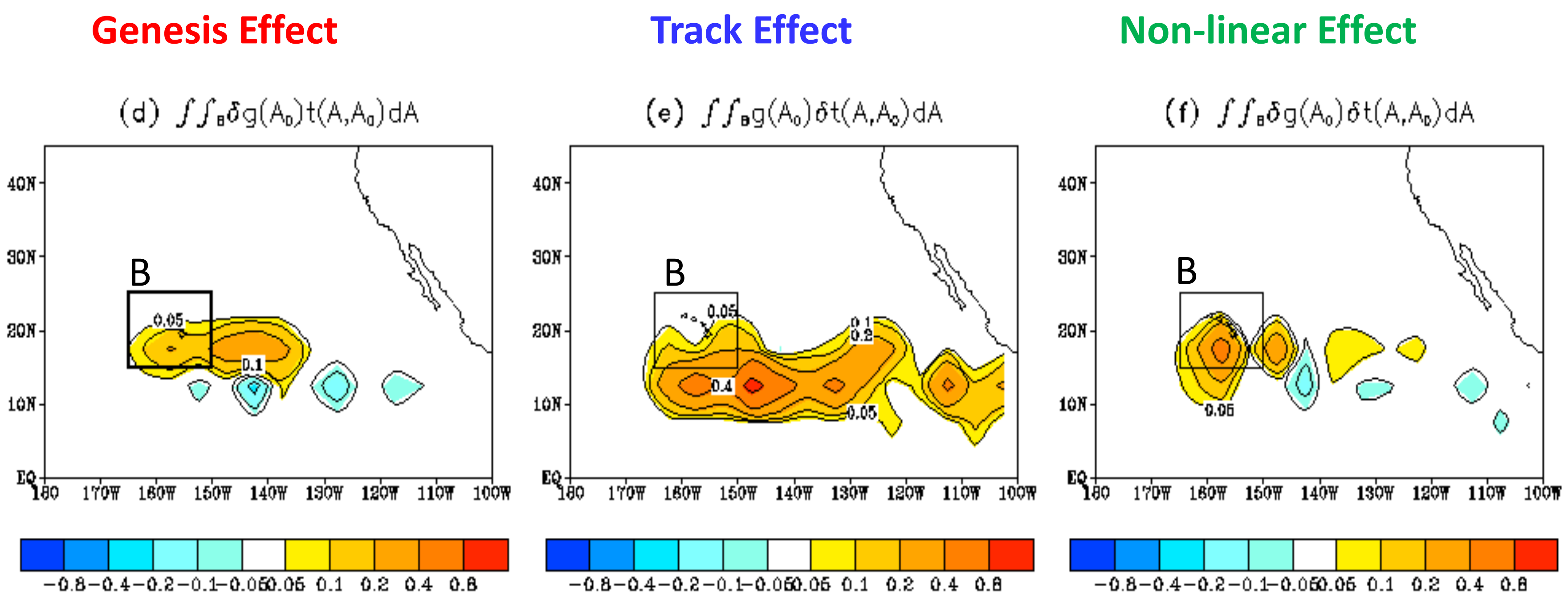


B : Region including multiple grid cells
g (A_0): Frequency of TC genesis in a grid cell A_0
t (A, A_0): Probability that a TC generated in grid cell A_0 travels to the grid cell A.

Murakami et al. (2013, *Nat. Clim. Change*)

$f_p(A) = \iint_C g_p(A_0) \times t_p(A, A_0) dA_0$

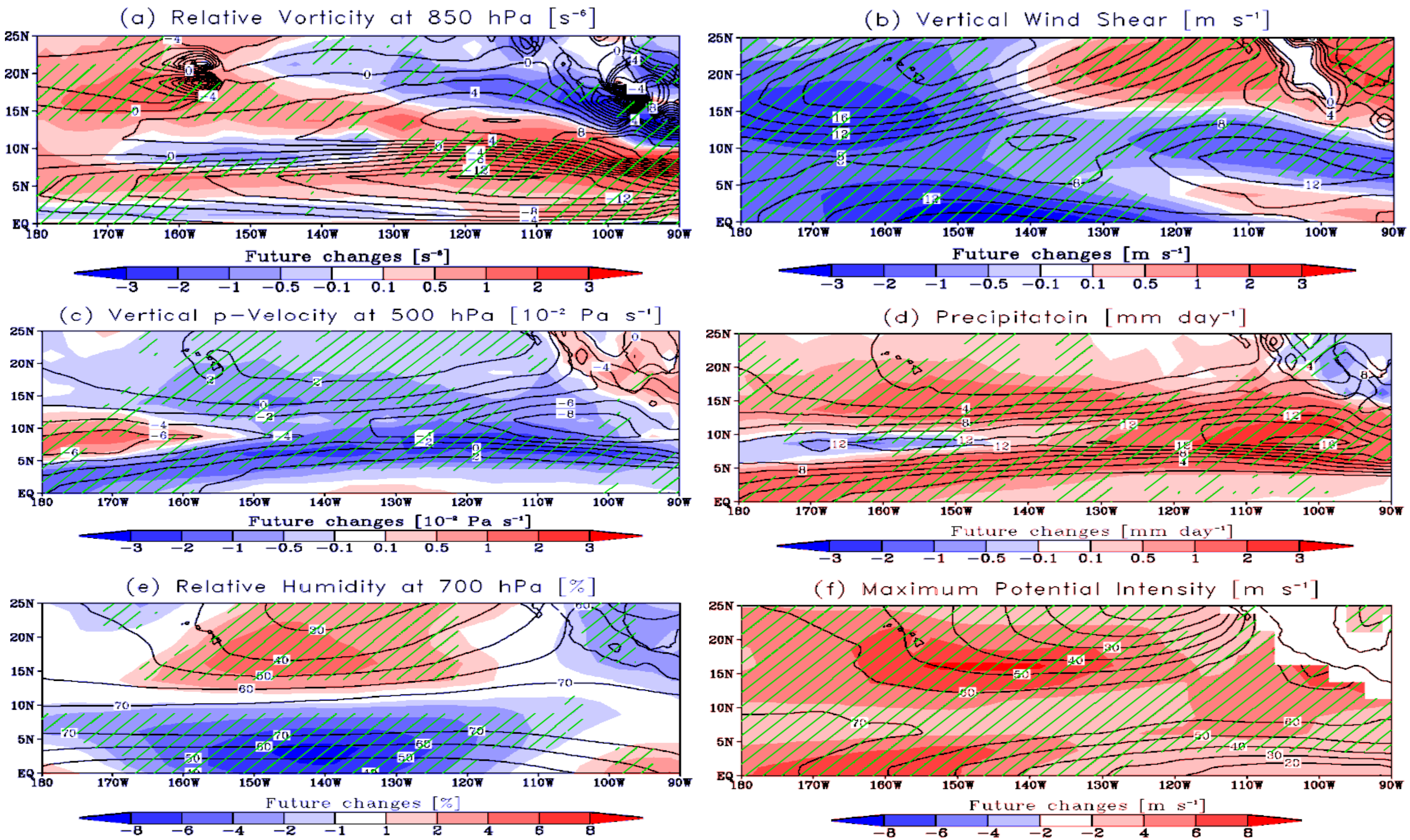
Empirical Statistical Analysis (Origin Analysis)



- Contribution of TC track change (middle) is the largest southeast of the Hawaiian domain, indicating that TCs generated southeast of the domain tend to propagate to the Hawaiian domain regardless of projected changes in TC genesis frequency.
- TC genesis change and nonlinear change nearby the domain partly contributes TCF increase in the domain.

Murakami et al. (2013, *Nat. Clim. Change*)

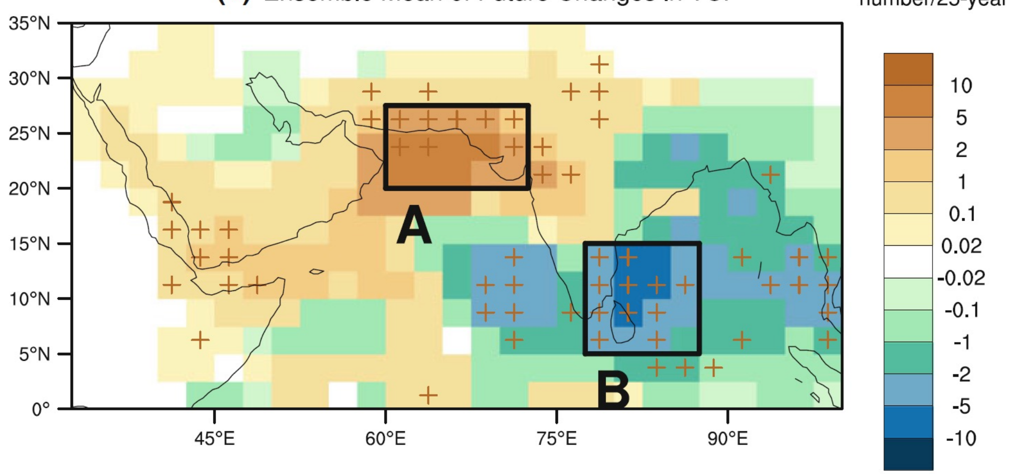
Projected future changes in large-scale parameters in the Central Pacific



All variables show significant and robust future changes
that are more favorable for TC activity in the subtropical central Pacific.

Murakami et al. (2013, *Nat. Clim. Change*)

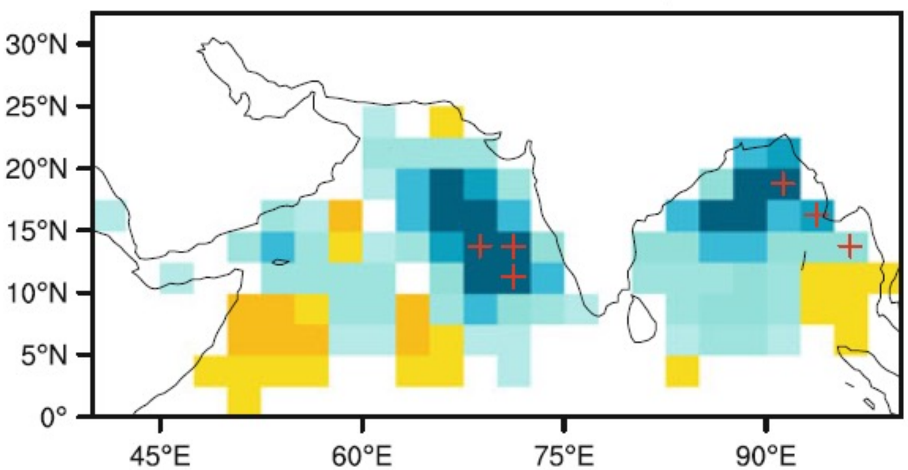
Projected increases in TCs in the Arabian Sea



Climate models commonly project Increased TCs over the Arabian Sea, specifically during post-monsoon season.

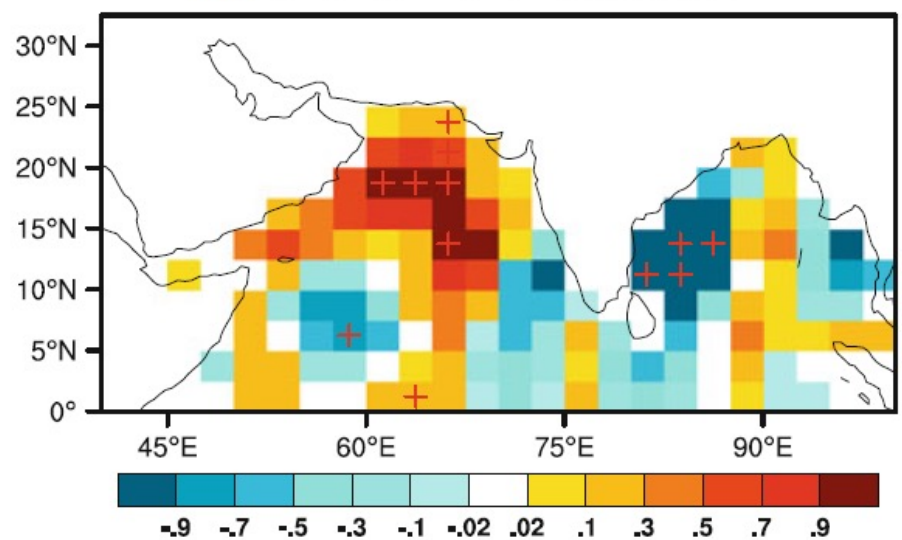
Pre-Monsoon (Apr-May)

(a) δTGF [AM, 10^{-2} number yr^{-1}]



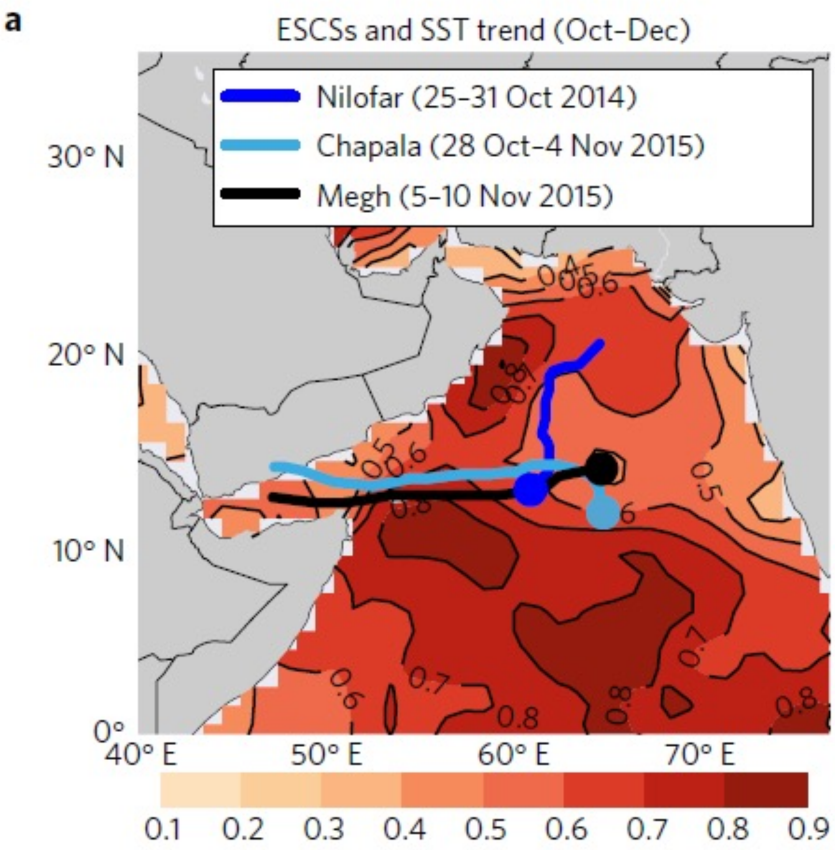
Post-Monsoon (Oct-Dec)

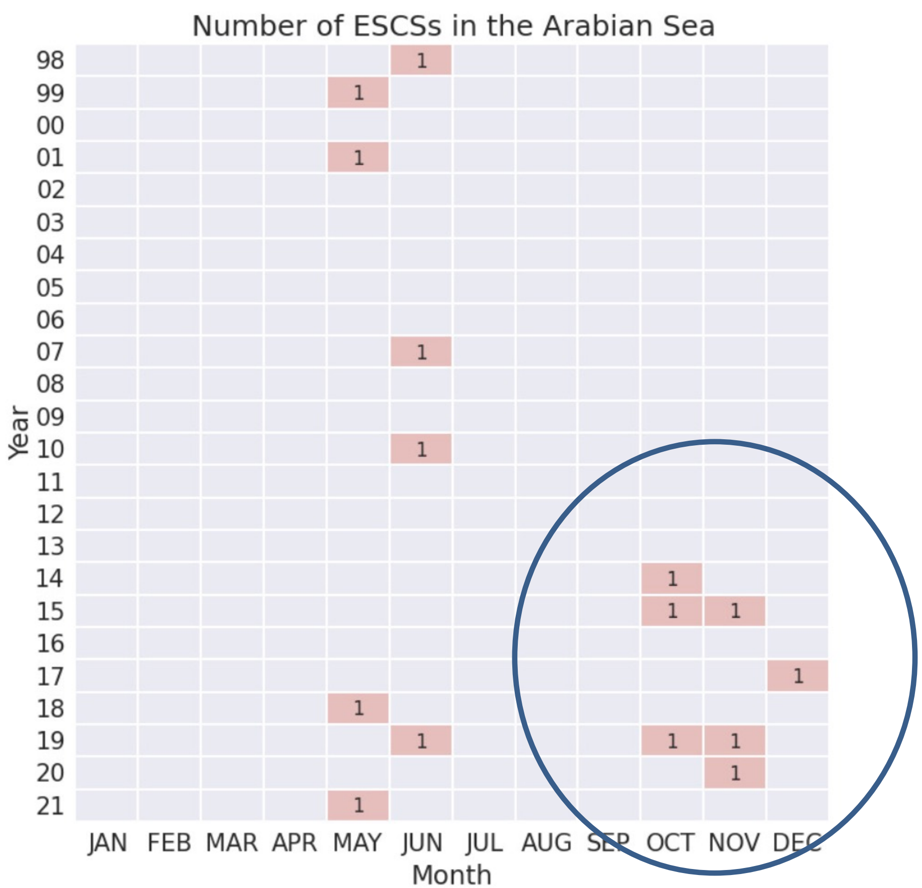
(c) δTGF [OND, 10^{-2} number yr^{-1}]



Murakami et al. (2014 Clim. Dyn., 2017 Nat. Clim. Change)

Projected increases in TCs in the Arabian Sea

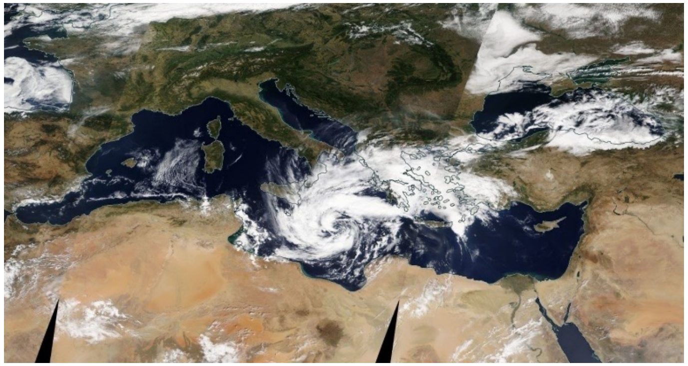




Arabian Sea experiences increasing frequency of intense storms as the climate models project for the future.

Murakami et al. (2017, *Nature Climate Change*)

Projected changes in Medicanes



<u>Medicane (Mediterranean TC-like Cyclone)</u>

- Hybrid and shallow warm-core with extratropical cyclones developed in the Mediterranean Sea
- Tropical cyclone transition sometimes occurs
- One or two storms a year
- A few hundred kilometers in size (smaller than a TC)
- Induces serious societal and ecological threats

- A decrease in frequency but an increase in intensity

  Tous et al. (2016), Romera et al (2017), Romero and Emanuel (2017), Gonzalez-Alman et al. (2019)

- Increased rainfall associated with medicanes

  Gonzalez-Alman et al. (2019), Gutierrez-Fernandez et al. (2021)

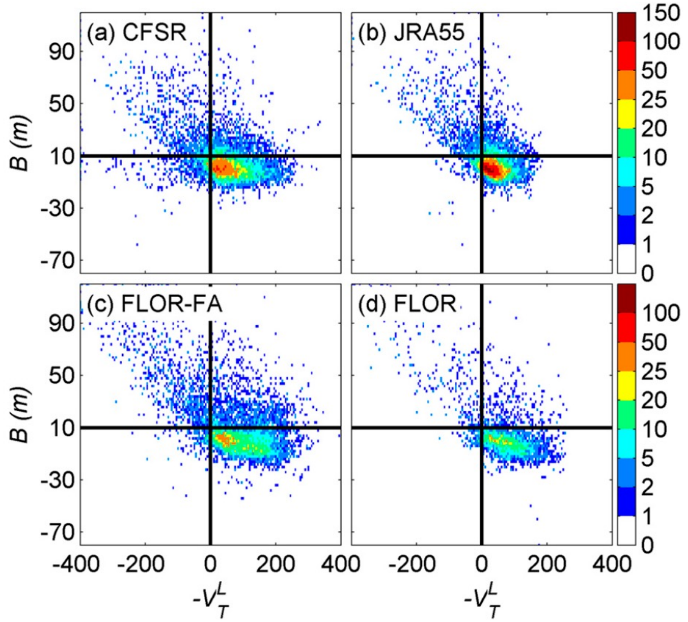
- Changes in SST and atmospheric stability would be important for future changes in medicanes

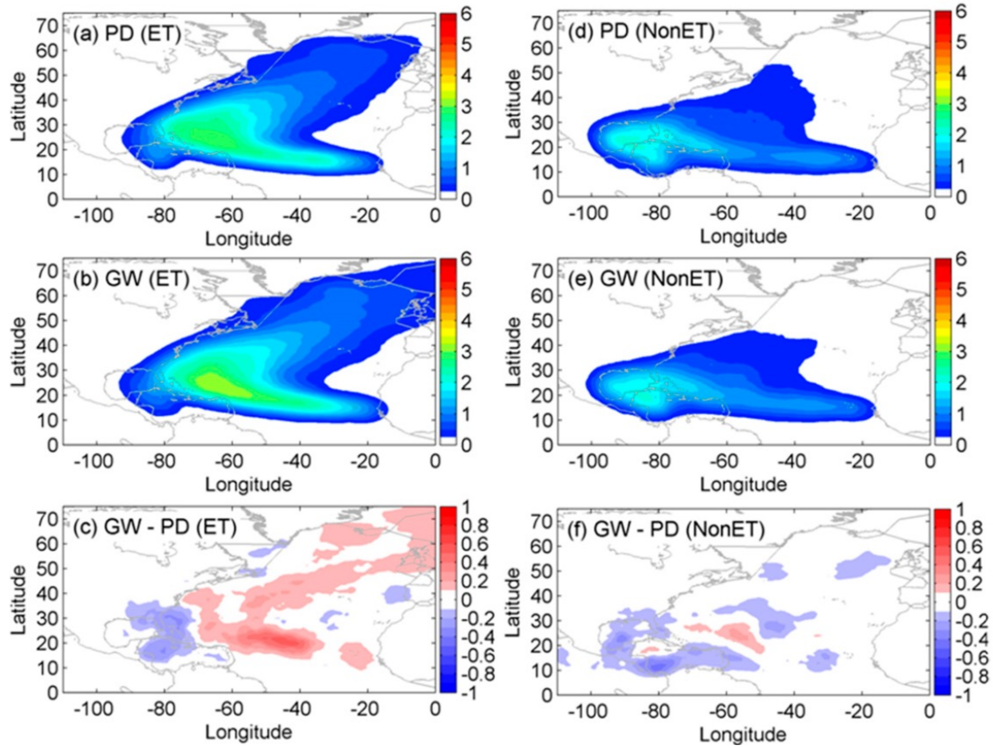
  Koseki et al. (2021)

Remained Issue:

- Limited availability of reliable historical records of medicanes
- The subjective identification of medicanes
- Less attention paid by the TC climate modeling society

Projected changes in Extra-tropical transition storms





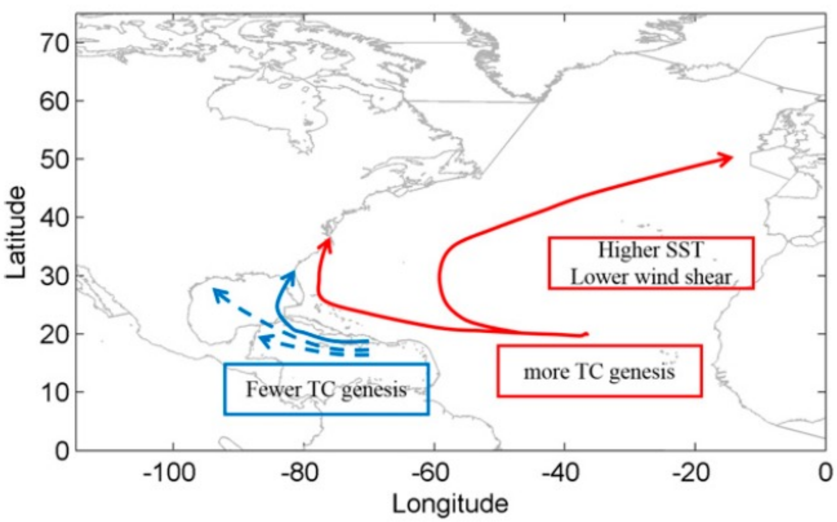


FIG. 17. The schematic map of regional TC density change. The red (blue) arrow denotes increase (decrease) of TC density for typical tracks. The ET (non-ET) event is in solid (dashed) line.

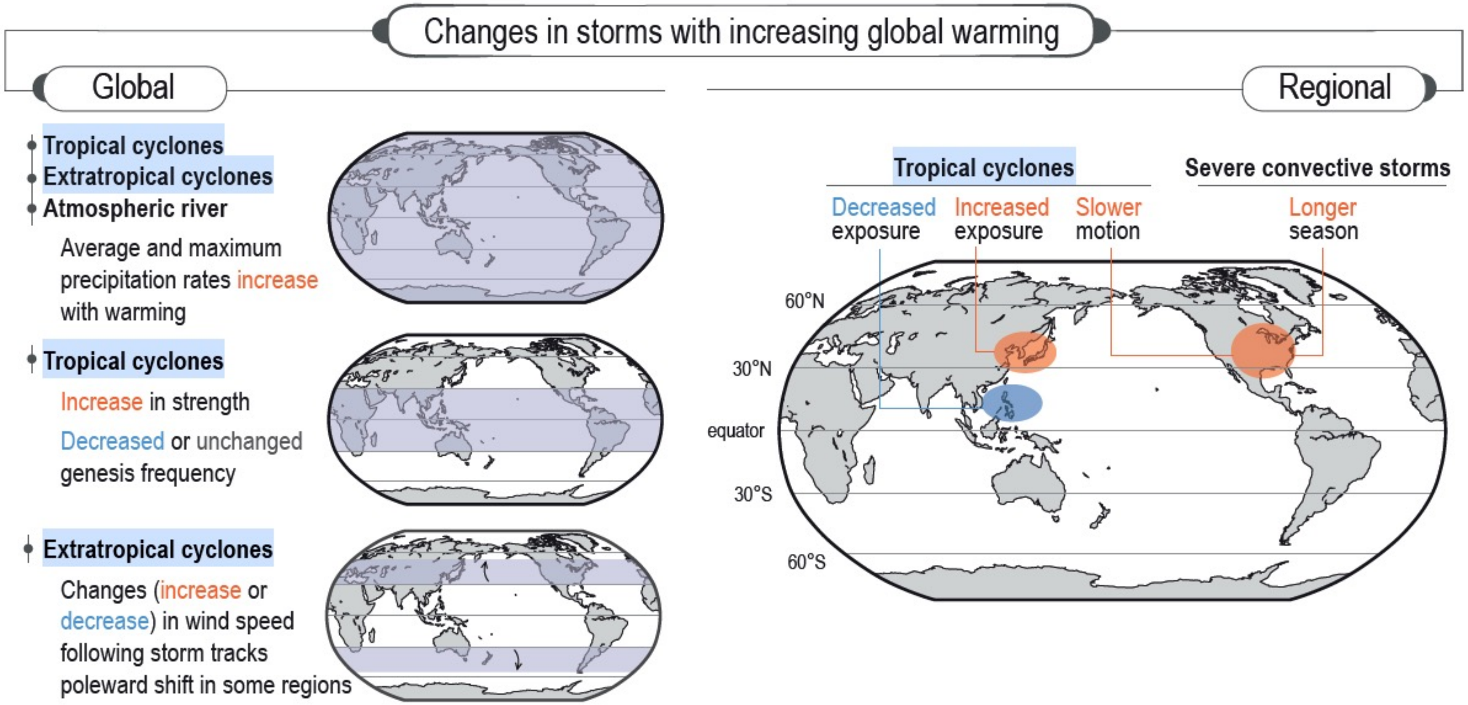
FLOR, FLOR-FA (50-km mesh coupled model)

The models show increased number of ET storms in the eastern Part of the North Atlantic at the end of this century under the RCP4.5 scenario.

Liu et al. (2017, *J. Climate*)

IPCC AR6

<u>2022</u> IPCC AR6



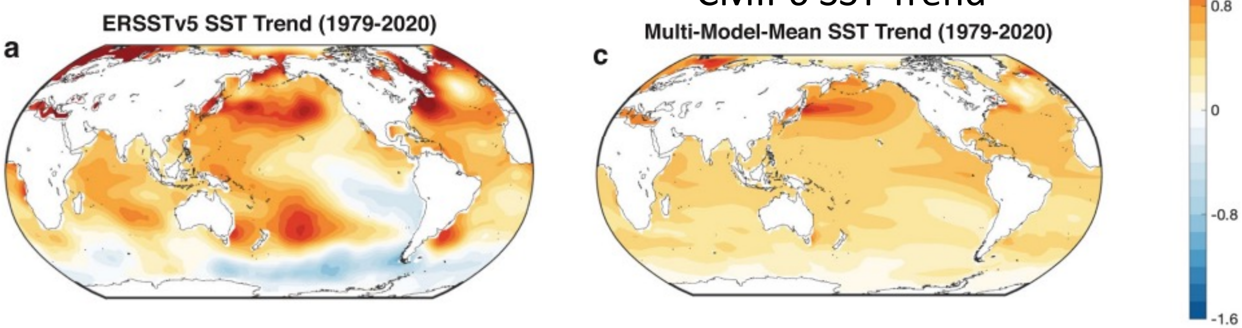
- Average peak TC wind speeds and the proportion of Category 4-5 TCs will *very likely* increase globally with warming.
- It is *likely* that the frequency of Category 4-5 TCs will increase in limited regions over the western North Pacific.
- It is *very likely* that average TC rain rates will increase with warming and *likely* that the peak rain rates will increase at rate greater than the Clausius-Clapeyron scaling rate of 7% per 1°C of warming in some regions due to increased low-level moisture convergence caused by regional increases in TC wind intensity.
- It is *likely* that the average location where TCs reach their peak wind intensity will migrate poleward in the WNP as the tropics expand with warming.
- The global frequency of TCs over all categories will decrease or remain unchanged.

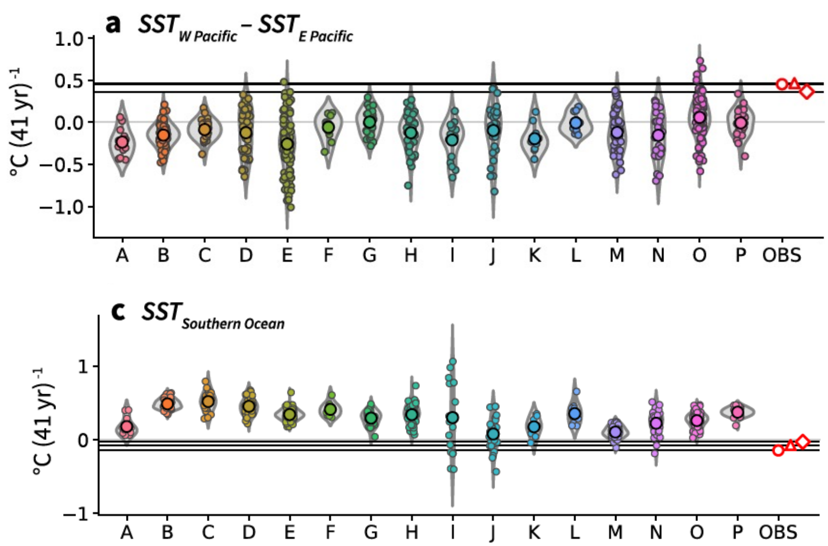
Inconsistent historical trends in simulated SSTs by dynamical models relative to observations (1979-2020)

- Marked model biases in the historical SST trend
- Exaggerated Pacific warming and extreme El Nino in the future (Tang et al. 2021)
- ENSO characteristics may change in the future (e.g., teleconnection) (Cai et al. 2020)

Observed SST Trend

CMIP6 SST Trend





A: ACCESS-ESM1.5
B: CanESM2
C: CanESM5
D: CESM1
E: CESM2
F: CNRM-CM6.1
G: CSIRO-Mk3.6
H: EC-Earth3
I: GFDL-CM3
J: GFDL-ESM2M
K: GISS-E2.1-G
L: IPSL-CM6A-LR
M: MIROC6
N: MIROC-ES2L
O: MPI-ESM
P: NorCPM1

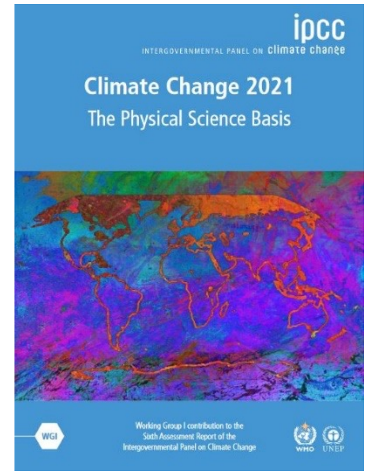
Wills et al. (2022, *GRL*)

A short summary

- TC intensity and TC precipitation are likely projected to increase in the future.
- The total number of TCs is of great uncertainty even at a global scale.

1990

2022



Almost no difference

- Projected change in regional TC activity is also uncertain because of different model results.
- Observations are unreliable for analyzing long-term trends, inhibiting scientists from identifying the effect of anthropogenic climate change.
- We are still beginning a new era for tropical cyclone future projections. New works using high-resolution climate models, long-term observations, and theories are desired to shed further light on the uncertainties in the future projections of TCs.

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