Tropical cyclone climate projections by a 20-km-mesh high-resolution MRI/JMA global atmospheric model

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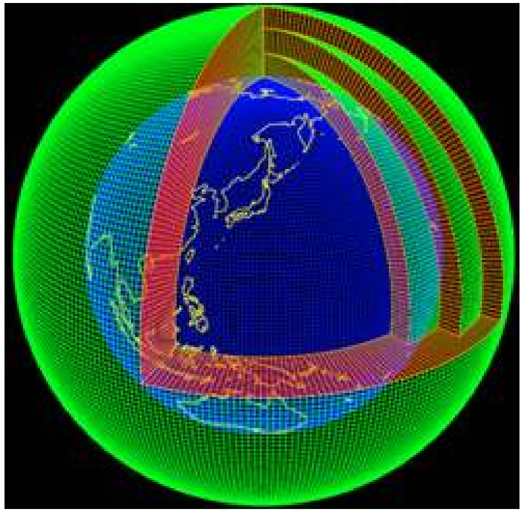
Hiroyuki Murakami (JAMSTEC/MRI)

Japan Agency for Marine-Earth Science and Technology (JAMSTEC), and
Meteorological Research Institute

Outline

- Review of previous studies on projected future changes in tropical cyclones (TCs)
- KAKUSHIN program conducted by MRI
- Projected future changes in TC activities in the western North Pacific (WNP) using the 20-km mesh MRI-AGCM.
- Up-to-date results.
- Summary



20 km-mesh grids

Review on impact of global warming on TC activities

▪ Global models (CGCMs or AGCMs)

Broccoli and Manabe, 1990; Haarsma et al., 1993; Bengtsson et al., 1996; Krishnamurti et al., 1998; Royer et al., 1998; Sugi et al., 2002; Tsutsui, 2002; McDonaldet al., 2005; Chauvin et al., 2006; Oouchi et al., 2006; Yoshimura et al., 2006; Bengtsson et al., 2007; Gualdi et al., 2008; Zhao et al., 2009

▪ Regional models

Knutson et al., 1998; Knutson and Tuleya, 1999; Nguyen and Walsh, 2001; Knutson and Tuleya, 2004; Walsh et al., 2004; Stowasser et al., 2007; Knutson et al., 2008; Bender et al., 2010

etc.

1. **Consistent results** (consensus)
   - A reduced frequency of TCs globally
   - A future increase of intense TCs

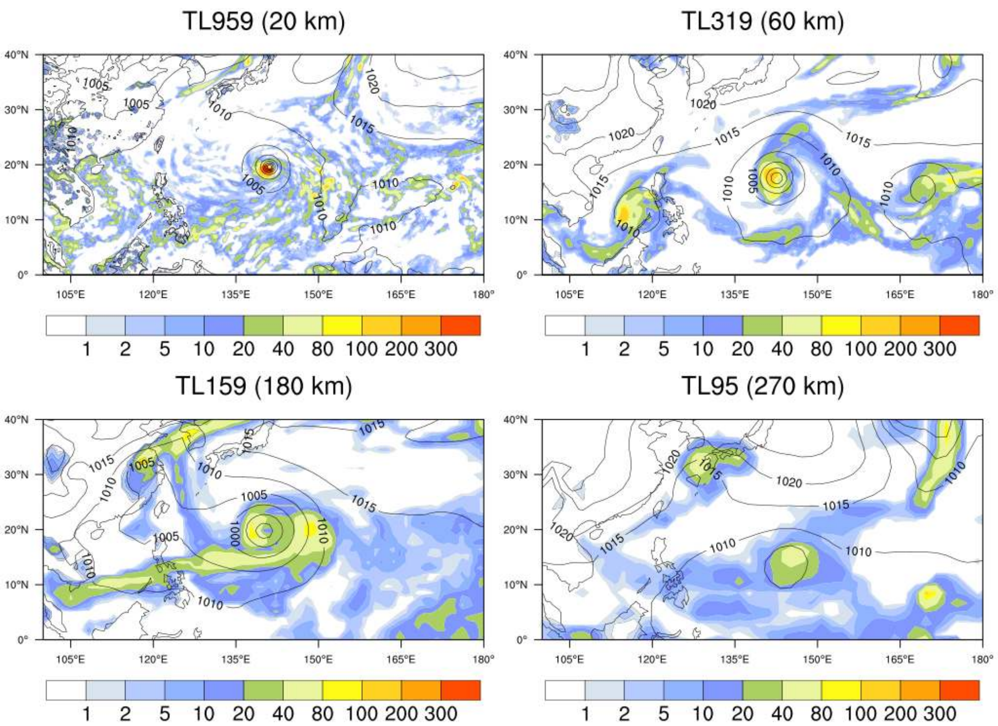
2. **Inconsistent results** (uncertainty)
   - Difference in projected future changes in TC frequency in a specific ocean basin

     Among 14 previous numerical studies, 5 indicated an increase in the NA, while 9 reported a decreasing frequency (Murakami and Wang, 2010)

3. **Not investigated** (unknown)
   - Effect of global warming on TC activities in a specific ocean basin

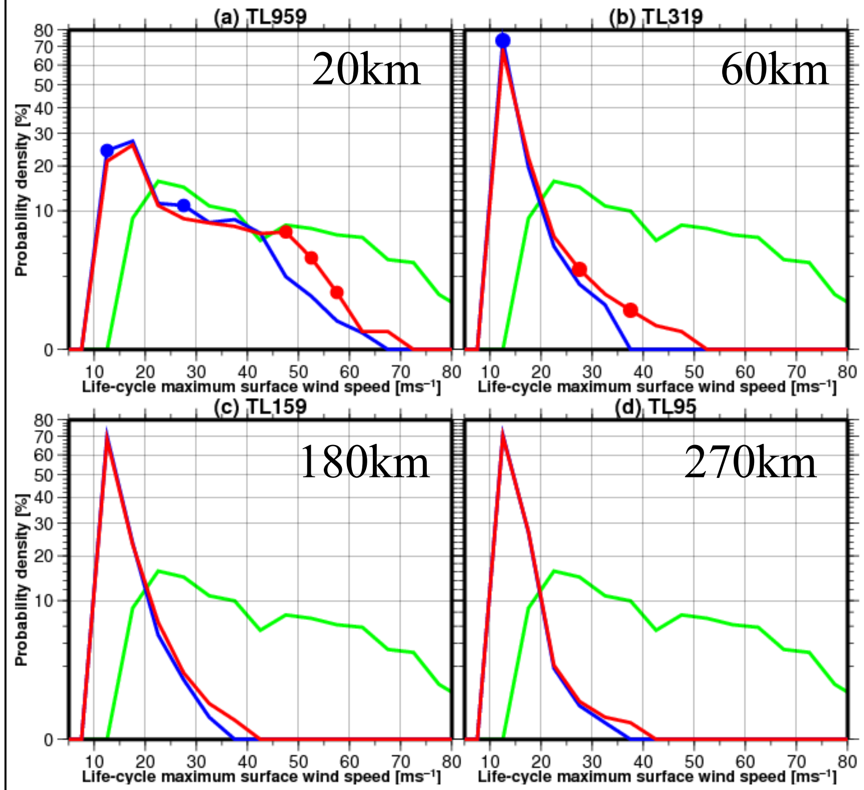
Why do we need a high resolution model?

·Projections by previous climate models are not reliable because the models are too coarse to resolve TC structures.



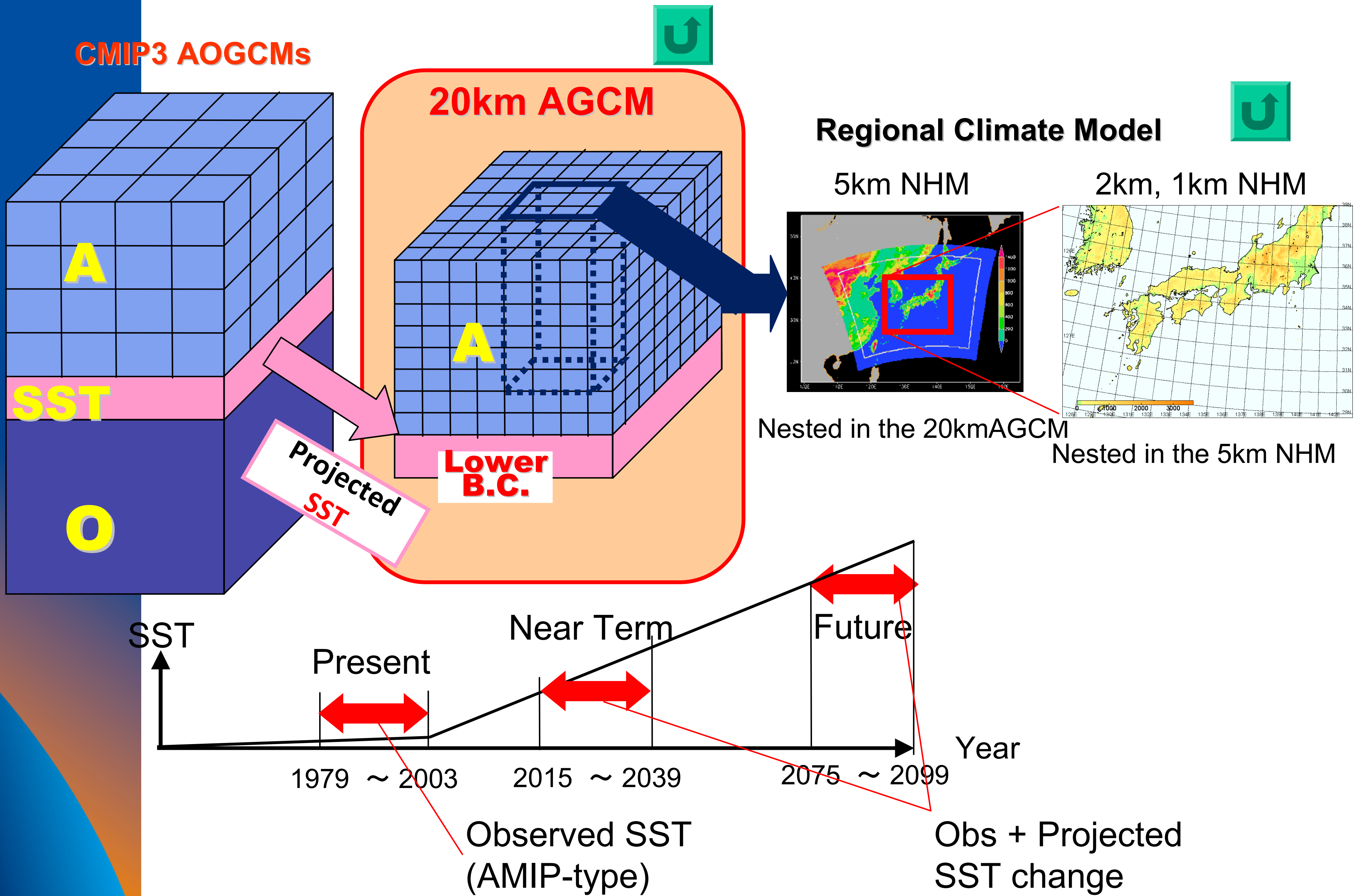
<u>High resolution model yields realistic TC structure.</u>

·Only models finer than 60 km-mesh show future increase in intense TCs (Murakami and Sugi, 2010).

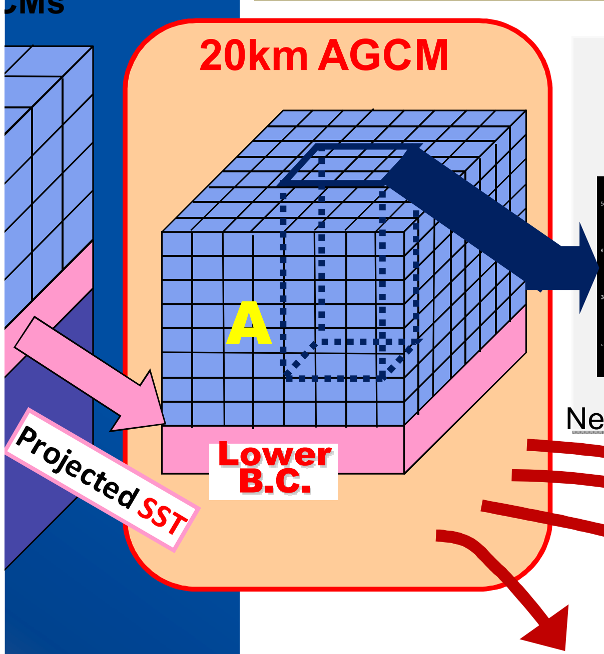


Observations (1979-2003)
Present 25year (1979-2003)
Future 25year (2075-2099)
: significant increase at 95% level
: significant decrease at 95% level

KAKUSHIN Program (2007 – 2012) conducted by MRI



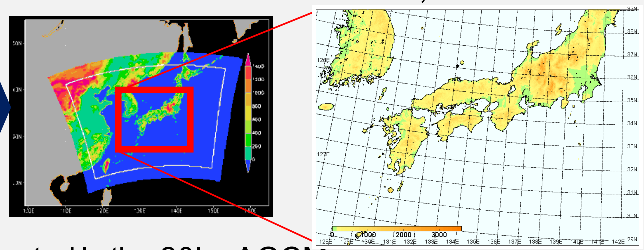
KAKUSHIN Program (2007 – 2012) conducted by MRI



Regional Climate Model

5km NHM

2km, 1km NHM



Nested in the 20kmAGCM

Nested in the 5km NHM

Detailed Projection around Japan

Impact Assessments

– Disasters
– Agriculture
– Water Resources

Regional Climate Change

– Outputs provided to researchers of each region (Korea, China, Taiwan, Philippines, Thailand, Indonesia, Viet Nam, Bangladesh, India, Israel, Saudi Arabia, Senegal, Spain, Netherland, UK, Ireland, Denmark, Switzerland, Germany, USA, Mexico, Columbia, Barbados, Belize, Bolivia, Peru, Ecuador, Brazil, Argentina, Australia, Papua New Guinea)

Study of Future Change in Extreme Events

Tropical Cyclones (e.g.Murakami et al. 2011)
→less number, more intense
East Asia Monsoon (e.g.Kusunoki et al.2011)
→seasonal migration delayed
Extreme Rainfall (e.g.Kamiguchi et al. 2006)
→more frequent
Blockings (e.g.Matsueda et al. 2009)
→less frequent
Extratropical Cyclones

MRI-AGCM

	Previous version (contributed to IPCC AR4)	New version (for IPCC AR5)
	MRI-AGCM 3.1 (Mizuta et al. 2006, *JMSJ*)	MRI-AGCM 3.2 (Mizuta et al., 2011, submitted)
Horizontal resolution	TL959 (20km)	
Vertical resolution	60 levels (top at 0.1hPa)	64 levels (top at 0.01hPa)
Time integration	Semi-Lagrangian	
Time step	6minutes	10minutes
Cumulus convection	Prognostic Arakara-Schubert	Yoshimura (Tiedtke-based)
Cloud	Smith (1990)	Tiedtke (1993)
Radiation	Shibata and Aoki (1989) Shibata and Uchiyama(1992)	JMA (2007)
GWD	Iwasaki et al. (1989)	
Land surface	SiB ver0109(Hirai et al.2007)	
Boundary layer	MellorYamada Level2	
Aerosol (direct)	Sulfate aerosol	5 species
Aerosol (indirect)	No	

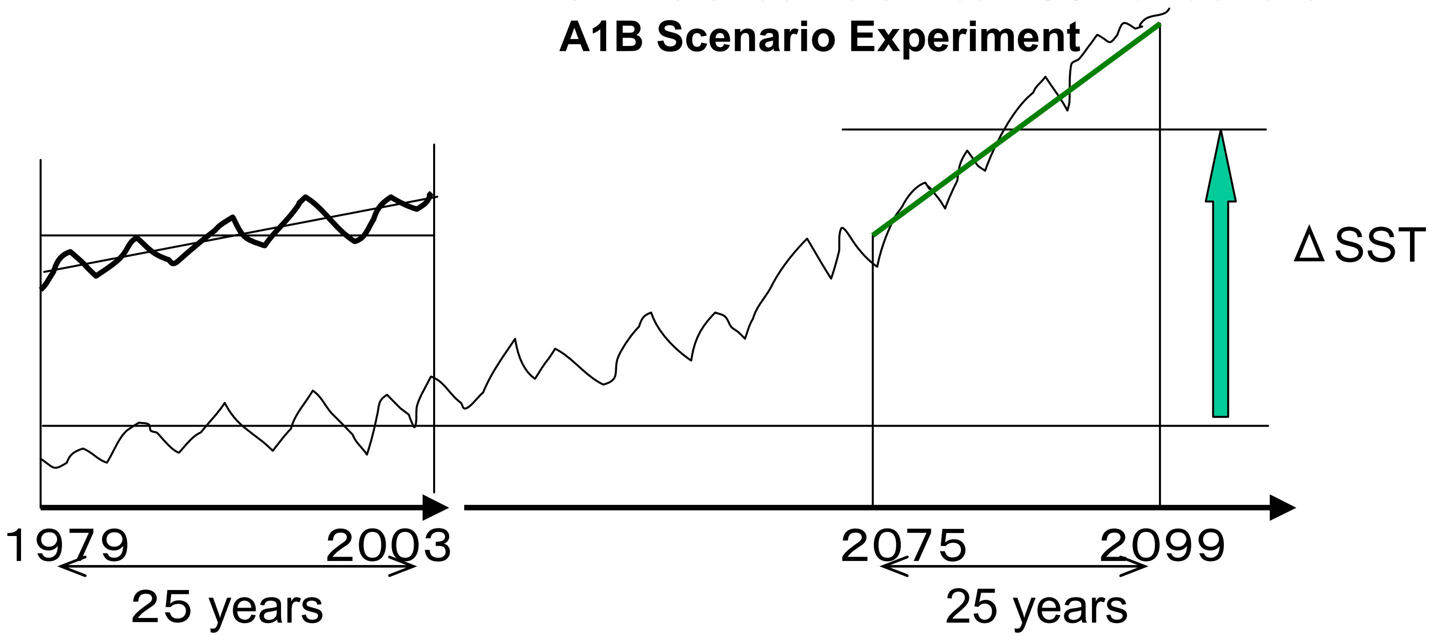
How to prescribe SST

Mizuta et.al (2008)

Present SST

Observed SST
1979～2003

AR4_20thCentury
Exp. SST -2001



also applies for 2015-2039

Future SST

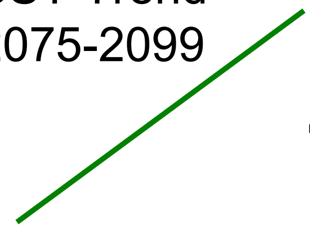
CMIP3 SST change

Δ SST

Mean SST(2075-2099) – Mean SST(1979-2003)

+

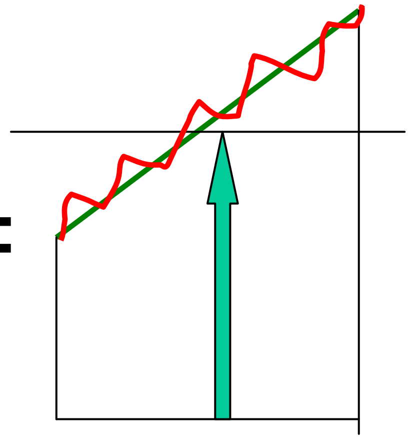
CMIP3
SST Trend
2075-2099



+

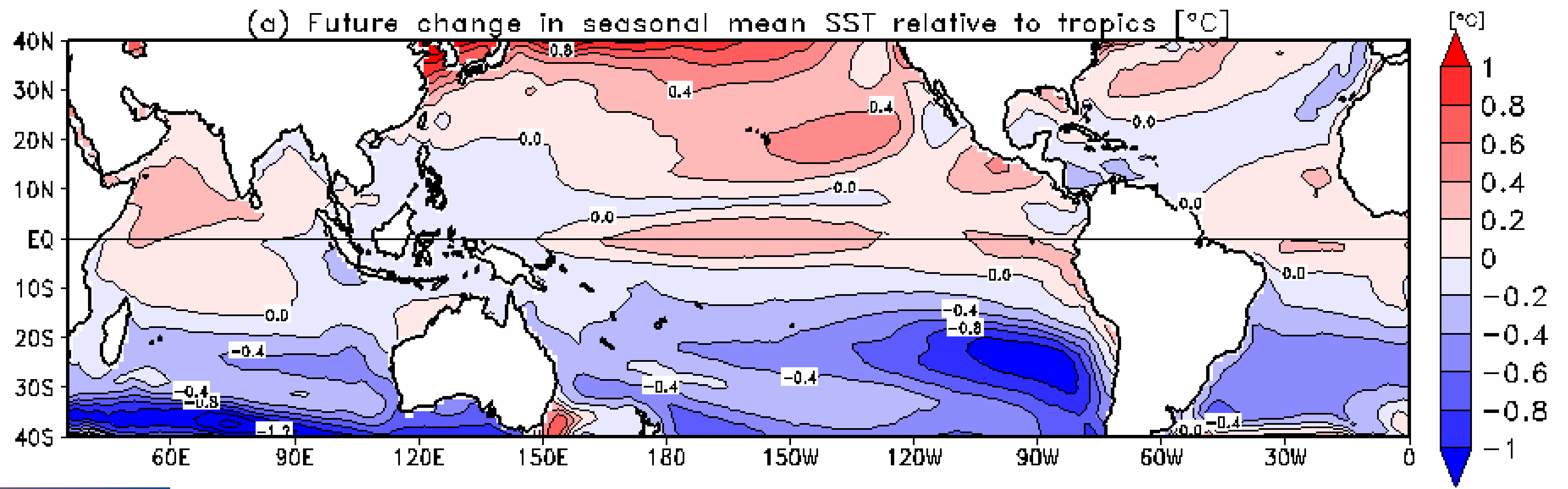
Inter-annual variability
of Observed SST
1979-2003

=



Spatial pattern of prescribed future changes in SST

21st (2075-2099) – Present (1979-2003)



- Relatively larger increase in SST in the Northern Hemisphere than in the Southern Hemisphere.
- The SST increase is the largest in the tropical Central Pacific.

Future change of western North Pacific typhoons: Projections by a 20-km-mesh global atmospheric model

Reference:

Murakami, H, B. Wang, and A. Kitoh, 2011:Future change of Western North Pacific typhoons: Projections by a 20-km-mesh Global atmospheric model., *J. Climate*, **24**,1154-1169.

TC detection criteria

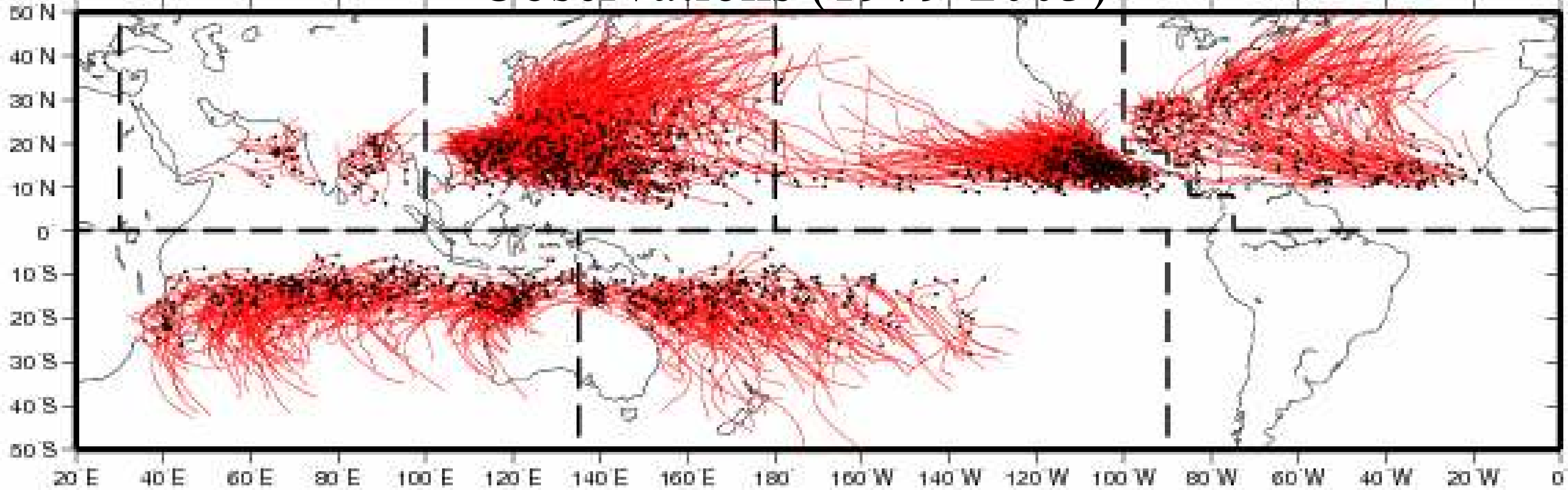
Simulated TCs are detected using 6-hourly data by following 6 criteria.

- Sea level pressure = 2.0 hPa lower than the surroundings area.
- 850 hPa Relative volticity = 3.0×10^{-5} /s
- 850 hPa Maximum wind speed = 10.0 m/s
- Warm Core: 1.0 K
- Duration =36 hours
- Maximum wind speed at 850 hPa should be greater than the 300 hPa (to exclude extra-tropical cyclones).

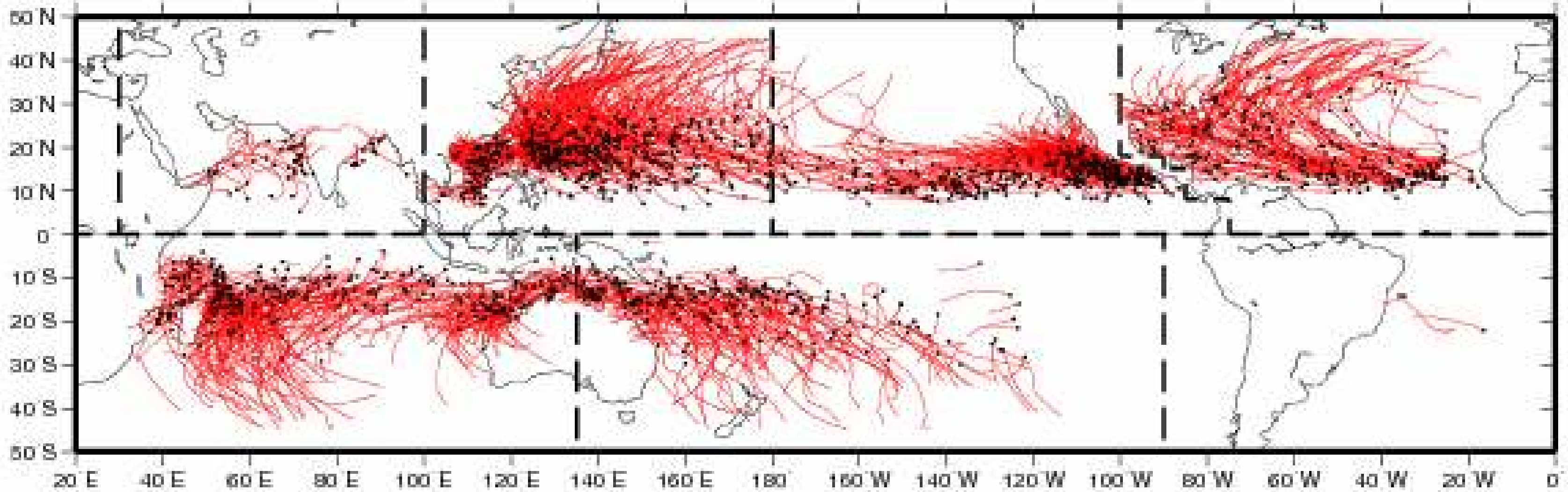
Based on Oouchi et al. (2006)

Simulated TC trakcs

Observations (1979-2003)



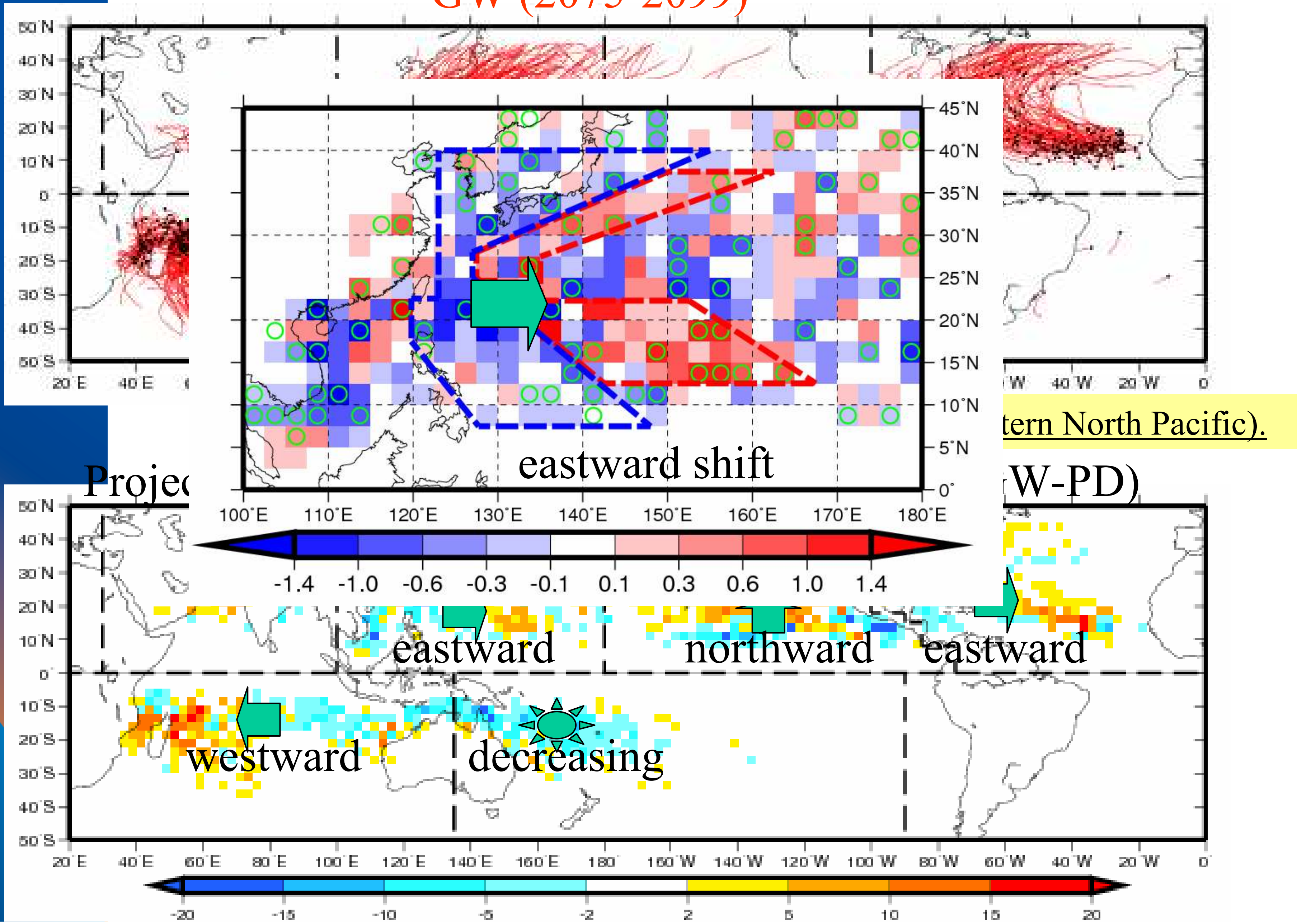
PD (1979-2003)



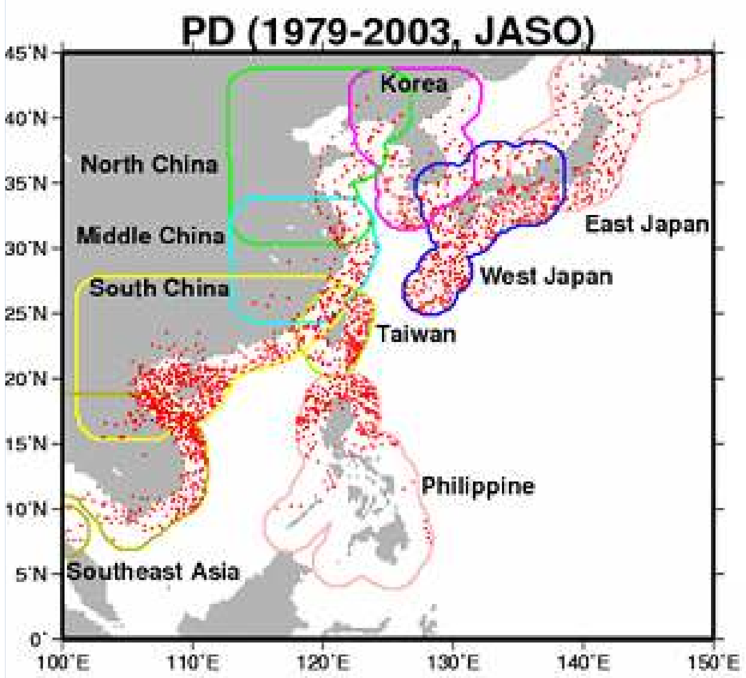
TC tracks are well simulated by the PD experiment.

Projected future changes in the TC tracks

GW (2075-2099)



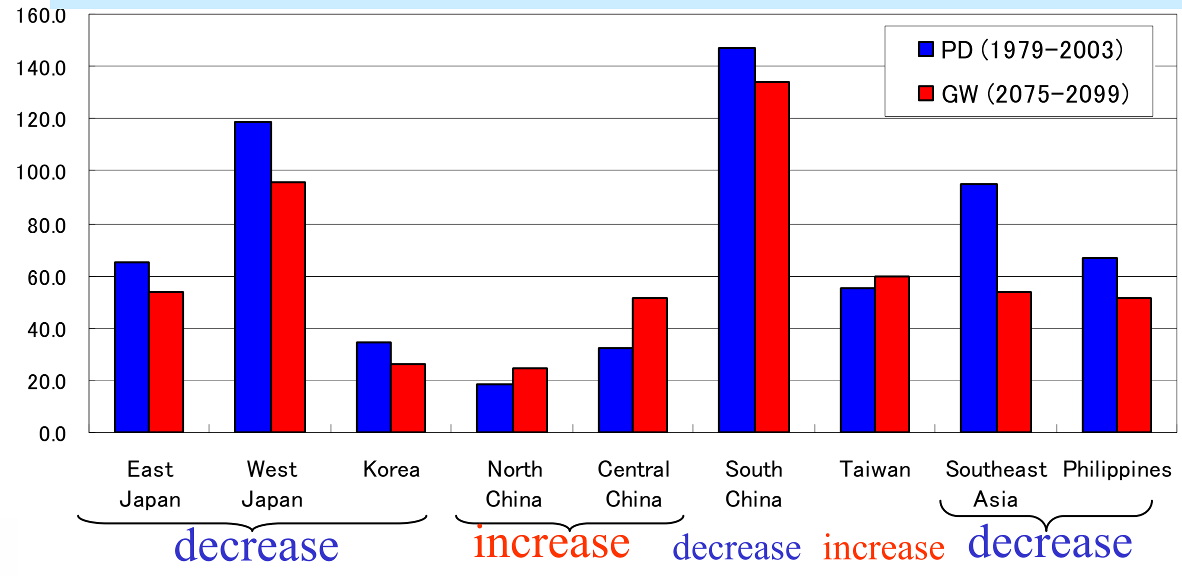
Future change in "Landing" tropical cyclones



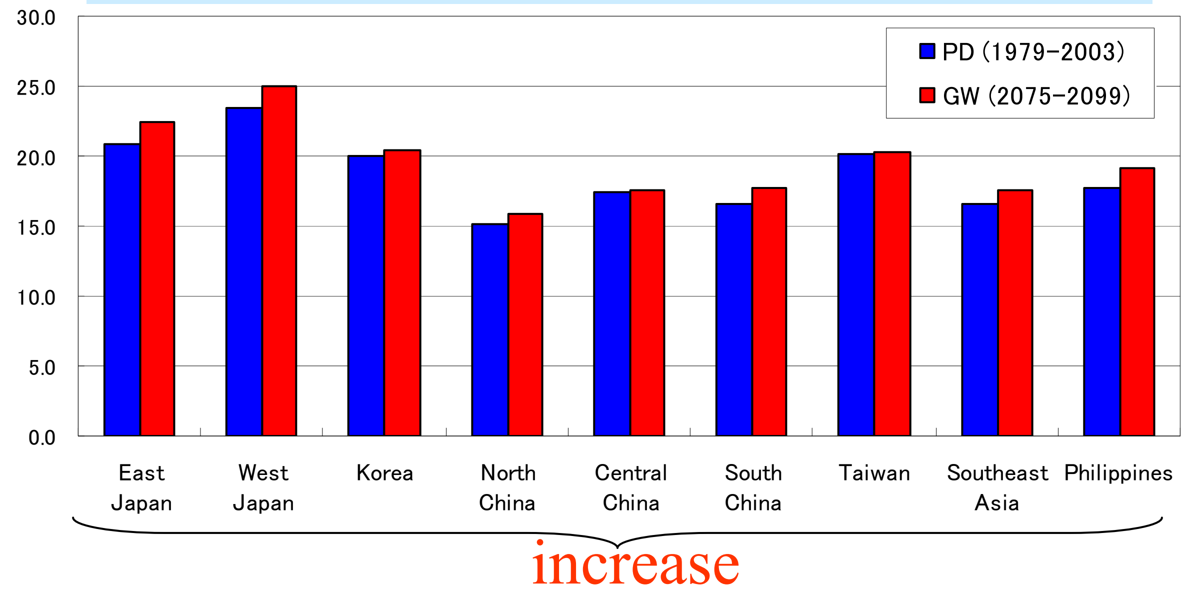
The frequency of tropical cyclones approaching Japan and Korea may decrease in the future.

However, once a TC approaches the coast lines, mean of maximum wind velocity is larger than the present climate, leading to a catastrophic damage in the future.

(a) July-October mean of TC frequency near coasts

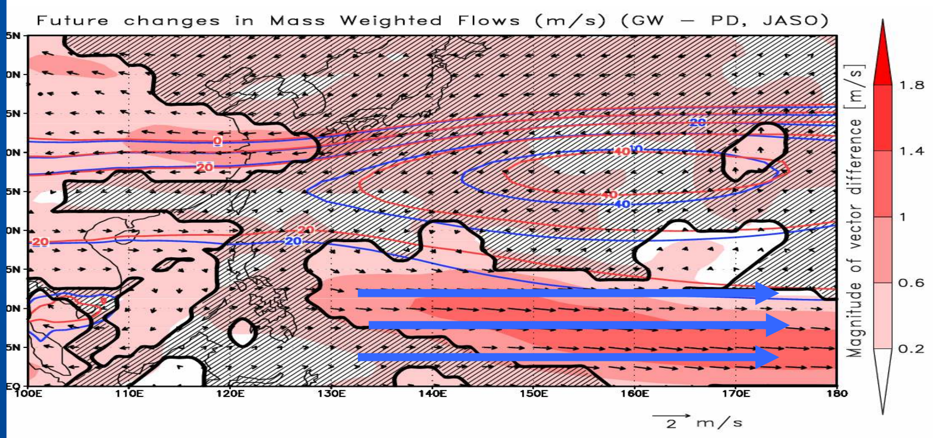


(b) Mean maximum wind velocity of TCs near coasts



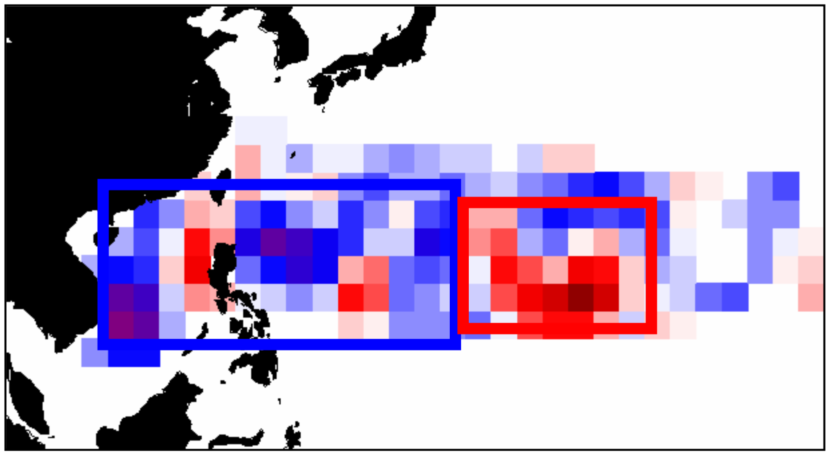
What causes TC track changes?

Steering flow (850-300hPa) changes



Steering flow changes (westerly flow anomaly) **partly** explain TC track changes by inhibiting westward TC motion.

TC genesis frequency changes



TC genesis location changes (eastward shift) **mainly** explain TC track changes.

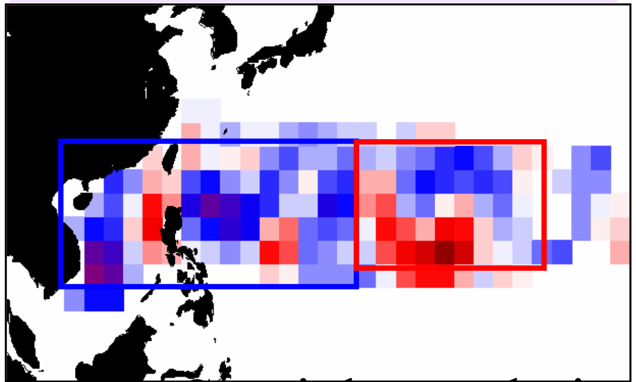
Genesis Potential Index (GPI)

To determine the factors behind such genesis changes, we used a Genesis Potential Index (GPI) by Emanuel and Nolan (2004) with some modifications.

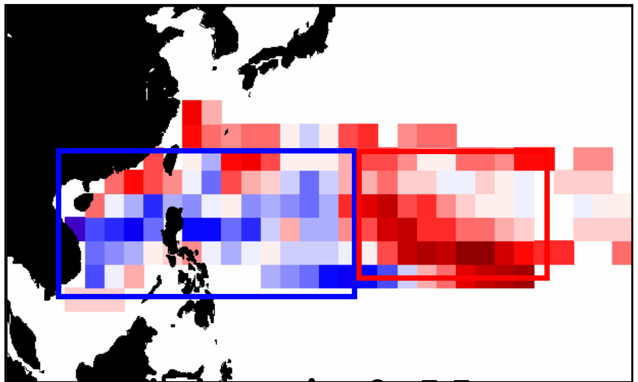
$$GPI' = \left|10^5 \eta\right|^{\frac{3}{2}} \left(\frac{RH}{50}\right)^3 \left(\frac{V_{pt}}{70}\right)^3 \left(1 + 0.1V_s\right)^{-2} \left(\frac{-\omega + 0.1}{0.1}\right),$$

Absolute Vorticity at 850hPa	Relative Humidity at 700hPa	Maximum Potential Intensity	Vertical Wind Shear (850-200hPa)	Vertical Wind Velocity at 500hPa

Future changes in TC genesis frequency



GPI changes

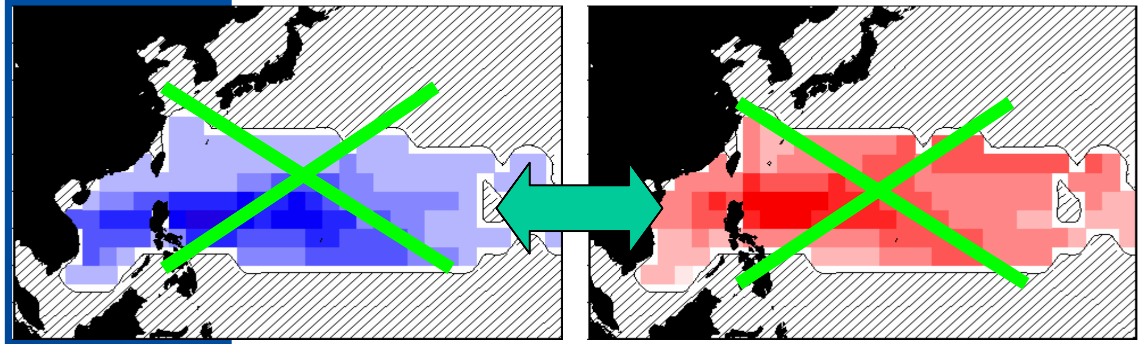


Spatial correlation coefficient is 0.55.

GPI performs reasonably well in reflecting the changes in TC genesis frequency.

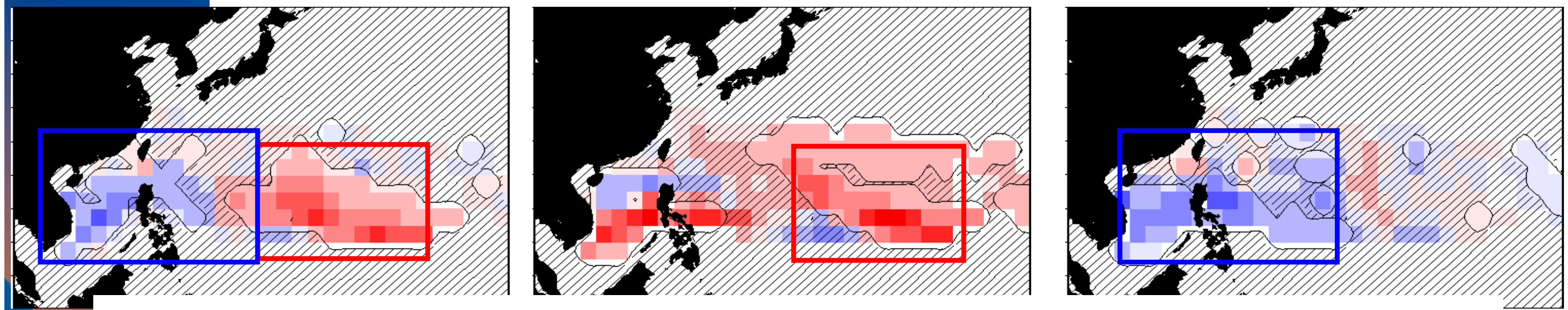
Each term contribution to the changes in GPI

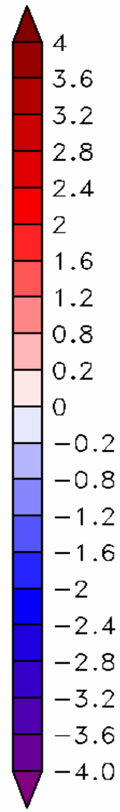
Relative humidity | **Potential Intensity**



1. **Thermodynamic changes has less influence.**
 =>Relative humidity and Potential intensity tend to cancel each other.

Vorticity | **Vertical Wind Shear** | **Vertical Wind Velocity**





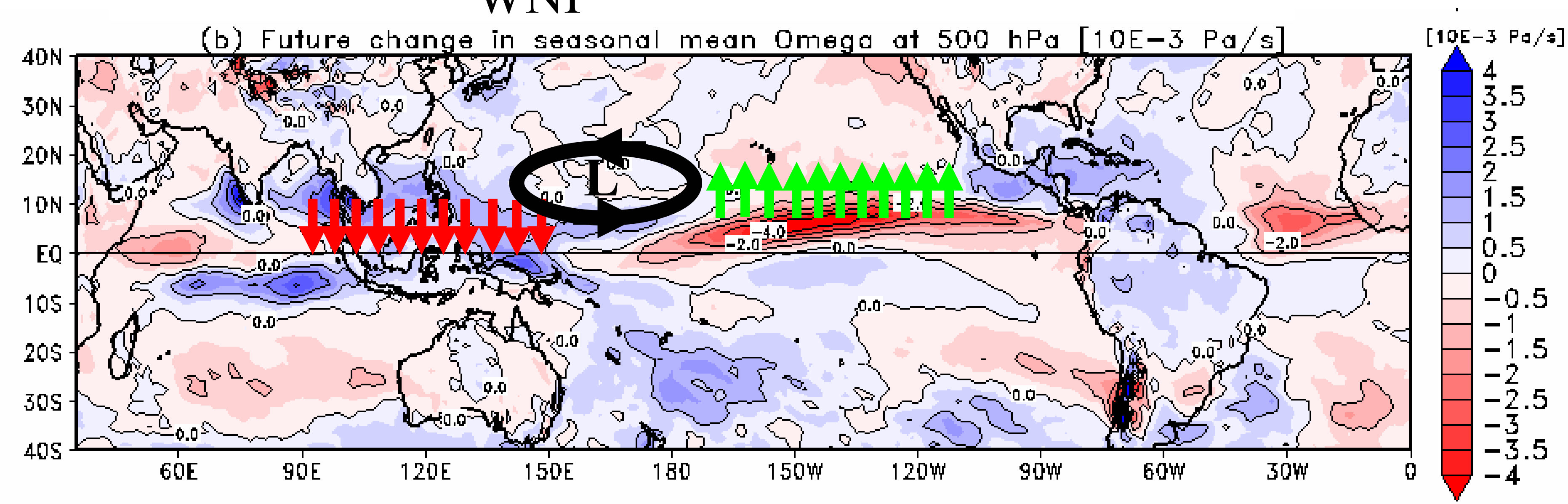
2. **Dynamical changes have great influences.**
 =>Vorticity and vertical wind shear contribute to the increase in GPI in the eastern WNP.
 =>Vorticity and vertical wind velocity contribute to the decrease in GPI in the western WNP.

Mechanisms of future changes in TC genesis

Future changes in vertical wind velocity at 500 hPa

Rossby wave response:
Positive vorticity => Increase in TC genesis in the eastern WNP

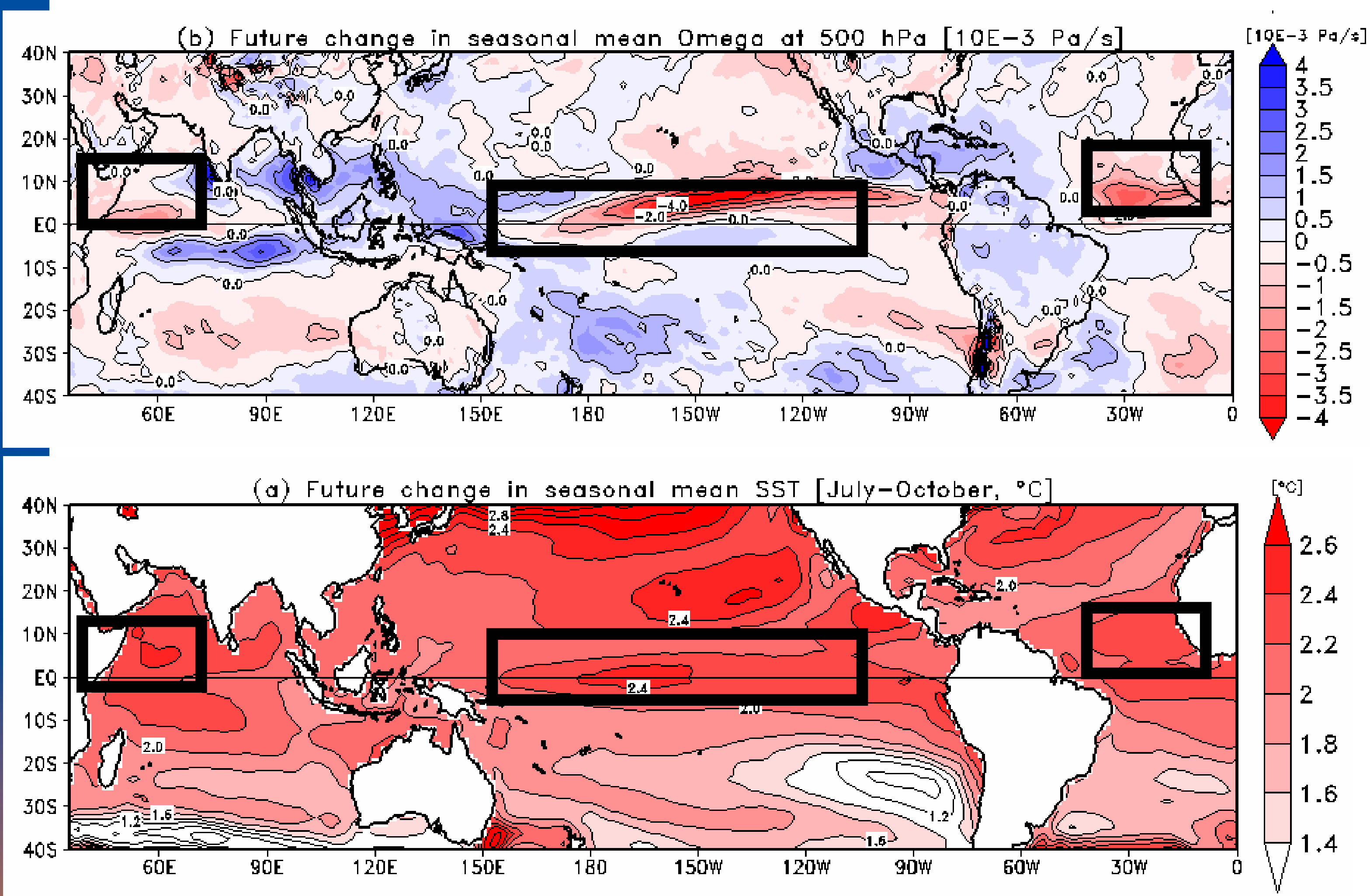
Downward anomaly



Weakening of the Walker circulation:
Decrease in upward motion => Decrease in TC genesis in the western WNP

Upward anomaly

Why is upward motion changes in the tropical central Pacific?



Future changes in vertical motions (top) appear to be strongly related to the prescribed SST anomaly (bottom), indicating that spatial distribution of tropical SST may be a key factor for TC activities.

Conclusion (I)

The projected TC activity change during the peak typhoon season (JASO) indicates:

(a) Positions of the prevailing northward recurving TC tracks will shift eastward over the open ocean of the WNP;

(b) TC track changes are partially due to changes of the large scale steering flows, but primarily owning to the changes in TC-genesis locations: TC formation will be less to the west of 140°E, whereas more in eastern WNP (0–17°N, 140–180°E)

(c) The decrease in the TC genesis frequency in the western WNP are mainly due to *in situ* reduction of the large scale ascent, which is caused by the enhanced descending branch of the zonal circulation (i.e., weakening of the Walker circulation).

(d) The enhanced TC genesis in the eastern WNP is due to the increased in situ low-level cyclonic vorticity, reduced vertical wind shear, caused by Rossby wave response induced by enhanced diabatic heating in the central tropical Pacific.

Preliminary results with the new 20-km mesh model

Murakami et al. (J. Climate, submitted)

MRI-AGCM

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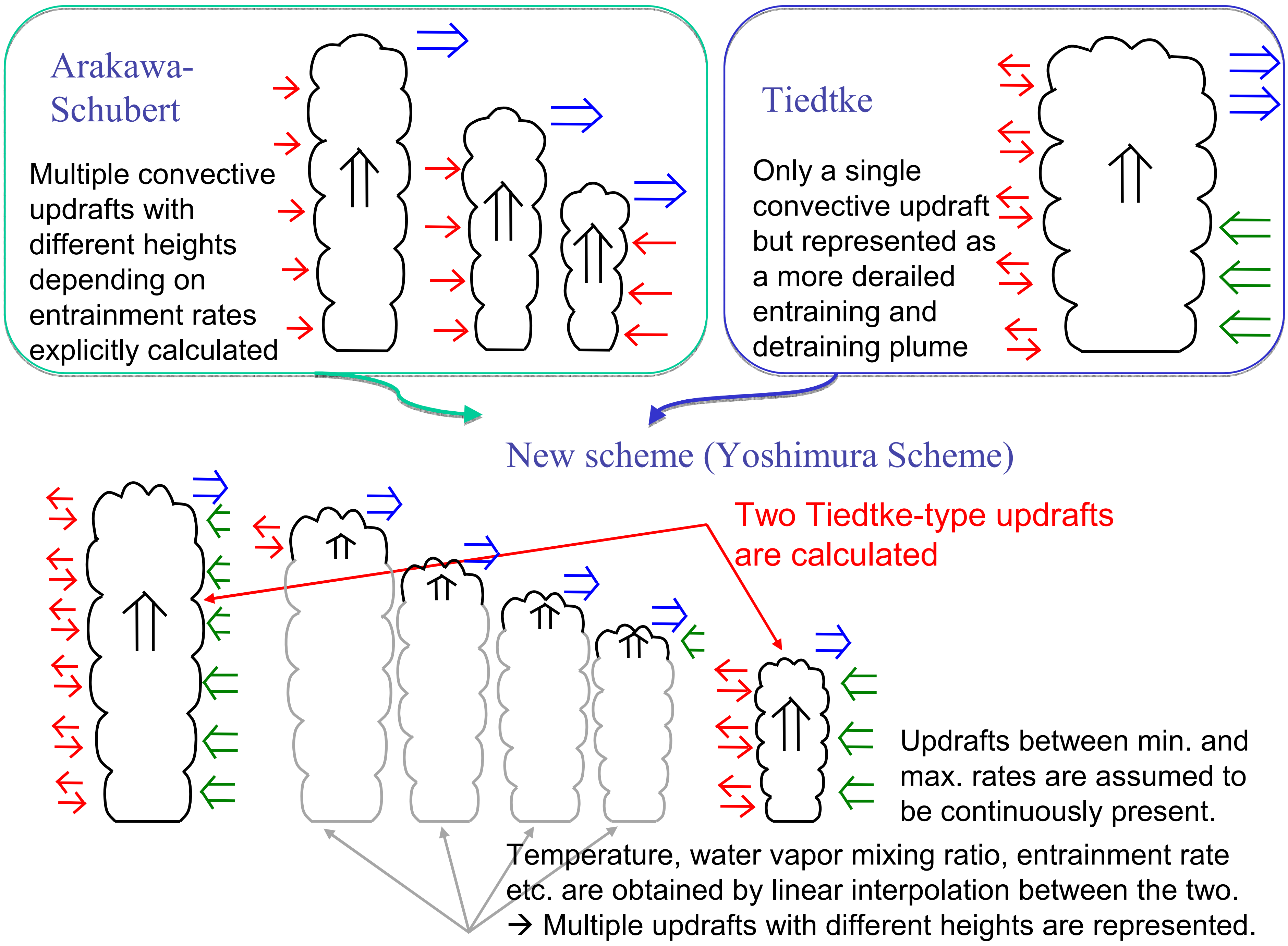
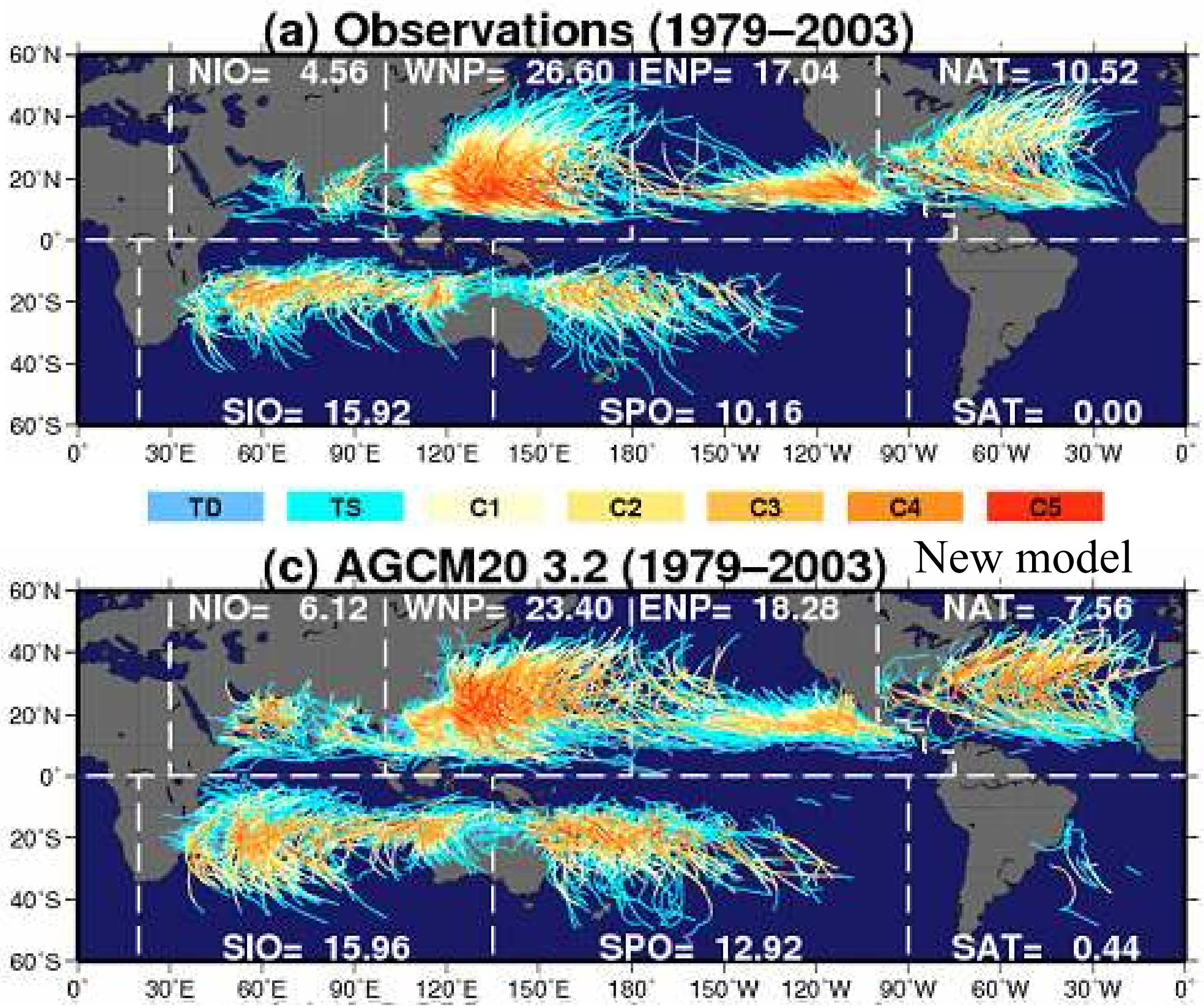
Land surface	SiB ver0109(Hirai et al.2007)	
Boundary layer	MellorYamada Level2	
Aerosol (direct)	Sulfate aerosol	5 species
Aerosol (indirect)	No	



Arakawa-Schubert
Multiple convective updrafts with different heights depending on entrainment rates explicitly calculated
Tiedtke
Only a single convective updraft but represented as a more derailed entraining and detraining plume
New scheme (Yoshimura Scheme)
Two Tiedtke-type updrafts are calculated
Updrafts between min. and max. rates are assumed to be continuously present.
Temperature, water vapor mixing ratio, entrainment rate etc. are obtained by linear interpolation between the two.
→ Multiple updrafts with different heights are represented.

Problems with the previous 20-km mesh MRI-AGCM



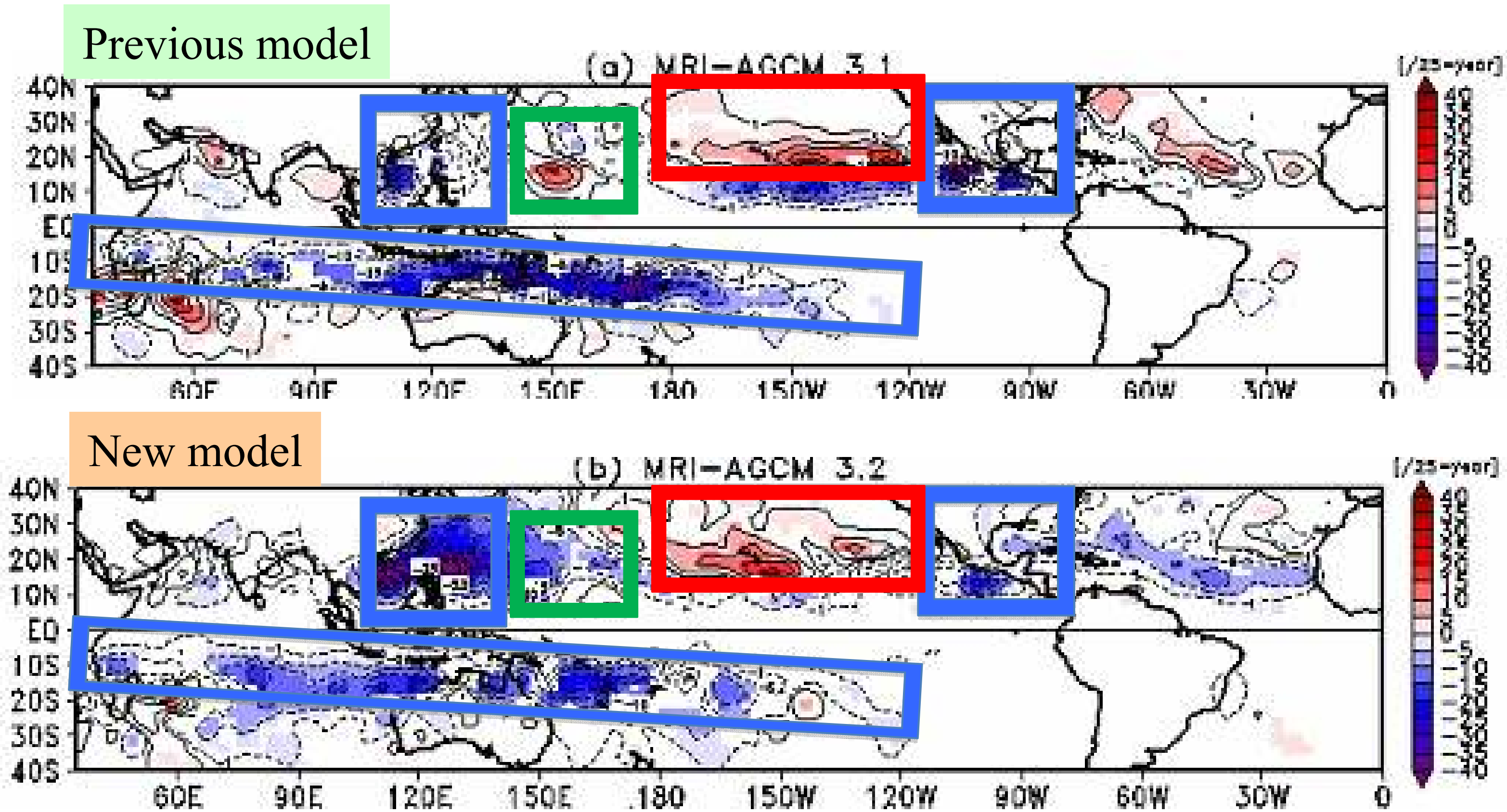
The number for each basin show the annual mean number of TCs.

·Predicted TC number in the WNP is underestimated. Improved

·TC intensity is weak compared with observations Improved

Murakami et al. (2011, submitted)

Comparison of projected future changes between models
– Frequency of TC occurrence –

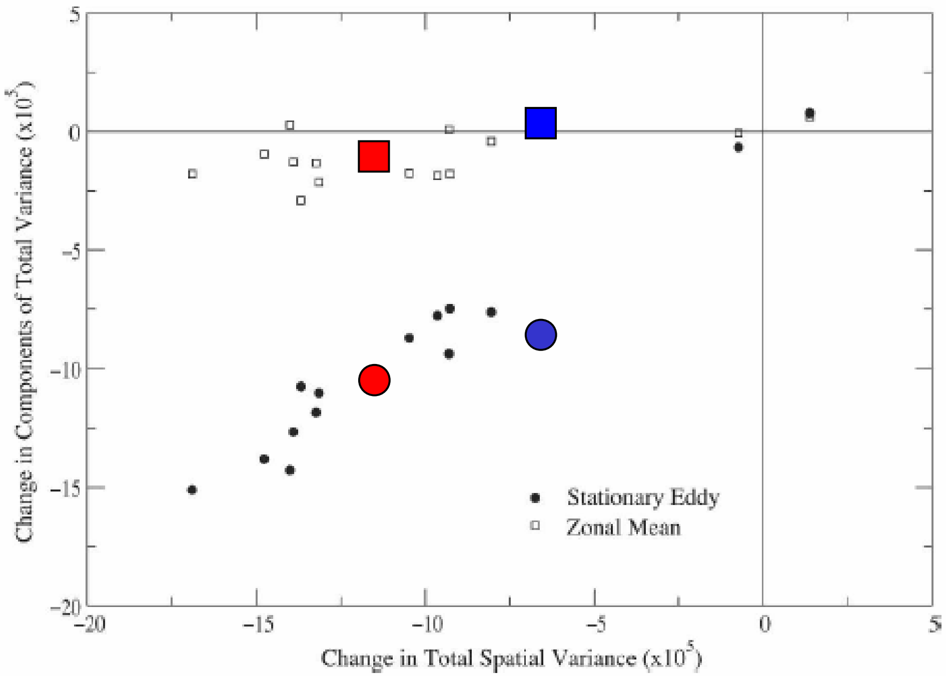


·Both models show significant decrease in TC frequency over the South Pacific and western portion of WNP.

·Both models show significant increase in TC frequency over the central Pacific.

·Inconsistent in the eastern quadrant of WNP

Weakening of Walker Circulation

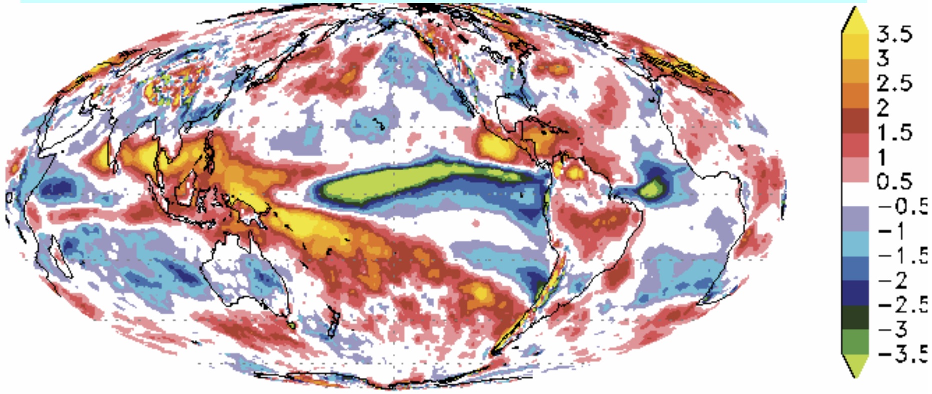


赤 : New model　　□ : zonal

青: Previous model　　● : asymetric

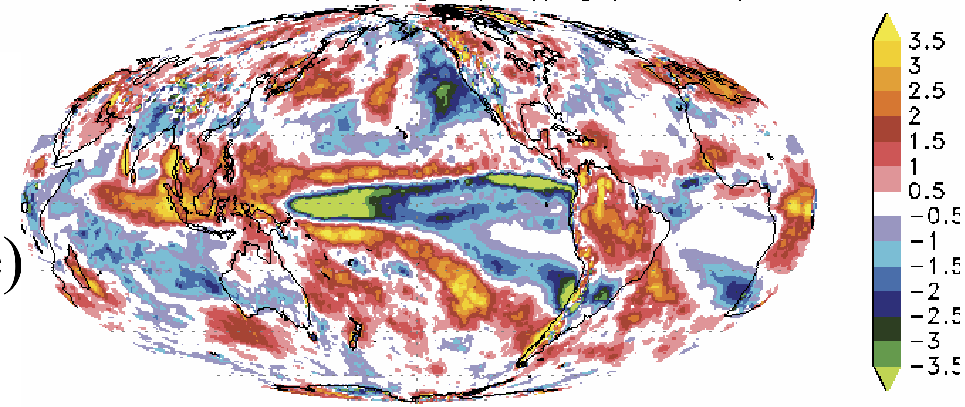
Vecchi and Soden (2007, J.Climate)

Previous model ($d\omega 500$)



Tropical total upward (downward) mass flux: -6.3% (-6.4 %)

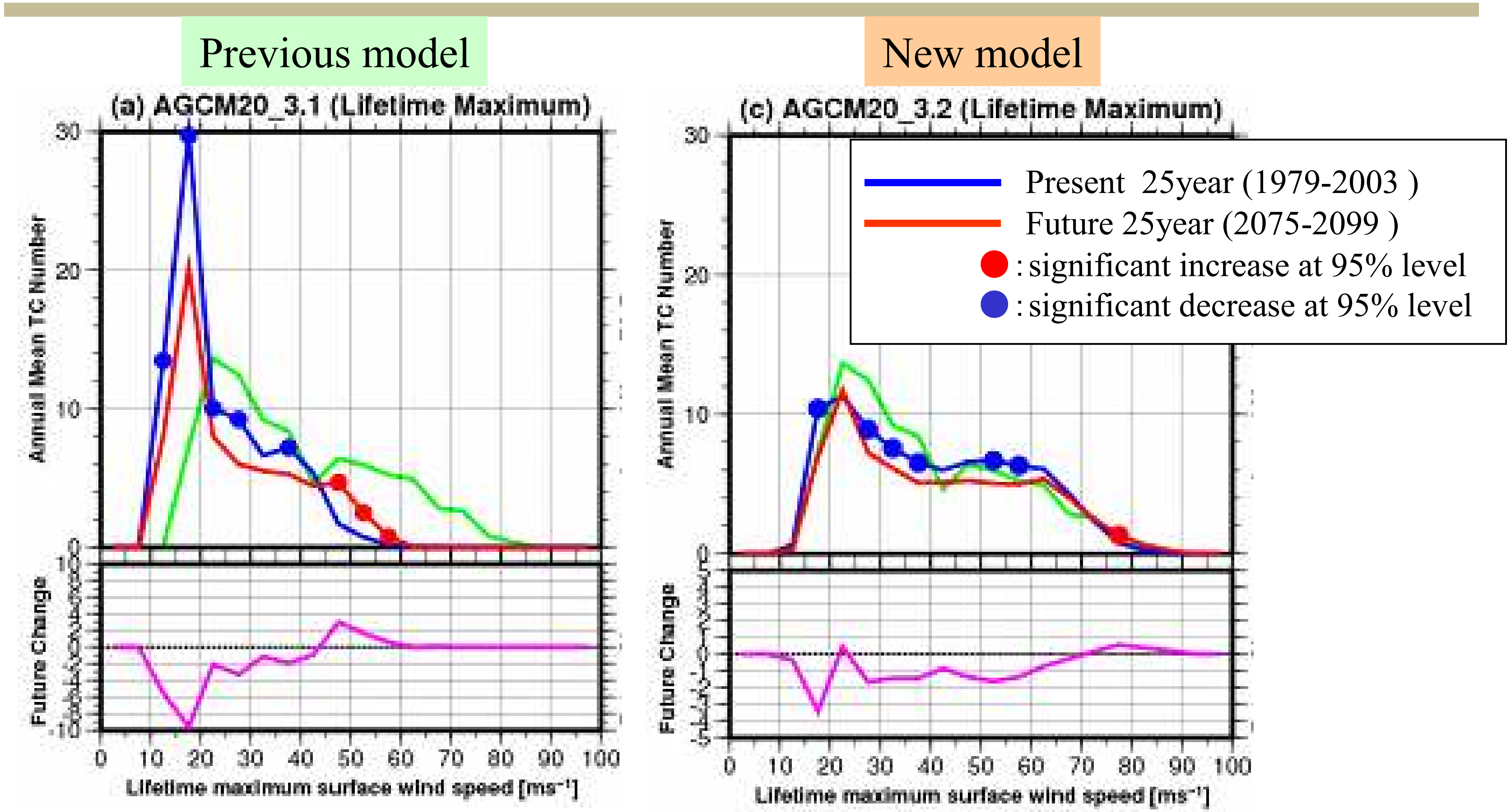
New model ($d\omega 500$)



Tropical total upward (downward) mass flux: -5.1% (-5.1 %)

Projected Walker circulation is weakened in both models

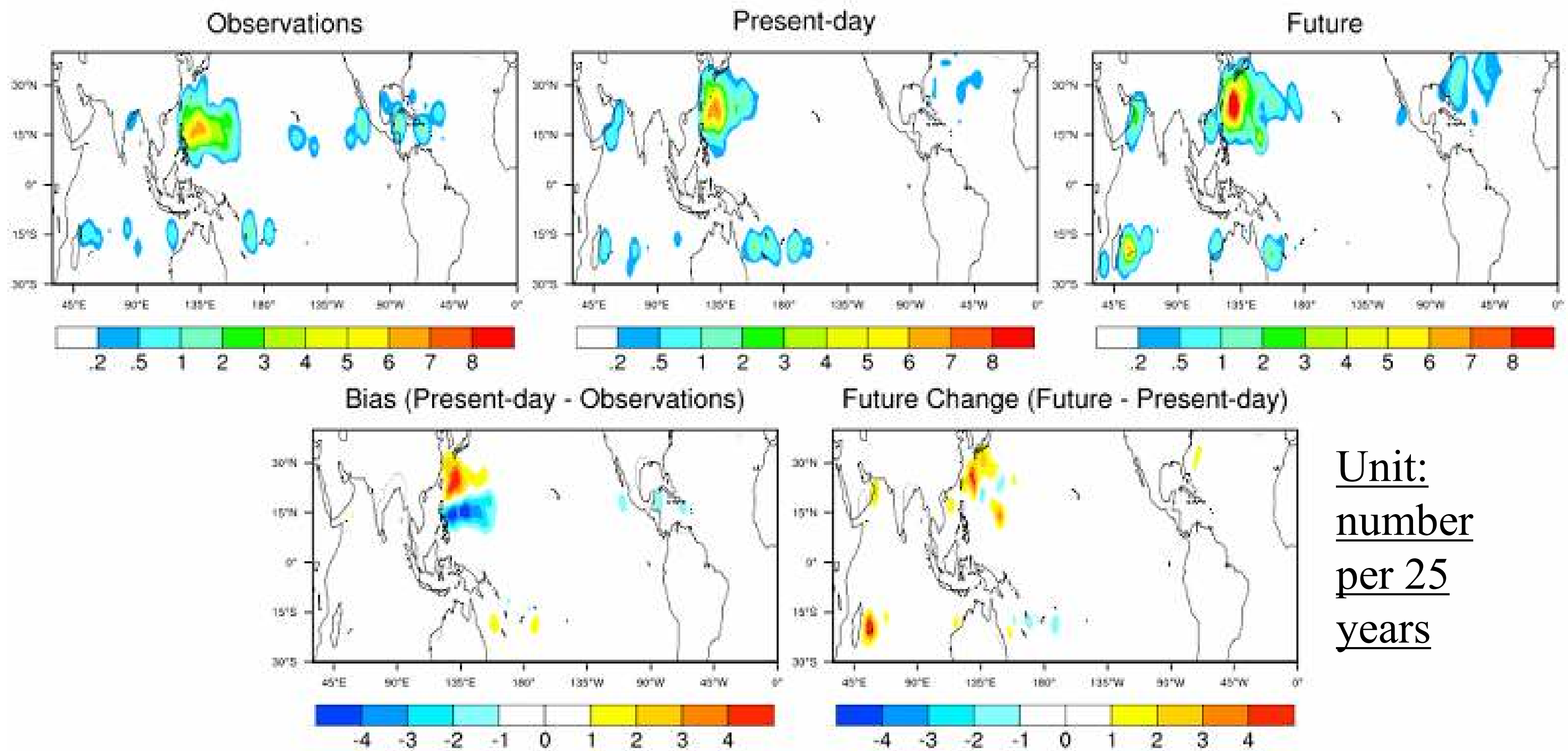
Comparison of projected future changes between models – TC intensity –



·Both models show significant decrease in the frequency of weak TCs.

·New model projects a more subtle increase in the frequency of intense TCs.

Category 5 TC frequency of occurrence



Unit: number per 25 years

·The frequency of C5 TCs appears to increase in the northern portion of the WNP basin.

·Note that the tracks of C5 TCs in the present-day simulation show a northward shift relative to observations.

Conclusion (II)

We developed a new high-resolution AGCM for more reliable climate projections especially in extreme events such as TCs. Projected results are characterized as:

(a) A significant increase in the frequency of intense TCs with global warming occurs in both models. However, the increase is smaller in the new model than the previous model.

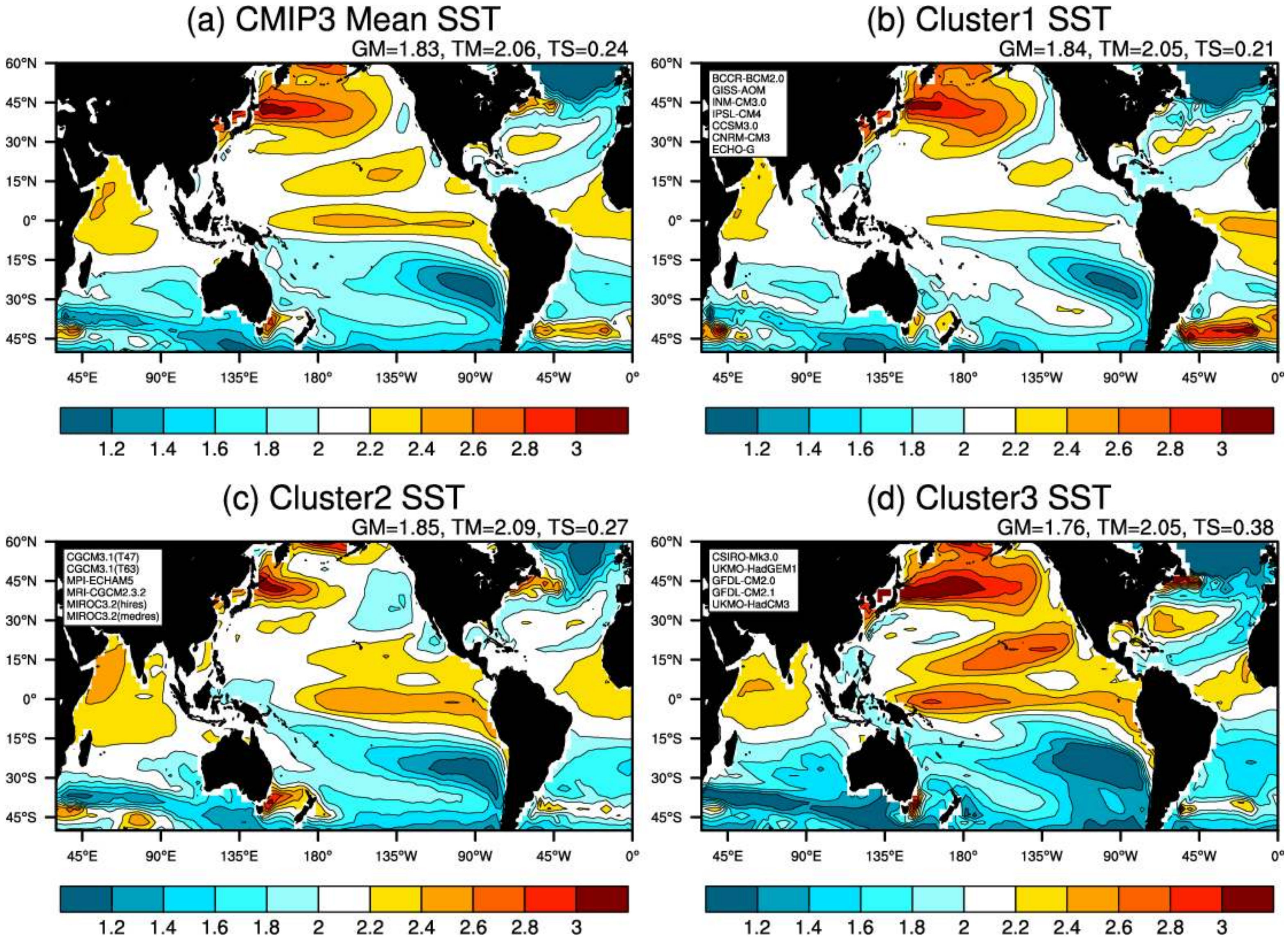
(b) The projected future changes in the TC frequency of occurrence show large spatial variations: significant decrease in the western quadrant of WNP and SPO, and significant increase in the Central Pacific.

(c) The new model suggests that the frequency of Category 5 TCs increases in the northern portion of the WNP, indicating that TC-related socioeconomic damage may become more severe under global warming.

Preliminary results of multi-model and multi-SST experiments using the new 60-km mesh model

Murakami et al. (In preparation)

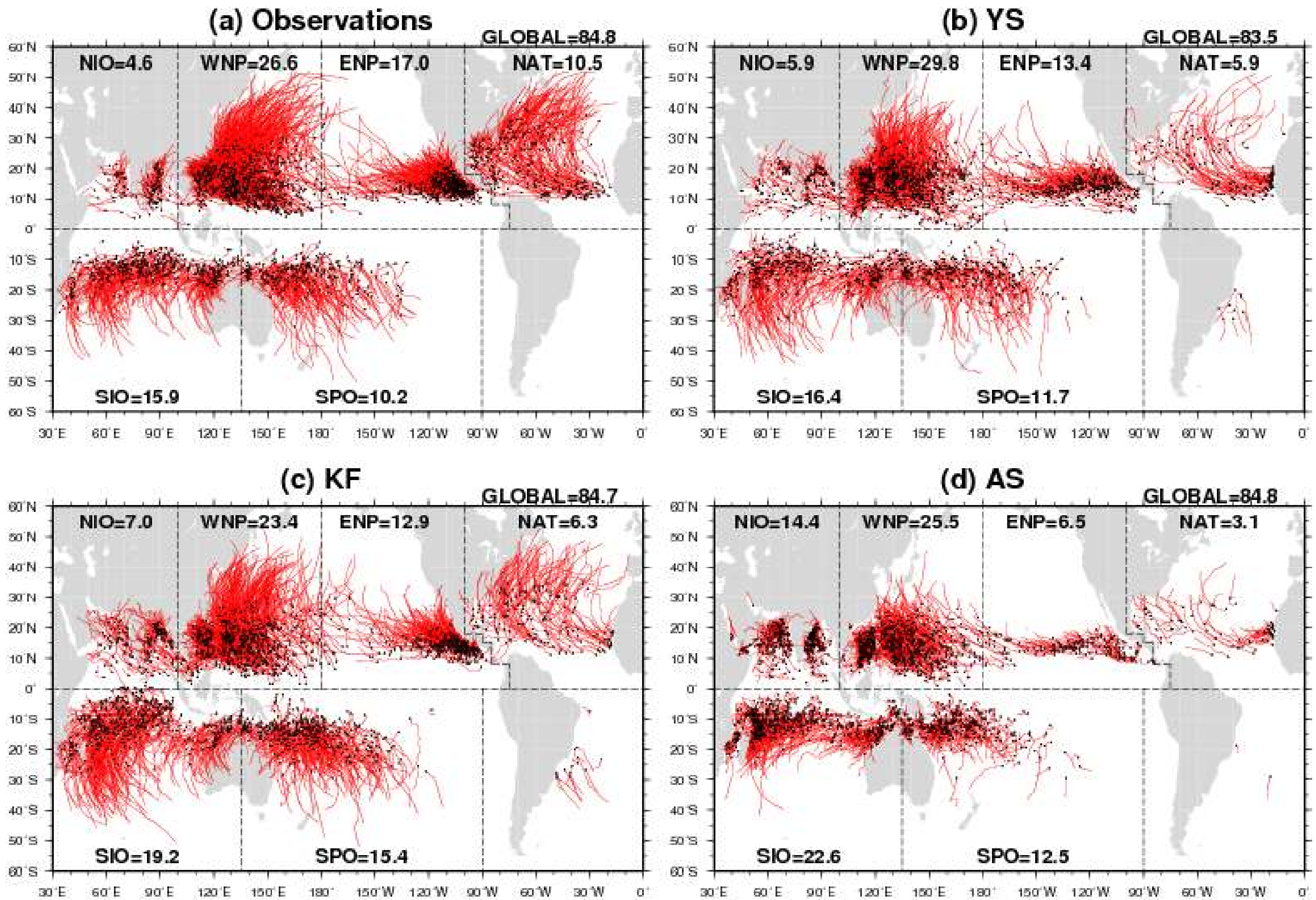
Multi-model & Multi-SST Ensemble Projections using 60-km-mesh model



Multi-model & Multi-SST Ensemble Projections using 60-km-mesh model

Abbreviation	Cumulus Convection Scheme	Prescribed Future SST
Y0	Yoshimura Scheme (YS)	18 CMIP3 Models Ensemble Mean
Y1	Yoshimura Scheme (YS)	Cluster 1
Y2	Yoshimura Scheme (YS)	Cluster 2
Y3	Yoshimura Scheme (YS)	Cluster 3
K0	Kain-Fritsch Scheme (KF)	18 CMIP3 Models Ensemble Mean
K1	Kain-Fritsch Scheme (KF)	Cluster 1
K2	Kain-Fritsch Scheme (KF)	Cluster 2
K3	Kain-Fritsch Scheme (KF)	Cluster 3
A0	Arakawa-Shubert Scheme (AS)	18 CMIP3 Models Ensemble Mean
A1	Arakawa-Shubert Scheme (AS)	Cluster 1
A2	Arakawa-Shubert Scheme (AS)	Cluster 2
A3	Arakawa-Shubert Scheme (AS)	Cluster 3
YG	Yoshimura Scheme (YS)	+1.83 K Global Uniform SST Increase

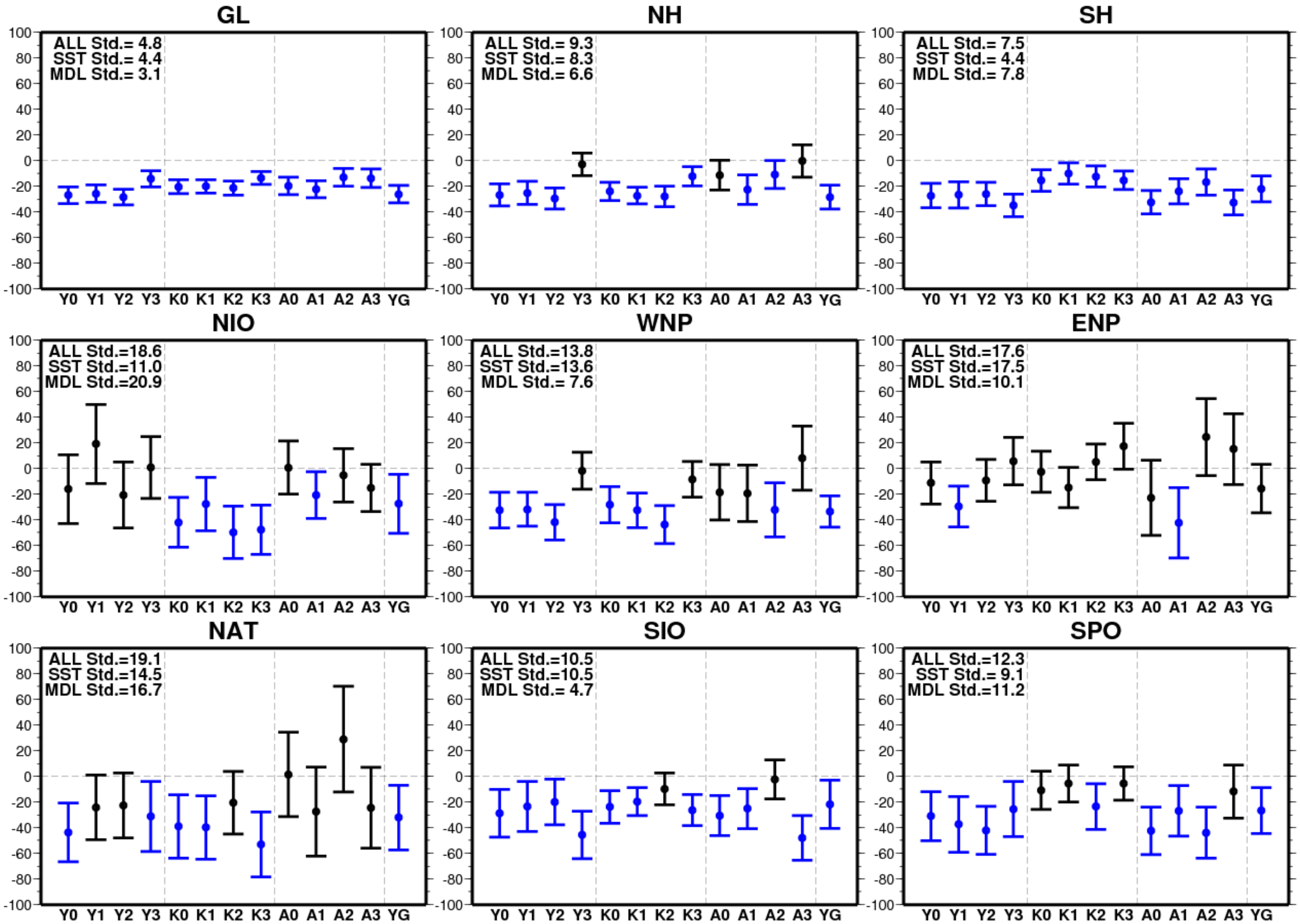
Performance of control simulation



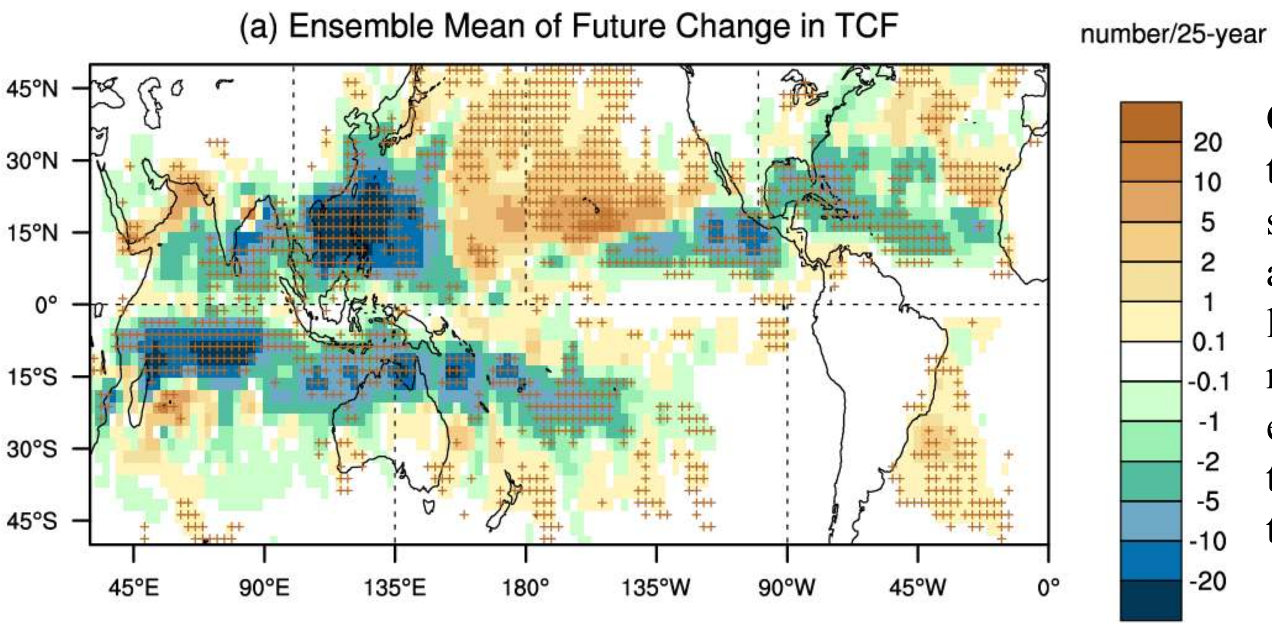
Future changes in TC number [%]

Y: Yoshimura, K:Kain-Fritsch, A: Arakawa Shubert

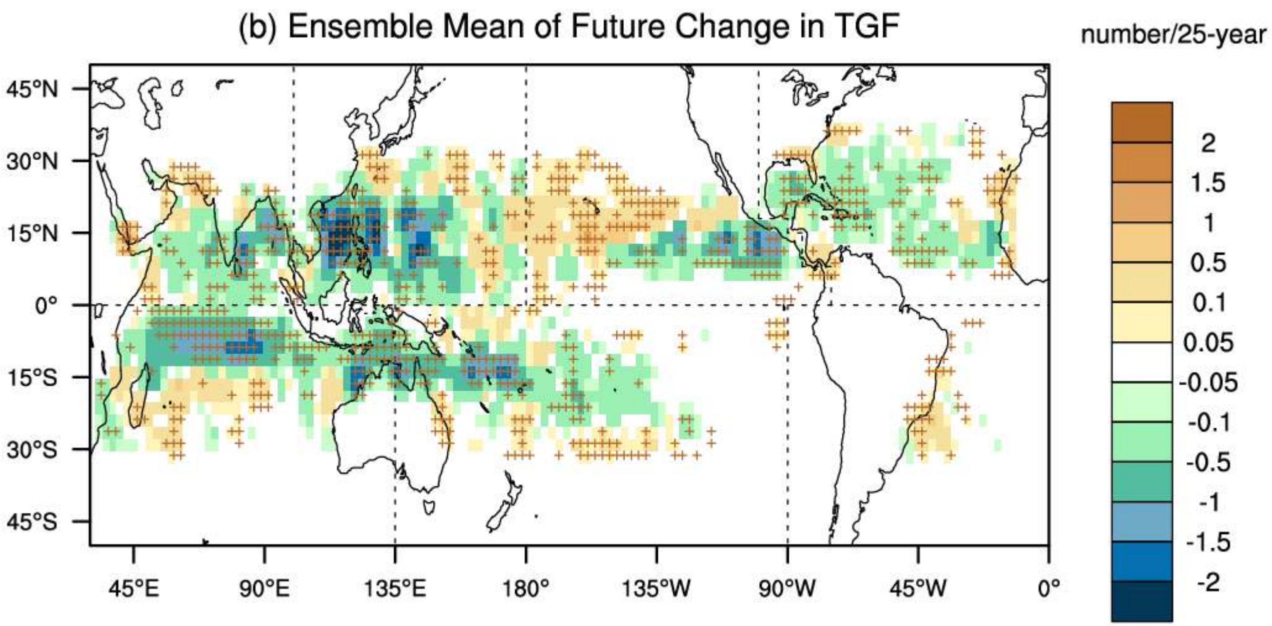
0: CMIP3 SST, 1:Cluster 1, 2:Cluster 2, 3: Cluster 3, G: Global uniform



Future changes in TC frequency and genesis frequency



Cross mark indicates that the difference is statistically significant at the 90 % confidence level or above and more than 10 experiments show the same sign of the mean change.



Conclusion (III)

In order to evaluate uncertainties, we conducted multi-SST and multi-model ensemble projections.

(a) Every ensemble simulation commonly shows decrease in global and hemispheric TC genesis numbers by about 5–35% under the global warming environment regardless of the difference in model cumulus convection schemes and prescribed SSTs.

(b) All experiments tend to project future decreases in the number of TCs in the western North Pacific (WNP), South Indian Ocean (SIO), and South Pacific Ocean (SPO), whereas they commonly project increase in the central Pacific.

(c) The projected changes in the North Atlantic, North Indian (NIO), and eastern North Pacific (ENP) are inconsistent among the experiments and even the sign of future changes is inconsistent.

Reference

Murakami, H. and M. Sugi, 2010: Effect of model resolution on tropical cyclone climate projections. *SOLA*, **6**, 73–76.

Murakami, H., and B. Wang, 2010: Future change of North Atlantic tropical cyclone tracks: Projection by a 20-km-mesh global atmospheric model. *J. Climate*, **23**, 2699–2721.

Murakami, H., B. Wang, and A. Kitoh, 2011: Future change of western North Pacific typhoons: Projections by a 20-km-mesh global atmospheric model. *J. Climate*, **24**, 1154–1169.

Murakami, H., and co-authors, 2011: Future changes in tropical cyclone activity projected by the new high-resolution MRI-AGCM. *J. Climate* submitted.

Murakami, H., R. Mizuta, and E. Shindo, 2011: Future changes in tropical cyclone activity projected by multi-model and multi-SST ensemble experiments using 60-km mesh MRI-AGCM. in preparation.

MPI (Maximum Potential Index)

$$MPI^2 = \frac{C_k}{C_D}\frac{T_s}{T_0}\left(CAPE^* - CAPE^b\right)$$

where C_k is the exchange coefficient for enthalpy, C_D is the drag coefficient, T_s is the SST (K), and T_0 is the mean outflow temperature (K). The quantity $CAPE^*$ is the value of convective available potential energy (CAPE) of air lifted from saturation at sea level, with reference to the environmental sounding, and $CAPE_b$ is that of the boundary layer air.

Both quantities are evaluated near the radius of maximum wind which is theoretically determined.

In recent years, TCs become more active.

- **Hurricane activity in the North Atlantic (NA) showed an increase over the past 30 years.**

  Hurricane Katrina (2005) : the most damaging storm in USA

  Hurricane Rita (2005) : the most intense (895 hPa) TC observed in the Gulf of Mexico

  Hurricane Wilma (2005) : the most intense (882 hPa) TC in NA

- **Abnormal TC number in the western North Pacific in 2004.**

- **Typhoon Morakot in 2009 caused catastrophic damage in Kaohsiung in Taiwan.**

Previous studies have proposed that these recent changes are due to global warming.

Emanuel, 2005; Anthes et al., 2006; Hoyos et al., 2006; Mann and Emanuel,2006; Trenberth and Shea, 2006; Holland and Webster, 2007; Mann et al., 2007a; Mann *et al.,* 2007b

However, this view has been challenged by the following points:

a) The observation before satellite era (before 1979) is not reliable.

Landsea *et al*., 2006; Landsea, 2007

b) Recent increases in the frequency of NA TCs are within the range of multi-decadal variability.

Pielke *et al*., 2006; Bell and Chelliah, 2006

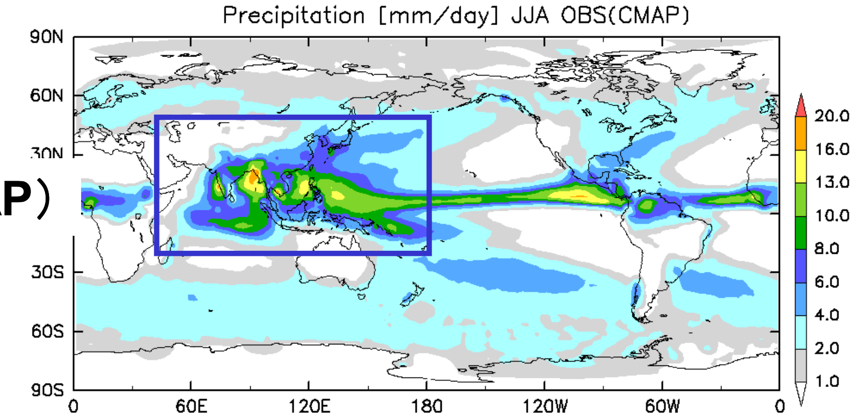
c) Projectons by climate models are not reliable because the models are too coarse to resolve TC structures.

Goldenberg et al. 2001.

TC scale is 100–1000 km, while typical horizontal resolution of climate models is 100–300 km mesh.

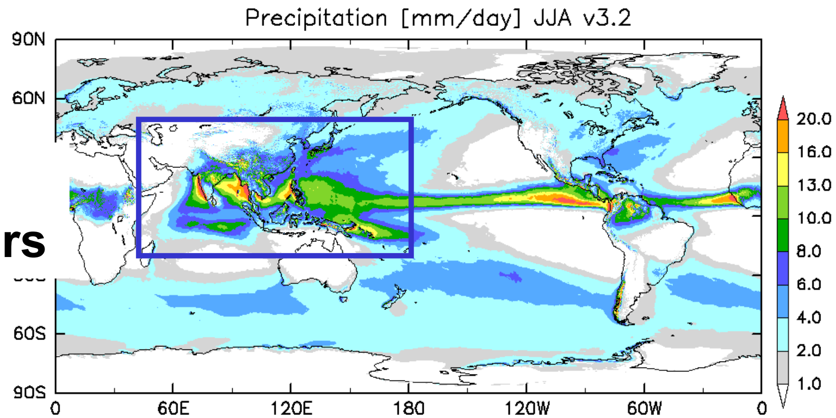
Global Precipitation (JJA)

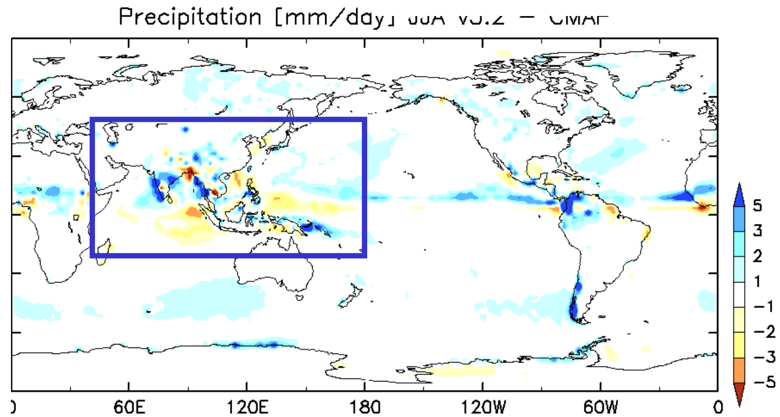
OBS（CMAP）



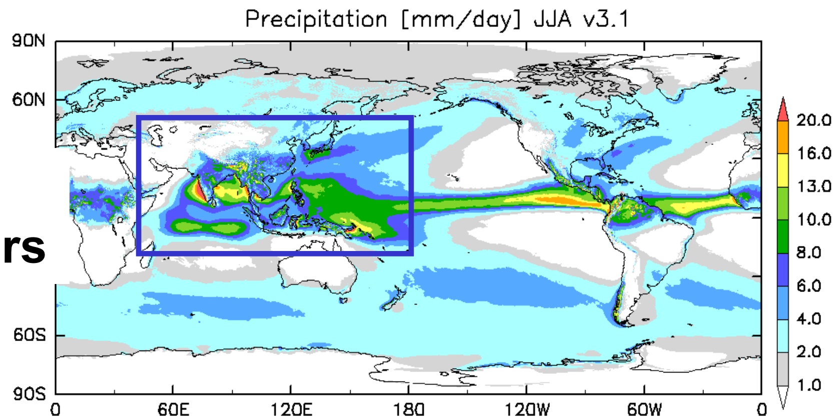
diff from OBS

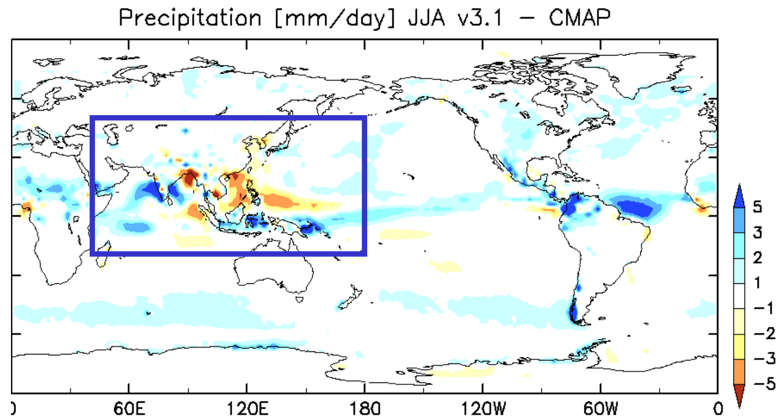
New Model
20km25years





Prev Model
20km25years

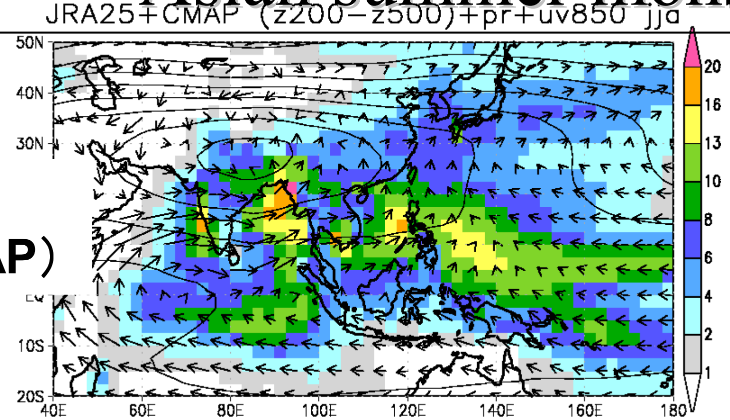




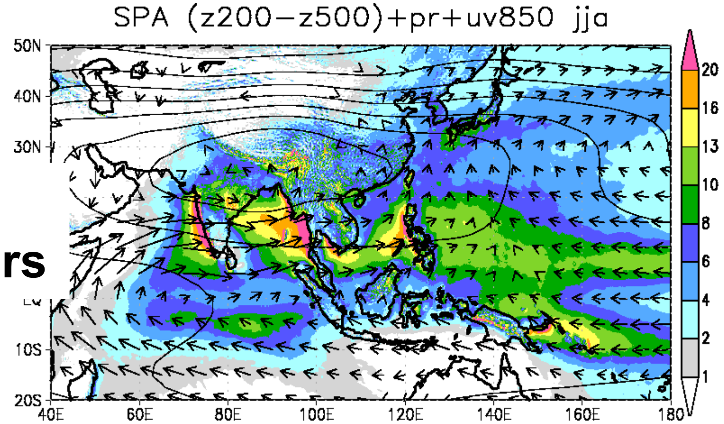
Asian summer monsoon (JJA mean)

Colors: Precipitation
Arrows: 850hPa wind
Contours: Thickness(200-500hPa)

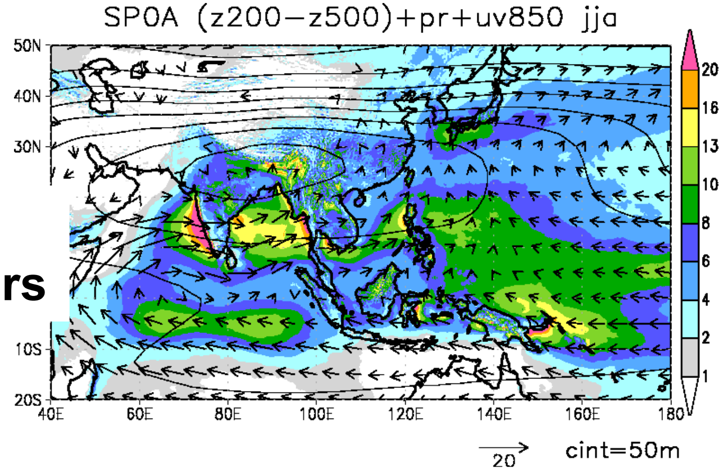
OBS
（JRA+CMAP）



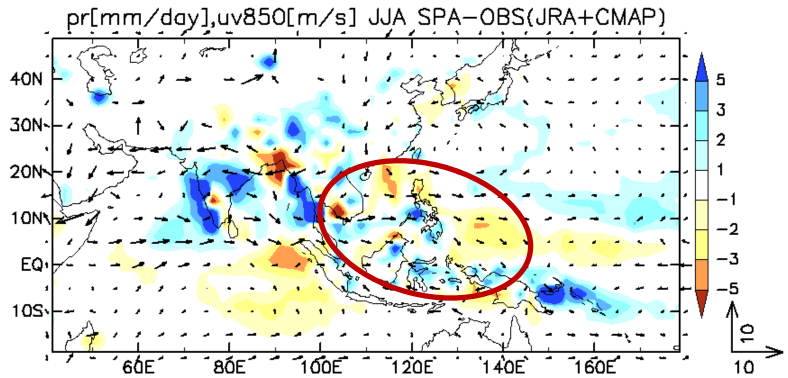
New Model
20km25years

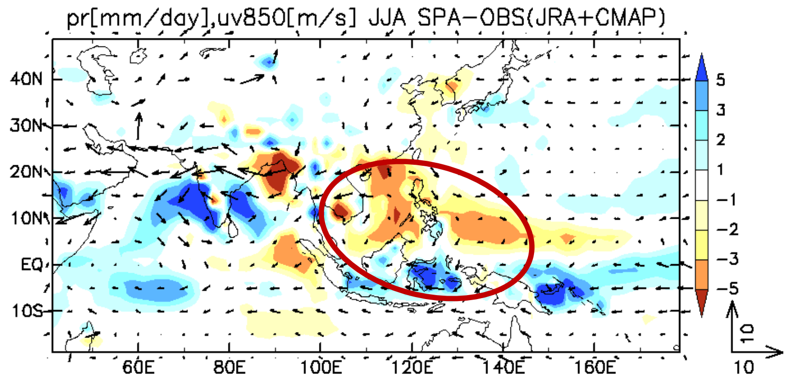


Prev Model
20km25years



diff from OBS





Skill score of 25-year climatology

- Skill Score by
  Taylor (2001)

σ : standard deviation (model/obs),
R: correlation coefficient

■ Better at New Model
■ Better at Prev Model

Global

variable	vs	region	Jan v3.1	Jan v3.2	Jul v3.1	Jul v3.2
Precip	CMAP	Global	0.7716	0.803	0.7862	0.8189
Precip	GPCP	Global	0.746	0.7814	0.7429	0.7566
Z500	JRA25	Global	0.9928	0.997	0.9951	0.9943
SLP	JRA25	Global	0.9322	0.9735	0.9529	0.9533
T850	JRA25	Global	0.9949	0.995	0.9908	0.9943
U850	JRA25	Global	0.9363	0.9651	0.9435	0.9401
U200	JRA25	Global	0.958	0.9702	0.9648	0.9778
V200	JRA25	Global	0.8198	0.8584	0.7758	0.8085
Netrad	ERBE	Global	0.9577	0.9714	0.9499	0.9644
OLR	ERBE	Global	0.9387	0.9503	0.9425	0.9539
OSR	ERBE	Global	0.8778	0.9076	0.855	0.8873
GZ5eddy	JRA25	Global	0.8918	0.9145	0.8108	0.8503
SLPeddy	JRA25	Global	0.9062	0.9137	0.871	0.8909
T850eddy	JRA25	Global	0.9401	0.9443	0.9291	0.9342
U850eddy	JRA25	Global	0.8433	0.8629	0.8722	0.9028
U200eddy	JRA25	Global	0.8959	0.9154	0.8463	0.9137

Asia

variable	vs	region	Jan v3.1	Jan v3.2	Jul v3.1	Jul v3.2
Precip	TRMM3B4:	Asia	0.7724	0.8153	0.3886	0.497
Precip	CMAP	Asia	0.7378	0.8034	0.4523	0.5616
Precip	GPCP	Asia	0.6488	0.7468	0.3441	0.4088
Z500	JRA25	Asia	0.9823	0.9806	0.7266	0.7813
SLP	JRA25	Asia	0.9553	0.9562	0.7894	0.8836
T850	JRA25	Asia	0.9676	0.9632	0.9195	0.9776
U850	JRA25	Asia	0.9387	0.9454	0.8395	0.8547
U200	JRA25	Asia	0.9849	0.9944	0.8866	0.9641
V200	JRA25	Asia	0.5805	0.4717	0.7945	0.7923
GZ5eddy	JRA25	Asia	0.8594	0.9162	0.8161	0.868
SLPeddy	JRA25	Asia	0.8744	0.8817	0.8185	0.902
T850eddy	JRA25	Asia	0.8837	0.8654	0.8785	0.936
U850eddy	JRA25	Asia	0.8633	0.8683	0.8393	0.8833
U200eddy	JRA25	Asia	0.9216	0.95	0.7995	0.9217