

Towards Attribution of Extreme Rainfall Events Using Convection-Permitting Simulations

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Convection-permitting simulations reveal expanded rainfall extremes of tropical cyclones affecting South Korea due to anthropogenic warming

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Understanding how global warming affects tropical cyclone (TC) intensity and precipitation for target regions is essential to preparing for associated damages but detailed processes remain uncertain. This study provides the first quantification of anthropogenic influences on TC characteristics affecting South Korea using convection-permitting model (CPM) simulations (3 km resolution). For the observed four recent TCs that strongly affected South Korea, CPM simulations were performed under current (ALL) and counterfactual conditions without human influences (NAT). The observed sea surface temperature and lateral boundary conditions were used for ALL while changes attributable to human influences (estimated using CMIP6 multimodel simulations) were removed from observed boundary conditions for NAT runs. ALL experiments captured the observed TC intensity and precipitation reasonably. After removing human influences, TC intensity and precipitation were reduced in NAT experiments. Importantly, areas with extreme precipitation (i.e., having precipitation larger than 150 mm) were found to expand by 16–37% in ALL compared to NAT, which was induced by an enhanced upward motion near the TC core and an increase of background water vapor in line with warming. Further, the role of increased moisture was found to become important as TC moves to mid-latitudes. This study provides valuable insights into how greenhouse warming can intensify TC-induced extreme precipitation over East Asia.

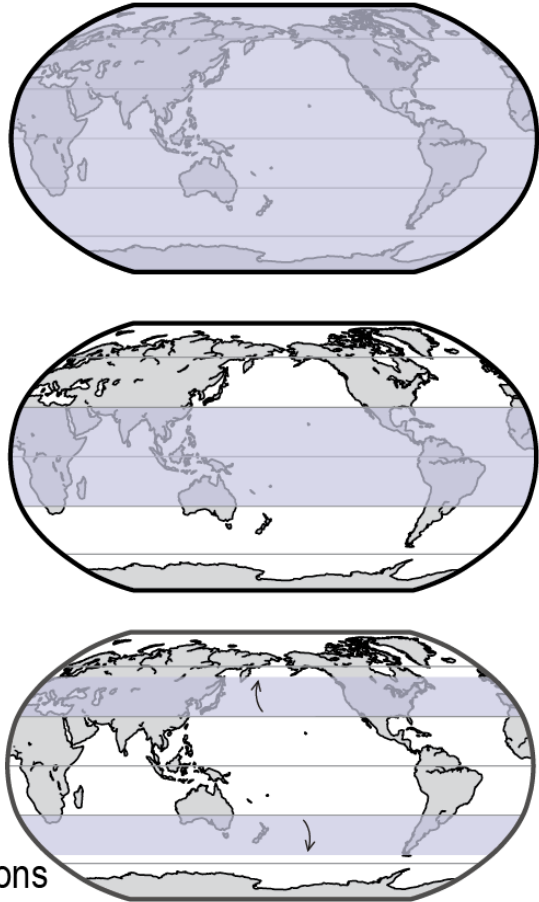
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◆ Collaborators: Minkyu Lee (Korea Institute of Energy Research), Dong-Hyun Cha (Ulsan National Institute of Science & Technology)

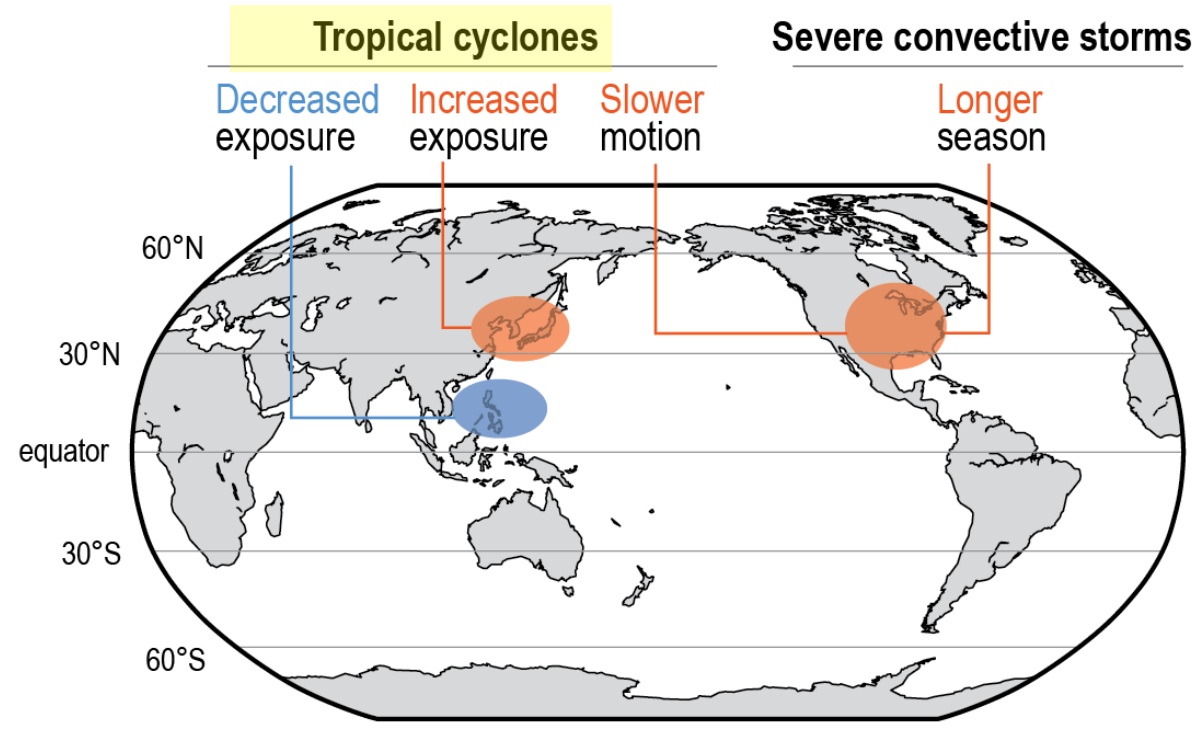
Changes in storms with increasing global warming

Global

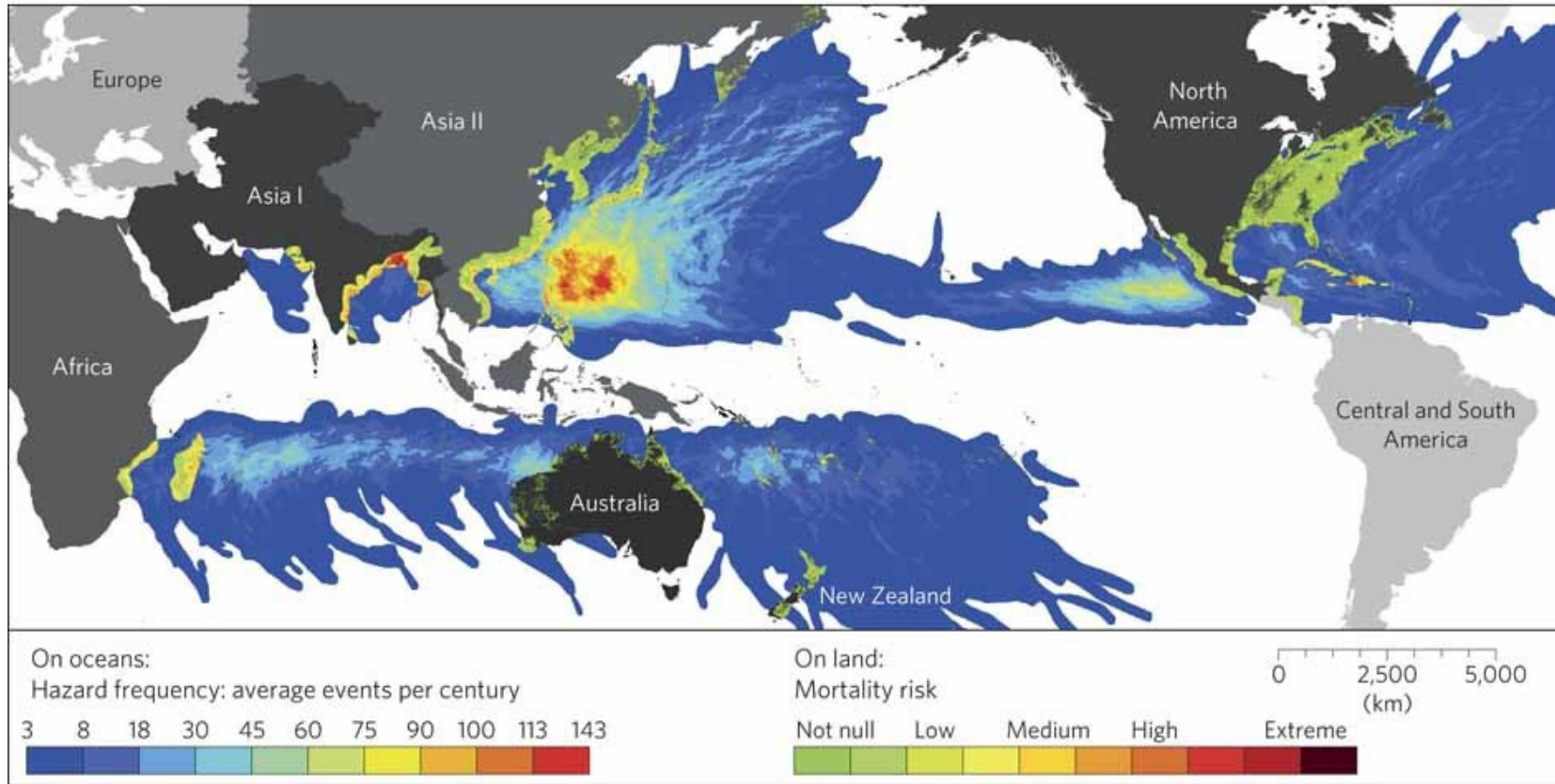
- Tropical cyclones
 - Extratropical cyclones
 - Atmospheric river
- Average and maximum precipitation rates **increase** with warming
- Tropical cyclones
- Increase** in strength
Decreased or unchanged genesis frequency
- Extratropical cyclones
- Changes (**increase** or **decrease**) in wind speed following storm tracks
poleward shift in some regions



Regional



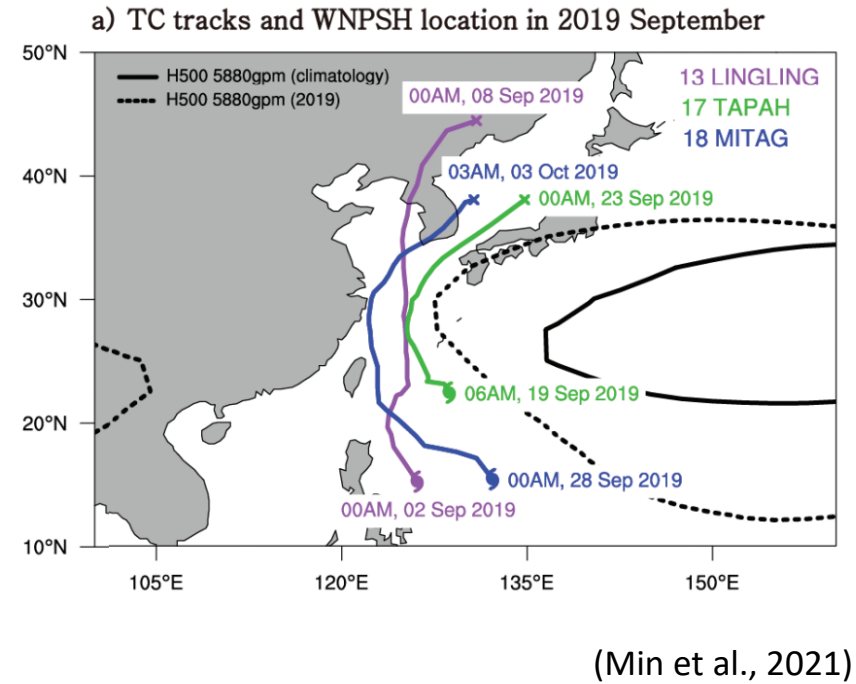
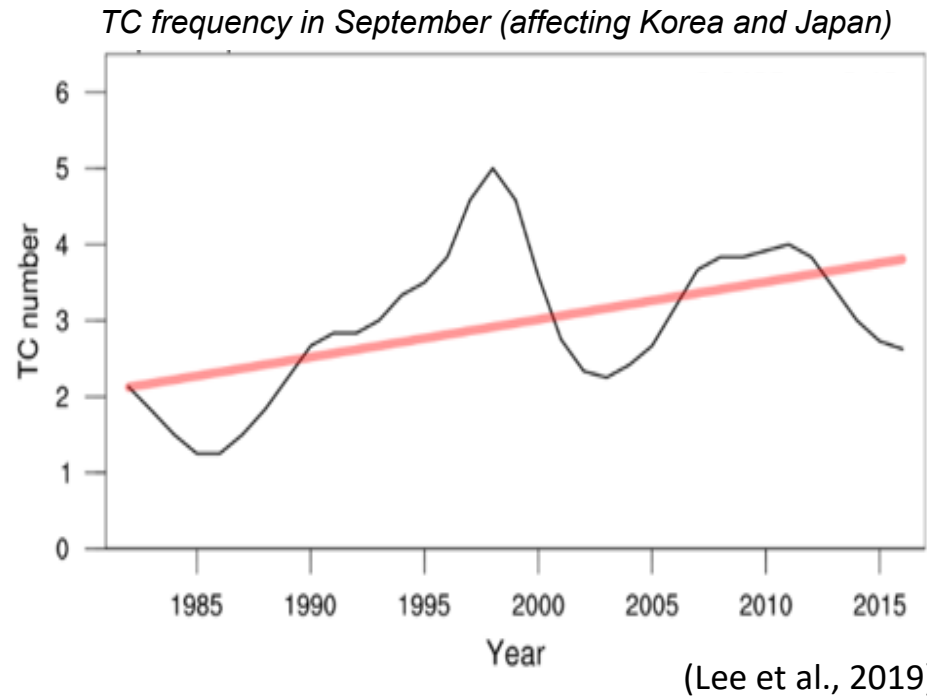
(IPCC, 2021, Figure 11.20)



(Peduzzi et al., 2012)

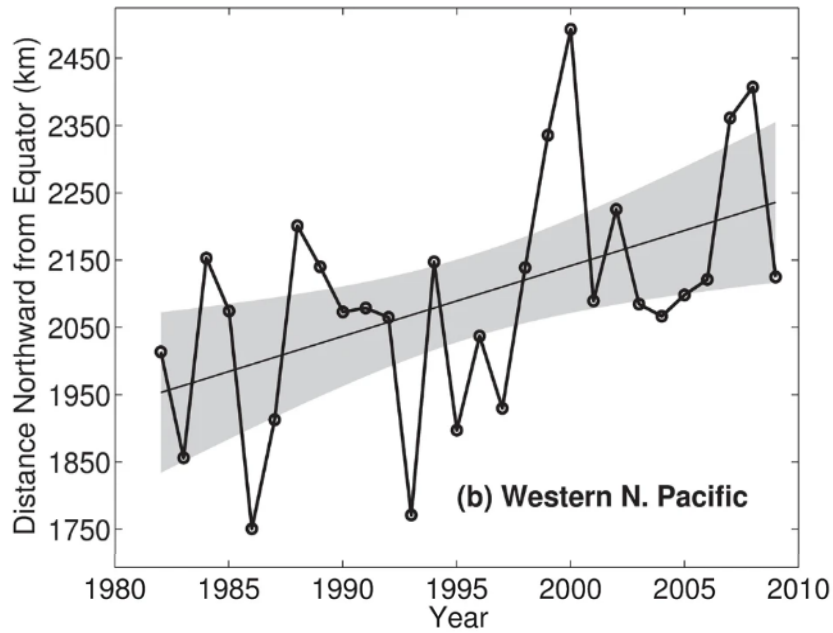
- ◆ 25-30 TCs occur every year over the **western North Pacific**, accounting for 30% of global TCs
- ◆ More than **60% TCs make landfall in Asian countries**, causing tremendous economic losses and casualties

Increasing September TCs affecting Korean Peninsula

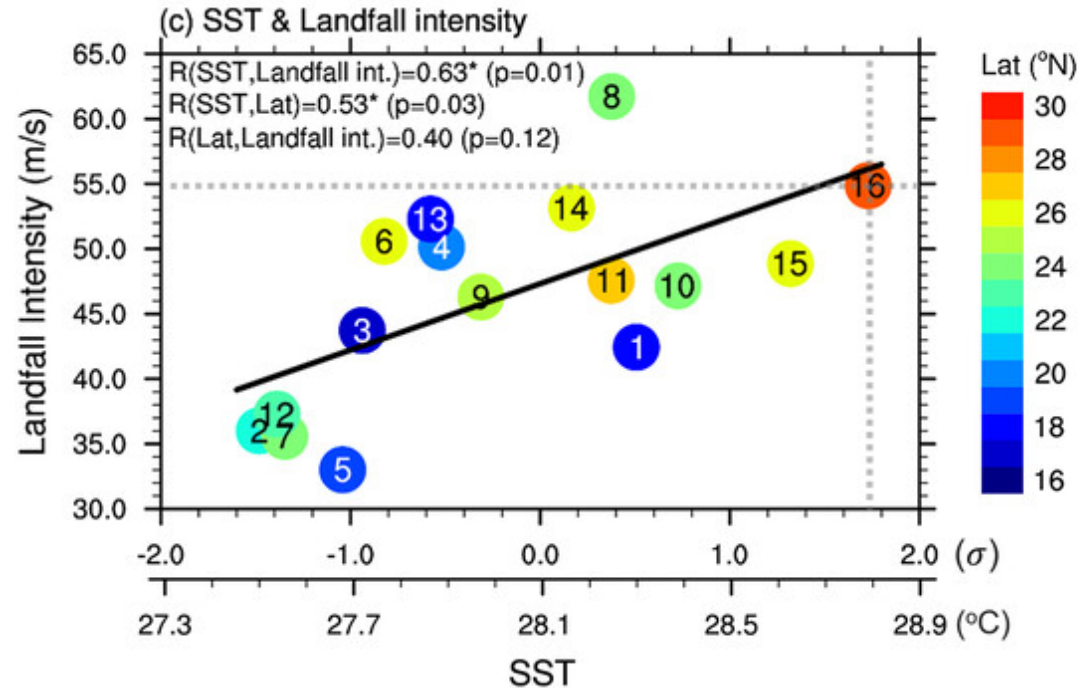


- ◆ The frequency of TCs affecting Korea and Japan has increased in September due to favorable large-scale environments
- ◆ In 2019, seven TCs affected the Korean Peninsula, including three TCs in September, which was a record high number since 1959

Northward Shift of Strong Tropical Cyclone Location



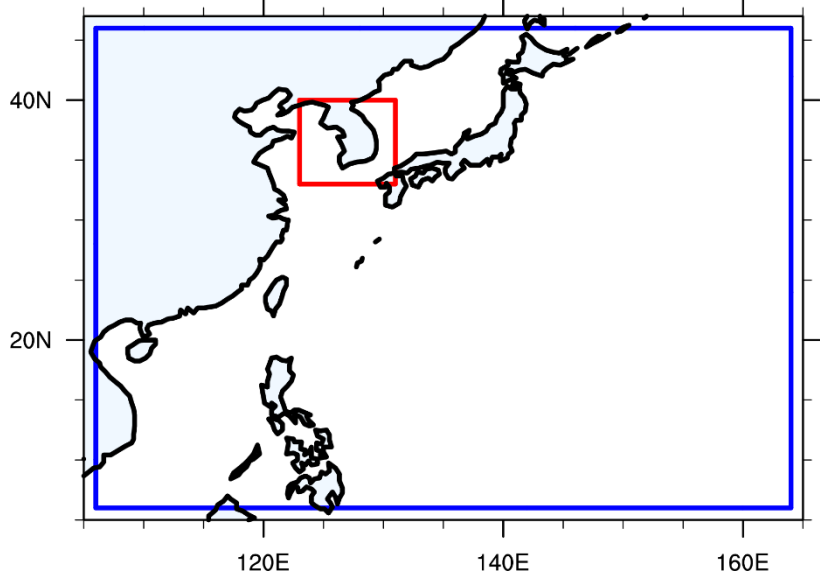
(Kossin et al., 2014)



(Kim et al., 2024)

- ◆ Northward shift in location of the maximum intensity over the western North Pacific
- ◆ Indo-Pacific warm pool expansion into East China Sea provides a favorable condition to TCs intensifying higher latitudes with stronger landfall intensity on the Korean Peninsula

TC case thresholds



1. TC genesis in 2011-2020 (10 years)
2. Landfalling on the Korean Peninsula
3. Maximum wind speed near the Korean Peninsula (33-40°N and 123-131°E) should exceed 35 ms^{-1}
4. Lifetime maximum intensity should exceed 60 ms^{-1}



Four TC cases selected:
SANBA (2012), CHABA (2016), MAYSAC (2020), HAISHEN (2020)

Simulation period

- Initial time → TC was intensified from tropical depression (TD, maximum wind speed $< 17 \text{ ms}^{-1}$) to tropical storm (TS, $17 \text{ ms}^{-1} \leq$ maximum wind speed $< 32 \text{ ms}^{-1}$)
- Last time → TC was weakened to TS

Selected TCs and Model Configuration

TC information

TC name	Simulation period	Lifetime maximum intensity
SANBA	2012/09/11 06 UTC ~ 2012/09/17 18 UTC (6 days 12 hours)	79.7 m/s, 907 hPa
CHABA	2016/09/29 06 UTC ~ 2016/10/05 06 UTC (5 days)	77.2 m/s, 911 hPa
MAYSAK	2020/08/28 12 UTC ~ 2020/09/03 06 UTC (5 days 18 hours)	61.7 m/s, 930 hPa
HAISHEN	2020/09/01 00 UTC ~ 2020/09/07 12 UTC (6 days 12 hours)	69.4 m/s, 913 hPa

Model configuration

Model	Weather Research & Forecasting Model (WRF) v4.0
Horizontal dimensions (lat x lon)	1601 x 2001
Horizontal resolution	3 km
Lateral boundary condition	ERA5
SST data	OISST
Vertical levels	50
Microphysics	WSM6
Planetary boundary layer	YSU
Convection scheme	Turn off

Experimental design

< CMIP6 : 9 models >

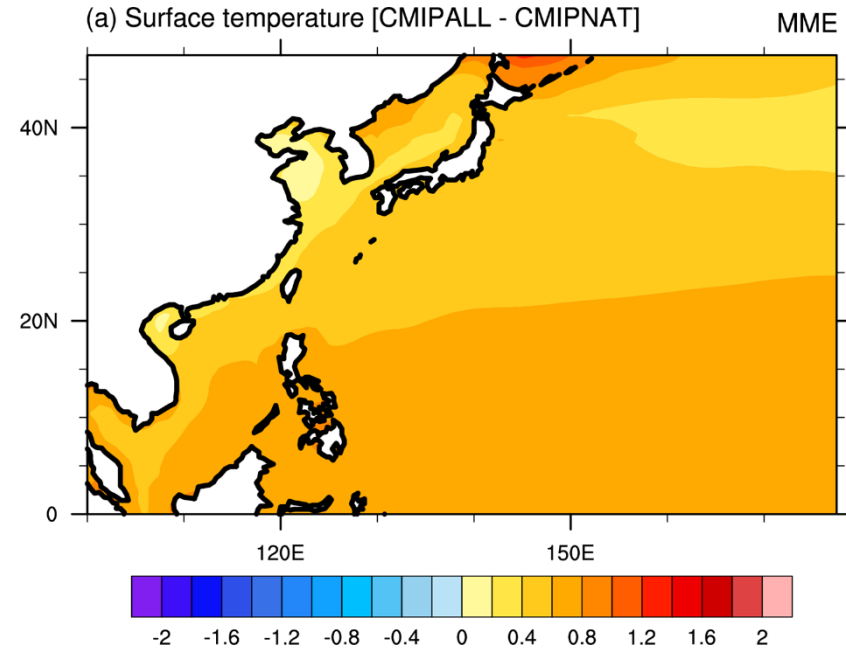
CMIP ALL → Natural + Human forcing

CMIP NAT → Only natural (solar & volcanic) forcing

CMIP ALL – CMIP NAT = **Attributable human influences**

Variables: SST, atmospheric temperature and humidity

Period: recent 10 years (2011-2020)



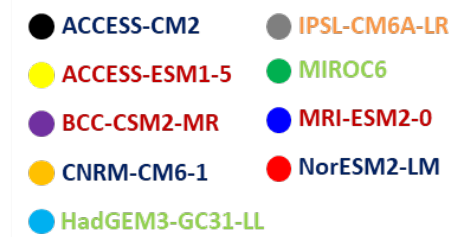
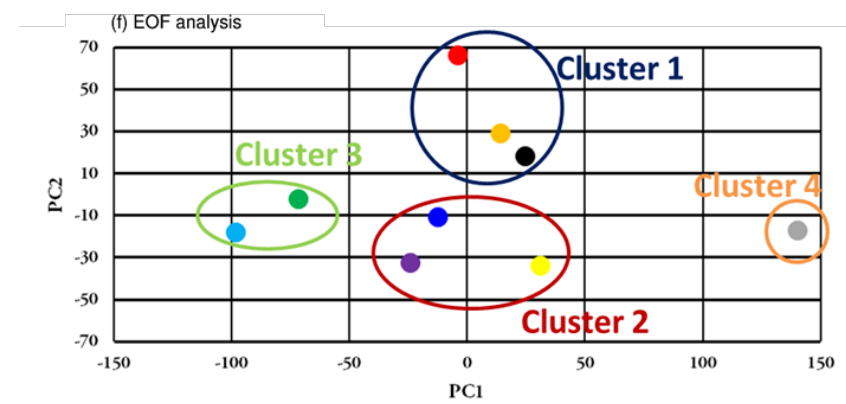
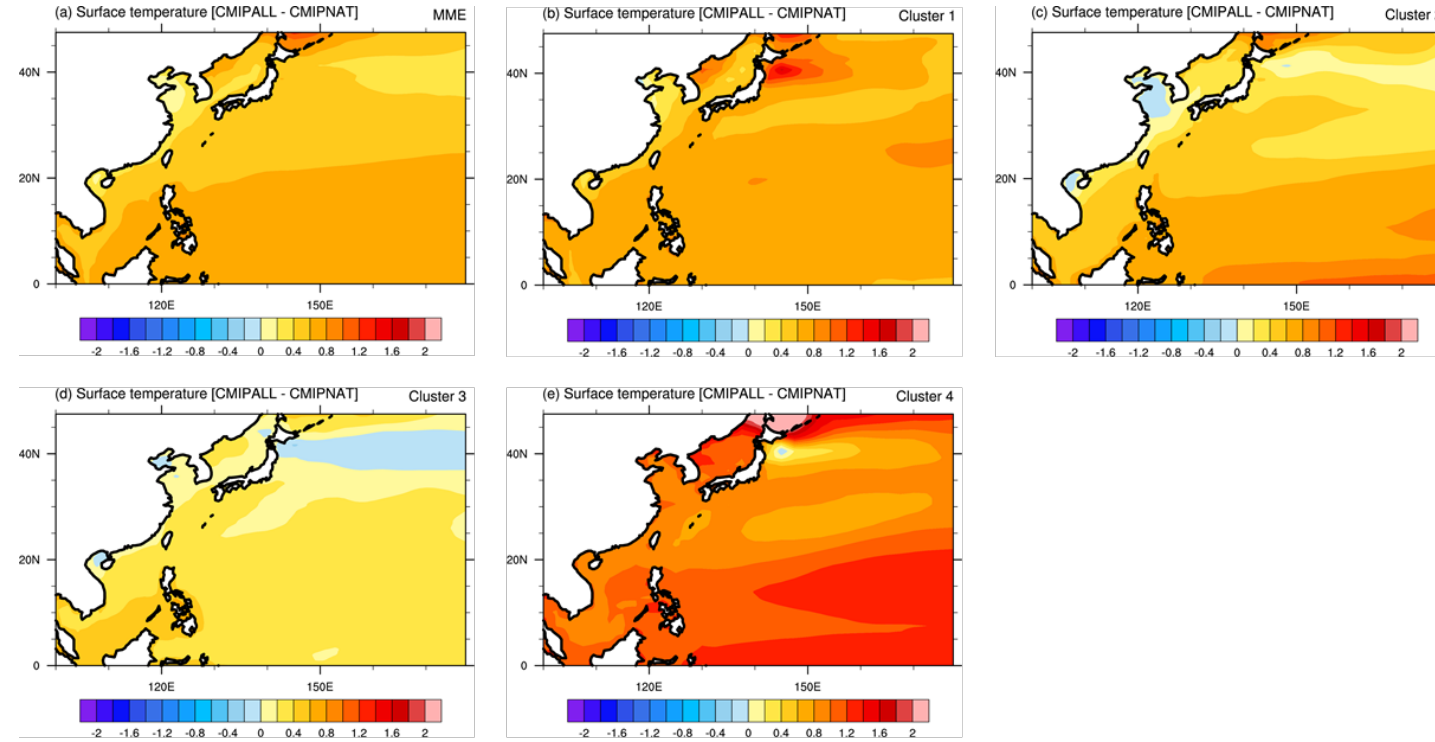
<WRF experiments>

	ALL (current climate)	NAT (Pre-industrial climate)
Boundary condition	ERA5	ERA5 – [ALL - NAT]
SST	OISST	OISST – [ALL - NAT]
Initial condition	ERA5	ERA5
GHGs	CO2: 379 ppm, CH4: 1774 ppb, N2O: 319 ppb	CO2: 284 ppm, CH4: 808 ppb, N2O: 273 ppb

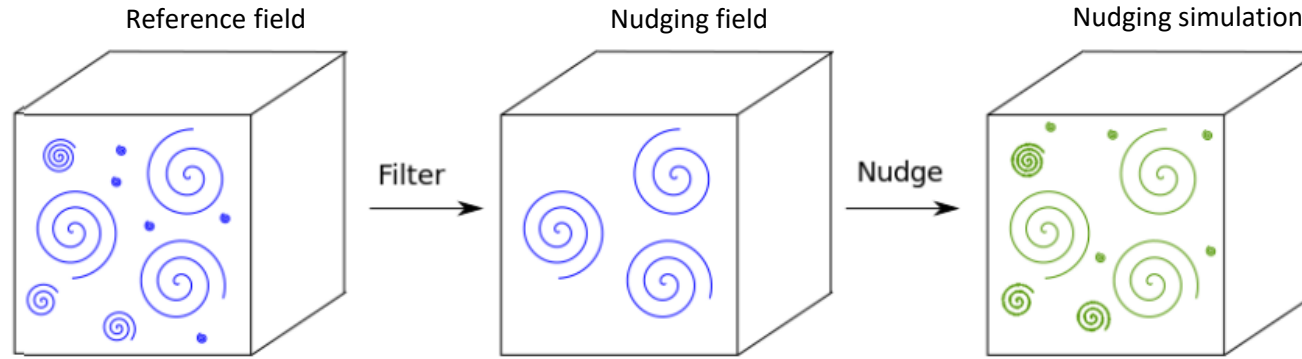
Considering Uncertain Warming Patterns

Ensemble method

- ◆ Different warming patterns estimated from CMIP6 models
- ◆ 5 ensemble simulations performed based on different warming patterns



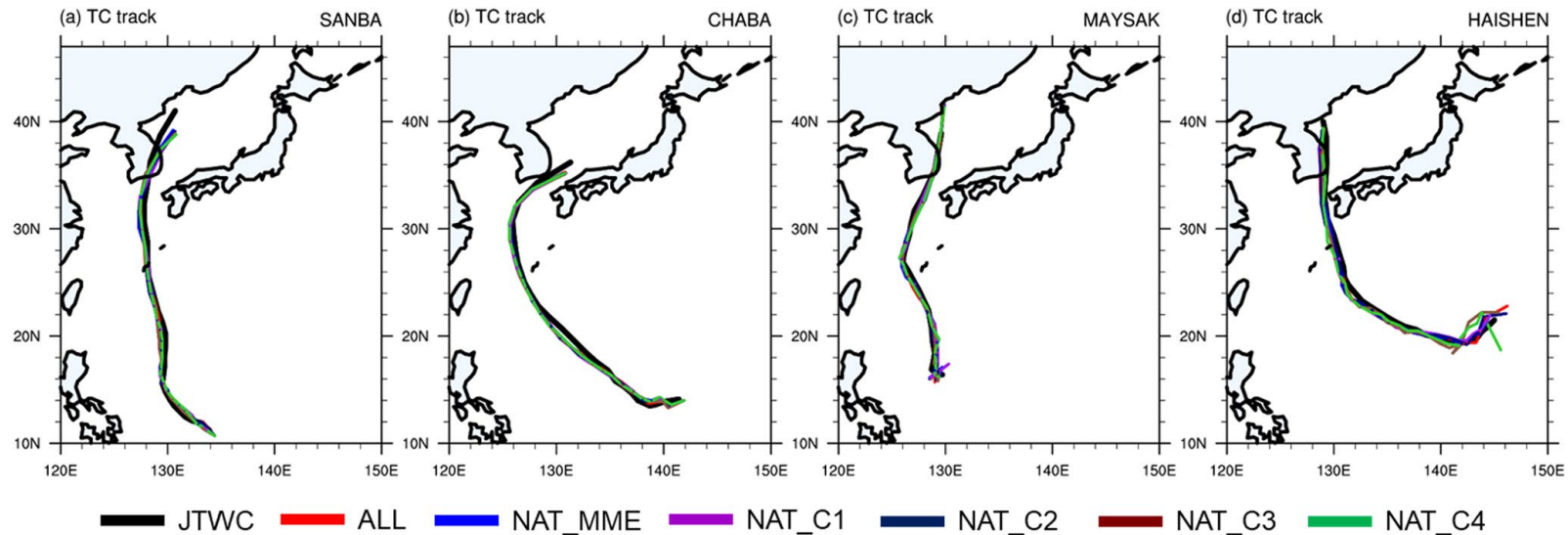
Spectral nudging



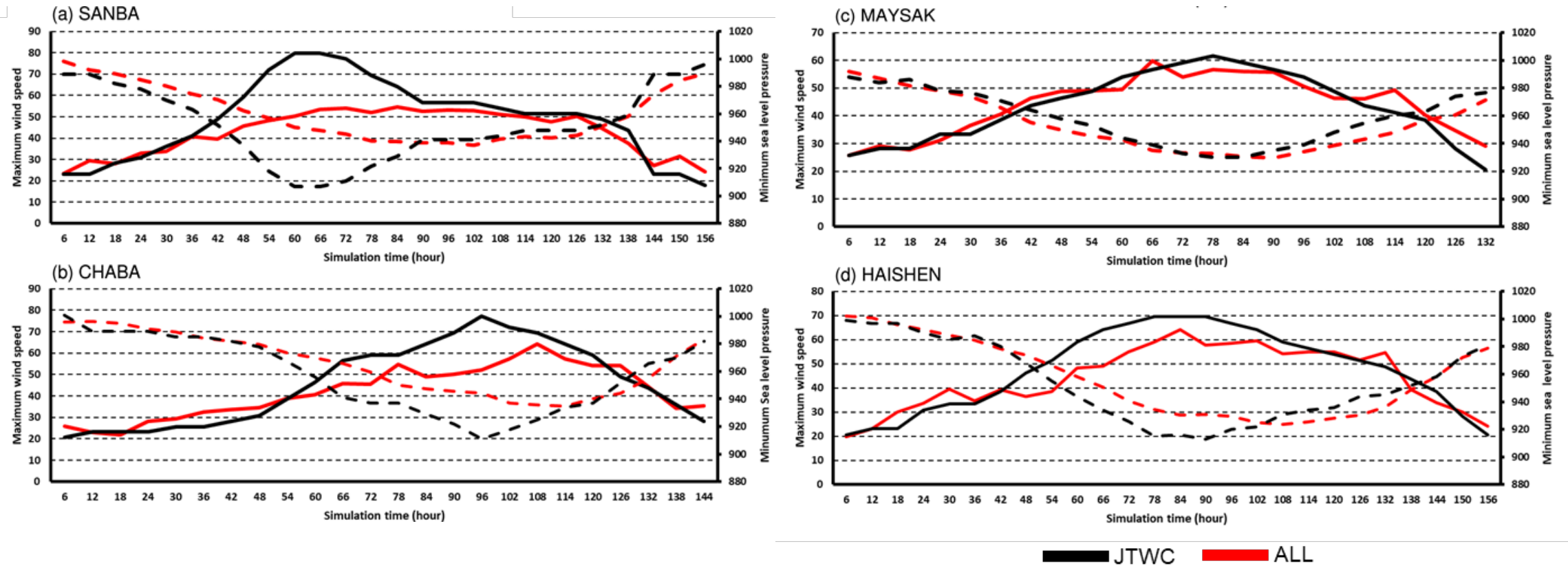
(Leoni et al, 2018)

- ◆ The spectral nudging can change the large-scale circulation to the inside of the model efficiently
- ◆ The spectral nudging technique was applied to **simulate TC tracks realistically**

Simulated TC tracks

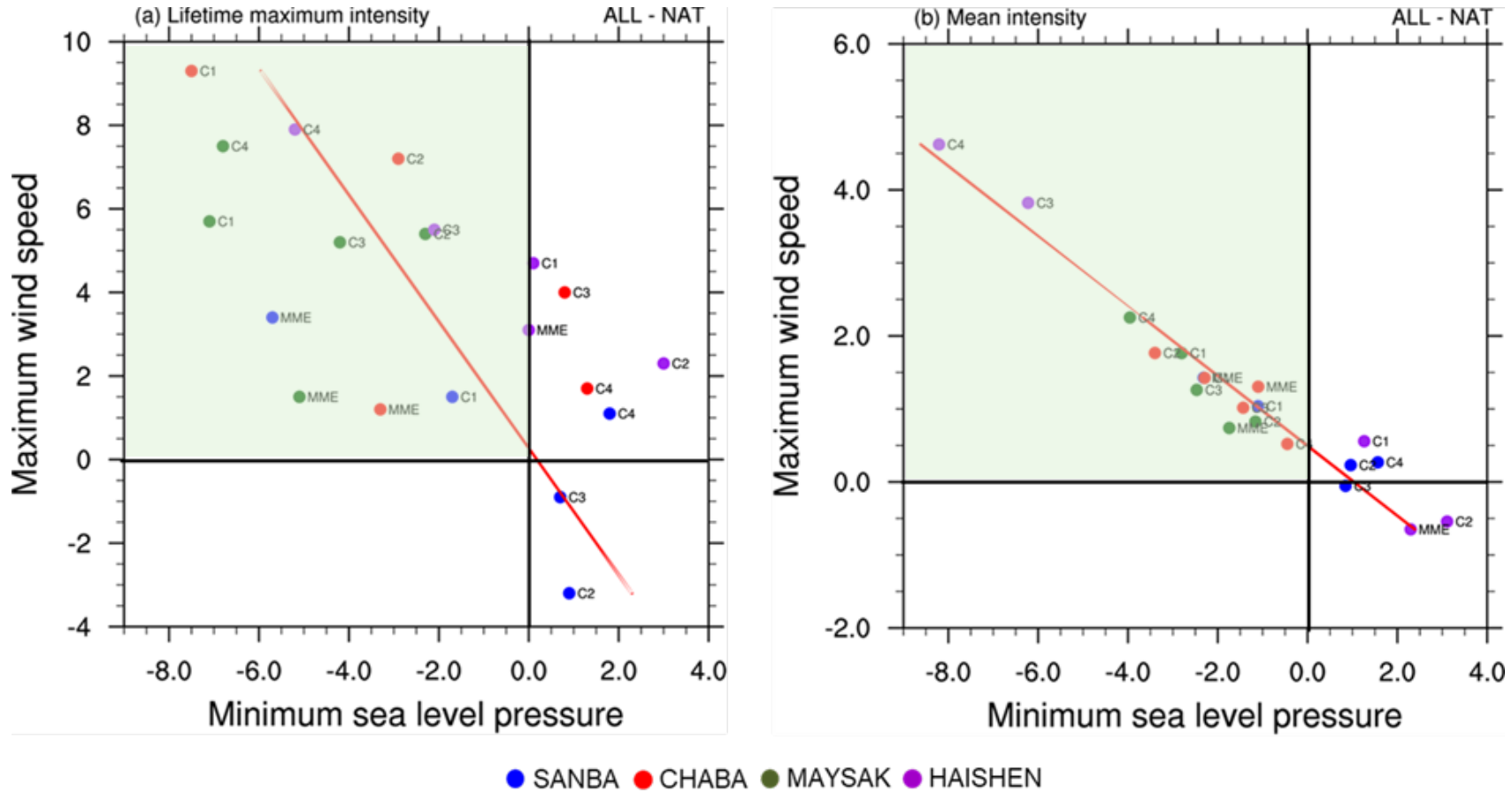


TC intensity : Maximum wind speed (m/s) and Minimum SLP (hPa)



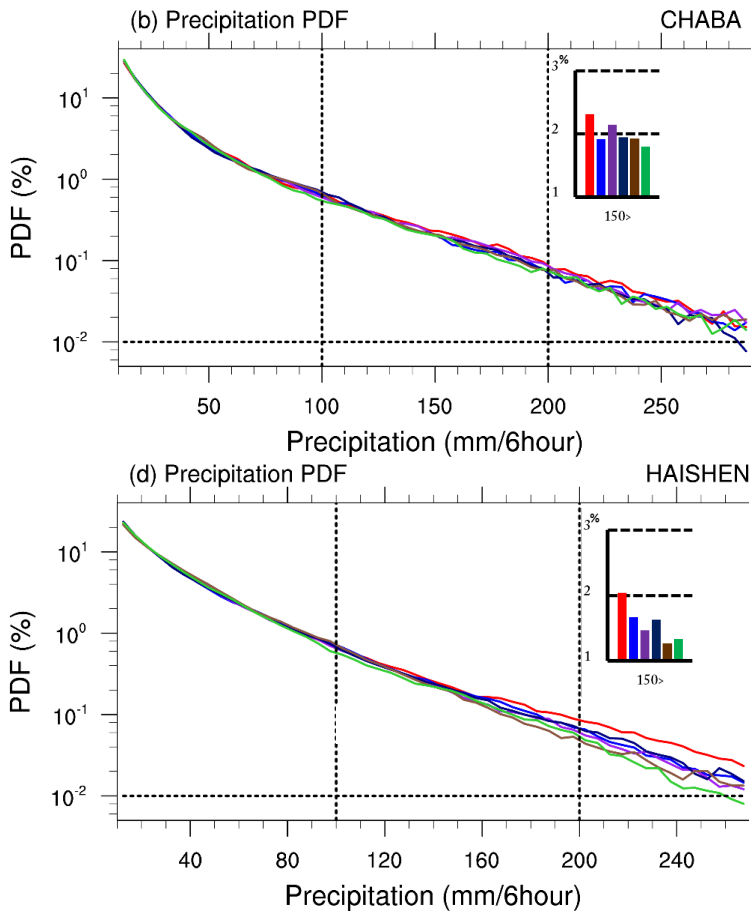
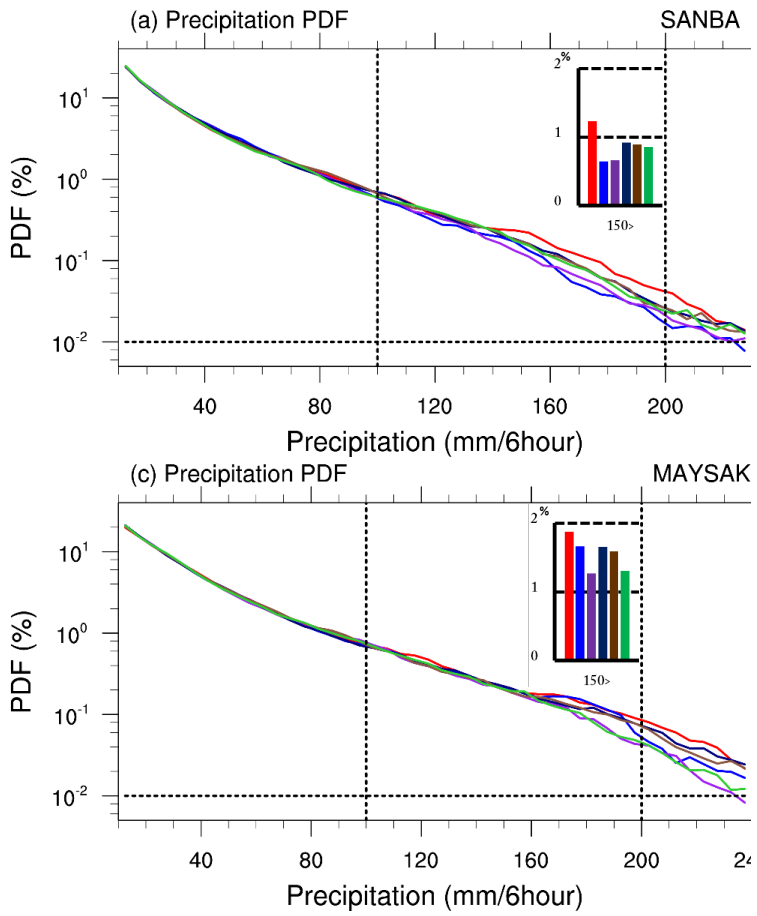
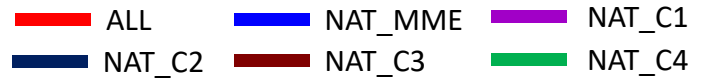
◆ The WRF CPM simulations can capture observed TC intensities reasonably well although some underestimation remained for TC SANBA and CHABA

TC intensity response



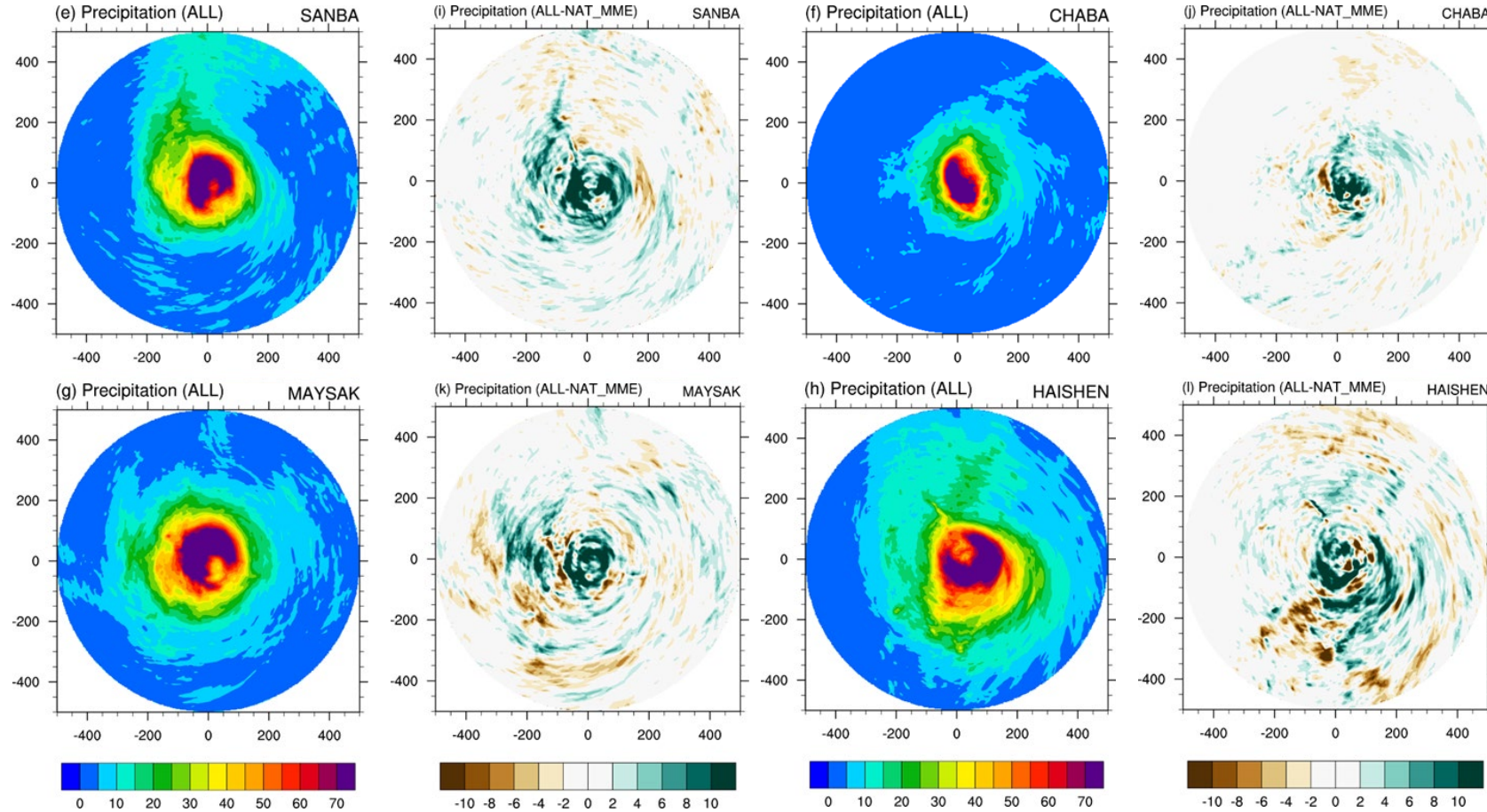
- ◆ Intensities of TC in ALL experiments are overall stronger than those of NAT experiments
- ◆ The difference in lifetime maximum intensity is much stronger than the mean intensity

TC rainfall distribution



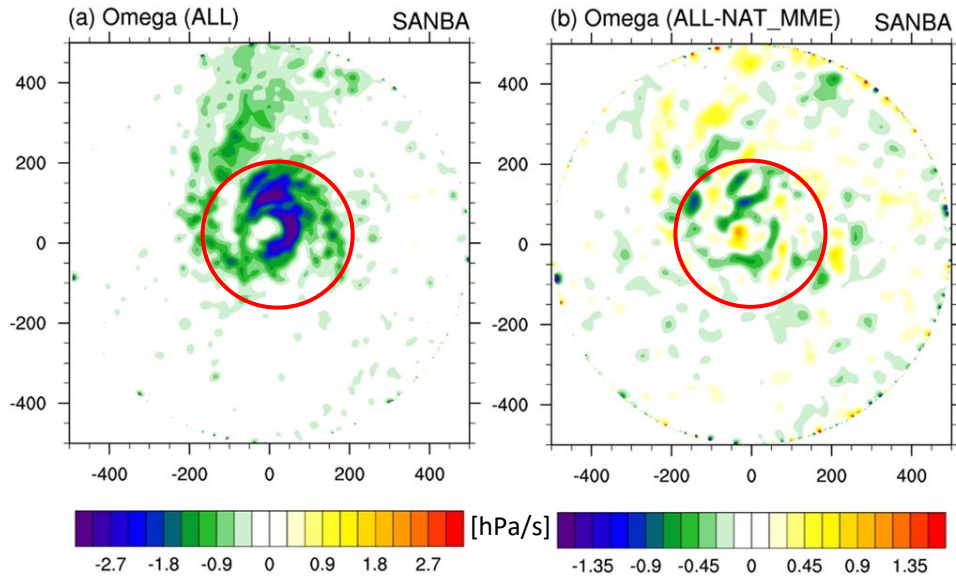
- ◆ ALL simulate increased probability in extreme rainfall (> 150 mm / 6 hr) compared to NAT in all four TCs and all delta SST clusters
- ◆ ALL-NAT differences are small in light to moderate precipitation (< 100 mm / 6 hr)

Precipitation

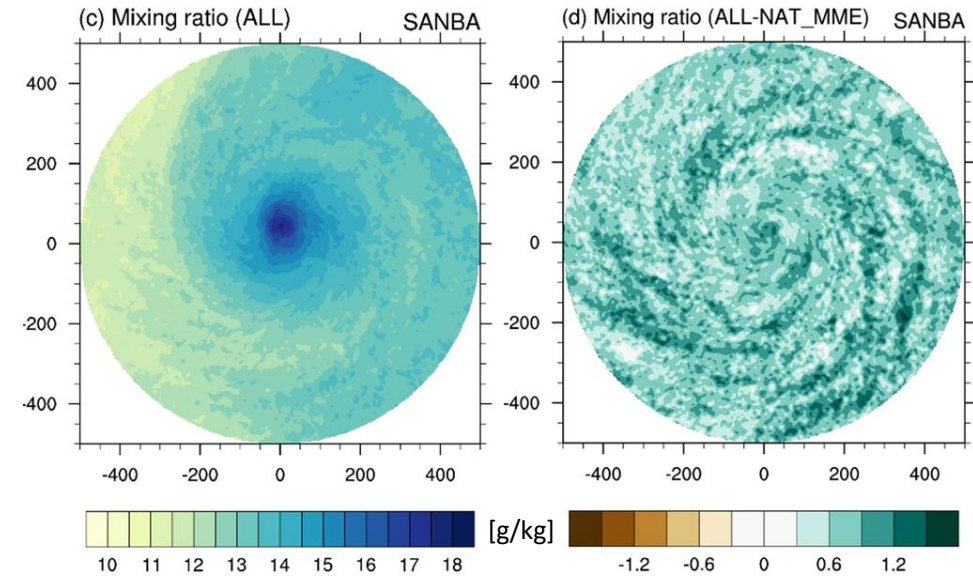


- ◆ Heavy precipitation commonly develops around the TC's inner core regions and intensifies under warming

Omega (500 hPa)



Water vapor mixing ratio (850 hPa)

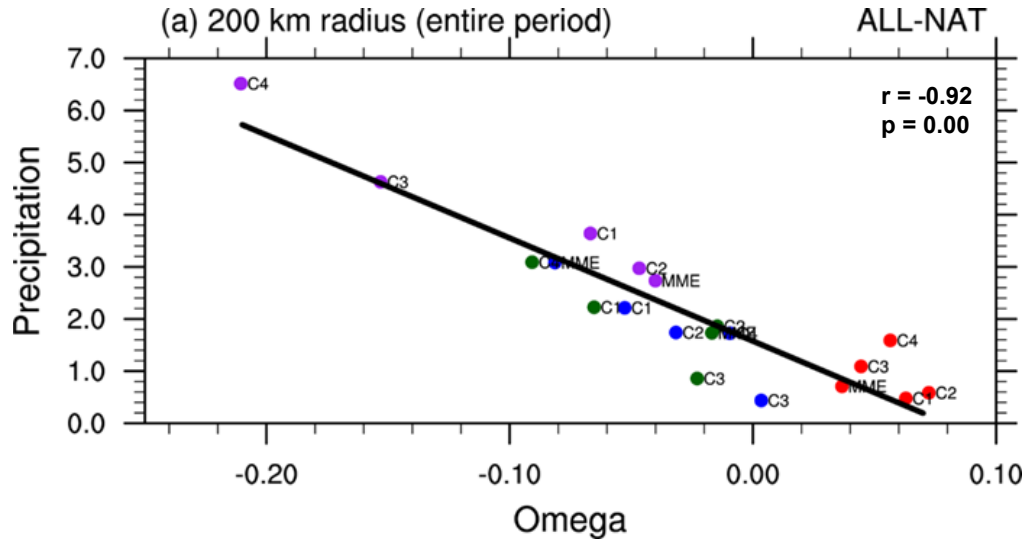


- ◆ Strong ascending motion observed near the eyewall and along spiral rainbands
- ◆ Enhance upward motion in ALL compared to NAT around the TC core

- ◆ More water vapor resides around the TC core
- ◆ Uniform increases in moisture in ALL compared to NAT over all areas within a 500 km radius

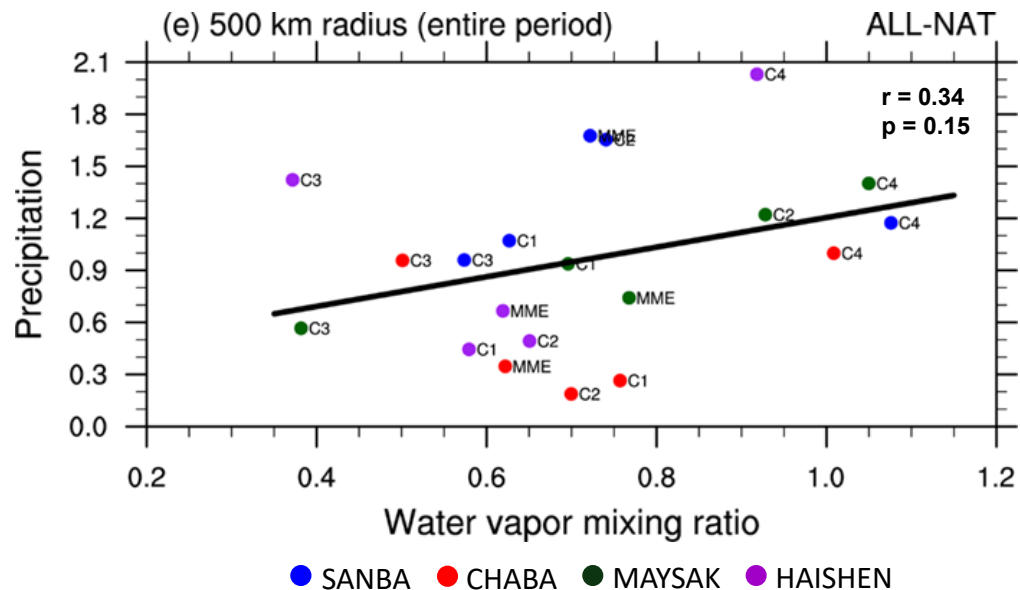
Role of Ascending Motion & Water Vapor (ALL-NAT)

Precipitation vs. Omega



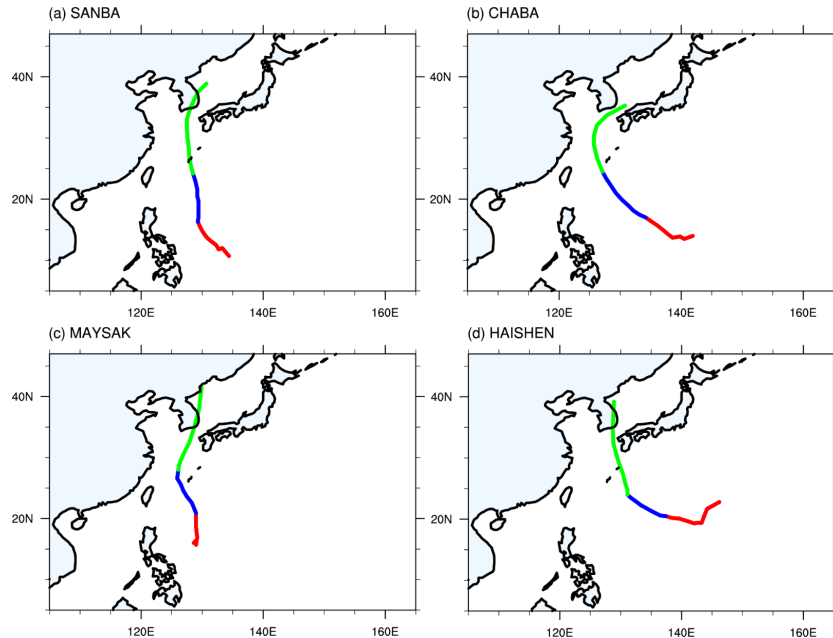
- ◆ Scatter diagrams for the precipitation ALL-NAT (y-axis) and corresponding differences in omega (x-axis)
- ◆ Very strong inter-simulation correlation ($r = -0.92$), indicating **stronger upward motion induces stronger increase in precipitation**

Precipitation vs. Water vapor



- ◆ Positive correlation between precipitation and water vapor
- ◆ C4 runs (largest ALL-NAT warming) show largest ALL-NAT in water vapor, contributing the stronger precipitation

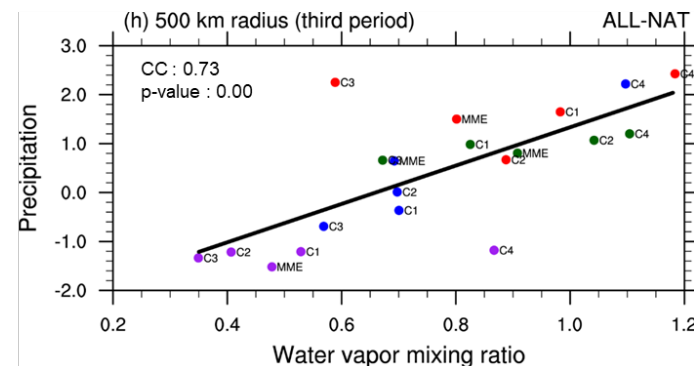
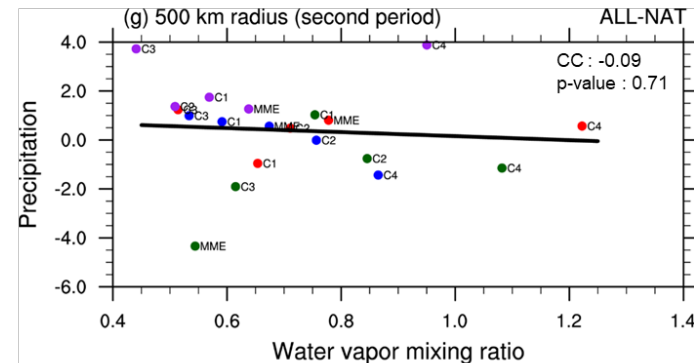
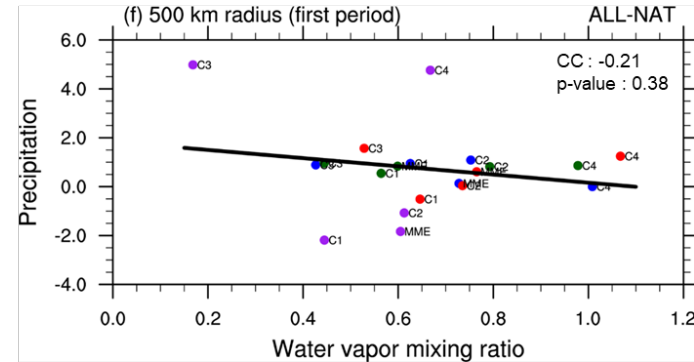
Moisture becomes important near landfall



First Period

Second Period

Third Period



Precipitation vs.
Water vapor
(500 km radius)

- ◆ Relationship between precipitation and water vapor varies depending on the TC period
- ◆ Water vapor significantly contributes to TC rainfall increase as TC to mid-latitudes

● SANBA ● CHABA ● MAYSAK ● HAISHEN

- ◆ **Convection-Permitting Model (CPM) simulations** are used to determine how human activities could affect precipitation and intensity of four strong TCs that recently struck the Korean Peninsula
- ◆ Ensemble CPM experiments are conducted for the current climate (ALL) and pre-industrial conditions (NAT)
- ◆ To **consider uncertainties in SST change patterns and associated atmospheric boundary conditions**, five SST warming patterns were used for ensemble simulations
- ◆ Simulation results show more intense TCs in ALL experiments than in NAT experiments
- ◆ **TC-driven extreme precipitation** (grids having 6-hourly precipitation > 150 mm) is **expanded by 16-37% due to global warming influence**
- ◆ **Stronger upward motion near the TC core and large-scale increase in water vapor** are identified as major causes of increased extreme precipitation
- ◆ **Caveats remain, including influences of model biases, no consideration of TC track responses, and uncertainties in anthropogenic warming patterns**

Thank You!

