EPESC – LEADER Science Meeting

Tropical cyclone response to ambitious decarbonization scenarios

Mincheol Moon[1], Seung-Ki Min[1*], Jung-Eun Chu[2], Soon-Il An[3], Seok-Woo Son[4], Ramsay Hamish[5], Wang Zhuo[6]
[1]Division of Environmental Science & Engineering, Pohang University of Science and Technology
[2]School of Energy and Environment, City University of Hong Kong
[3]Department of Atmospheric Sciences and Irreversible Climate Change Research Center, Yonsei University
[4]School of Earth and Environmental Sciences, Seoul National University
[5]Weather and Climate, School of Mathematical Sciences, Monash University
[6]Department of Atmospheric Sciences, University of Illinois at Urbana-Champaign

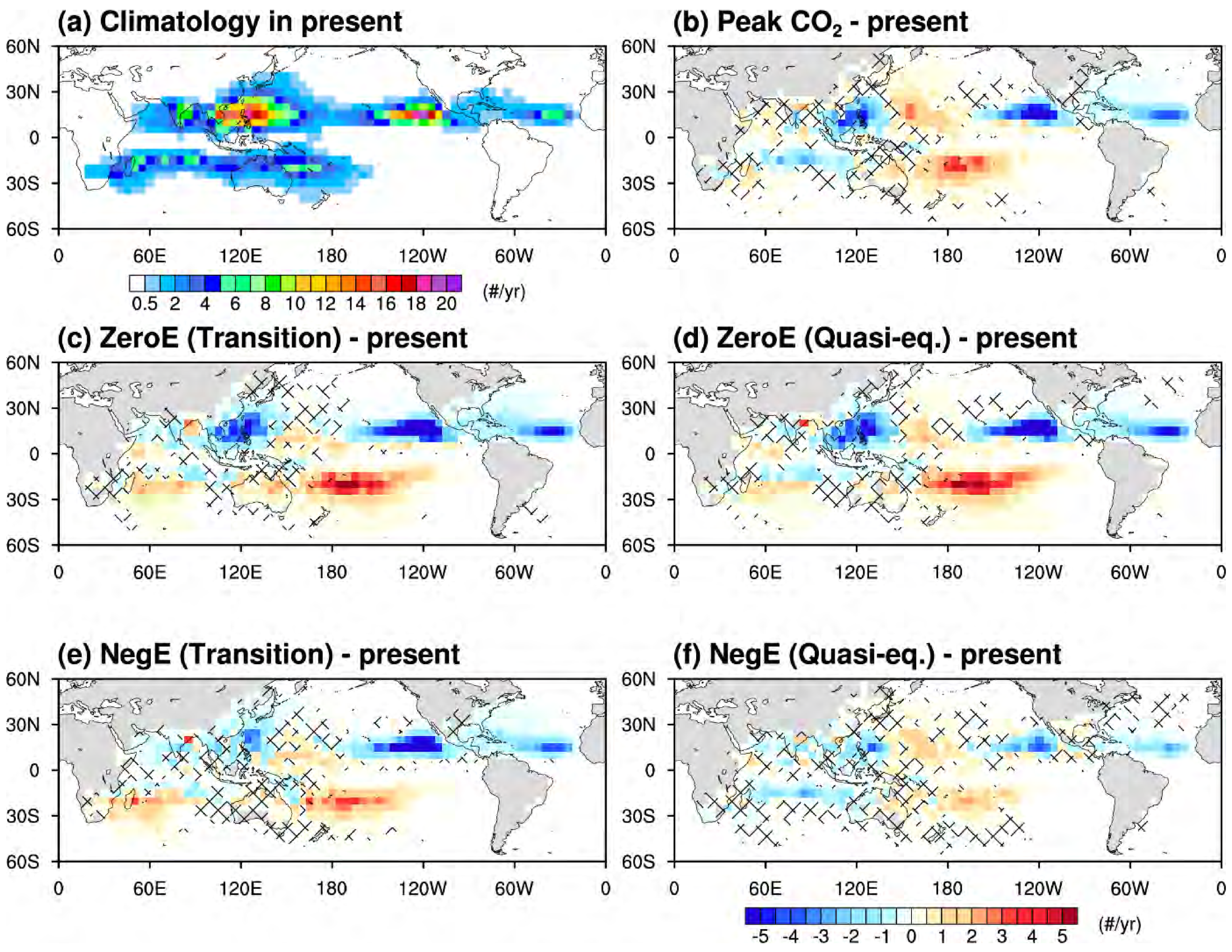
❖ Introduction

- **Under global warming**, tropical cyclones (TCs) are projected to become **stronger globally**, while their **genesis frequency decreases or remains unchanged**.
  Regional TC-related risk exposure is expected to **increase in the mid-latitudes**. *(IPCC Sixth Assessment Report)*
- Under **increased CO_2 concentrations**, the **total number of TCs decreases**, but the **frequency of intense TCs increases**. *(Chu et al., 2020)*
- Even if **CO_2 levels return to pre-industrial values**, the **hemispheric asymmetry** in TC response exhibits **hysteresis**, meaning it does not fully recover. *(Liu et al., 2024; Huan et al., 2024; Yoon et al., 2025)*

However, the **response of TCs after overcoming global warming** remains **largely unexplored**. Recent studies are **limited to genesis frequency** and overlook broader TC impacts.

- **This study aims to address this gap** by investigating how TCs respond:
  After achieving **net-zero CO_2 emissions**, and
  Under sustained **negative emission** scenarios.
- Using **an explicit TC tracking method,** we comprehensively assess future TC characteristics—including **frequency**, **intensity**, **rainfall**, and **landfall**—To better understand their **societal implications** in a post-warming climate.

❖ TC density response to decarbonization scenarios



•TC density response shows a spatial pattern consistent with previous studies
•Clear **hemispheric asymmetry** in TC frequency
•**Asymmetry persists** under ZeroE / **Asymmetry alleviated** under NegE

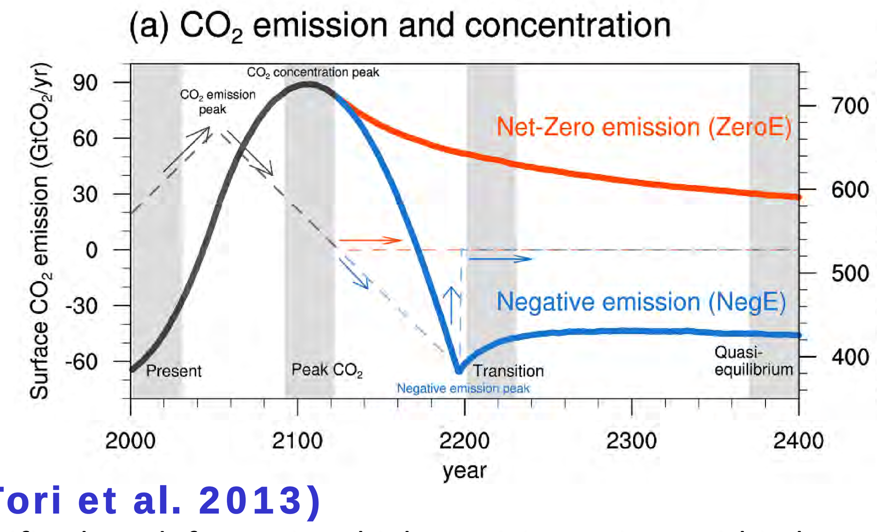
•Changes in **OWZP factor satisfaction ratios** reveal key drivers
•**RH700** and **VWS** identified as primary contributors to hemispheric asymmetry

(Moon et al. 2025)

❖ Data and Method

CESM2 experiments (CO_2 emission-driven scenarios)

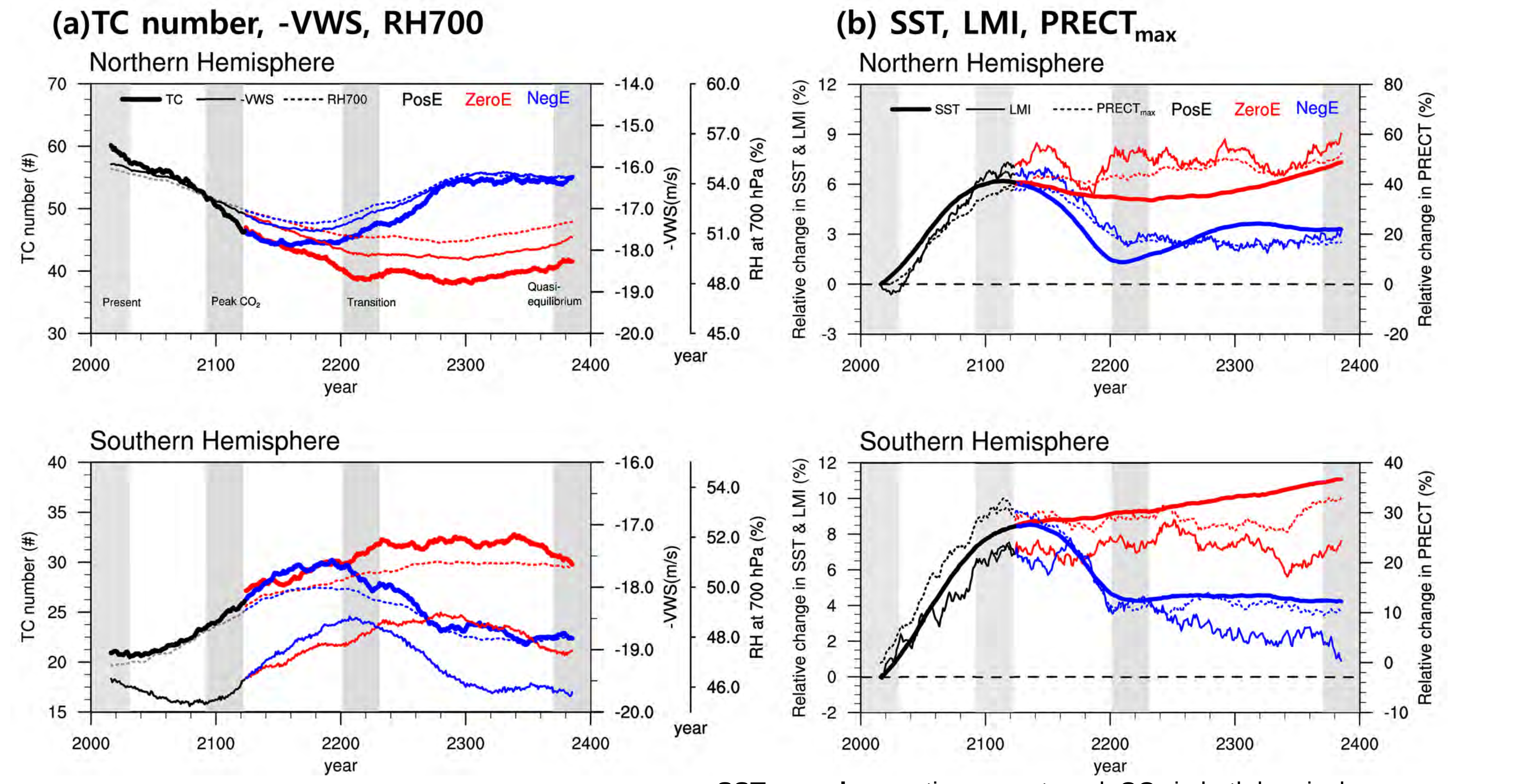
Experimental design: Initial condition (**PosE**), Net-zero emission (**ZeroE**), Negative emission (**NegE**)
Ensembles: **4** ensemble members
Period : **2000-2400**
Tracker: OWZ tracker
Analyze periods:
- **Reference period (Present: 2001-2031)**
- **Peak CO_2 (2092-2122)**
- **Transition period (ZEC/IRCC : 2201-2231)**
- **Quasi-equilibrium period (ZEC/IRCC : 2370-2400)**



Okubo-Weiss-Zeta Parameter detection (Tori et al. 2013)

The OWZP (Okubo-Weiss Zeta Product) tracking scheme identifies low-deformation, high-vorticity regions within large-scale disturbances that may lead to tropical cyclone (TC) formation. It uses the product of the normalized Okubo-Weiss parameter and absolute vorticity, combined with thermodynamic and dynamic thresholds.
The method includes:
1.Initial detection of candidate regions based on OWZ, humidity, and vertical wind shear conditions.
2.Time tracking of clusters, marking those meeting core thresholds as "True."
3.TC declaration if a track has 9 consecutive "True" detections over 48 hours (6-hour intervals). The 5th "True" point marks the genesis location.

❖ Temporal Evolution of TC Metrics and Environmental Drivers

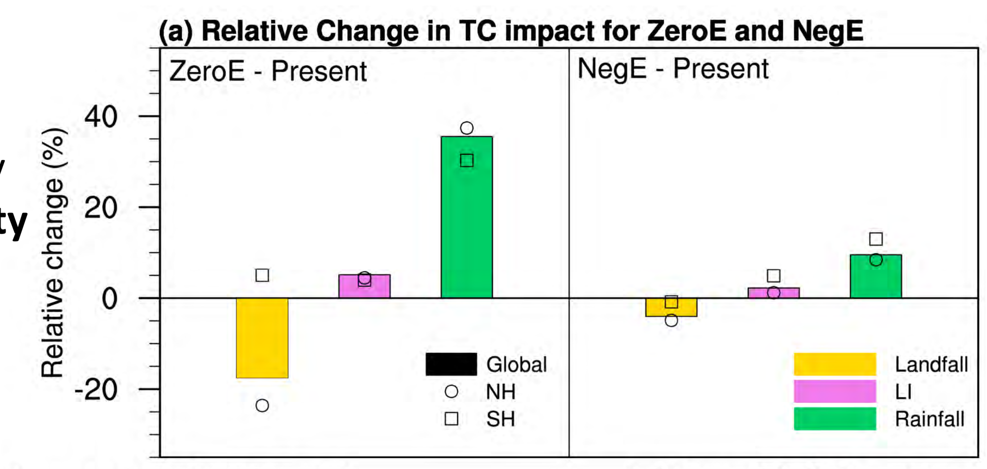


•NH: RH_{700}↓, VWS↑ → unfavorable for TC genesis
•SH: RH_{700}↑, VWS↓ → favorable for TC genesis
•These patterns explain hemispheric divergence in TC activity
•**Key drivers of hysteresis behavior**

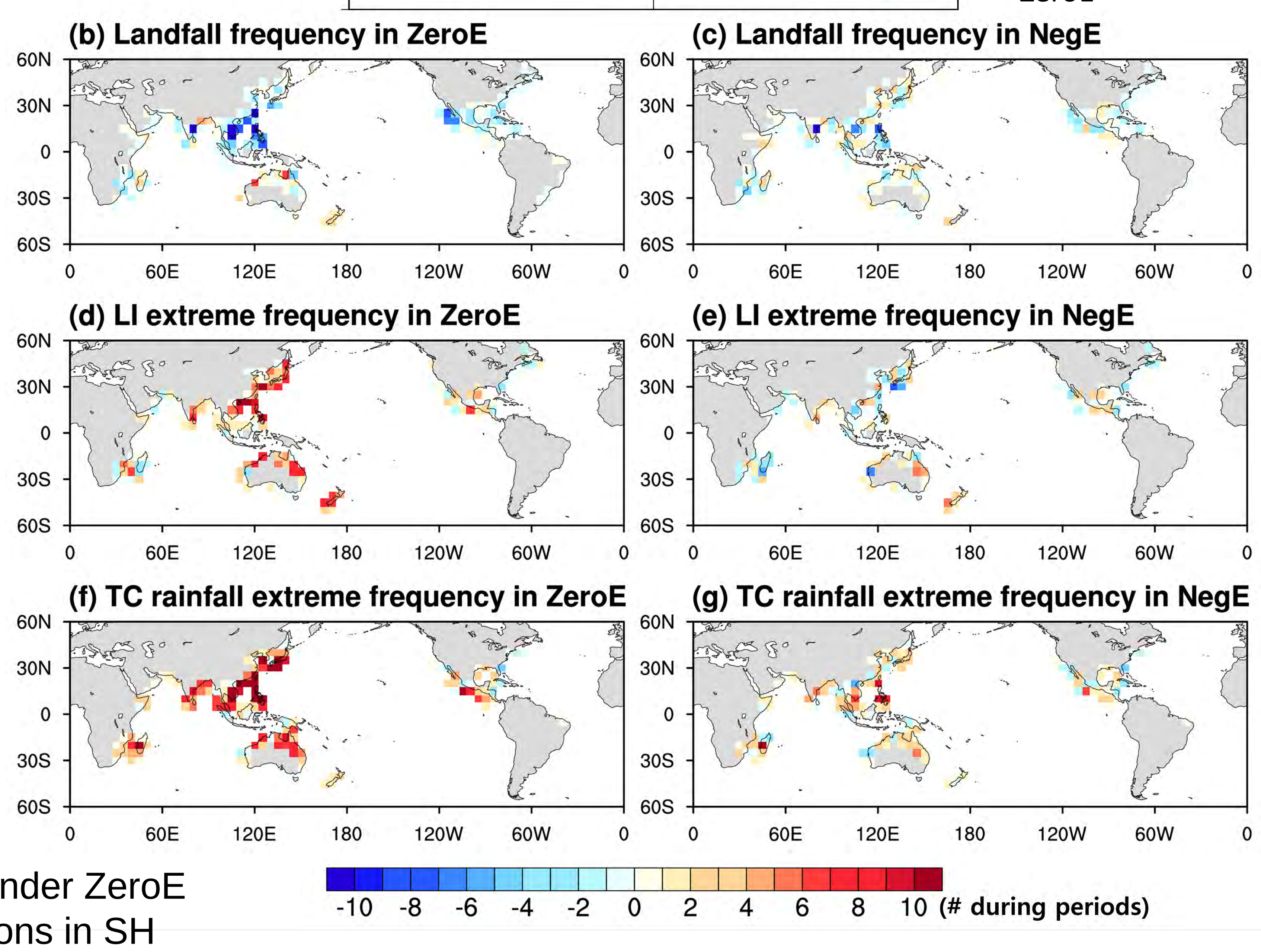
•**SST warming** continues post-peak CO_2 in both hemispheres
•**Lifetime Maximum Intensity (LMI)** increases, especially under ZeroE
•**Maximum TC rainfall ($PRECT_{max}$)** intensifies globally, particularly in SH
•Despite reduced frequency, **intensity & rainfall risks persist**

❖ Societal impacts of the future TC activities under decarbonization scenarios

ZeroE:
•**Landfall frequency** decreases (–10%) globally
•**Extreme landfall intensity** increases slightly
•**Extreme TC rainfall** increases **significantly** (>30%)



NegE:
•Landfall frequency nearly unchanged
•**Much weaker increases** in intensity & rainfall extremes
•**Suggests reduced hazard escalation** compared to ZeroE



•**Landfall Frequency (b, c)**:
Strong **decrease in WNP and EP** under ZeroE
Minor or negligible changes under NegE
•**Extreme Intensity (d, e)**:
More frequent, intense landfalls in **all Baisn** under ZeroE
Fewer changes under NegE, with some reductions in SH
•**Extreme Rainfall (f, g)**:
Substantial increase in rainfall extremes over the **all basin** under ZeroE
Smaller, more **localized increases** under NegE

❖ Summary

Net-zero emissions won't restore TC activities for about 300 years due to high **CO_2** concentration. **TC activity changes** could be **decrease, potentially intensity** and **rainfall intensifying broadly** and **raising overall risks.**
Even **if CO_2 concentration are restored through negative emissions**, TC activities return to current levels in about 100 years. Using **TCs** as an example, a **more aggressive carbon strategy** is **crucial** to **effectively reduce societal damage** by **hazards.**