# High-resolution Projections of the Extreme Wave Climate for Eastern Chinese Marginal Seas under Different Global Warming Levels

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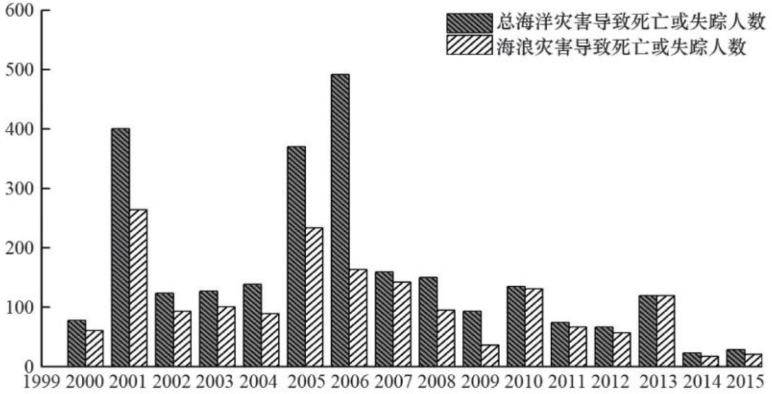
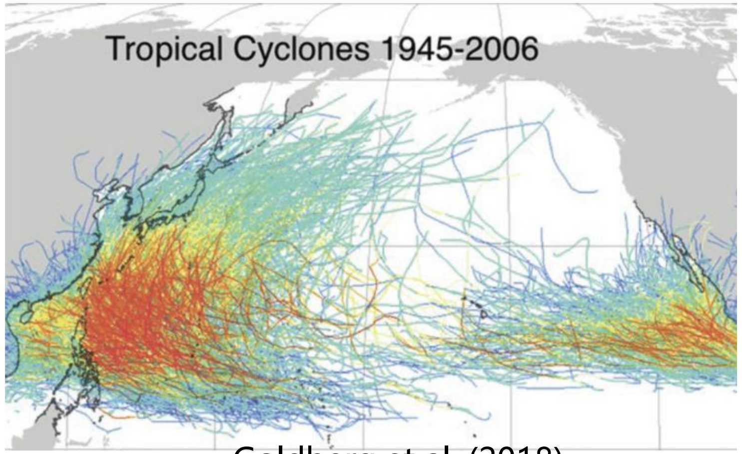
# 01 Introduction: extreme ocean waves and the impacts for China

## Extreme wave is one of the major marine hazards for China：

- the deadliest marine dynamic hazard (~74% of total deaths from marine hazards)
- Drivers: tropical cyclone, cold-air outbreak, extratropical cyclone
- Other impacts: coastal infrastructure damage, coastal erosion, coastal flooding …



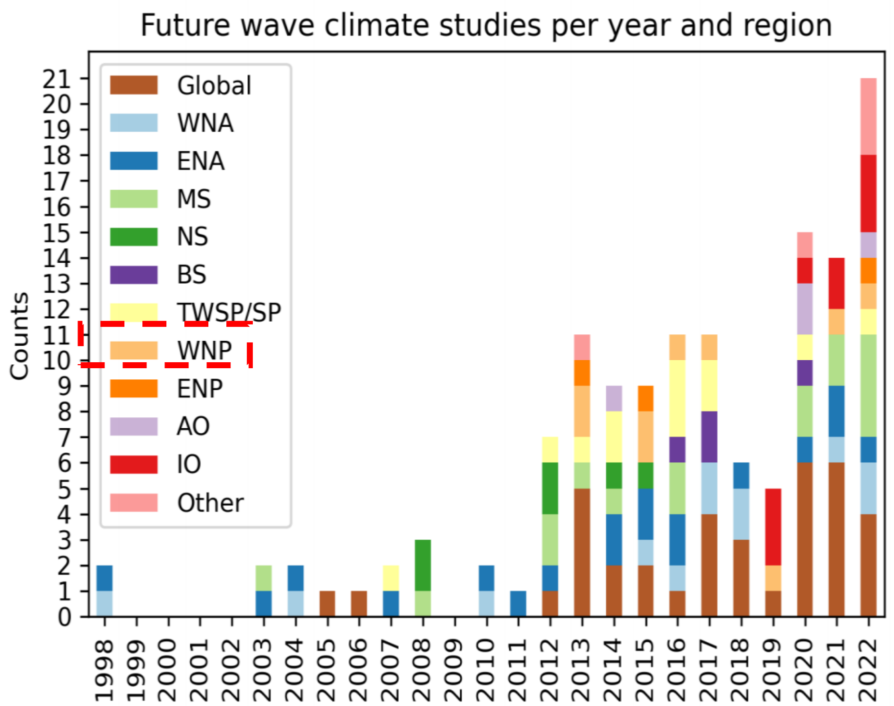

Annual deaths due to all marine hazards and extreme wave hazard (Tao et al. 2018)




Goldberg et al. (2018)

# 01 Introduction: future (extreme) ocean waves studies

- Since the launch of Coordinated Ocean Wave Climate Project (COWCLIP, Hemer et al. 2012), significant increase in future ocean wave climate studies
- Only one study focused on the Chinese mariginal Seas (Li et al. 2022)




Regional future wind-wave climate for the NWP

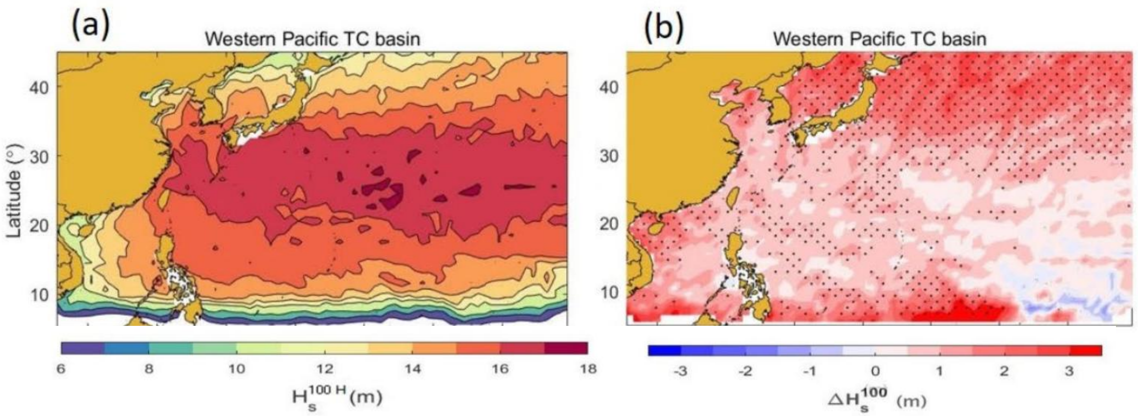
| # | Wave resolution | Method/Data | # GCM (-RCM) | Forcing resolution | Emission scenarios | IPCC | Paper |
|---|---|---|---|---|---|---|---|
| 8 | 0.1° | WAM | 1 | 0.22° | RCP2.6, RCP8.5 | AR5 | Li *et al.* (2022)[88] |
| 7 | 0.1° | SWAN | 6 | 1.1°-2.5° | RCP8.5 | AR5 | Ninomiya *et al.* (2021)[89] |
| 6 | 0.033° | WAM | 5 | 6 km | RCP4.5 | AR5 | Taniguchi (2019)[90] |
| 5 | 0.5° | WW3 | 8 | 0.9°- 1.8° | SSP2-4.5, SSP5-5.8.5 | AR6 | Badriana & Lee (2021)[91] |
| 4 | 60 km-1° | WW3 | 10 | 60 km-2.8° | RCP8.5 | AR5 | Shimura *et al.* (2017)[92] |
| 3 | 0.5° | Existing data[39] | 1 | 60 km | A1B | AR4 | Mori *et al.* (2016)[93] |
| 2 | 0.5° | Existing data[39] | 1? | 60 km | A1B | AR4 | Shimura *et al.* (2015a)[94] |
| 1 | 0.5° | WW3 | 1? | 60 km | A1B | AR4 | Shimura *et al.* (2015b)[39] |

Casas-Prat et al. (2024)

# 01 Introduction: future changes in extreme ocean waves in the NWP

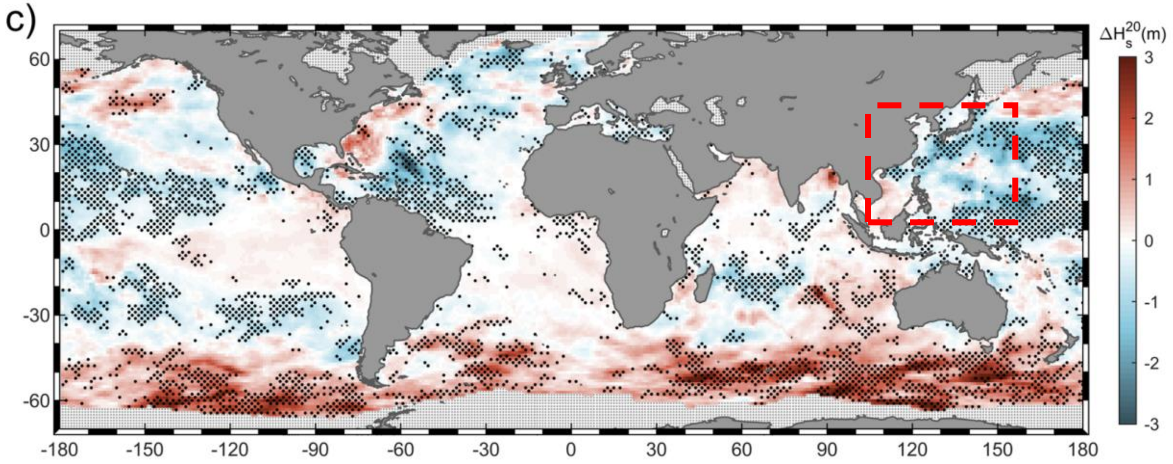
## Projections in the extreme ocean waves in the NWP are uncertain

**Increase of TC-wave $Hs^{100}$, end of 2050 - (1980-2017), SSP585**



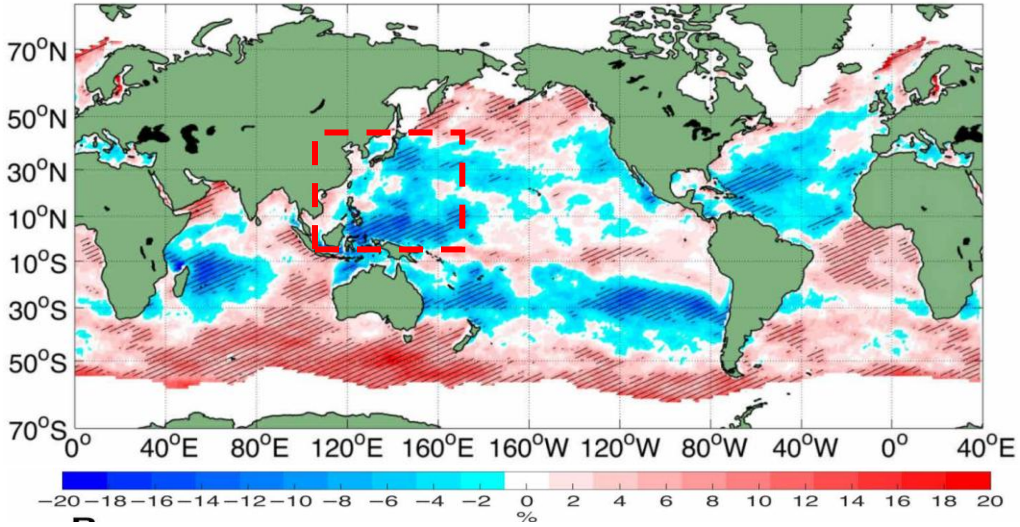

Grossmann-Matheson et al. (2024)

**General decrease of $Hs^{20}$, (2081-2100)-(1986-2005) RCP8.5**



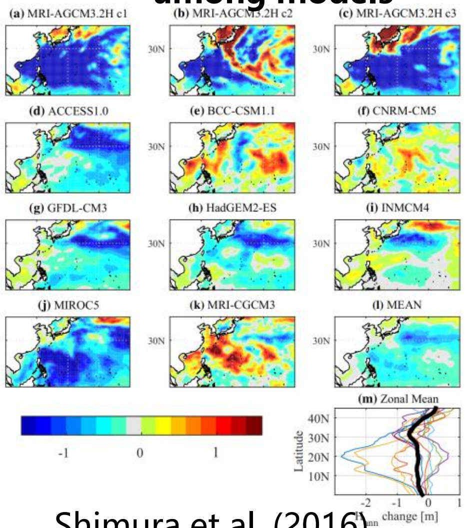

Lobeto et al. (2021)

**General decrease of $Hs^{100}$, (2081-2100)-(1979-2005) RCP8.5**



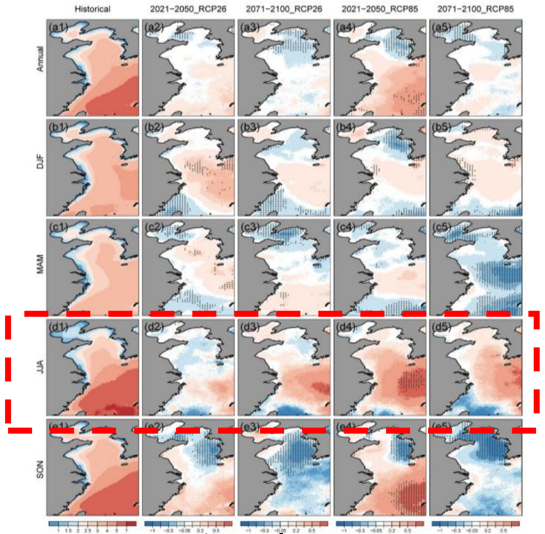

Meucci et al. (2020)

**Large variation in Hs_ann change among models**




Shimura et al. (2016)

**Increase in 99p Hs for summer, RCP26 and 85**




Li et al. (2022)

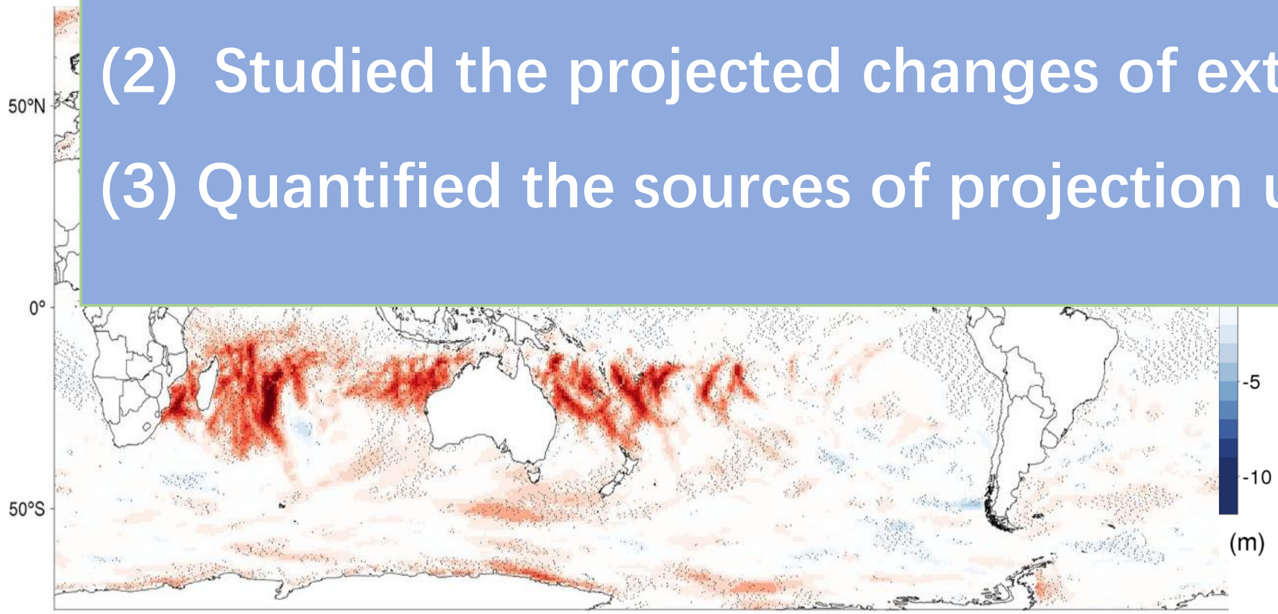
# 01 Introduction: potential limitations

- **Coarse CMIP5/6 GCMs wind forcings:** cannot well resolve regional (extreme) wind systems
- **One-single forcing projection:** limited representation of uncertainty and potentially inaccurate projections
- 

(1) Produced ensemble wave projections driven by high-resolution wind forcings

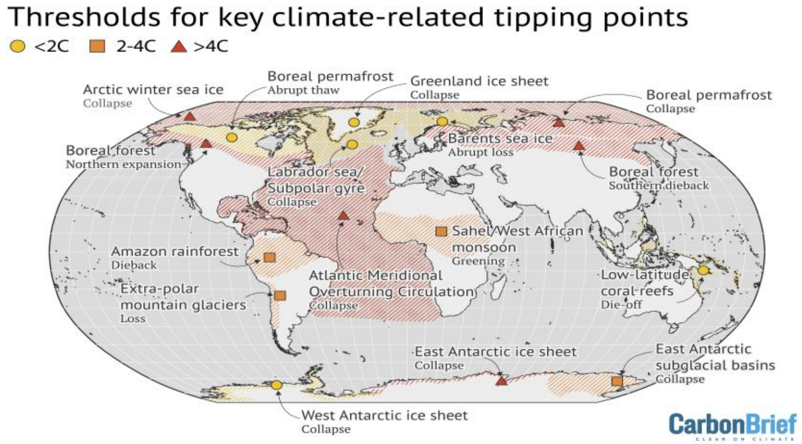
(2)  Studied the projected changes of extreme ocean waves under different GWLs

(3) Quantified the sources of projection uncertainties spatally and temporally




Differences between 0.25° and 1.0° forcing for Hs[20]
(Timmermans et al., 2017)

Casas-Prat et al. (2024)



# 02 Data and methods: high-resolution wind forcing data

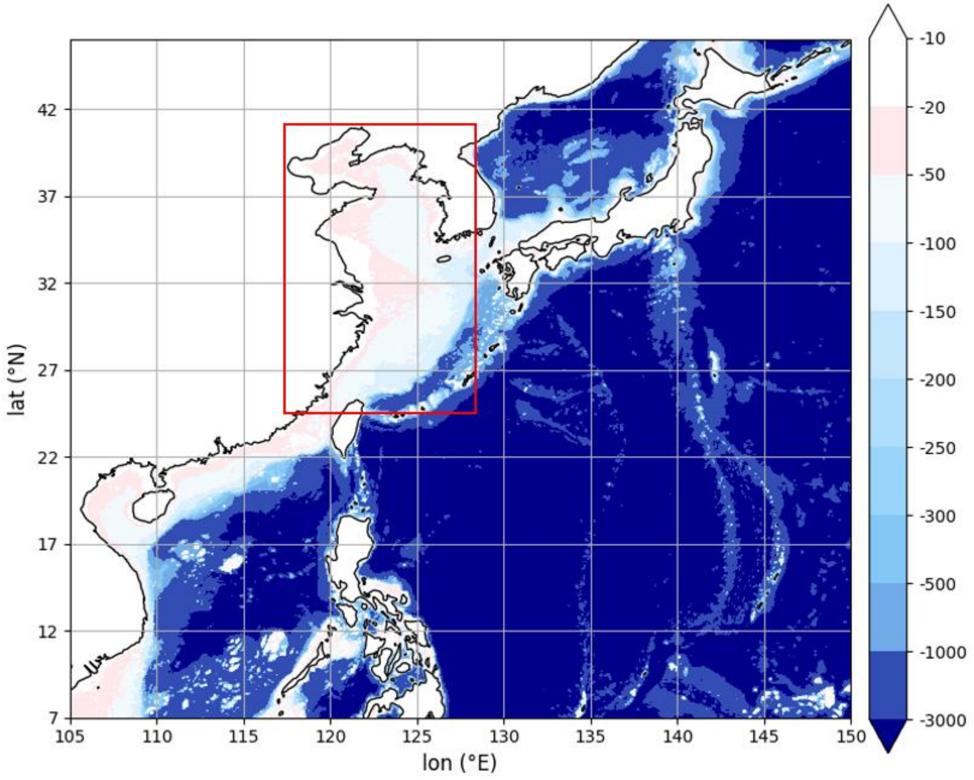
## Overview of six groups of RCM simulations from CORDEX-EA

| RCM | forcing GCM | Institution | Historical-runs | Future-projections | Senarios |
|---|---|---|---|---|---|
| CCLM | HadGEM2-AO | NIMR-KMA | 1979-2005 | 2006-2100 | RCP26, 85 |
| RegCM4-4 | HadGEM2-ES | MOHC | 1979-2005 | 2006-2099 | RCP26, 85 |
| CCLM | MPIESM-LR | MPI-M | 1979-2005 | 2006-2100 | RCP26, 85 |
| RegCM4-4 | MPIESM-MR | MPI-M | 1980-2005 | 2006-2098 | RCP26, 85 |
| RegCM4-4 | NorESM1-M | NCC | 1979-2005 | 2006-2100 | RCP26, 85 |
| CCLM | UKESM1 | NIMS-KMA | 1979-2014 | 2015-2100 | **SSP126, 585** |

Spatiotemporal Resolution: **0.22°, 3 hourly**

# Data and methods: Wave dynamical downscaling experiments

- **WAM Nesting simulations:** 24 directions and 25 frequencies from 0.04118 to 0.41145 Hz
- **Outer domain:** Northwest Pacific Ocean (0.5 degree) ·
- **Inner domain:** Bohai, Yellow Sea, East China Sea (0.1 degree)
- **Total numbers:** hindcast, historical, future projection simulations (6*3+1)*2=38 simulations



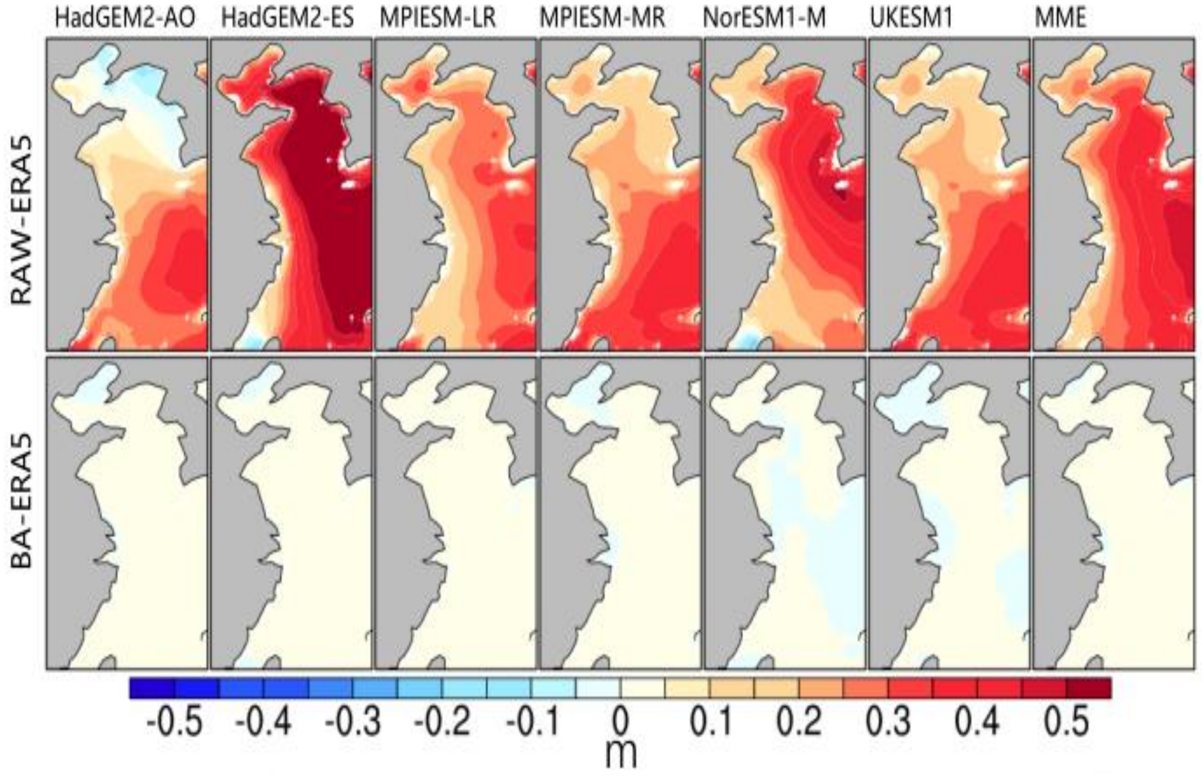

**Topography (in meters) of the modeling areas**

| Downscaling experiments | Type | Periods | Forcing | Resolution |
|---|---|---|---|---|
| WAM_ERA5 | Hindcast | 1979-2019 | ERA5 | NWP(0.5°) BYE (0.1°) |
| WAM_hist | Historical run | 1979-2005 | 6 RCM (0.22°) | NWP(0.5°) BYE (0.1°) |
| WAM_RCP26 | Future projection | 2006-2098 | 6 RCM (0.22°) | NWP(0.5°) BYE (0.1°) |
| WAM_RCP85 | Future projection | 2006-2098 | 6 RCM (0.22°) | NWP(0.5°) BYE (0.1°) |

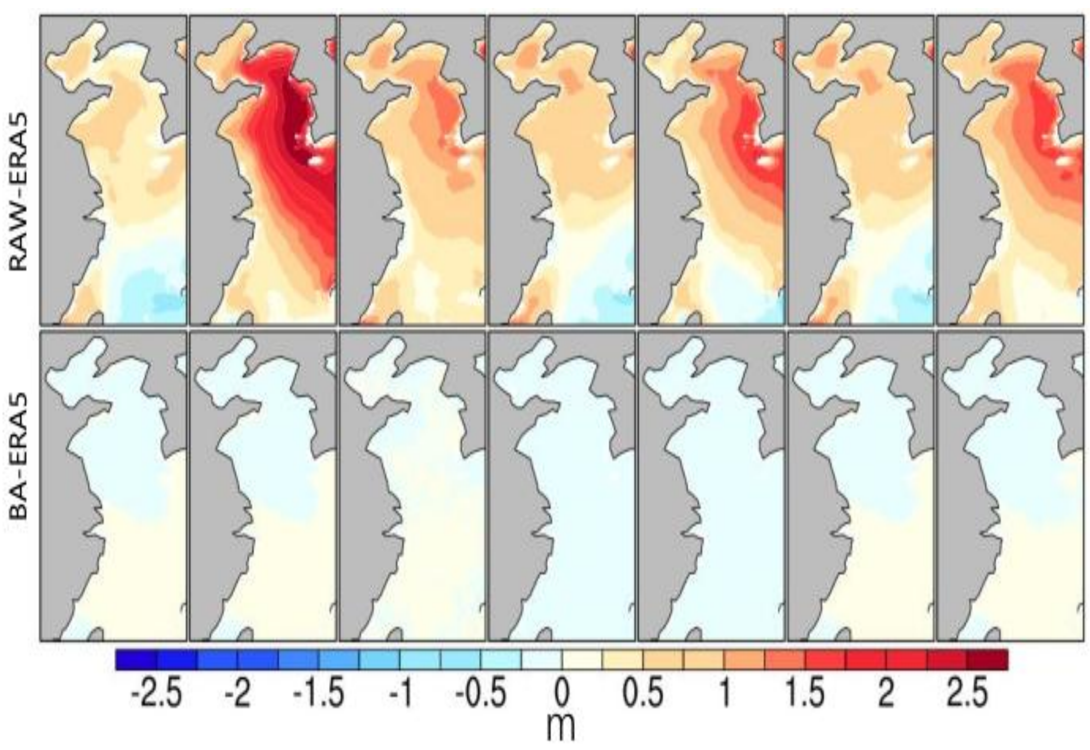
# Data and methods: Bias correction of wave fields

- Multivariate bias correction method (MBCn, Cannon, 2018) on Hs and MWP
- Correct biases in marginal distribution of individual wave variables and the multivariate dependence structure.

Mean Hs



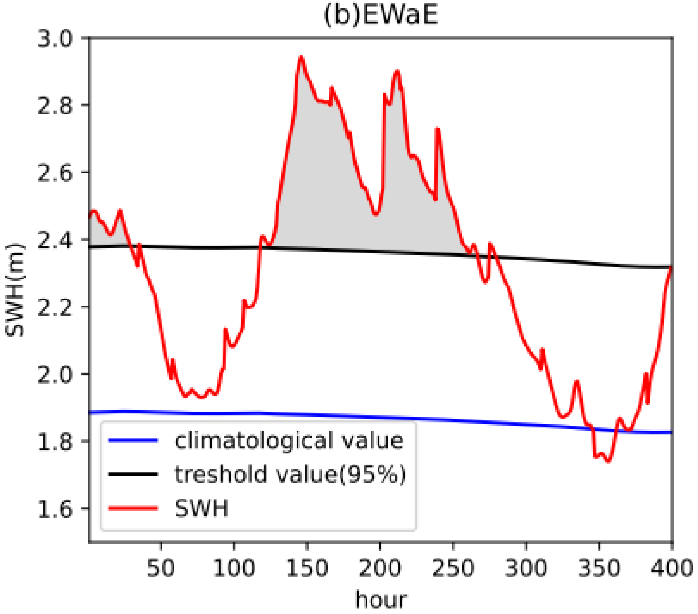

Hs_99p




The differences of raw and bias-adjusted WAM historical simulation against WAM hindcast

# Data and methods: Definition of extreme wave events

- ## Wave Storm




（Liu, Li* et al.2024, OE)

- ☐ Extreme wave event (EWE) should last for at least 12 consecutive hours and be separated from other events by at least 48 hours ( Weisse and Günther, 2007; and Lobeto et al. 2024).

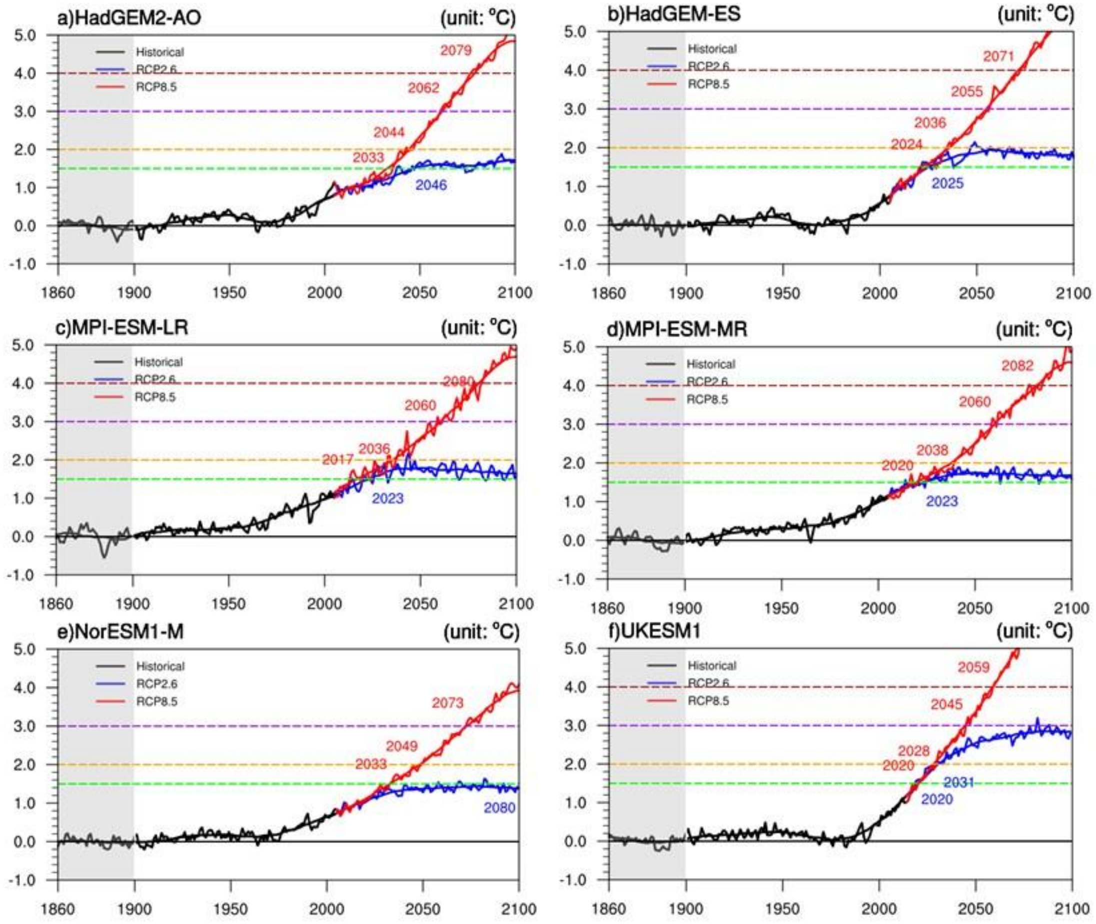
| Name | Definition | Unit |
| --- | --- | --- |
| count | The period from ts to te is recorded as an EWE, and thenumber of EWaE is count. | |
| duration | The hours of ts to te are the duration of an EWE. | hour |
| intensity_mean | i = Hsh− Hscl, averaging the intensities (i) within an EWE is noted as intensity_mean. | m |

- ## COWCLIP extreme wave indices

- ☐ **HsRo, rough wave days：** the number of days when the daily maximum SWH exceeds 2.5 m
- ☐ **HsHi, high wave days：** the number of days when the daily maximum SWH exceeds 6 m

# 02 Data and methods: GWLs and uncertainty analysis

- **Time windows of different global warming levels**




**Timing of 1.5° C, 2.0° C, 3.0° C and 4.0° C Global Warming Above the Pre-Industrial Level (1860–1900) Under different Scenarios.**

- **Uncertainty analysis methods——analysis of variance (Hawkins and Sutton, 2009, BAMS)**

$$\mathbf{X(m,s,t) = x(m,s,t) + i(m,s) + \varepsilon(m,s,t)}$$

$$\mathbf{M(t) = \frac{1}{N_s}\sum_s var_m(\ x(m,s,t))}$$

$$\mathbf{S(t) = var_s(\frac{1}{N_m}\sum_m x(m,s,t))}$$

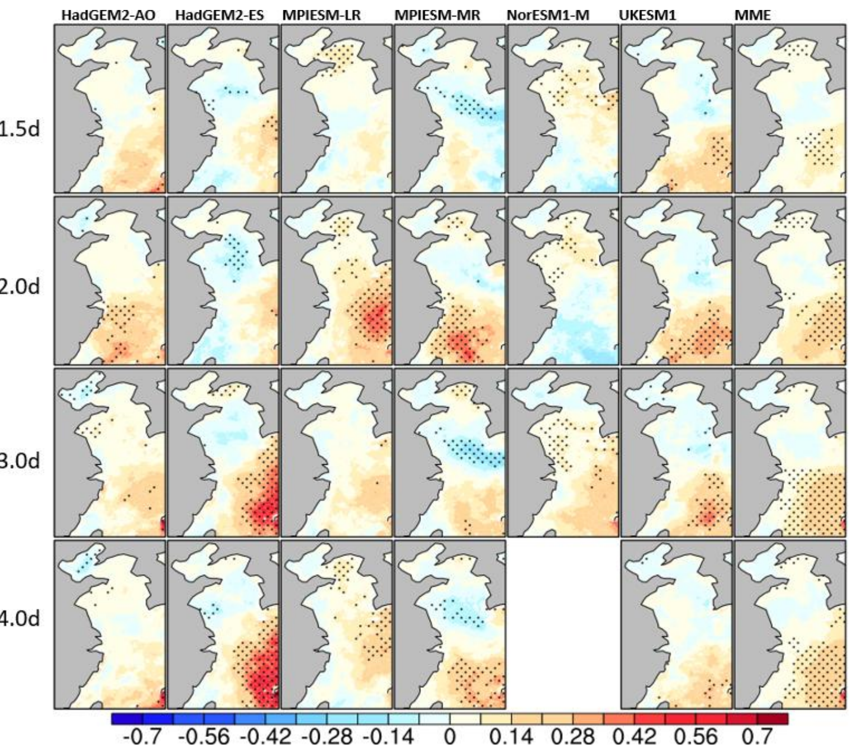
$$\mathbf{V = \frac{1}{N_m}\sum_m var_{s,t}(\ \varepsilon(m,s,t))}$$

$$\boldsymbol{T(t) = V + S(t) + M(t)}$$

**M: model variance; S: emission scenario variance; V: climate system internal variability variance; T: total variance**

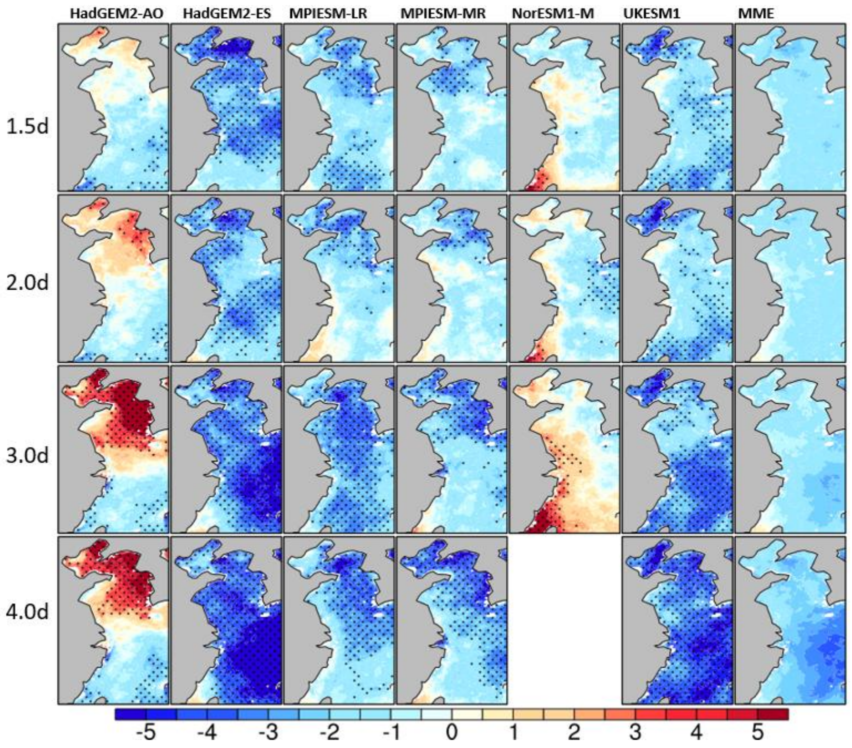
# Results: Projected changes in extreme wave events (EWE) under different GWLs

**Projected Changes of EWE mean intensity**



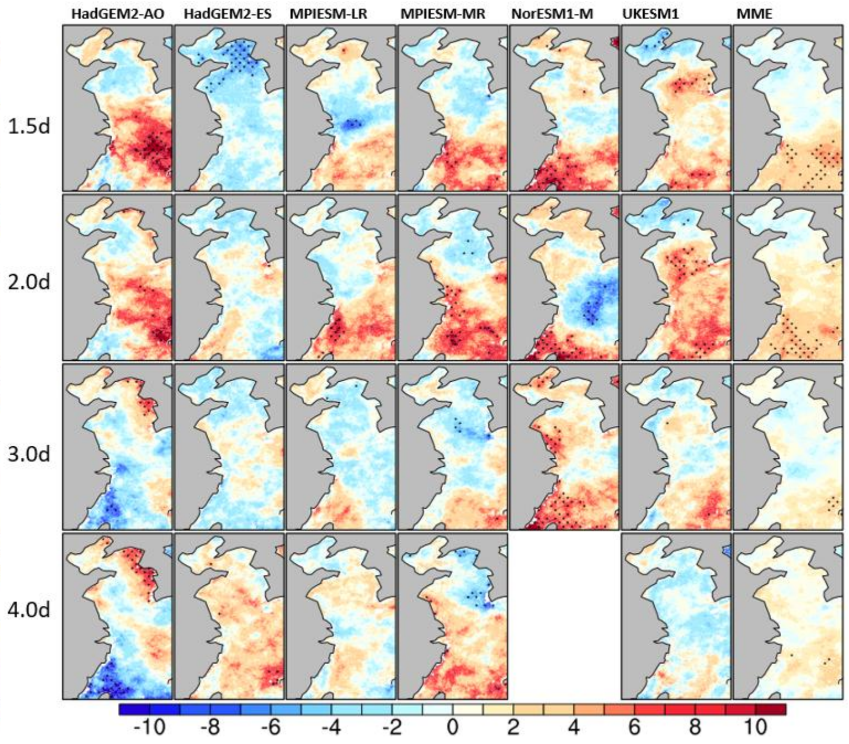

increasing mean intensity of EWE in the East China Sea, being high agreement across models

**Projected Changes of annual EWE counts**



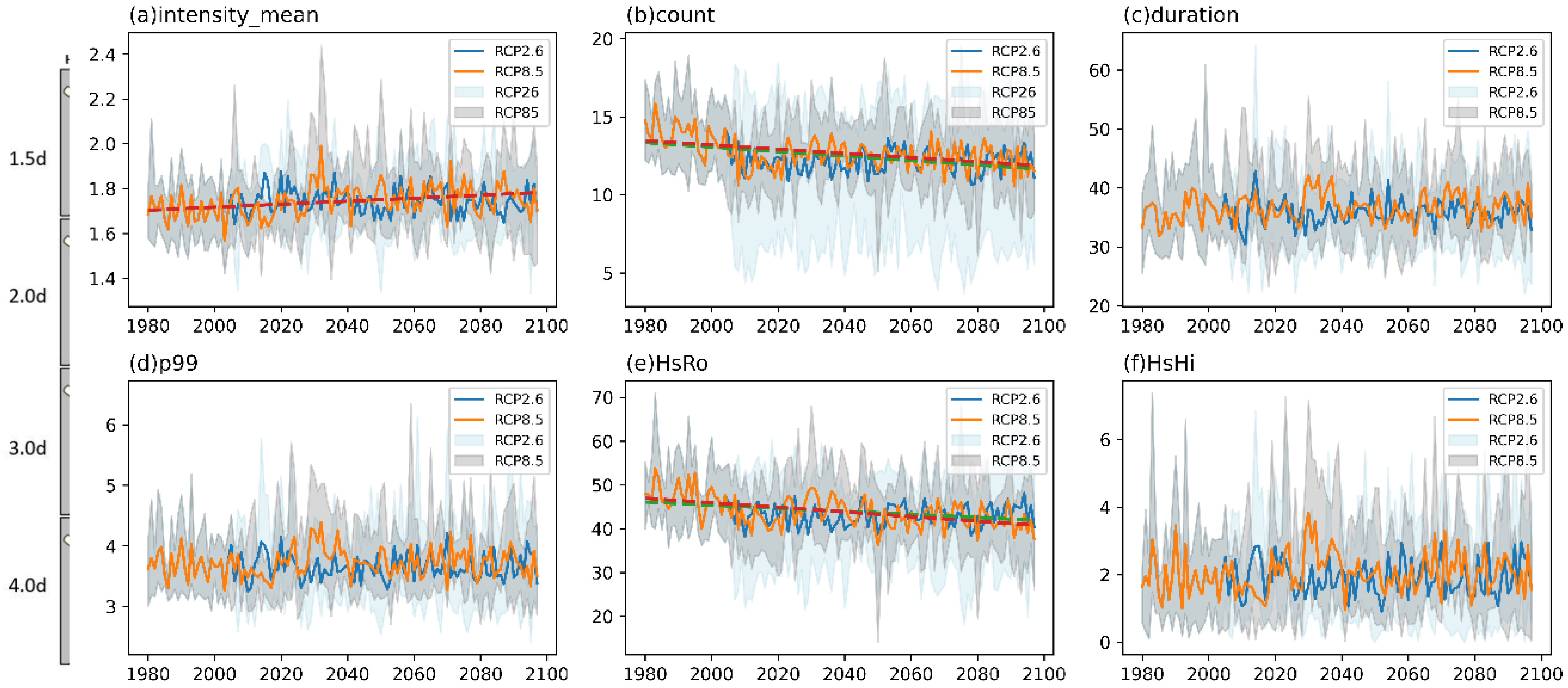

General decline of annual EWE counts, more pronounced with increasing GWL.

**Projected Changes of EWE mean duration**

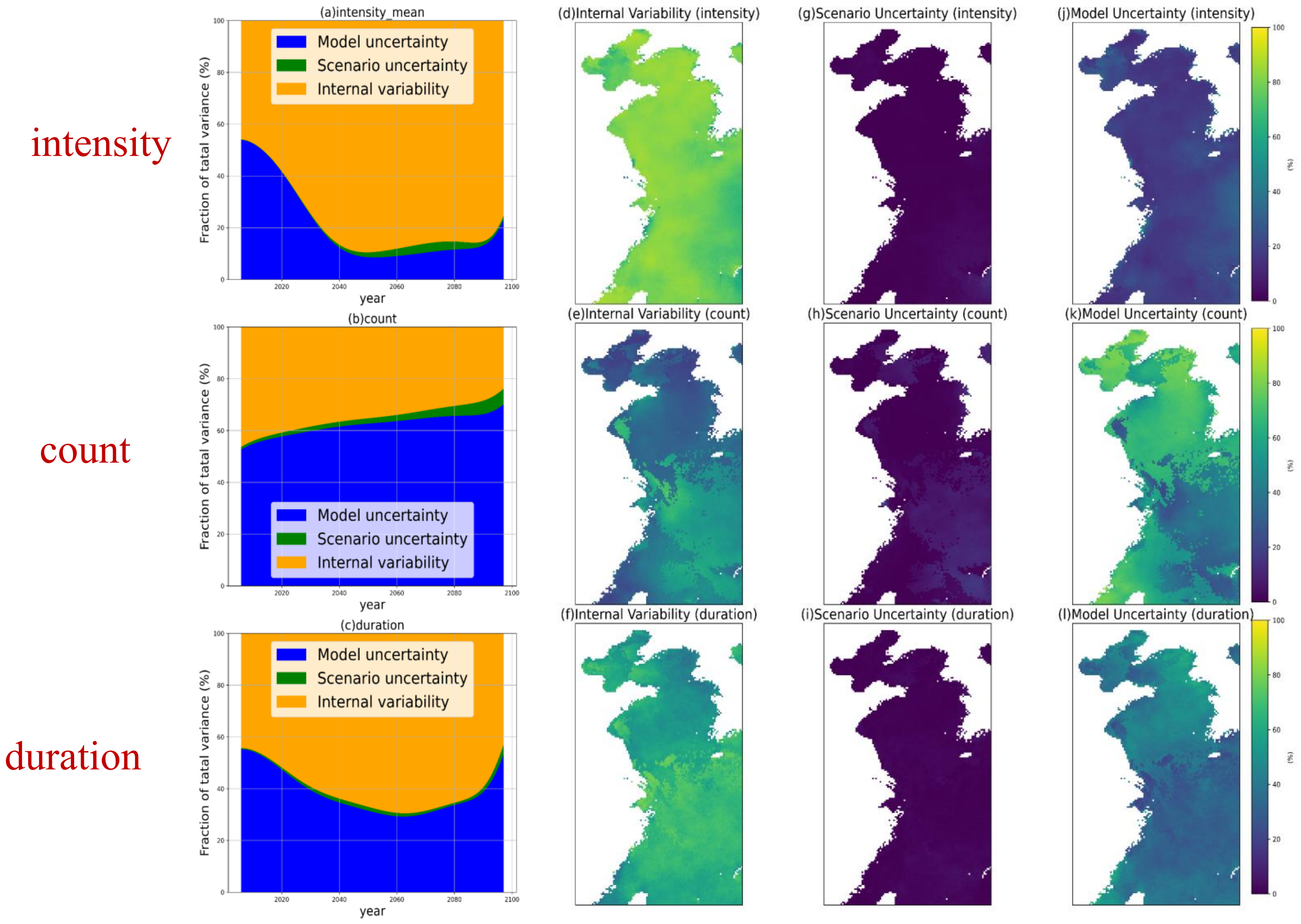



Increasing trend in the East China Sea and a decreasing trend in the Yellow Sea and Bohai Sea.

# 03 Results: Projected changes in extreme wave events (EWE) under different GWLs



# 03 Results: Sources of projection uncertainty temporally and spatially




**Percentage of projection uncertainty for mean intensity, count, and duration of extreme wave events**

- **Projection uncertainties of intensity and duration:** dominated by internal variability uncertainty, accounting for more than 50%
- **Projection uncertainties of count:** dominated by model uncertainty

# 04 Conclusions and outlook

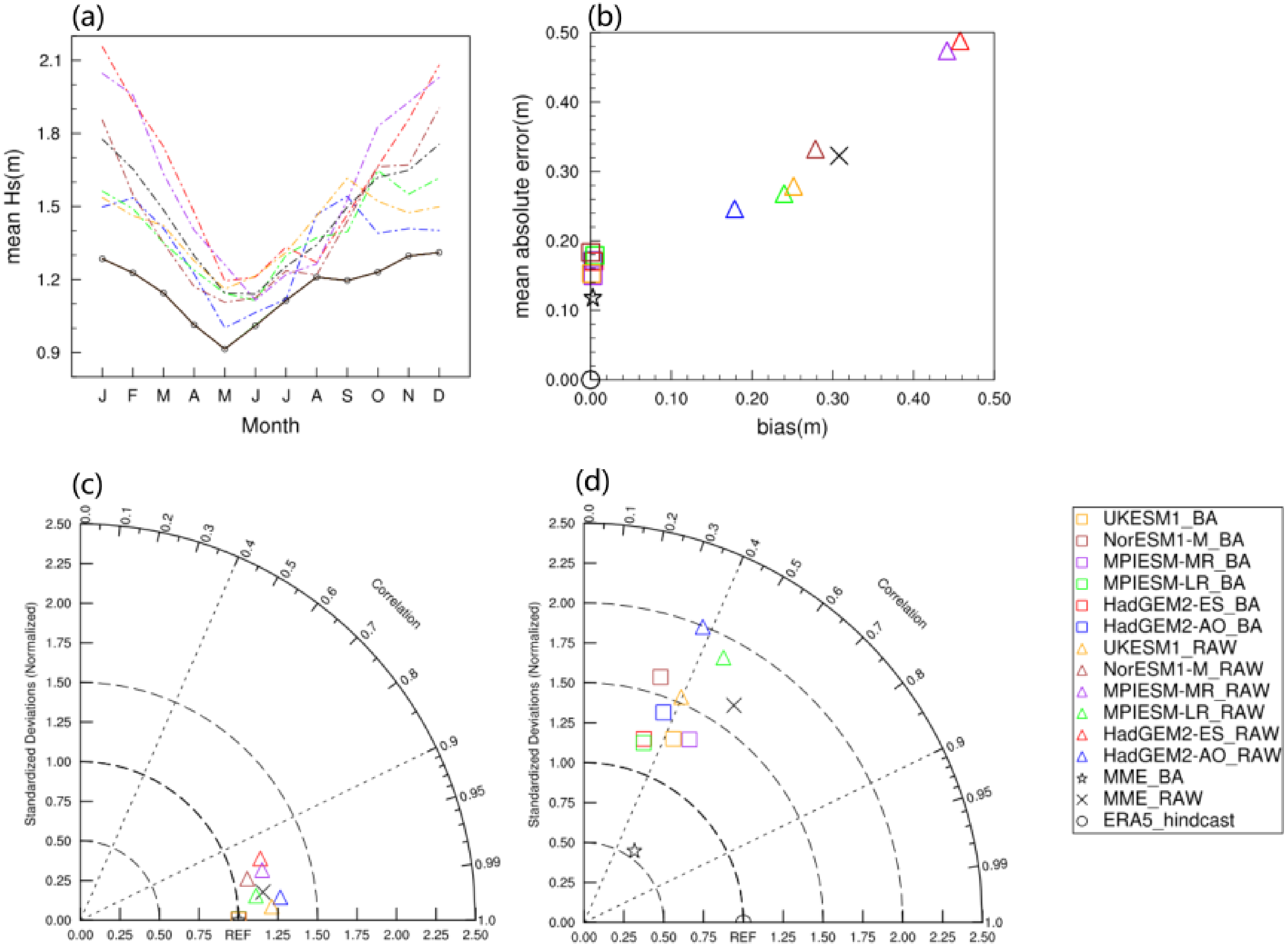
## • Conclusions

- The intensity of extreme wave events in the BYE region will experience a significant increasing trend under future high warming levels, especially in the East China Sea, featuring high consistency among models.
- The frequency of extreme wave events shows a decreasing trend, more prounced with increasing GWLs.
- Projection Uncertainty of intensity and duration is dominated by internal variability uncertainty , followed by uncertainty in the model uncertainty and emission scenarios.

## • Nest steps

- Investigate physical mechnisms for the extreme wave projections.
- The potential reasons for the dominant internal variability uncertainty
- Projected changes of TC-generated extreme waves/ocean wave energy

# Thanks！


(a)
mean Hs(m)
2.1
1.8
1.5
1.2
0.9
J F M A M J J A S O N D
Month
(b)
mean absolute error(m)
0.50
0.40
0.30
0.20
0.10
0.00
0.00 0.10 0.20 0.30 0.40 0.50
bias(m)
(c)
(d)
Standardized Deviations (Normalized)
Correlation
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 0.95 0.99 1.0
2.50 2.25 2.00 1.75 1.50 1.25 1.00 0.75 0.50 0.25 0.00
0.00 0.25 0.50 0.75 REF 1.25 1.50 1.75 2.00 2.25 2.50
UKESM1_BA
NorESM1-M_BA
MPIESM-MR_BA
MPIESM-LR_BA
HadGEM2-ES_BA
HadGEM2-AO_BA
UKESM1_RAW
NorESM1-M_RAW
MPIESM-MR_RAW
MPIESM-LR_RAW
HadGEM2-ES_RAW
HadGEM2-AO_RAW
MME_BA
MME_RAW
ERA5_hindcast

In this study, an analysis of variance (ANOVA) (Hawkins and Sutton, 2009) was used to quantify the three sources of uncertainty in the wave ensemble prognostic test (uncertainty in the emission scenarios, uncertainty in the modeled response, and uncertainty in the natural variability within the climate system), as described in the following calculation steps:

Assuming that $X(m,s,t)$ is an original time series, where $m$ is the mode, $s$ is the emission scenario, and $t$ is the simulation time, $X(m,s,t)$ is first fitted with a fourth-order polynomial. $X(m,s,t)$ can be expanded as:

$$X(m,s,t) = x(m,s,t) + i(m,s) + \varepsilon(m,s,t) \qquad (1)$$

where $x(m,s,t)$ is the fourth-order polynomial fitting equation for $X(m,s,t)$, $i(m,s)$ is the climatic state mean of the wave climate element in the reference phase under the $m$ model $s$ emission scenario, and $\varepsilon(m,s,t)$ represents the internal variability. Afterward, the model variance, the emission scenario variance, and the climate system internal variability variance were calculated as follows:

$$M(t) = \frac{1}{N_s}\sum_s var_m(\ x(m,s,t)) \qquad (2)$$

$$S(t) = var_s(\frac{1}{N_m}\sum_m x(m,s,t)\ ) \qquad (3)$$

$$V = \frac{1}{N_m}\sum_m var_{s,t}(\ \varepsilon(m,s,t)) \qquad (4)$$

$N_m$ and $N_s$ represent the number of models and emission scenarios, respectively, and $\sum_m var_{s,t}(\ \varepsilon(m,s,t))$ represents the sample variance of different emission scenarios and simulation times for model $m$. $\varepsilon(m,s,t)$ has undergone a 10-year moving average before the variance is calculated in Eq. (4). The variance obtained from Eqs. (2), (3) and (4) reflects the uncertainty of wave projection from model response, emission scenarios and internal variability of the climate system, respectively. We assume that there are no interactions between these three sources of uncertainty, resulting in a total variance of:

$$T(t) = V + S(t) + M(t) \qquad (5)$$

where $T(t)$ represents the total uncertainty of the prediction. Finally, the proportions of the three sources of uncertainty to the total uncertainty were calculated. Using the above methodology, we explored the temporal evolution characteristics and spatial distribution pattern of the three sources of uncertainty in the prediction of extreme waves offshore China in the 21st century.