THE UNIVERSITY OF MELBOURNE

EXTREME WAVE CLIMATOLOGY ACROSS ALL TROPICAL CYCLONE BASINS

Ian Young & Guisela Grossmann-Matheson

University of Melbourne
Department of Infrastructure Engineering

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Introduction

Source: wikipedia.org

- Tropical cyclones (TCs) => intense meteorological forcing events; important societal impacts.
- TC extreme waves => damage to offshore structures and coastal settlements; coastal flooding, beach erosion etc.

Hurricane Ian (2022)

AP Photo/Wilfredo Lee

Source: www.bbc.com

Typhoon Hinnamnor (2022)

Motivation

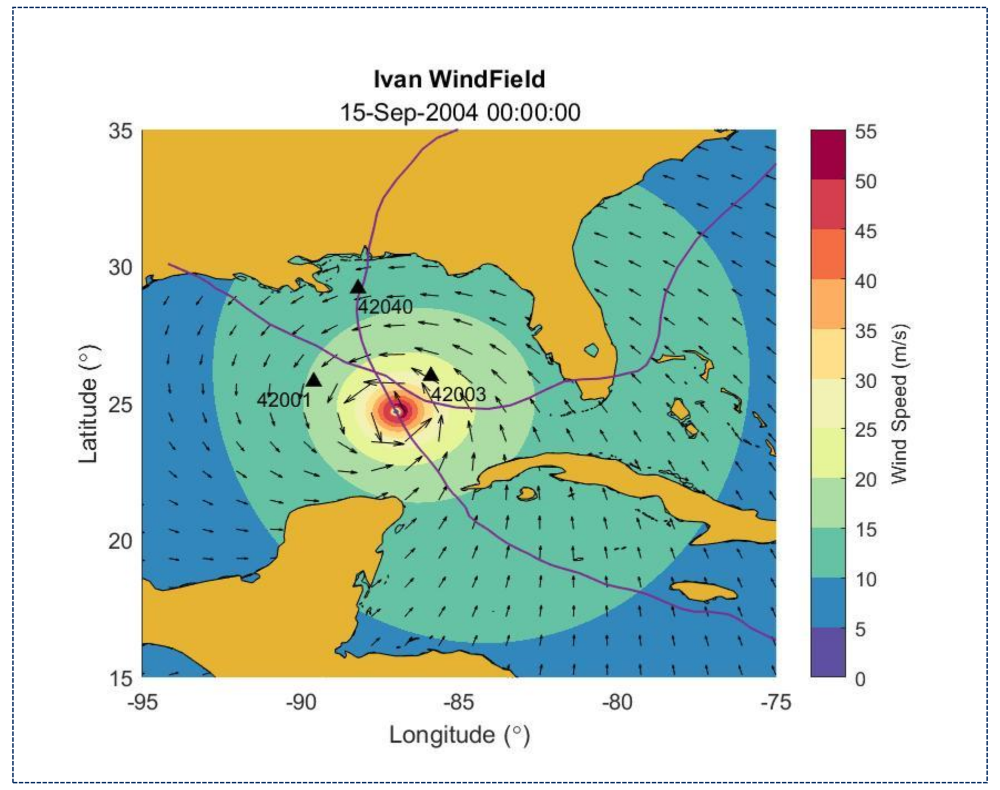
→ There is no global analysis of waves generated by TCs. Develop an understanding of the climatology of the extreme waves associated with TCs.

Source: Google

CLIMATOLOGY OF TROPICAL CYCLONE EXTREME WAVE HEIGHTS

Part I

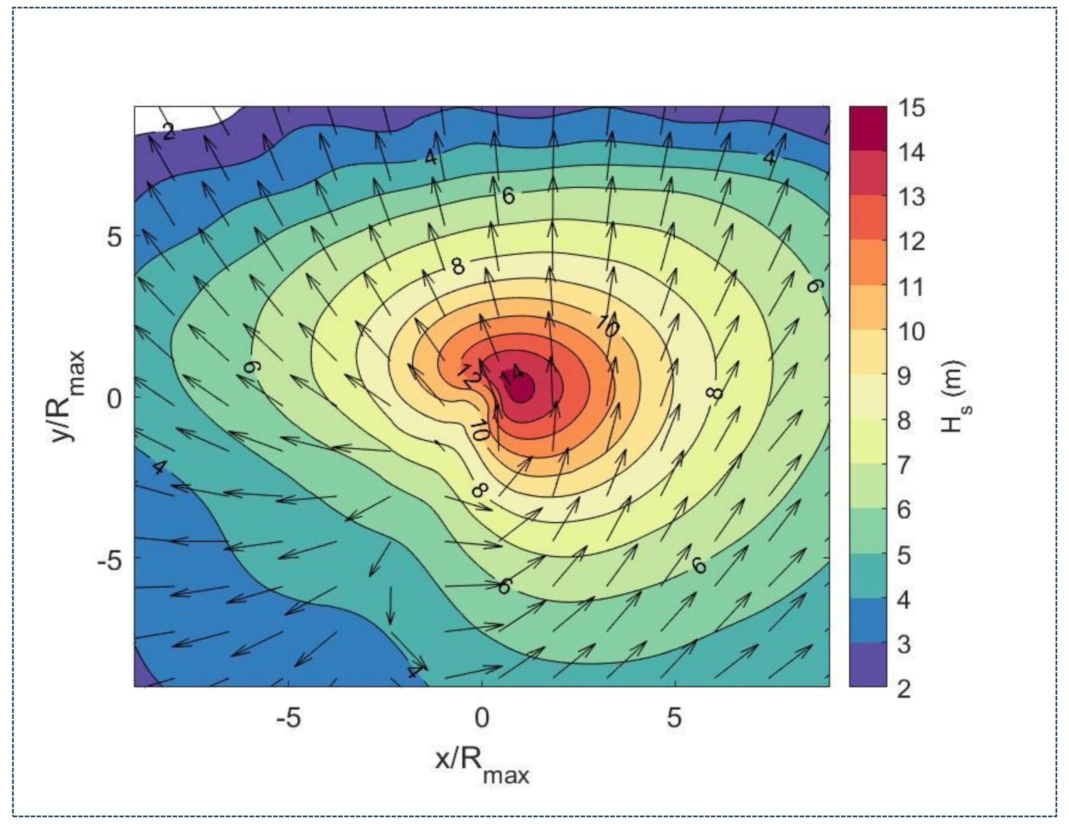
WIND VORTEX MODEL



Update the wind vortex model of Holland et al. (2010) including asymmetry and variable wind inflow angle to have a more realistic TC wind field to be used for wave generation studies.

Part II

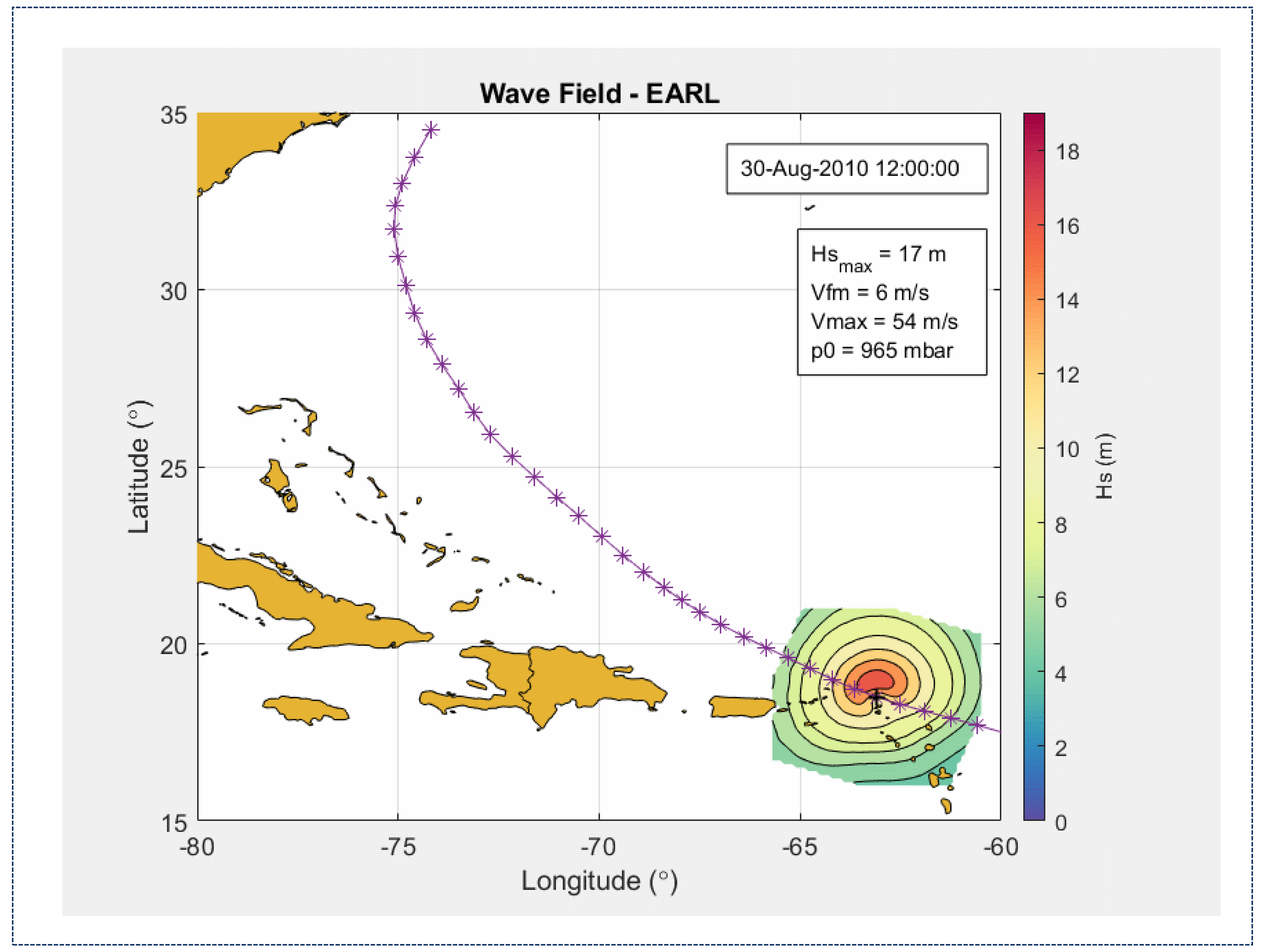
SYNTHETIC TC WAVE FIELD GENERATION



A broad range of parameter combinations of idealized TCs were used to force the WAVEWATCH III (WW3) to generate an extensive synthetic TC wave field database.

Part III

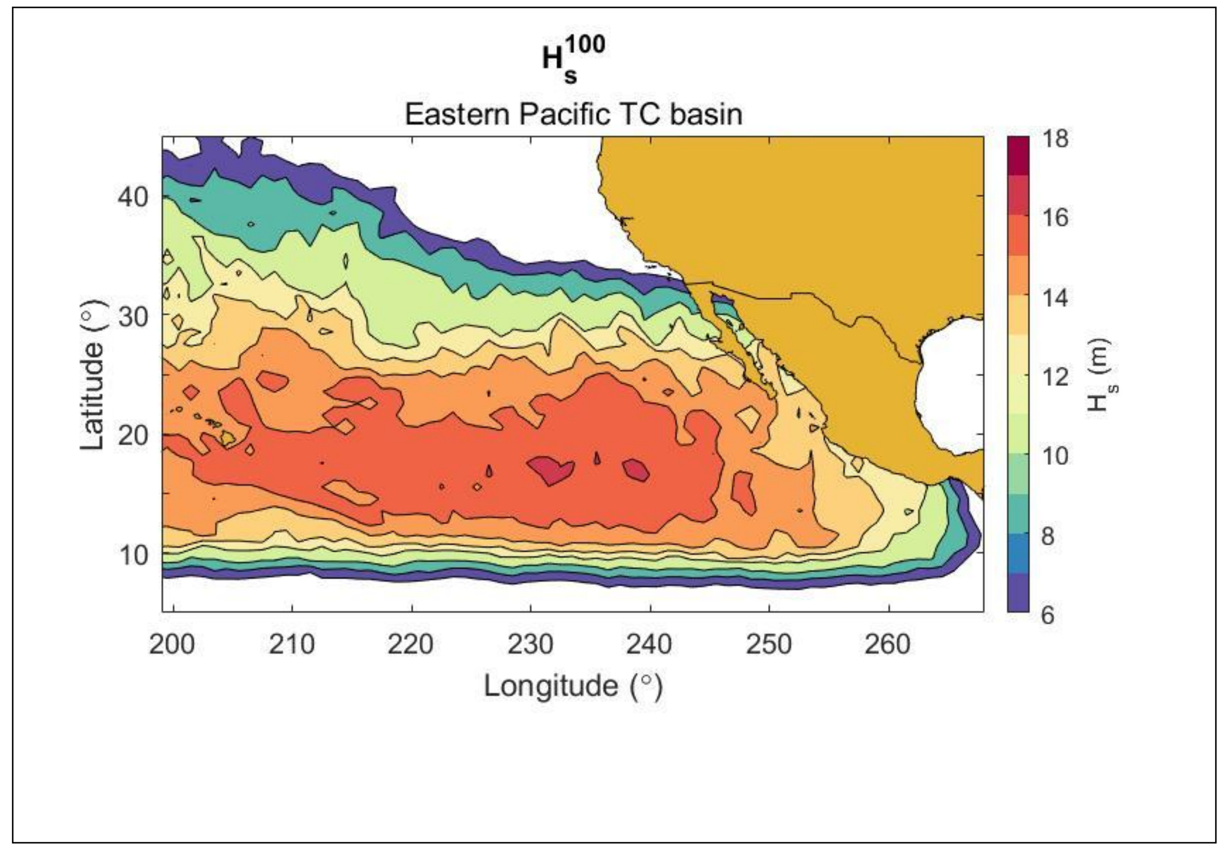
PARAMETRIC WAVE HEIGHT MODEL



The synthetic TC wave field database was used to parameterize a “Fetch” relationship to calculate significant wave height (H_s) spatial distribution in a TC and develop the PModel.

Part IV

TC EXTREME WAVE HEIGHT ANALYSIS



Simulation of wave heights for each track point for all possible TC tracks globally and estimate extreme wave heights (H_s^{100}) for historical data and future climate projections.

30,000yr simulations => efficient method => PModel

Validation parametric wind field for wave generation

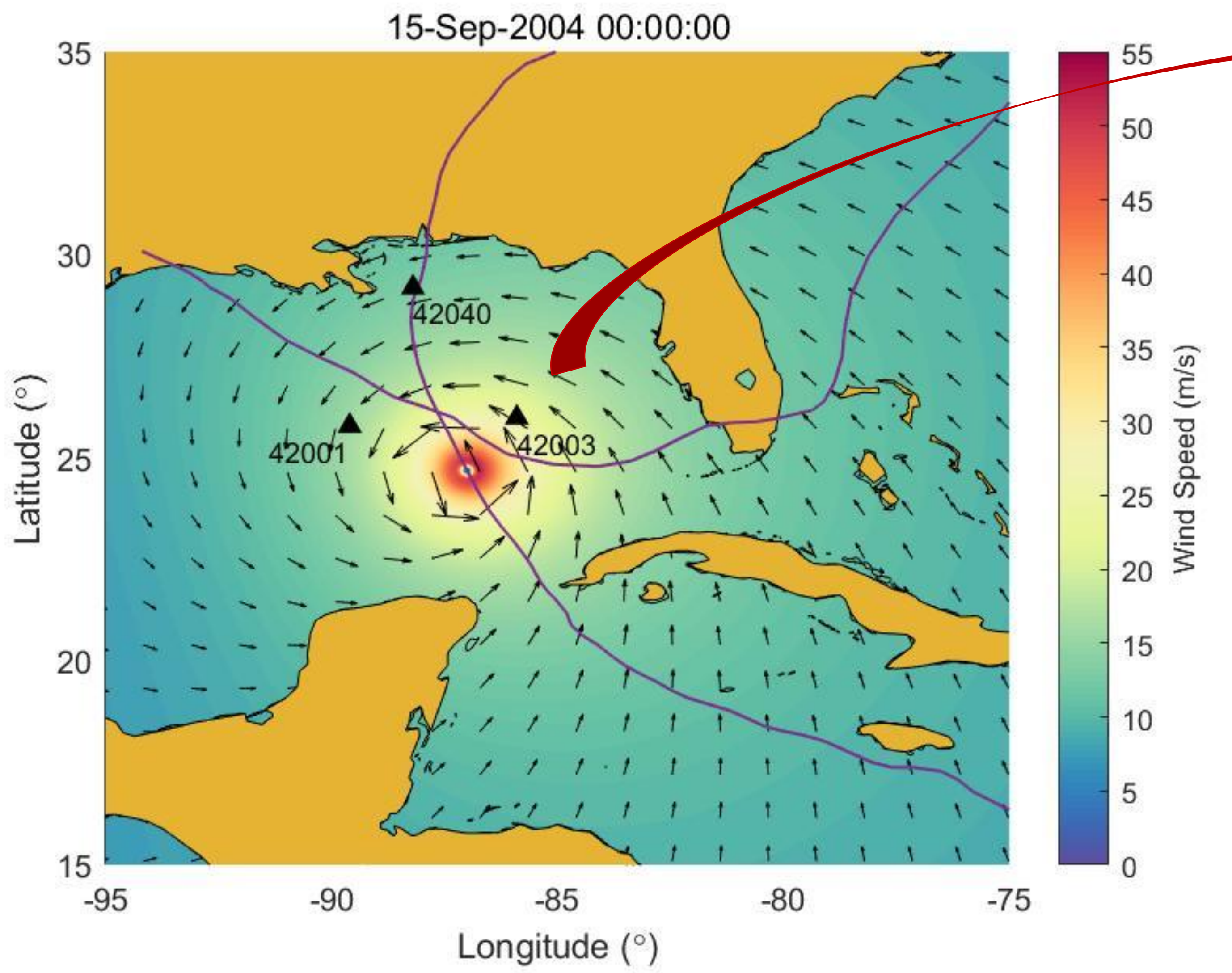
- Wind vortex model of Holland et al. (2010) model was improved using variable inflow angle (parameterized results Tamizi et al. (2020)) and asymmetry included (adding Vfm /2). Updated, and the wind field was validated against HWind* using wind parameters from IBTrACS** dataset;

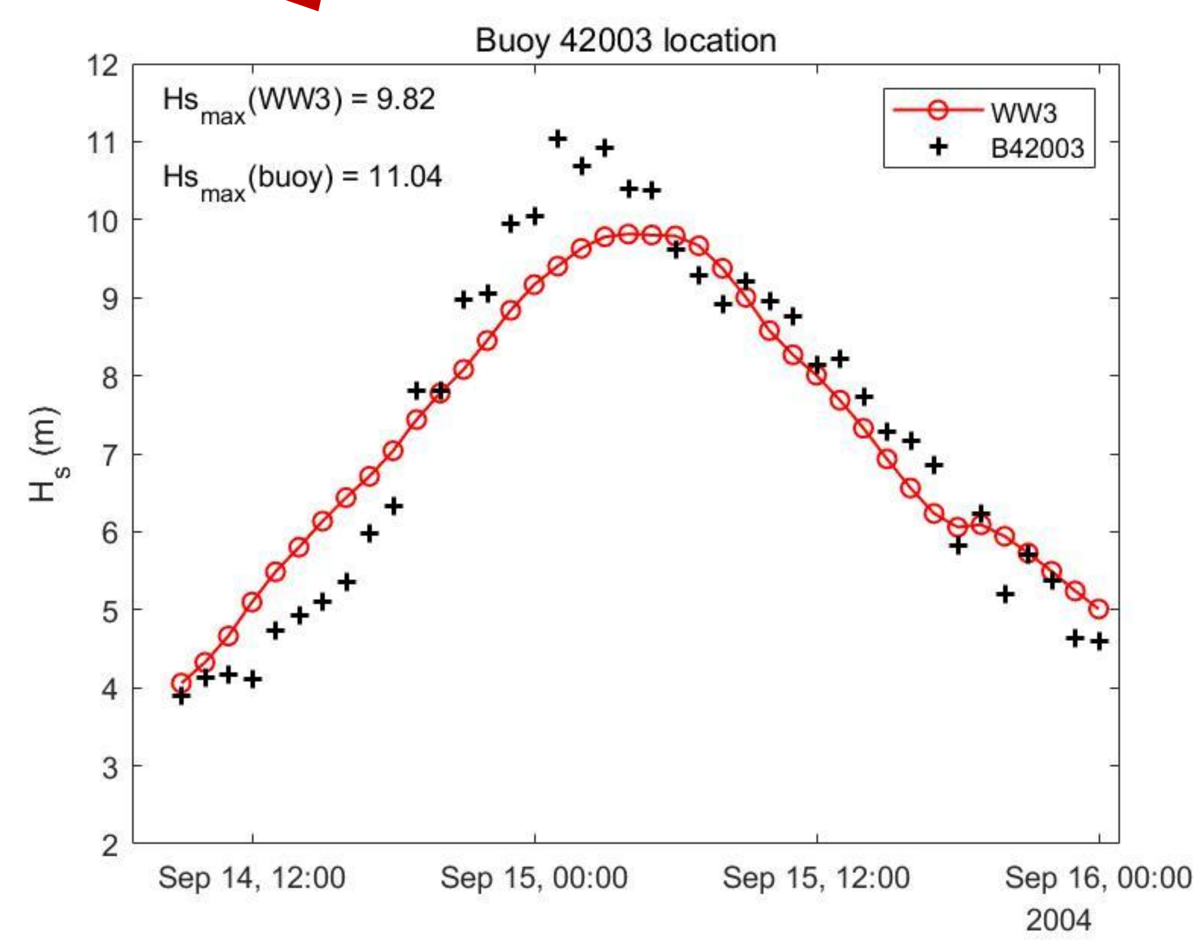
* HWind => post storm reanalysis
** IBTrACS => best track data for TCs

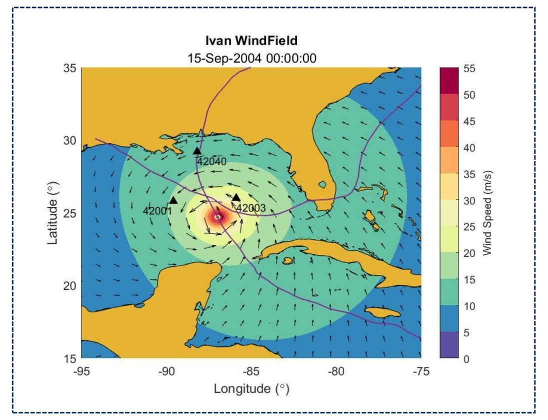
- Parametric wind field + WW3 model => Hindcast of historical hurricanes => **Validation of the wave parameters results** (Hs, Tp, Dir, spectra) **against NDBC buoys data;**

→ *Results compared reasonably well (noting simplistic vortex wind model) with the buoy data for integral wave parameters and directional spectra. These results provide confidence in the performance of the updated wind parametric model for use in simulations of TC wave generation.*

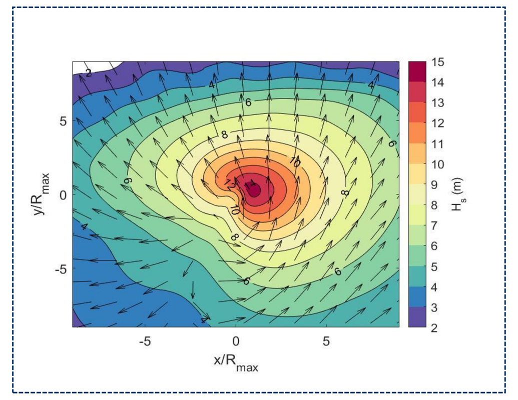
Hurricane Ivan (2004)



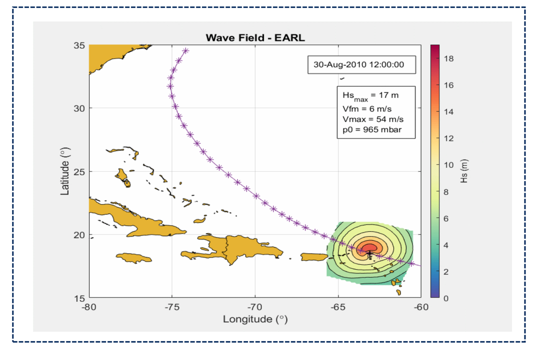




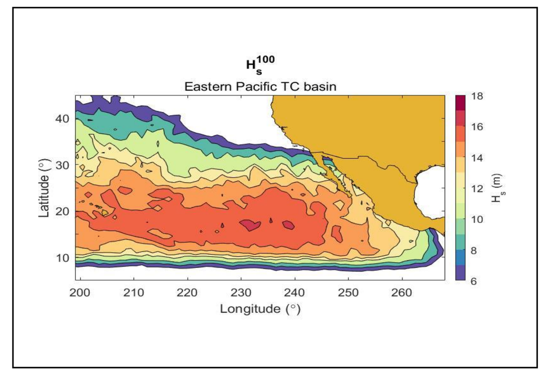
Part I - WIND VORTEX MODEL



Part II - SYNTHETIC TC WAVE FIELD GENERATION



Part III - PARAMETRIC WAVE HEIGHT MODEL



Part IV - EXTREME WAVE HEIGHT ANALYSIS

- Historical
- Future Projections

Part II – Tropical Cyclone Wave Field Generation

WW3 ST4 package
Grid resolution 2km
32 freqs (0.05 – 0.96Hz)
36 dir (10°)

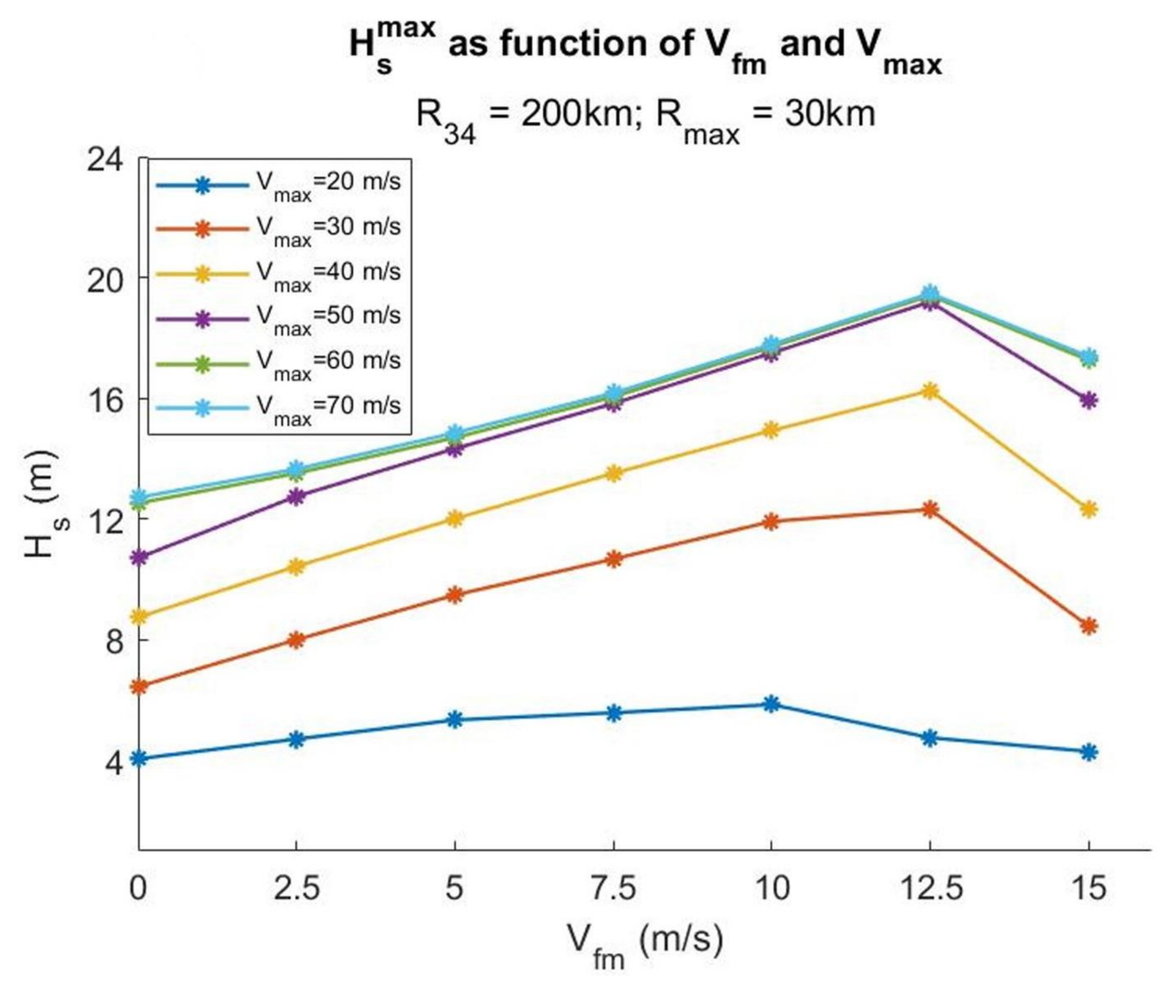
- Moving grid* implementation WW3 (Tolman and Alves, 2005) => run a broad range of combinations of idealized TCs to generate an extensive synthetic TC wave field database.

  **Grid moves forward with the TC. More computational efficient to build a robust TC wavefield dataset with a fine grid of large spatial extent.*

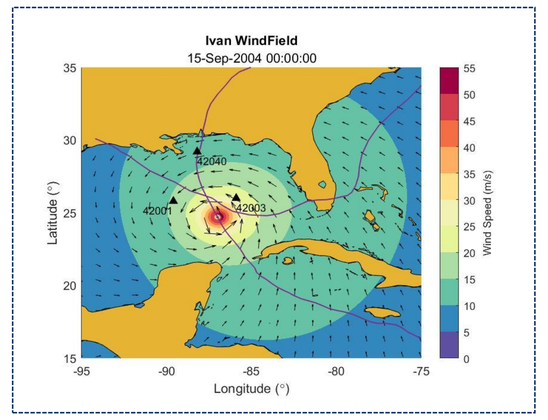
- *Combinations of TC parameters : V_{max}, V_{fm}, R_{34} and R_{max} generated 400 TC simulations;*

- *Results agree with the concept of an extended fetch => waves generated in intense wind regions can remain aligned with the wind for longer time and propagates ahead of the storm. For storms moving faster than wave group velocity, the waves are left behind the storm and H_s decrease.*

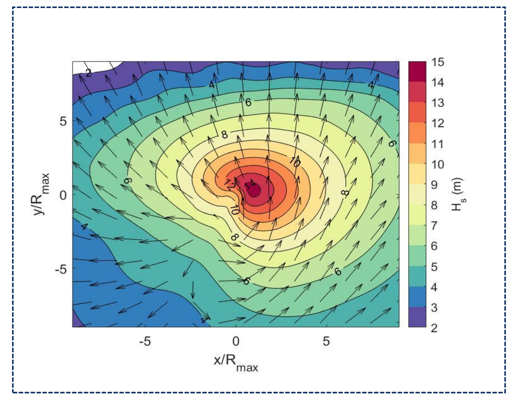
- *Compared to the results of Young (1988): inclusion of the nonlinear terms in the wave model => stronger transfer of energy to longer waves => wave growth can be sustained for faster moving TC than previously believed.*



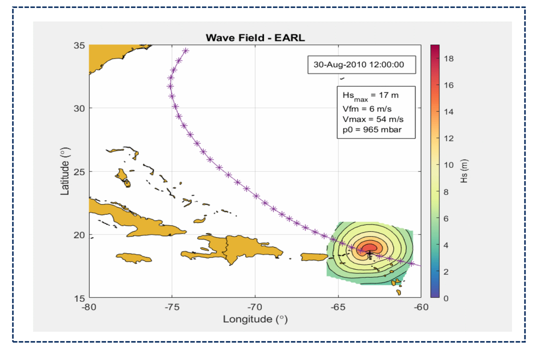
Tolman, H. L., Alves, J-H.G.M. (2005): Numerical modeling of wind waves generated by tropical cyclones using moving grids. Ocean Modelling, 9 (4), 305-323



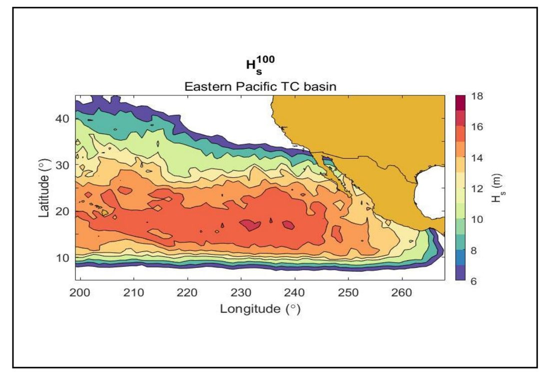
Part I - WIND VORTEX MODEL



Part II - SYNTHETIC TC WAVE FIELD GENERATION



Part III - PARAMETRIC WAVE HEIGHT MODEL



Part IV - EXTREME WAVE HEIGHT ANALYSIS

- Historical
- Future Projections

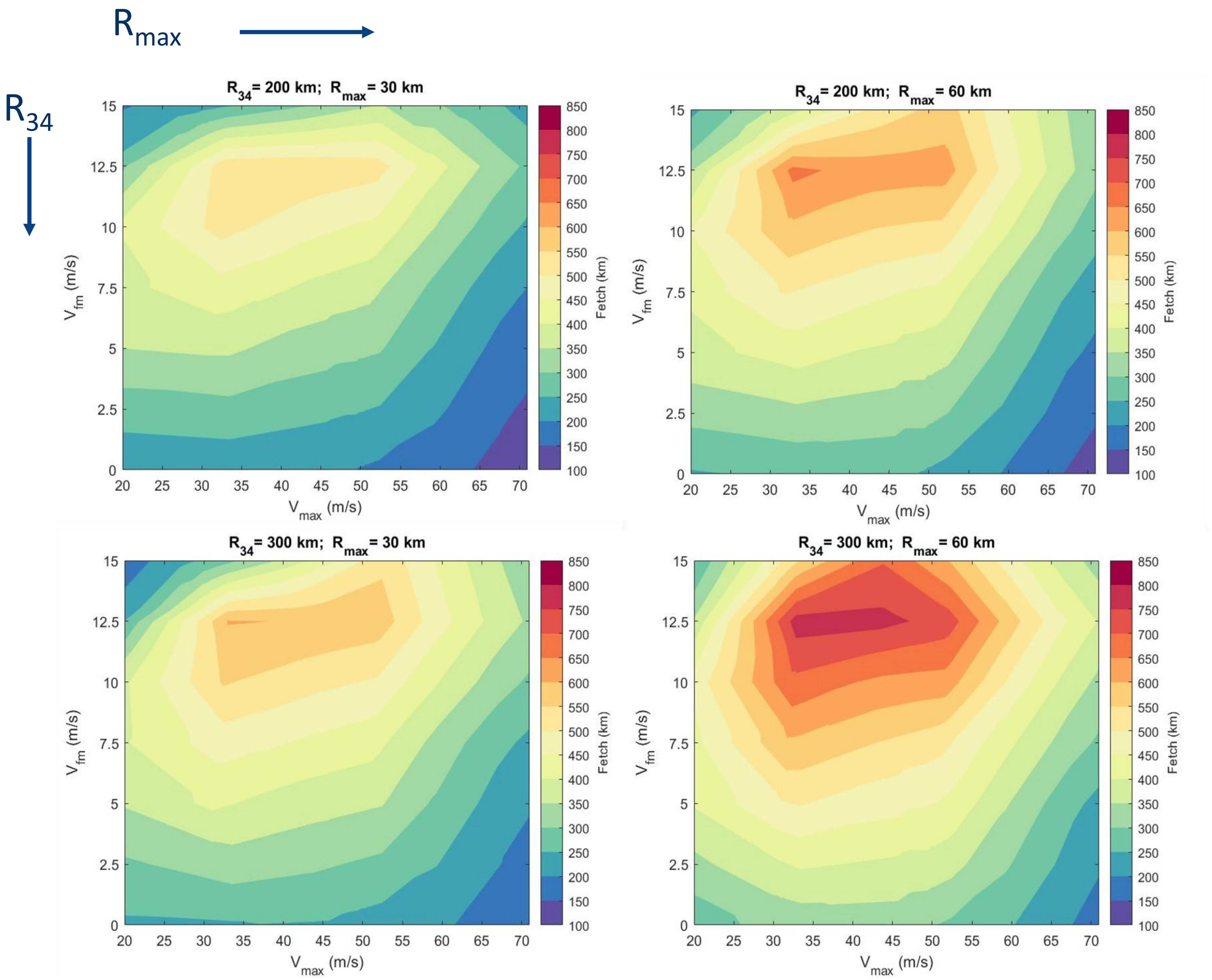
Part III – Parametric Wave Height Model

Following the concept of the Young (1988) an equivalent fetch (F) for each synthetic TC wave field was calculated using the JONSWAP fetch limited growth relationship.

$$\frac{g H_s^{max}}{V_{max}^2} = \alpha\ 0.0016\ \left(\frac{gF}{V_{max}^2}\right)^{0.5}$$

α: calibration term = 1.0 in fetch calculation.
After validation α set to 0.89 for use in the parametric model.

Results confirm extended fetch within a TC is defined by both V_{max} and V_{fm}, as well as there is a dependence on the spatial scale parameter R_{max}. In addition, it was found that there is also a dependence on the spatial scale parameter R_{34}.



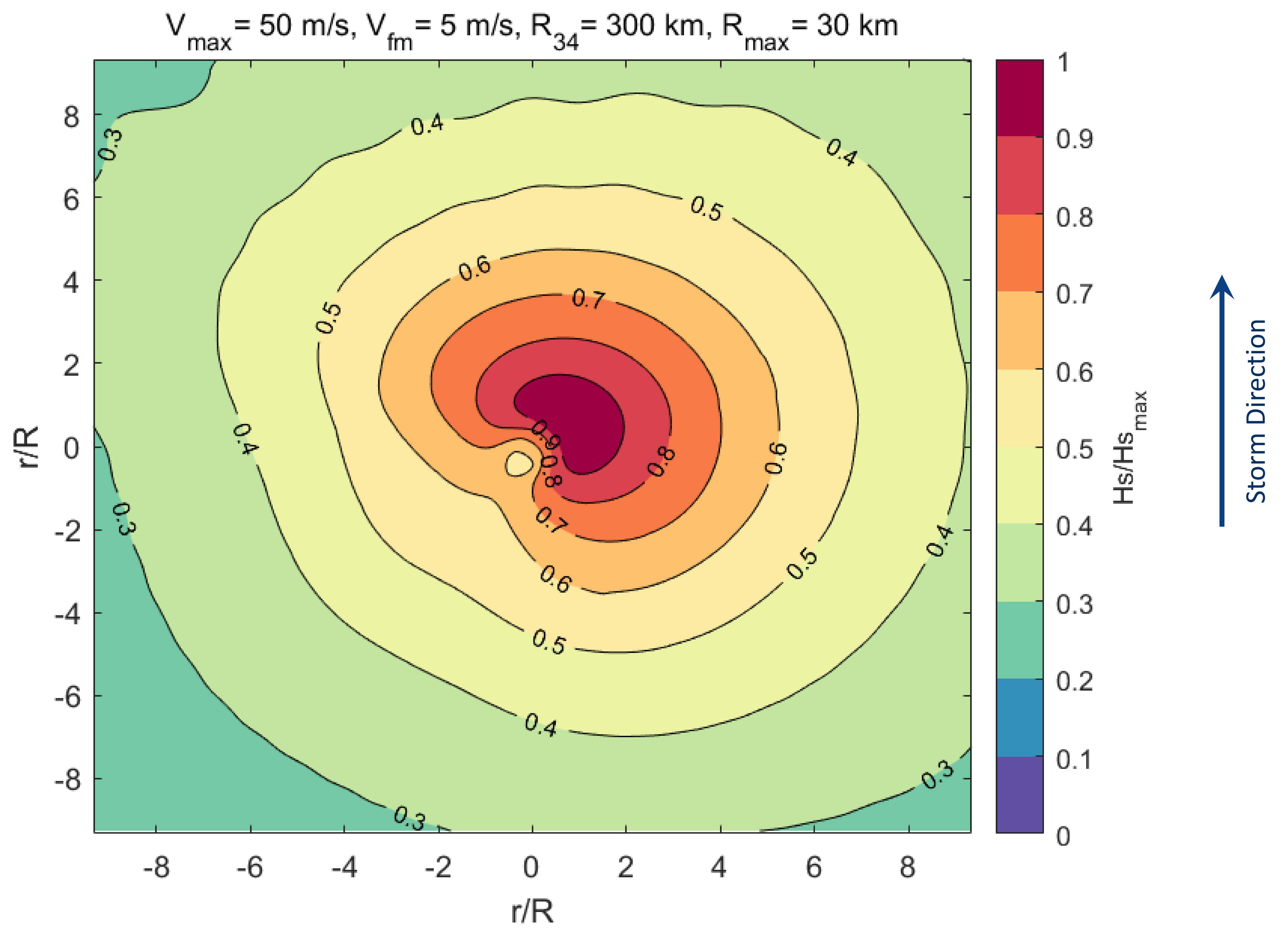
Parameterized Fetch equation:

$$\frac{F}{\lambda * \gamma} = (aV_{max}^3 + bV_{max}^2 + cV_{fm}^2 + dV_{max}^2 V_{fm} + eV_{max}V_{fm}^2 + fV_{max}V_{fm} + gV_{max} + hV_{fm} + i) * \exp(C\, V_{fm})$$

Scale correction factors: λ (R_{max}) and γ (R_{34})
Fitting coefficients: a to i
C = 0.1

Using the modified JONSWAP relationship the maximum H_s (H_s^{max}) associated to the Fetch is calculated. The H_s^{max} is applied to a normalized H_s/H_s^{max} spatial distribution for the selected synthetic TC wave field to determine the bidimensional H_s distribution within the storm.

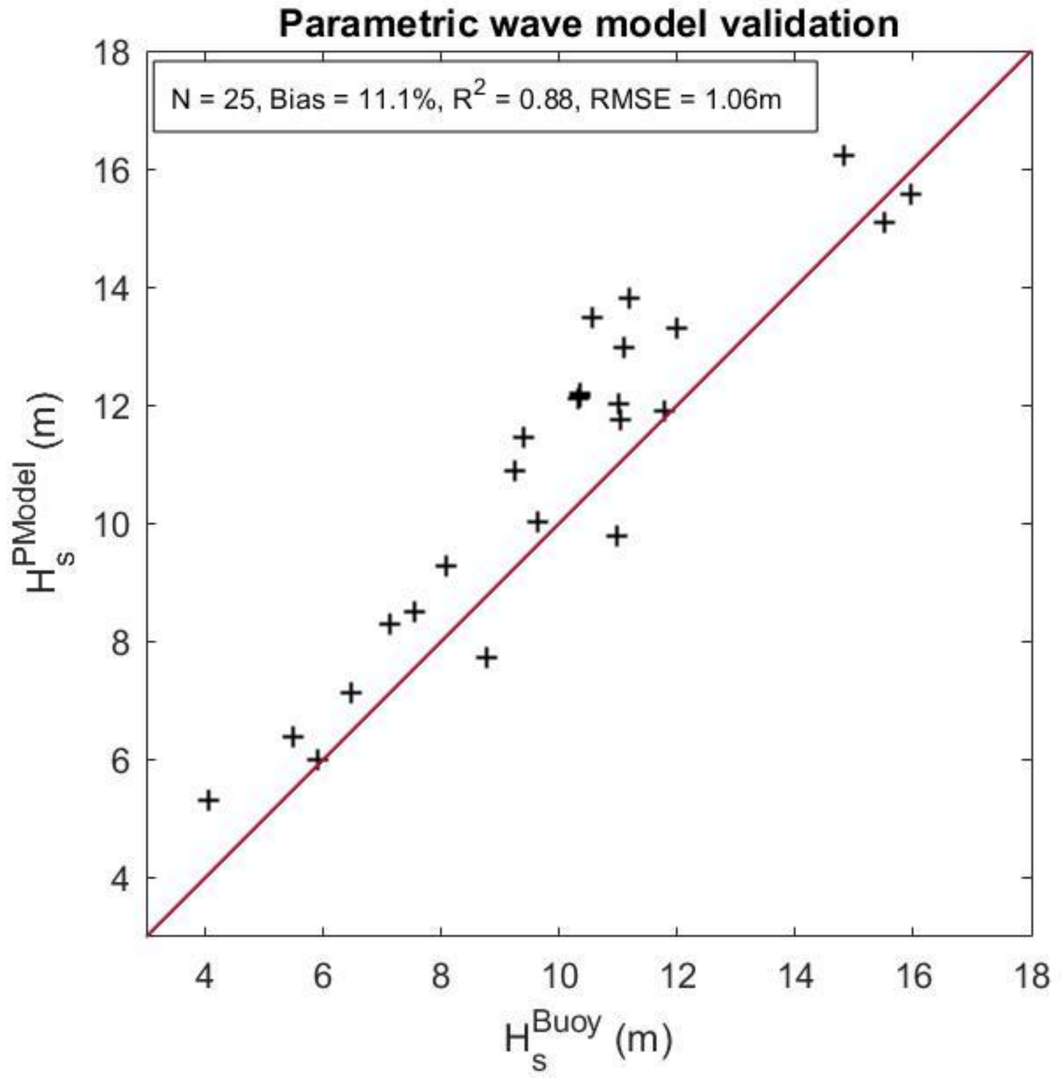
Parametric Significant Wave Height Model (PModel)



Validation Parametric Wave Height Model

PModel validated against altimeter and buoy data => historical hurricanes (North Atlantic), typhoons (Western Pacific) and tropical cyclones (Northwest coast of Australia)

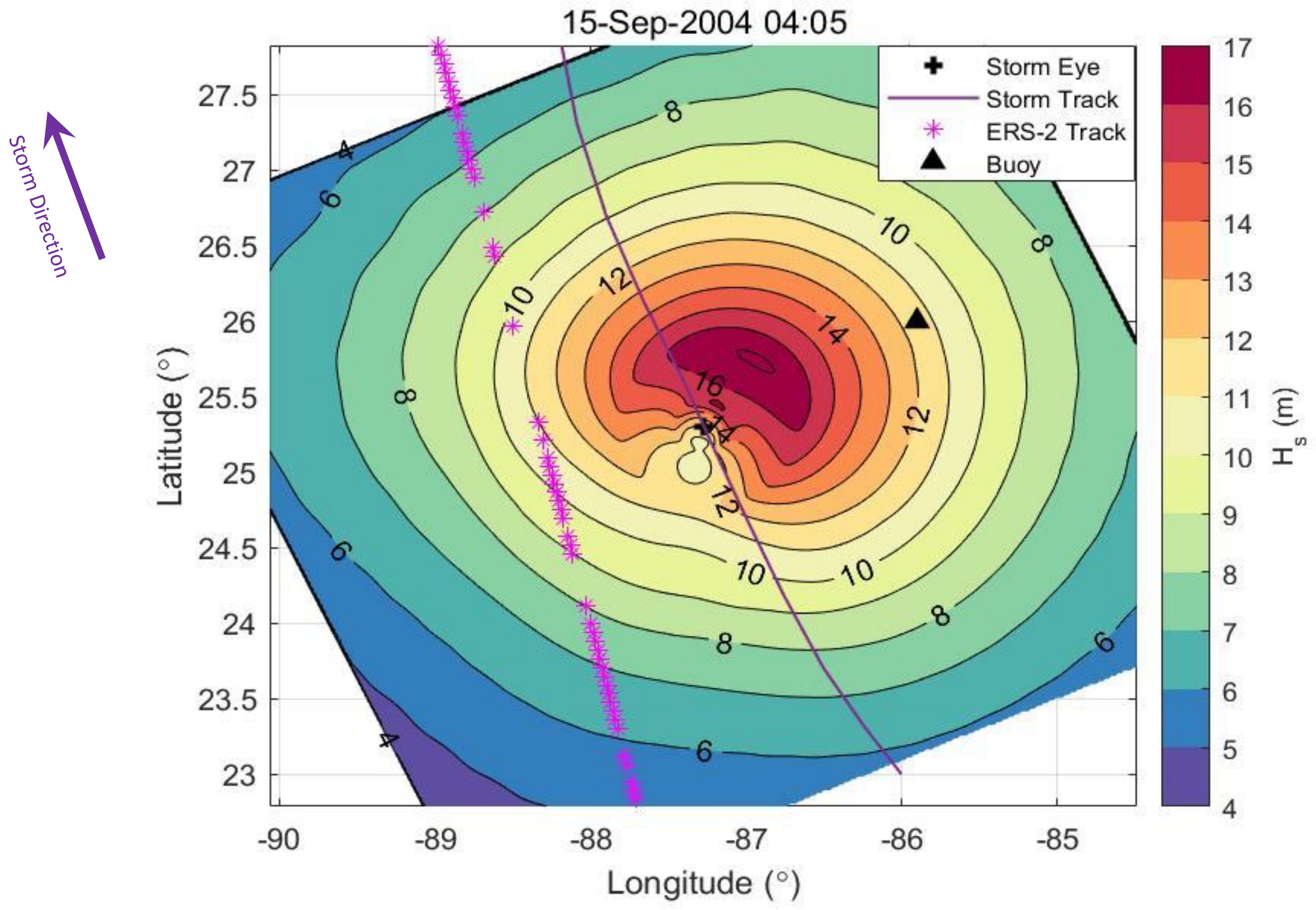
Limitations: PModel assumes fully developed storm, deep water, no changes in storm direction.



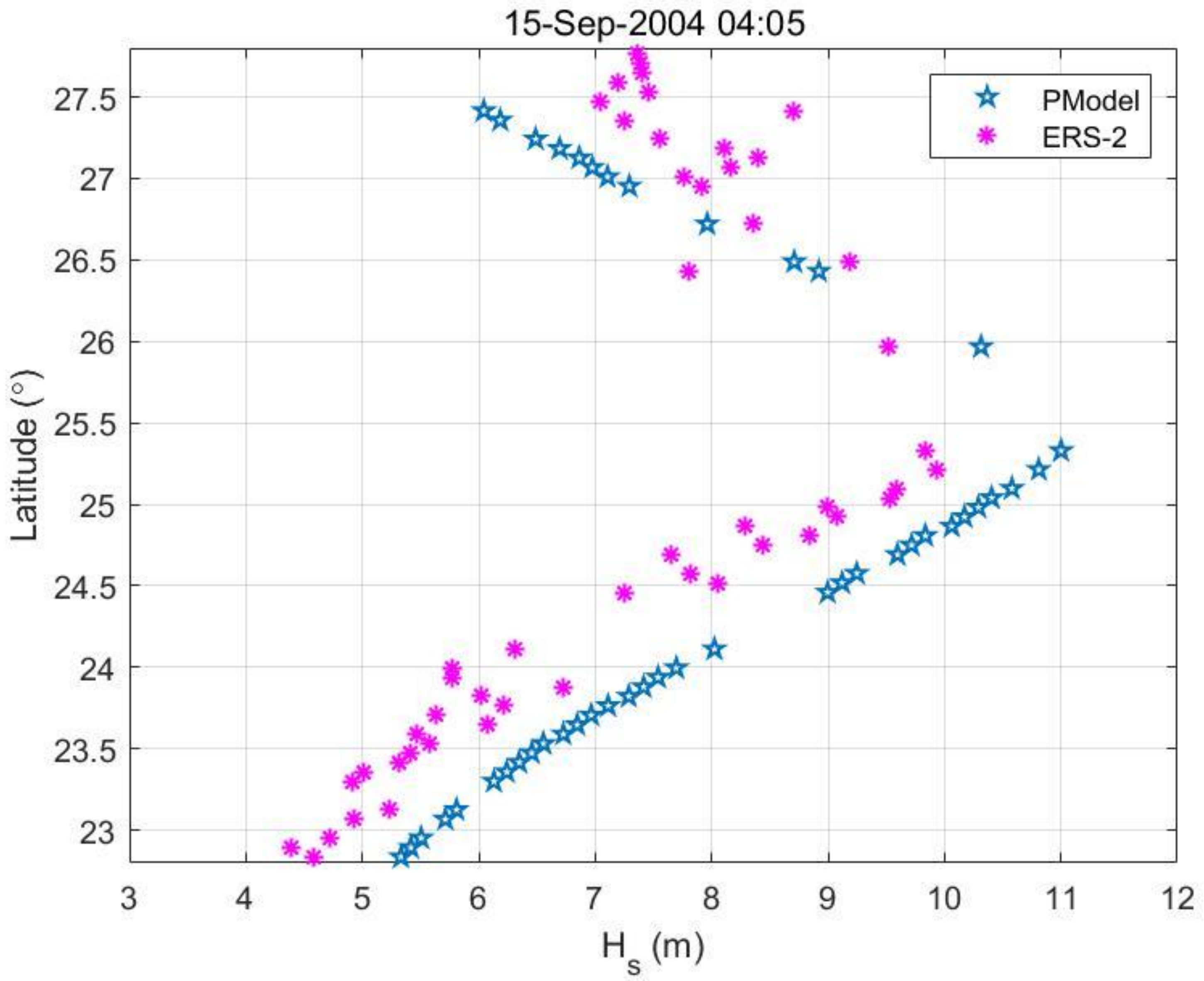
PModel against altimeter data

Hurricane Ivan (2004)

Wave field

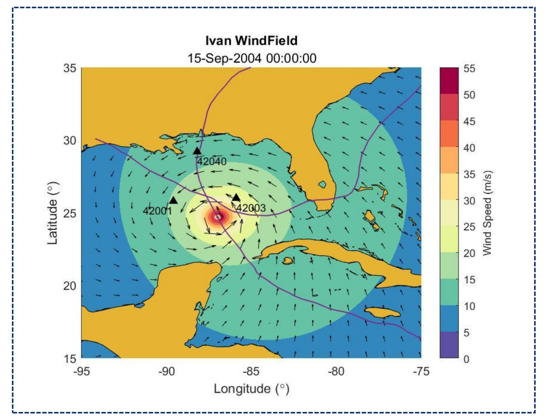


PModel x Altimeter (ERS-2)

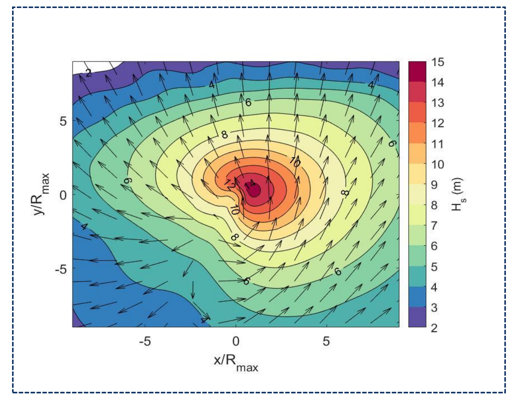


Grossmann-Matheson et al. (2023) Ocean Eng.

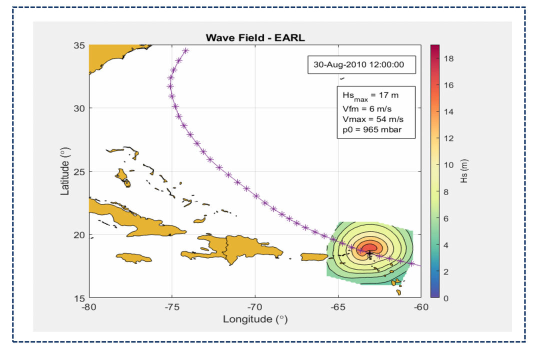
PModel underestimated wave heights ahead of the storm and overestimated the waves behind the storm eye (in the low wind side of the storm). *No calibration factor applied in this example.*



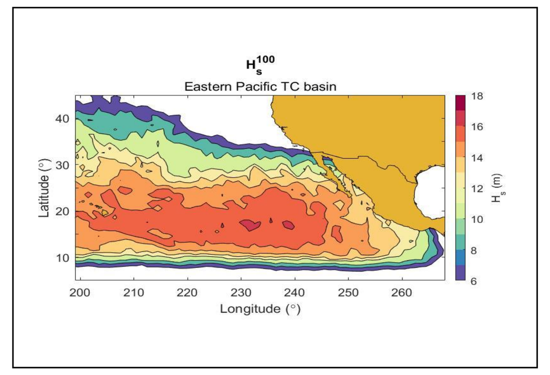
Part I - WIND VORTEX MODEL ✓



Part II - SYNTHETIC TC WAVE FIELD GENERATION ✓



Part III - PARAMETRIC WAVE HEIGHT MODEL ✓



Part IV - EXTREME WAVE HEIGHT ANALYSIS

- Historical
- Future Projections

Part IV – Extreme Wave Height Analysis

- Wind parameters from synthetic TC track database STORM (Bloemendaal et al. (2020)) + PModel => generation of H_s for each of the global TC basins;

  STORM: statistical TC model based on historical TCs (IBTrACS data 1980-2017)
  *1000-yr tracks within ± 5 to 45° latitude.

- Extreme value analysis through Direct Return Estimate applied to 1,000-yr annual maxima values resulting in100-yr return period significant wave height (H_s^{100});

- Predicted H_s^{100} validated against independent EVA studies (diverse statistical methods and data sources);

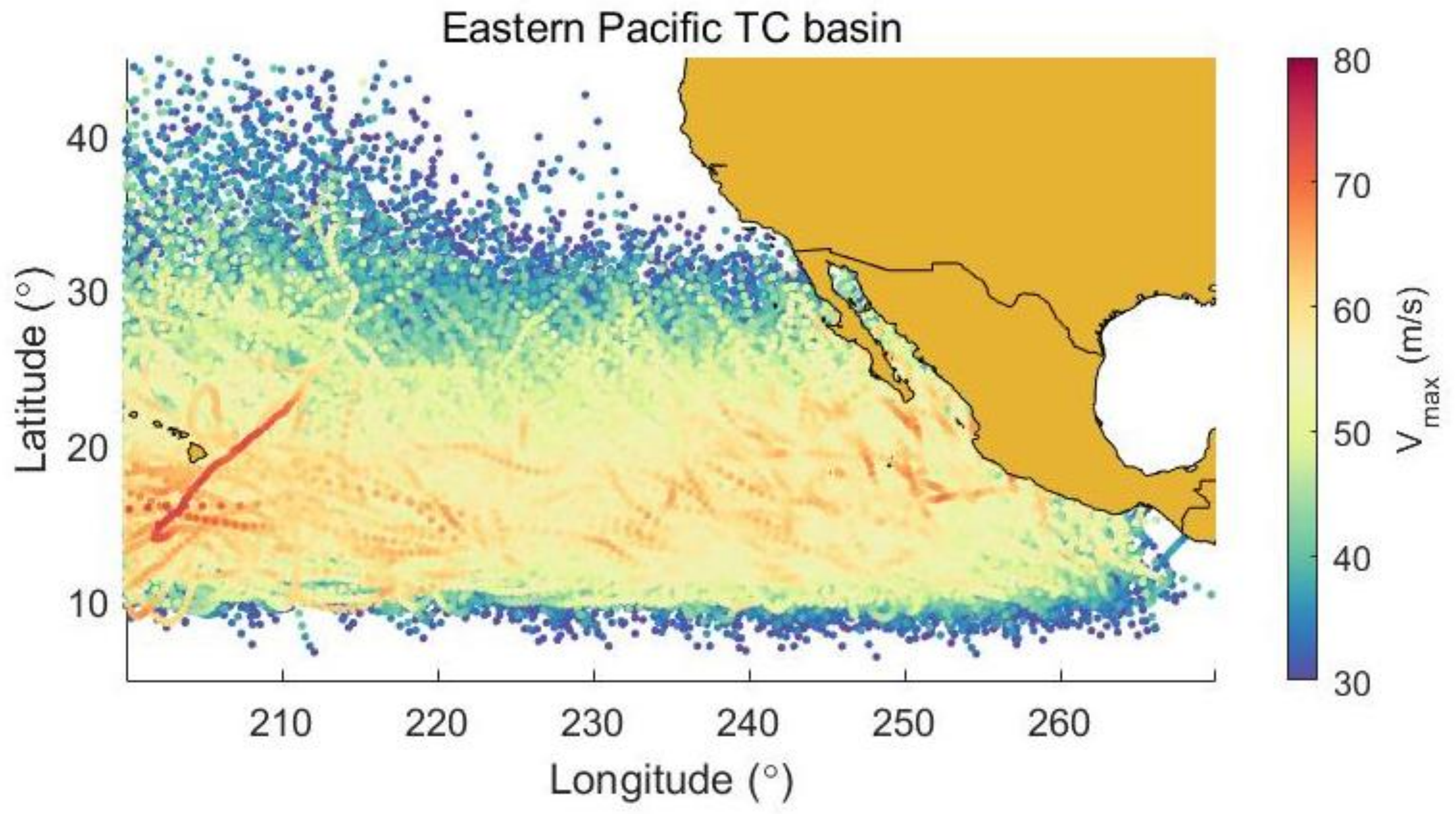
- Same approach using the version of the synthetic TC track database for future climate (STORM-C; Bloemendaal et al., 2022) to determine future global changes.

Bloemendaal, et al. (2020): Generation of a global synthetic tropical cyclone hazard dataset using STORM. Sci. Data 7, 40
Bloemendaal, et al. (2022): A globally consistent local-scale assessment of future tropical cyclone risk. Sci. Advances 8, eabm8438

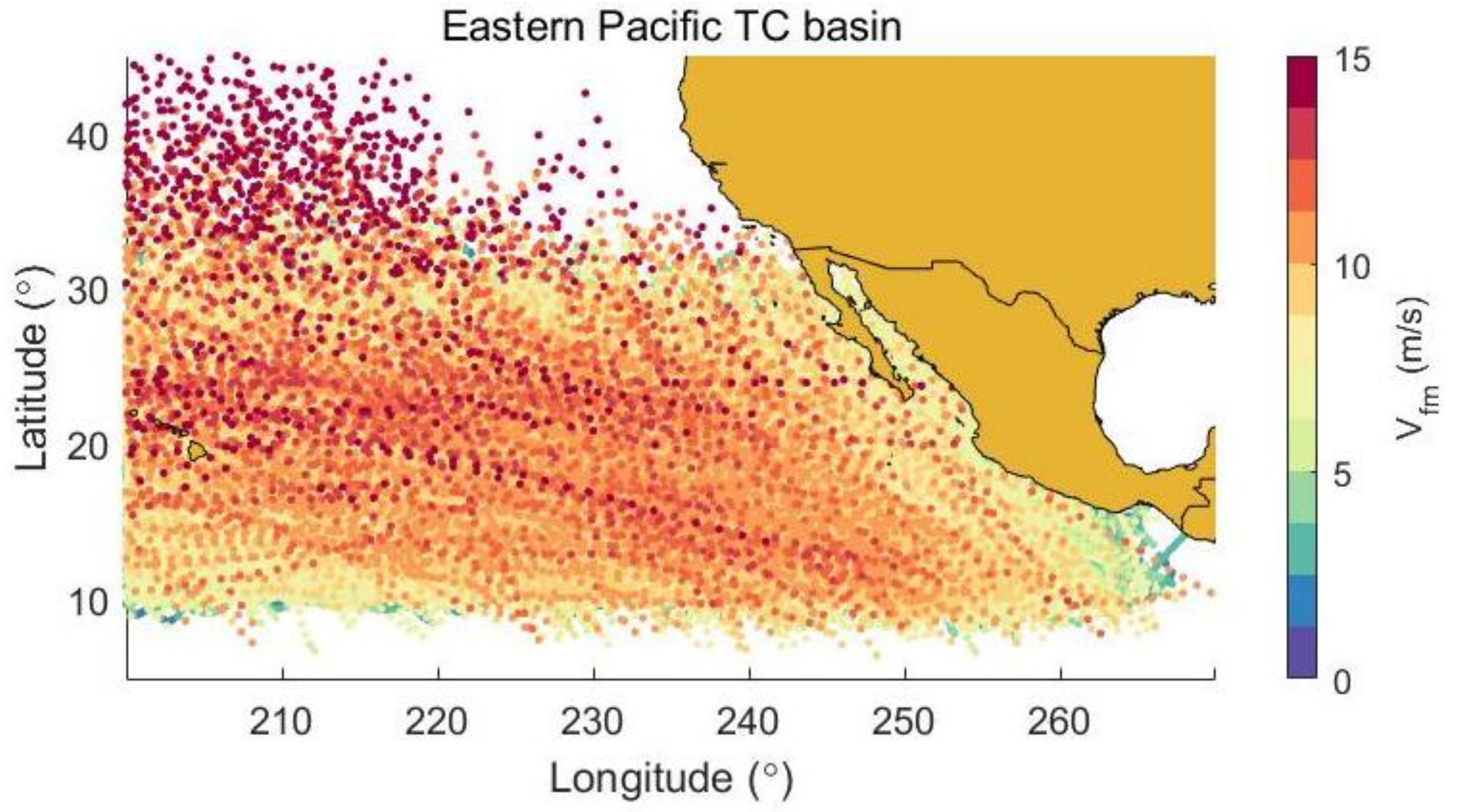
TC simulations results (Example for Eastern Pacific TC basin)

Synthetic TC tracks (1,000-yr STORM database)

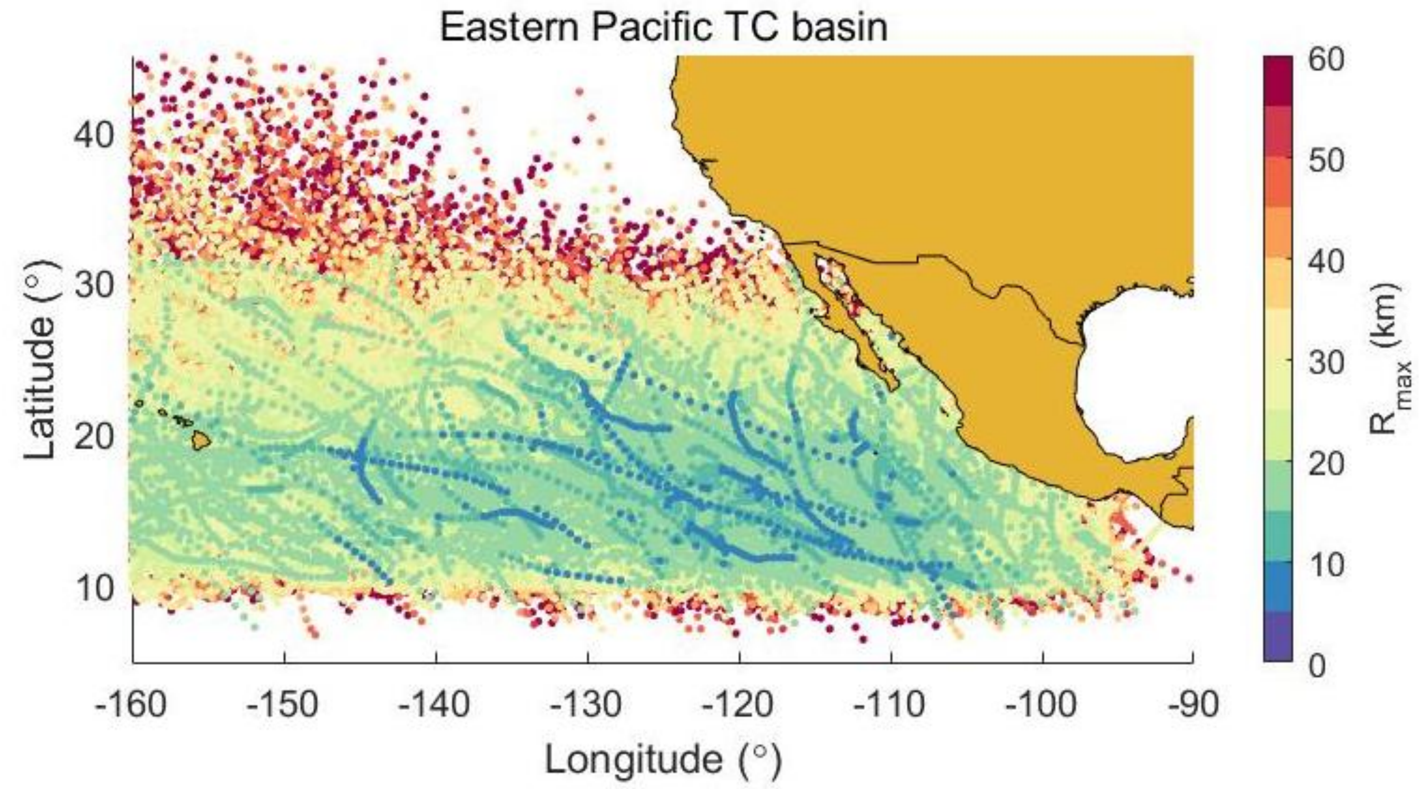
V_{max}



V_{fm}

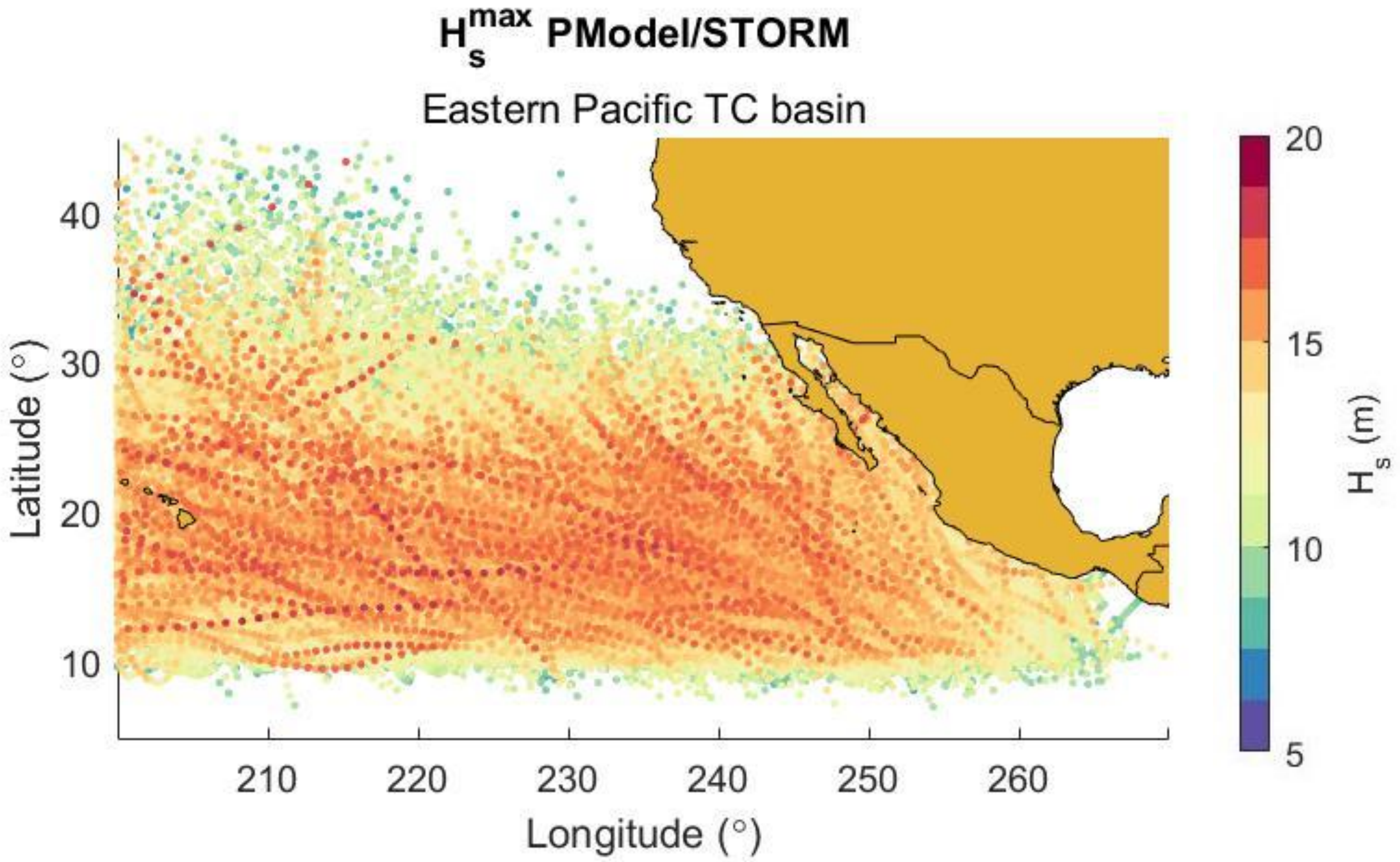


R_{max}



PModel simulation

Maximum H_s (H_s^{max}) for each TC track point

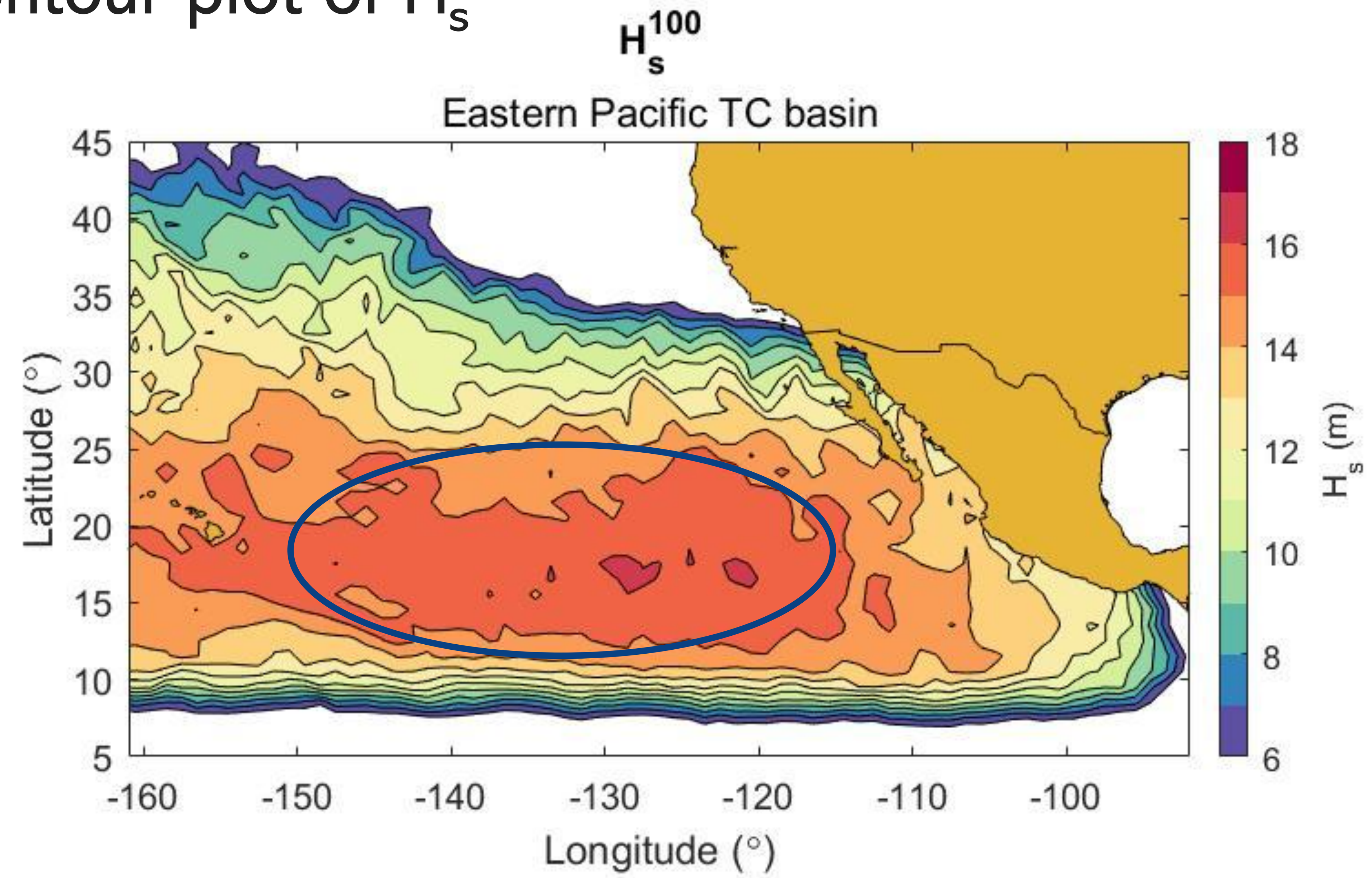


Tropical cyclone basin	V_{max} (m/s)	max H_s (m)
	*in 1000-yr	
Western Pacific	72.2	19.8
Eastern Pacific	76.9	19.3
North Atlantic	78.0	19.9
North Indian	82.8	18.1
South Indian	75.2	18.5
South Pacific	87.6	18.5

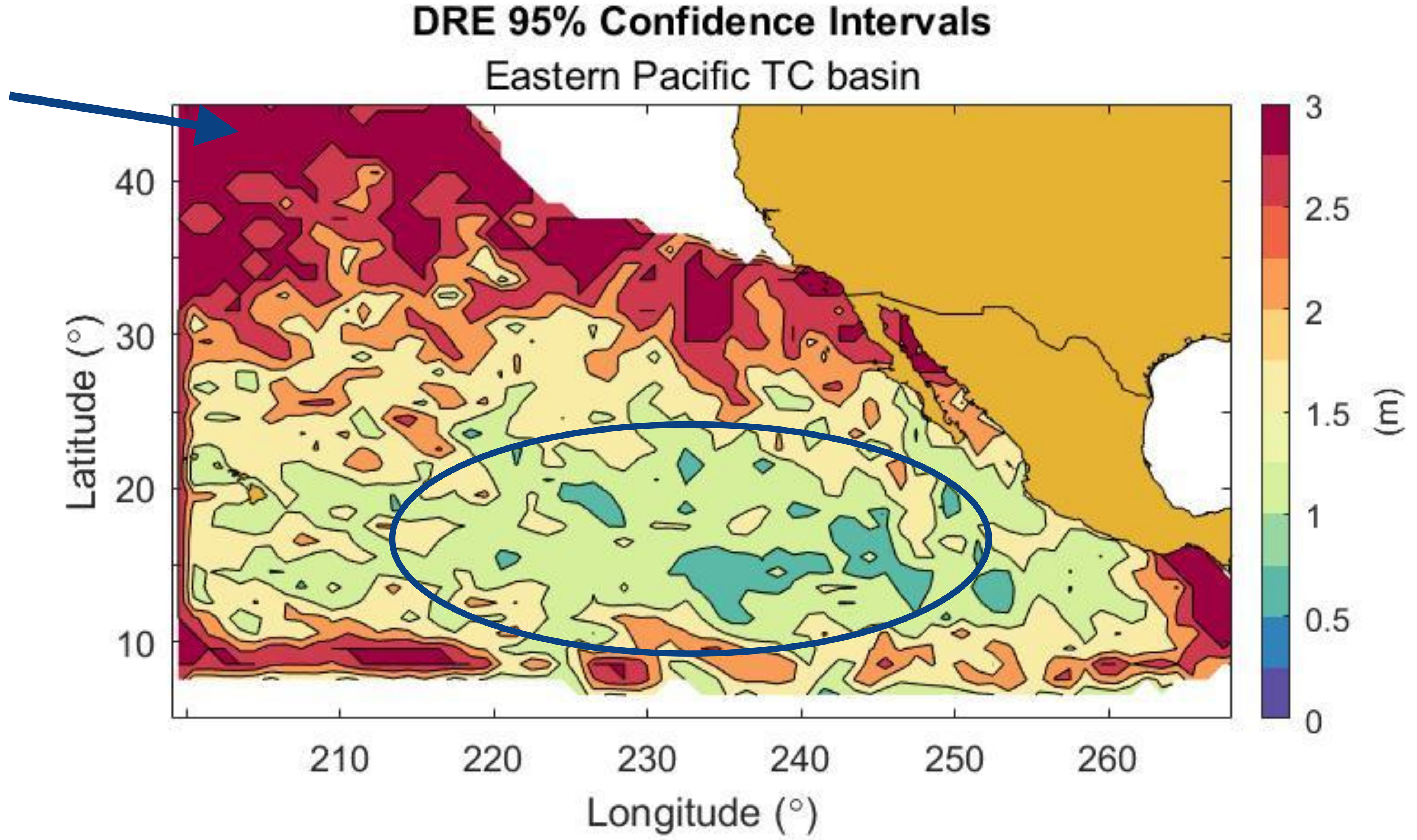
Extreme wave results (1 in 100-yr Hs by DRE approach)

Results for Eastern Pacific TC basin

Contour plot of H_s^{100}



95% CI span



Tropical cyclone basin	max H_s^{100} (m)
Western Pacific	17.4
Eastern Pacific	**16.8**
North Atlantic	17.2
North Indian	15.5
South Indian	14.6
South Pacific	15.0

Region with highest H_s^{100} => CI ± 1m.
Confidence interval can reach $\pm$ 3m in regions where the frequency of TC is low.

Global distribution of extreme Hs across TC basins (Present-day)

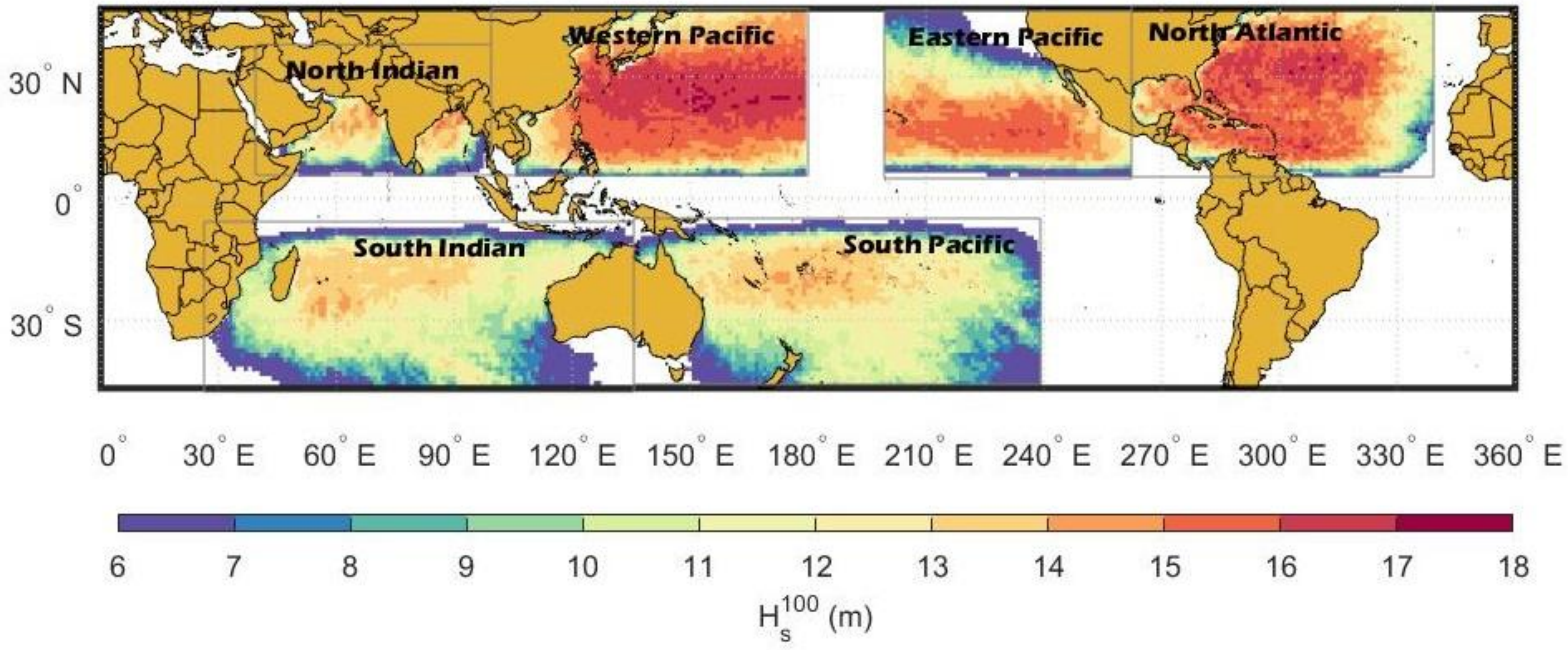
Northern Hemisphere

⇒ WP and NA basins have the largest extreme waves globally with similar maximum values of H_s^{100} (17.4 and 17.2);

⇒ EP and NI show lower values for the Northern Hemisphere basins (16.4 and 15.5);

Southern Hemisphere

⇒ Maximum values of H_s^{100} estimated for SI and SP basins have similar magnitudes (14.6 and 14.7);



Tropical cyclone basin	V_{max} (m/s)	max H_s (m)	max H_s^{100} (m)
	*in 1000-yr		
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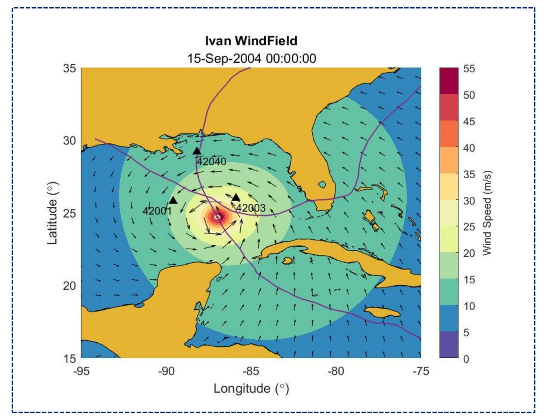
Grossmann-Matheson et al. (2024) Sci. Rep.



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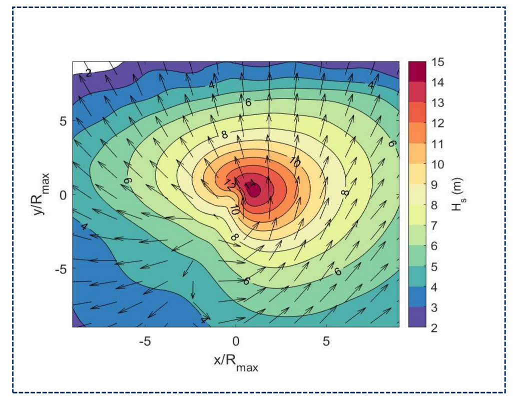
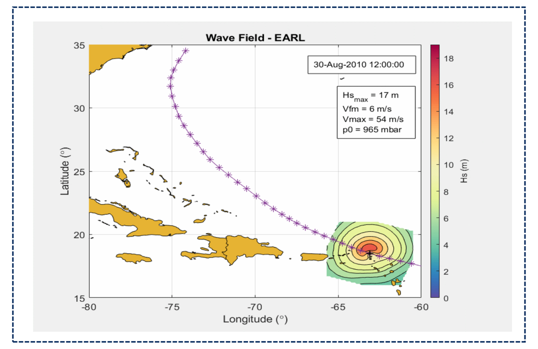
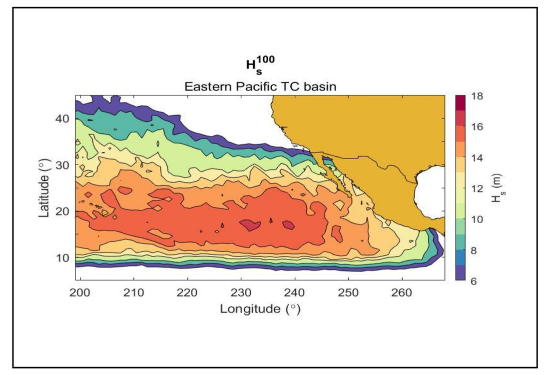


Part II - SYNTHETIC TC WAVE FIELD GENERATION



Part III - PARAMETRIC WAVE HEIGHT MODEL



Part IV - EXTREME WAVE HEIGHT ANALYSIS

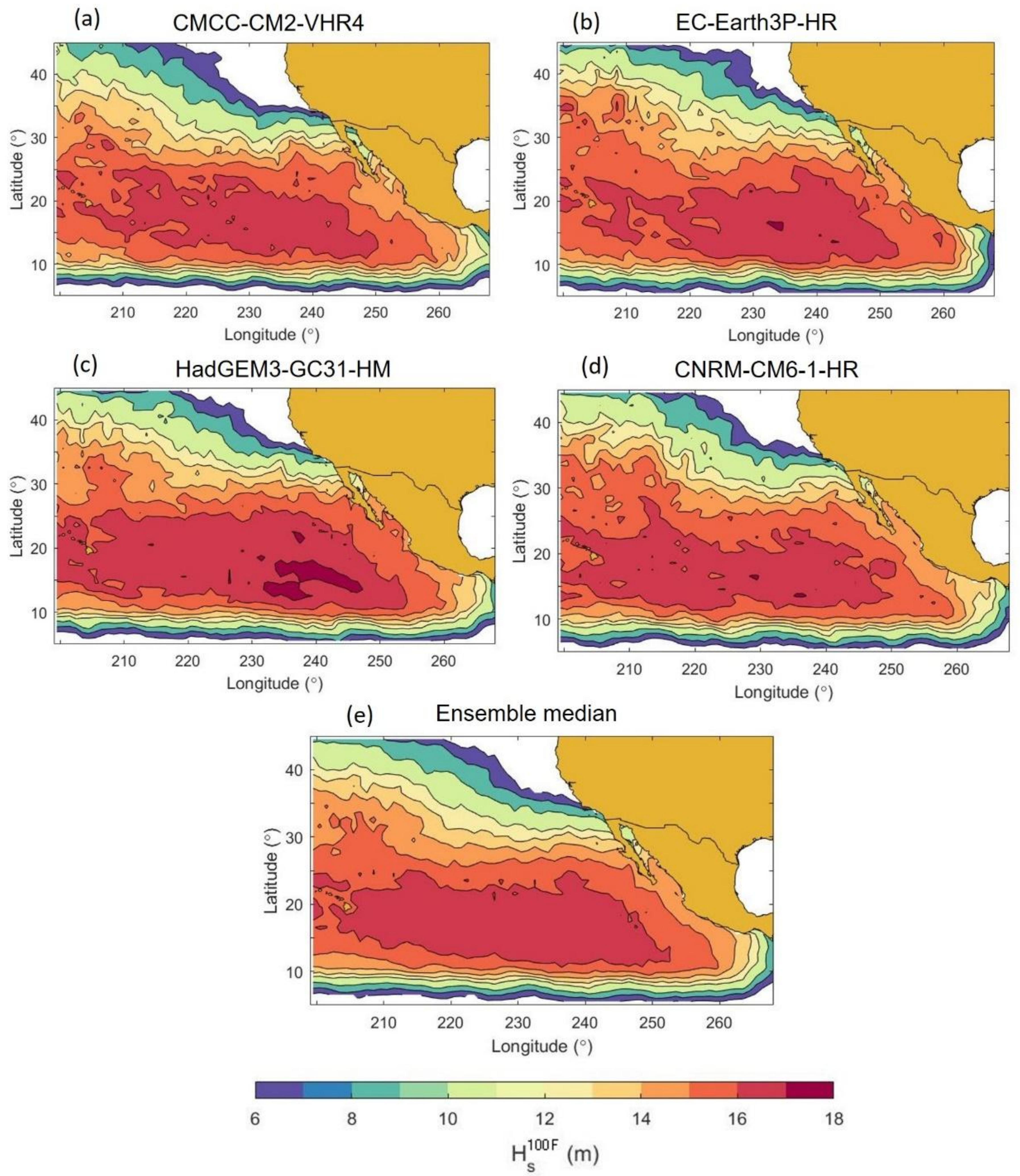
- Historical
- Future Projections

Future Climate projections

- Wind => STORM-C (synthetic TC track database for future climate)
  - 4-GCM datasets (25-50 km resolution);
  - CMIP6 scenario: SSP585 (2015-2050);

- Same method was applied to TC Hs simulations and H_s^{100} estimates (4-GCMs separately).
  Ensemble median H_s^{100} used to compare with the historical results.

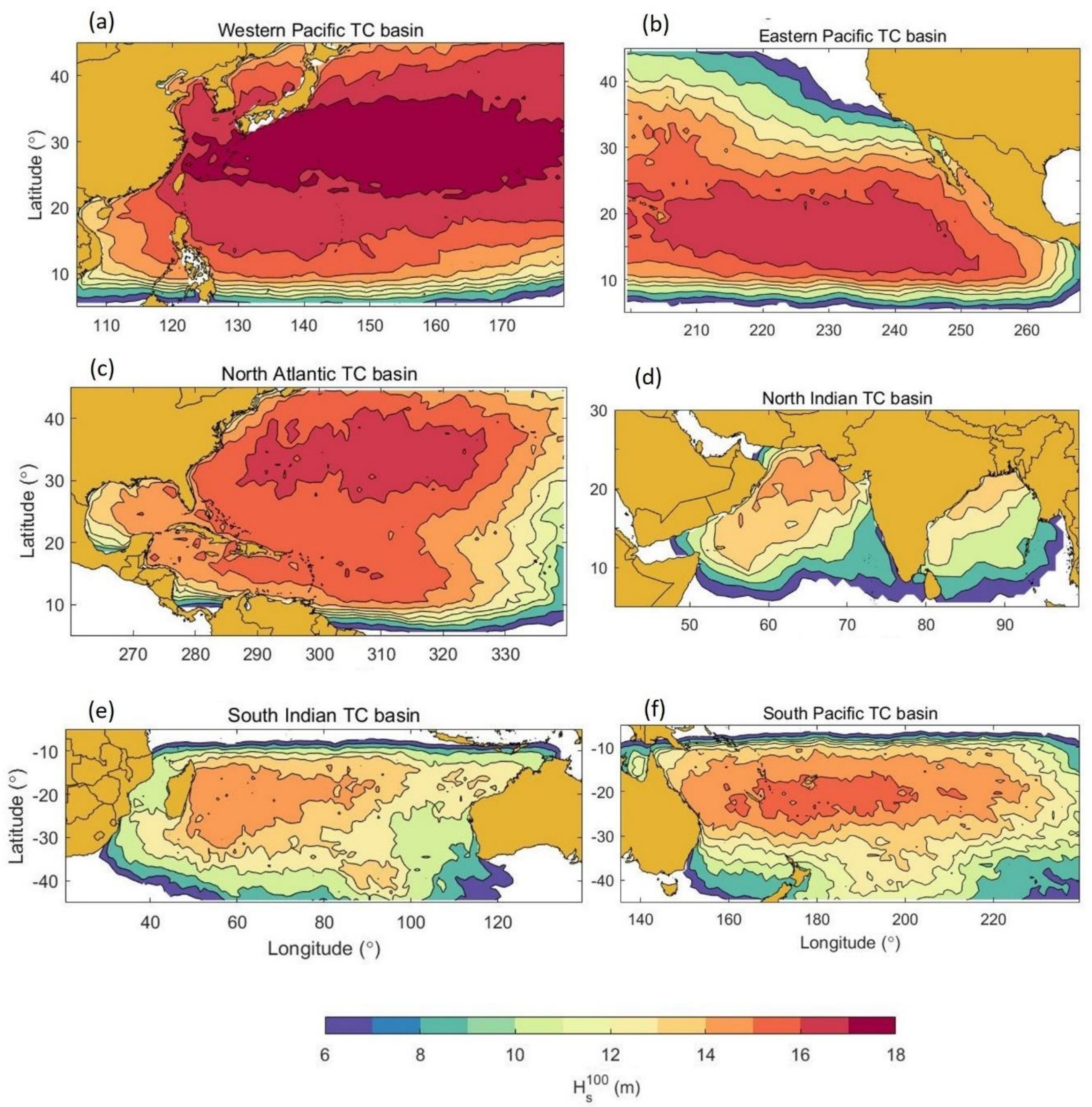
H_s^{100} future climate results for Eastern Pacific TC basin



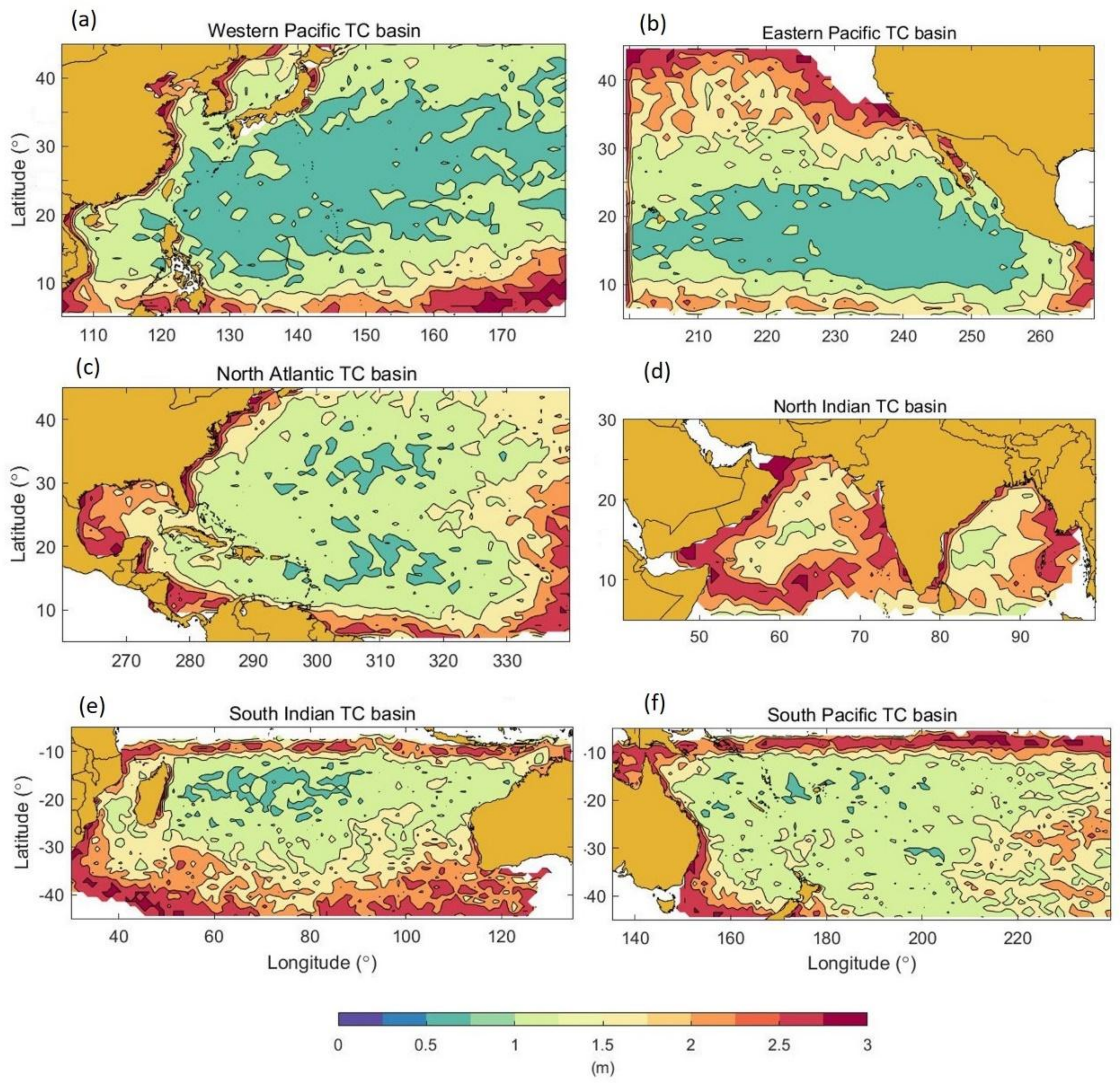
Future Climate projections (cont.)

Region with highest H_s^{100} => CI $\pm$1m.
Confidence interval can reach $\pm$ 3m in regions where the frequency of TC is low.

H_s^{100} (Ensemble median)



90% CI span

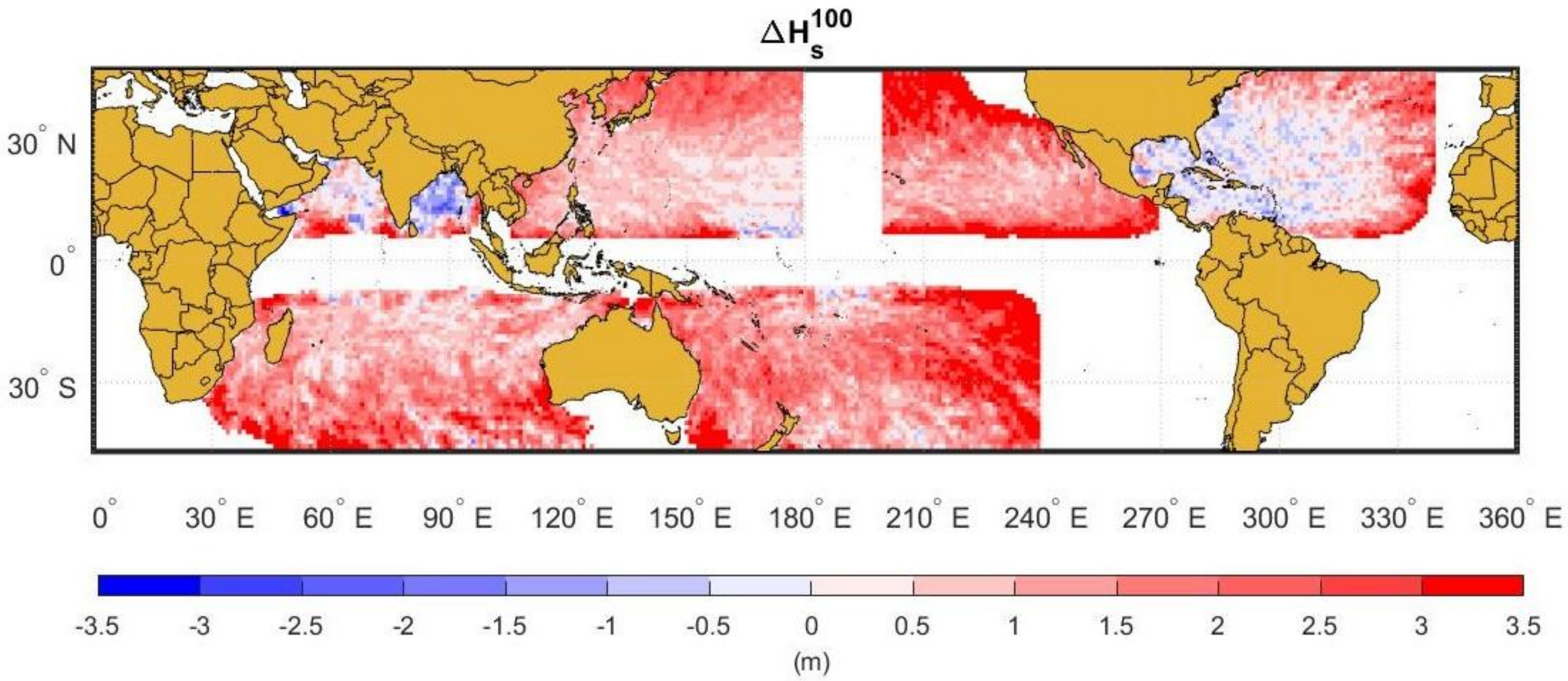


	max H_s^{100} (m)		
Tropical cyclone basin	**Future climate**		Present-day (Historical)
Western Pacific	**18.0**	↑	17.4
Eastern Pacific	**16.9**	↑	16.8
North Atlantic	**16.9**	↓	17.2
North Indian	**15.0**	↓	15.5
South Indian	**15.0**	↑	14.6
South Pacific	**15.6**	↑	14.7

Global changes in Extreme TC Wave Heights under Future Climate conditions

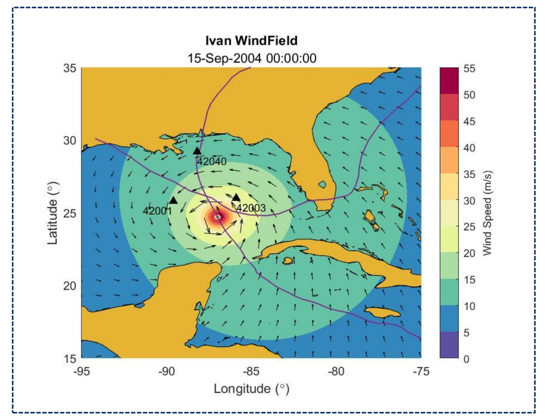
ΔH_s^{100} = H_s^{100} Future Climate* (2015 to 2050) – H_s^{100} Historical (1980 to 2017)

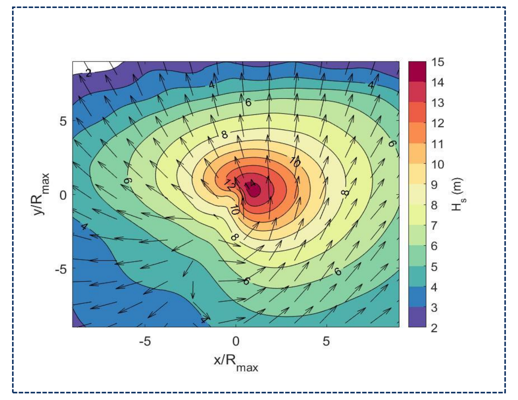
*SSP585;
4-GCMs ensemble



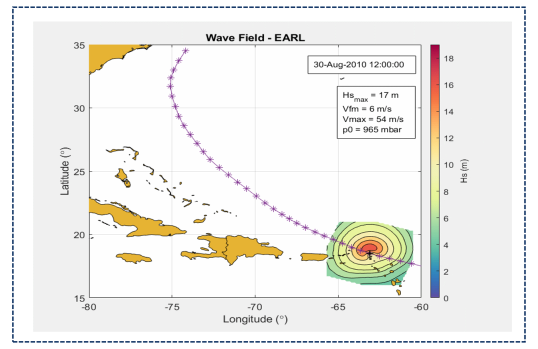
- Tendency of increasing extreme wave heights in WP, EP, SI and SP TC basins.
- NA and NI have a tendency in decreasing extreme wave heights, small in some parts of NA and significant in Bay of Bengal in NI.
- Results agree with the trend of changing in extreme maximum winds estimated by Bloemendaal et al. (2022).

Conclusions

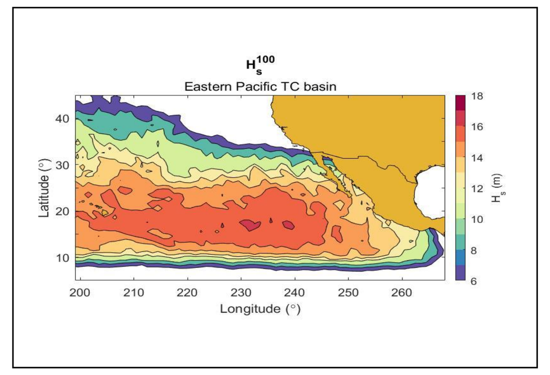




More realistic wind vortex model (asymmetry & wind inflow angle) + 3rd generation spectral wave model (WW3) which includes the nonlinear terms => essential for the construction of the synthetic wave database and development of the wave height parametric model.



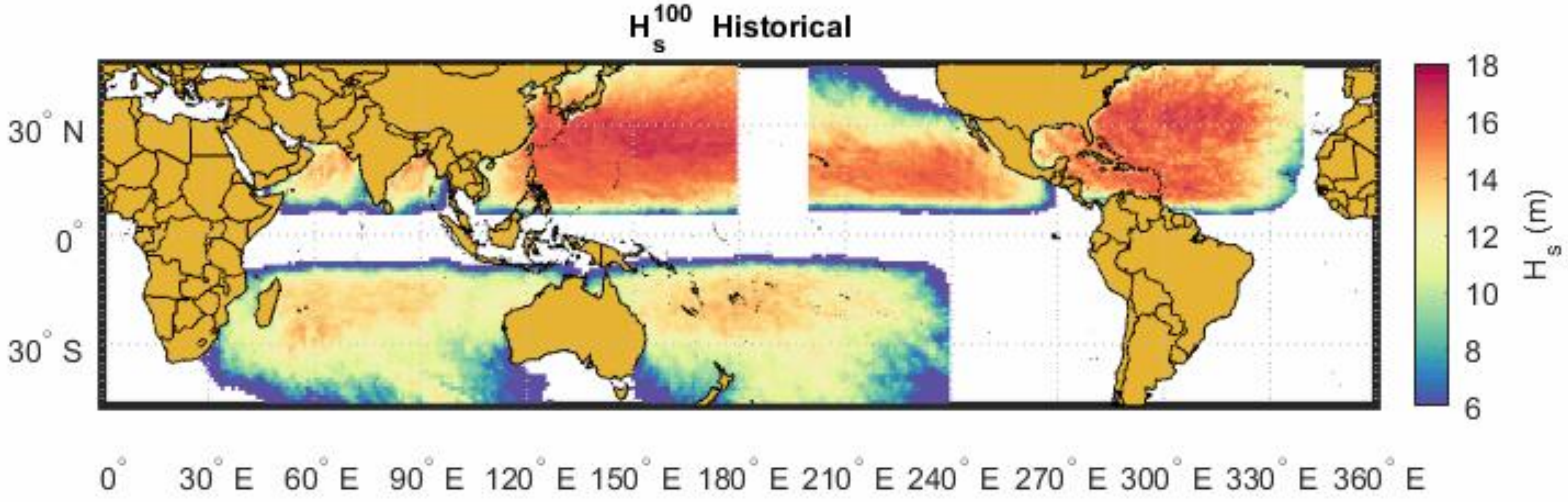
PModel => despite limitations => computationally best efficient solution to simulate wave heights in each TC track point for all TC ocean basins (30,000-yr of simulations).

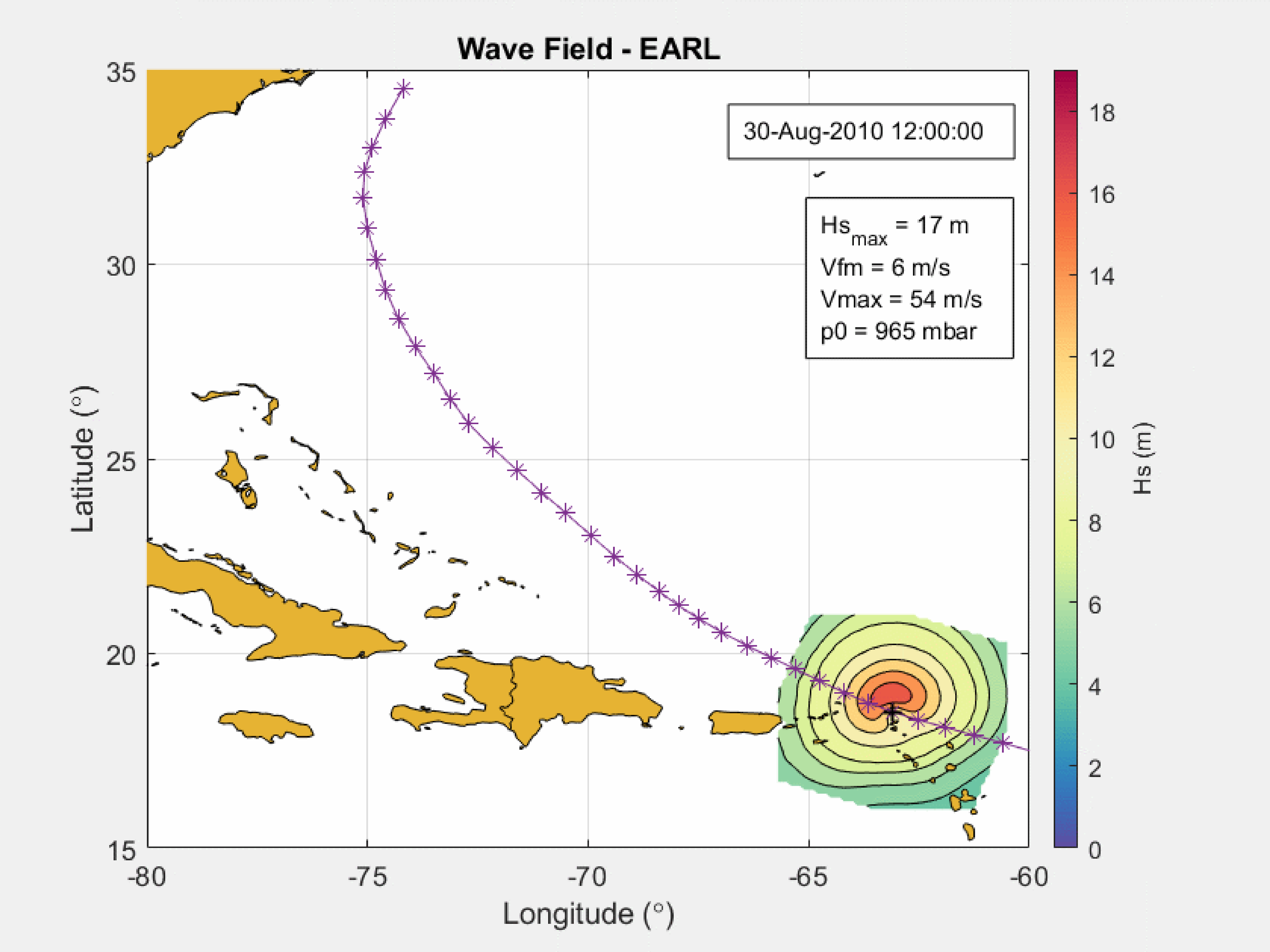


Present-day TC waves climatology: WP and NA present the largest extreme TC waves globally. SI and SP TC basins have very similar climatology.

Changes under global warming conditions: Tendency in increase magnitude of extreme TC waves for almost all TC basins, exception for NA and NI TC basins.

Thank you!





Questions?