Redefining Extreme Wave Design in the Gulf of Mexico with Synthetic Tropical Cyclones

Christian M. Appendini, Pablo Ruiz Salcines, Rodrigo Duran, Reza Marsooli, A.S.M. Alauddin Al Azad, Kerry Emanuel

NESDIS/STAR GOES-East GEOCOLOR

Note: The cone contains the probable path of the storm center but does not show the size of the storm. Hazardous conditions can occur outside of the cone.
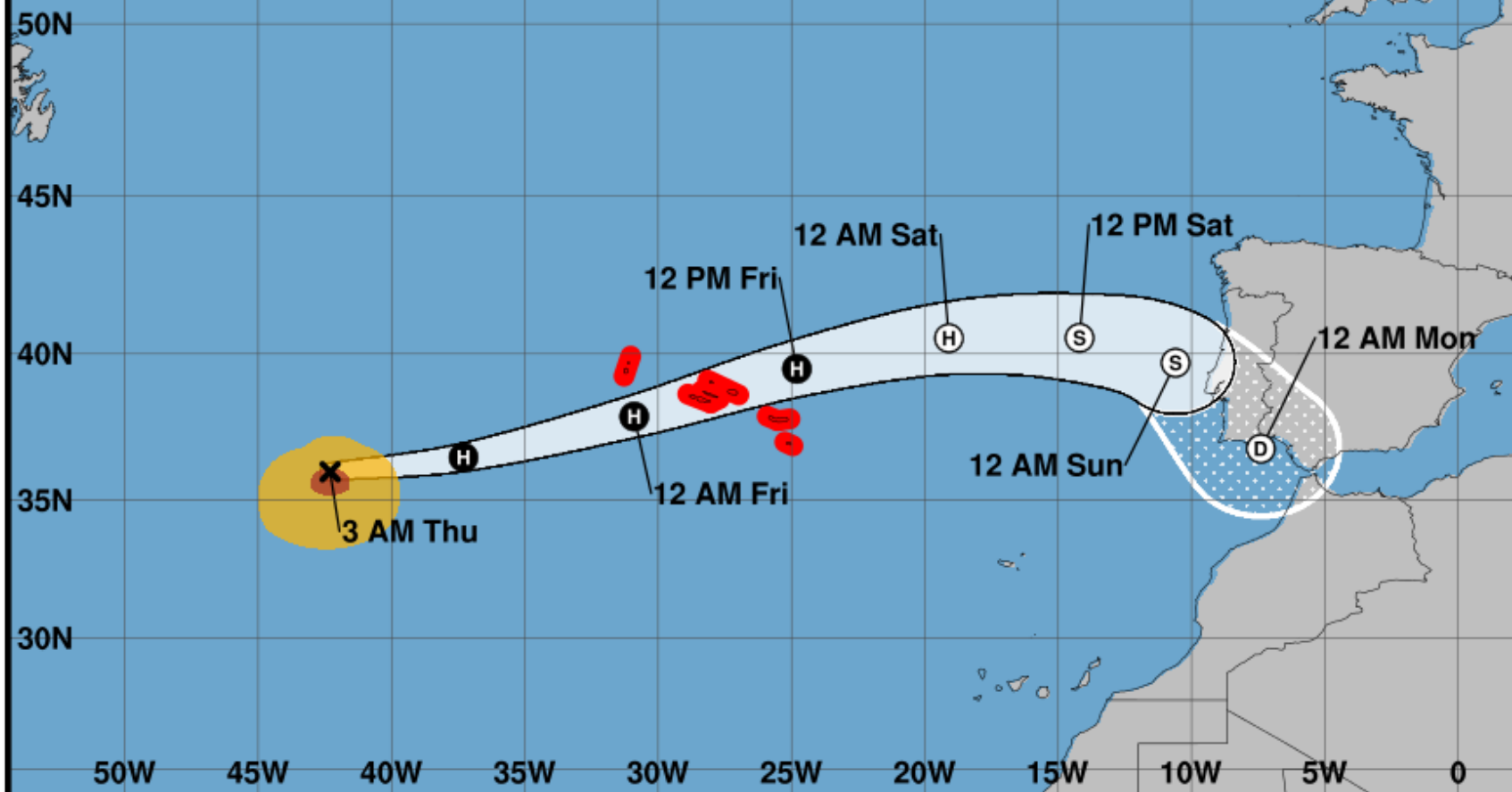
Hurricane Gabrielle
Thursday September 25, 2025
3 AM GMT Advisory 33
NWS National Hurricane Center

Current information: ✕
Center location 36.0 N 42.3 W
Maximum sustained wind 85 mph
Movement E at 31 mph

Forecast positions:
● Tropical Cyclone ○ Post/Potential TC
Sustained winds: D < 39 mph
S 39-73 mph H 74-110 mph M > 110 mph

Potential track area:
⬠ Day 1-3   ⬠ Day 4-5

Watches:
Hurricane   Trop Stm

Warnings:
Hurricane   Trop Stm

Current wind field estimate:
Hurricane   Trop Stm

Redefining Extreme Wave Design in the Gulf of Mexico with Synthetic Tropical Cyclones

Christian M. Appendini, Pablo Ruiz Salcines, Rodrigo Duran, Reza Marsooli, A.S.M. Alauddin Al Azad, Kerry Emanuel

NESDIS/STAR GOES-East GEOCOLOR

INSTITUTO DE INGENIERÍA UNAM

UNIVERSITAT ROVIRA i VIRGILI

PLANETARY SCIENCE INSTITUTE EST. 1972

STEVENS INSTITUTE OF TECHNOLOGY 1870

U.S. DEPARTMENT OF ENERGY

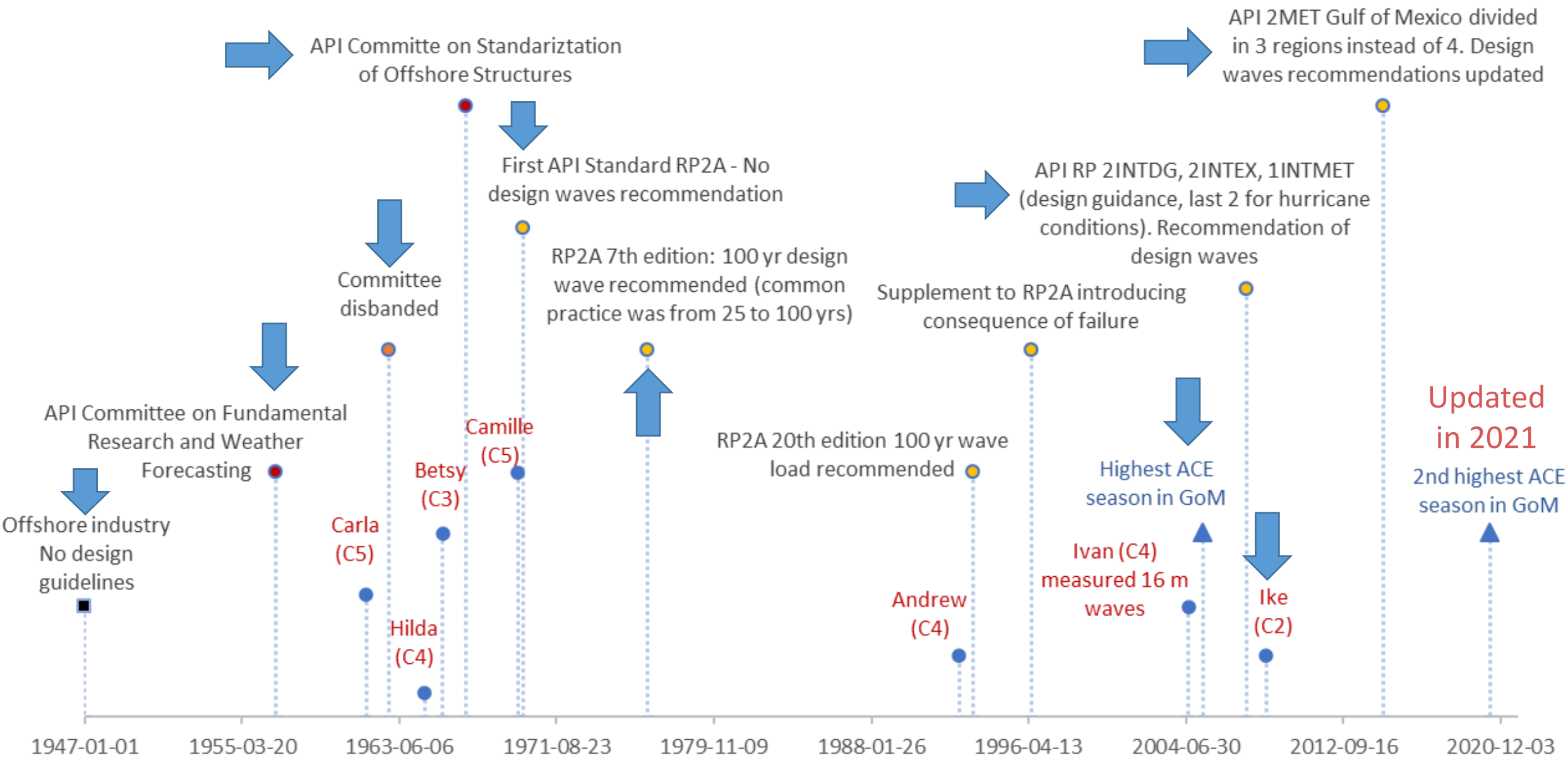MIT Massachusetts Institute of Technology

The American Petroleum Institute (API) has provided recommendation for metocean conditions since 1969, with wave data since 1976

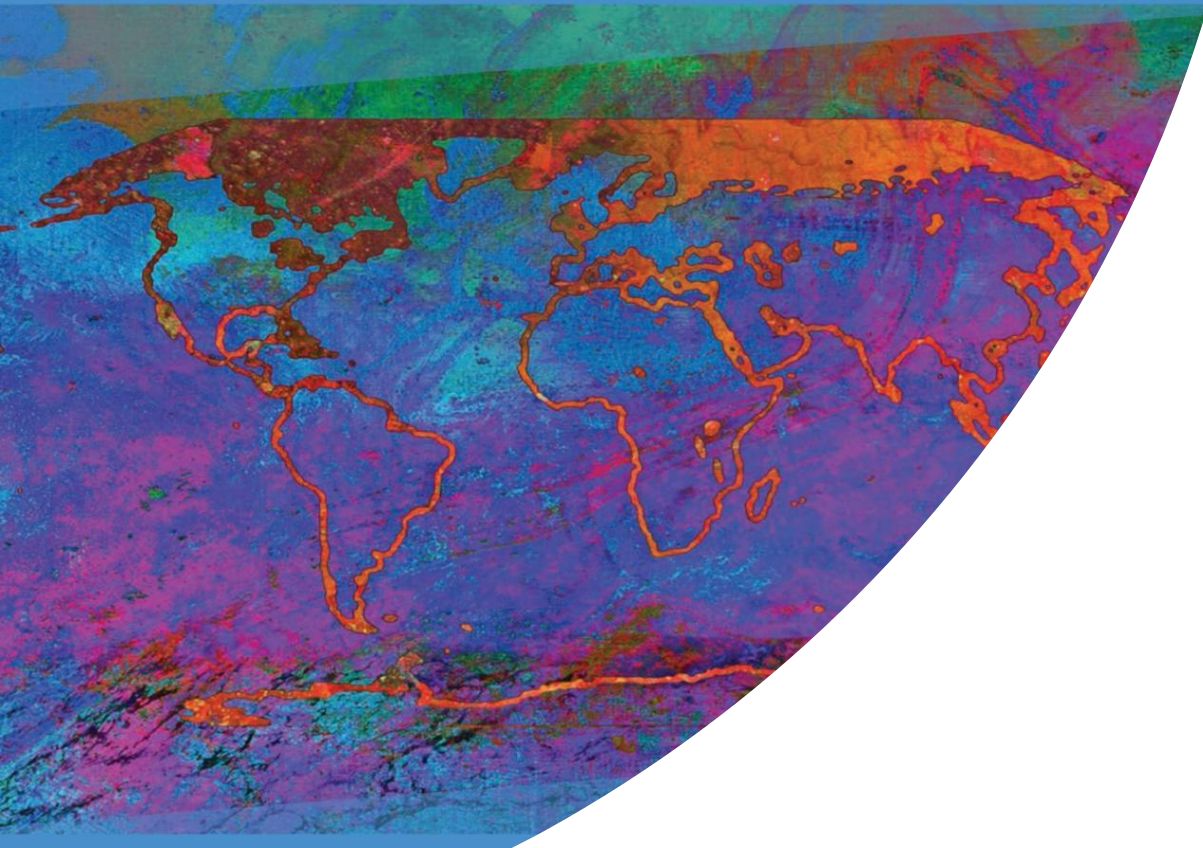**Derivation of Metocean Design and Operating Conditions**

ANSI/API RECOMMENDED PRACTICE 2 METSECOND EDITION, JANUARY 2021

ISO industries—Specific for Metocean design and operating considerations

Based on historical events

AMERICAN PETROLEUM INSTITUTE

Timeline for API guidelines in relation to events damaging oil rigs in the US Gulf of Mexico

API Committe on Standariztation of Offshore Structures

API 2MET Gulf of Mexico divided in 3 regions instead of 4. Design waves recommendations updated

First API Standard RP2A - No design waves recommendation

API RP 2INTDG, 2INTEX, 1INTMET (design guidance, last 2 for hurricane conditions). Recommendation of design waves

RP2A 7th edition: 100 yr design wave recommended (common practice was from 25 to 100 yrs)

Committee disbanded

Supplement to RP2A introducing consequence of failure

API Committee on Fundamental Research and Weather Forecasting

Camille (C5)

RP2A 20th edition 100 yr wave load recommended

Highest ACE season in GoM

Updated in 2021

2nd highest ACE season in GoM

Offshore industry No design guidelines

Betsy (C3)

Carla (C5)

Ivan (C4) measured 16 m waves

Ike (C2)

Andrew (C4)

Hilda (C4)

1947-01-01   1955-03-20   1963-06-06   1971-08-23   1979-11-09   1988-01-26   1996-04-13   2004-06-30   2012-09-16   2020-12-03

Climate Change 2021
The Physical Science Basis
Summary for Policymakers

HIGH CONFIDENCE
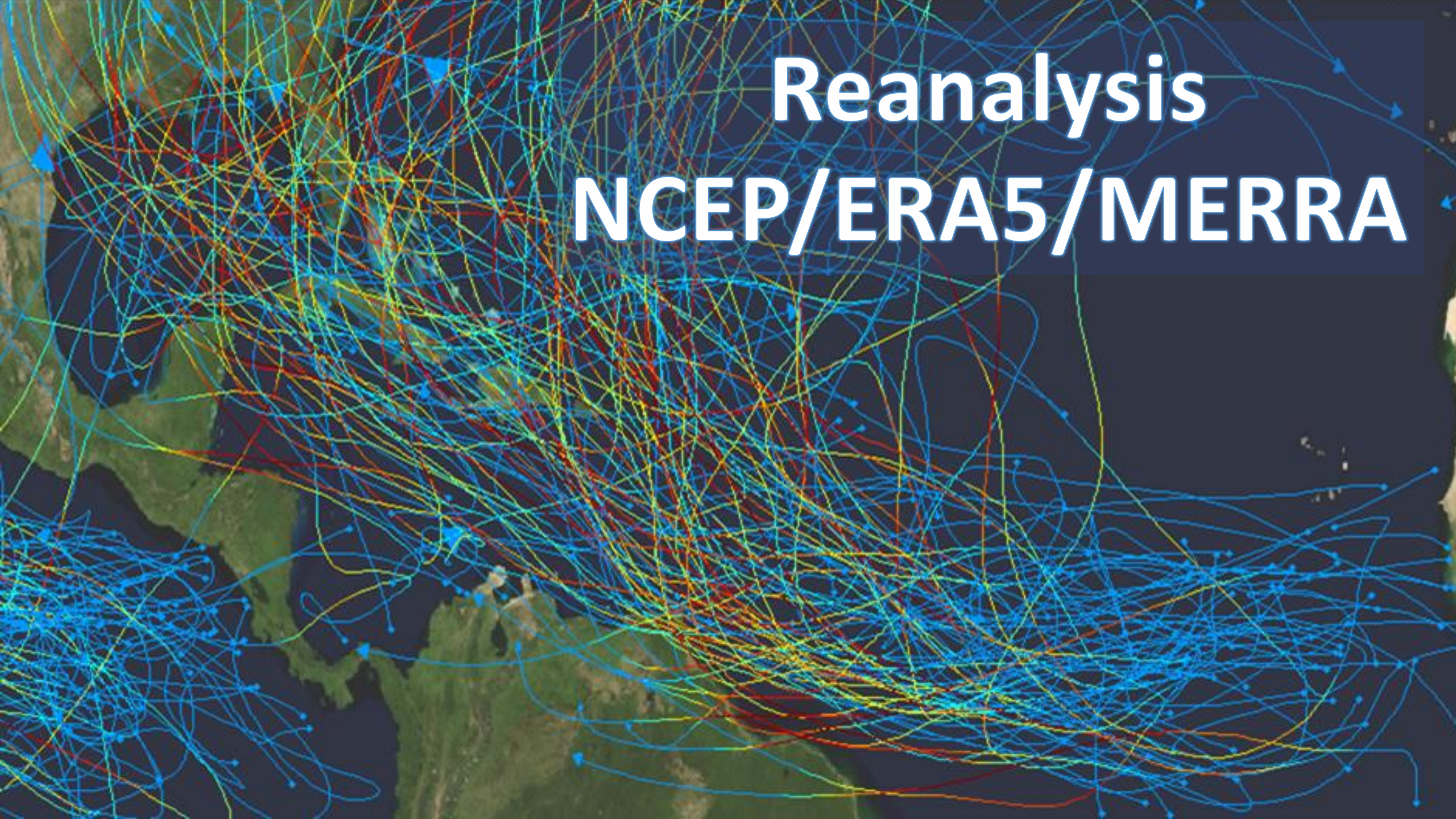
The **proportion of intense tropical cyclones (Category 4–5)** and **peak wind speeds** of the most intense tropical cyclones are **projected to increase** at the global scale with increasing global warming.

Global wave climate characterization (COWCLIP)

- ➤ Use of GCM's winds
  - Underestimation of maximum wind speeds
  - Underestimation of the number of TCs
- ➤ Low resolution for coastal areas and enclosed seas
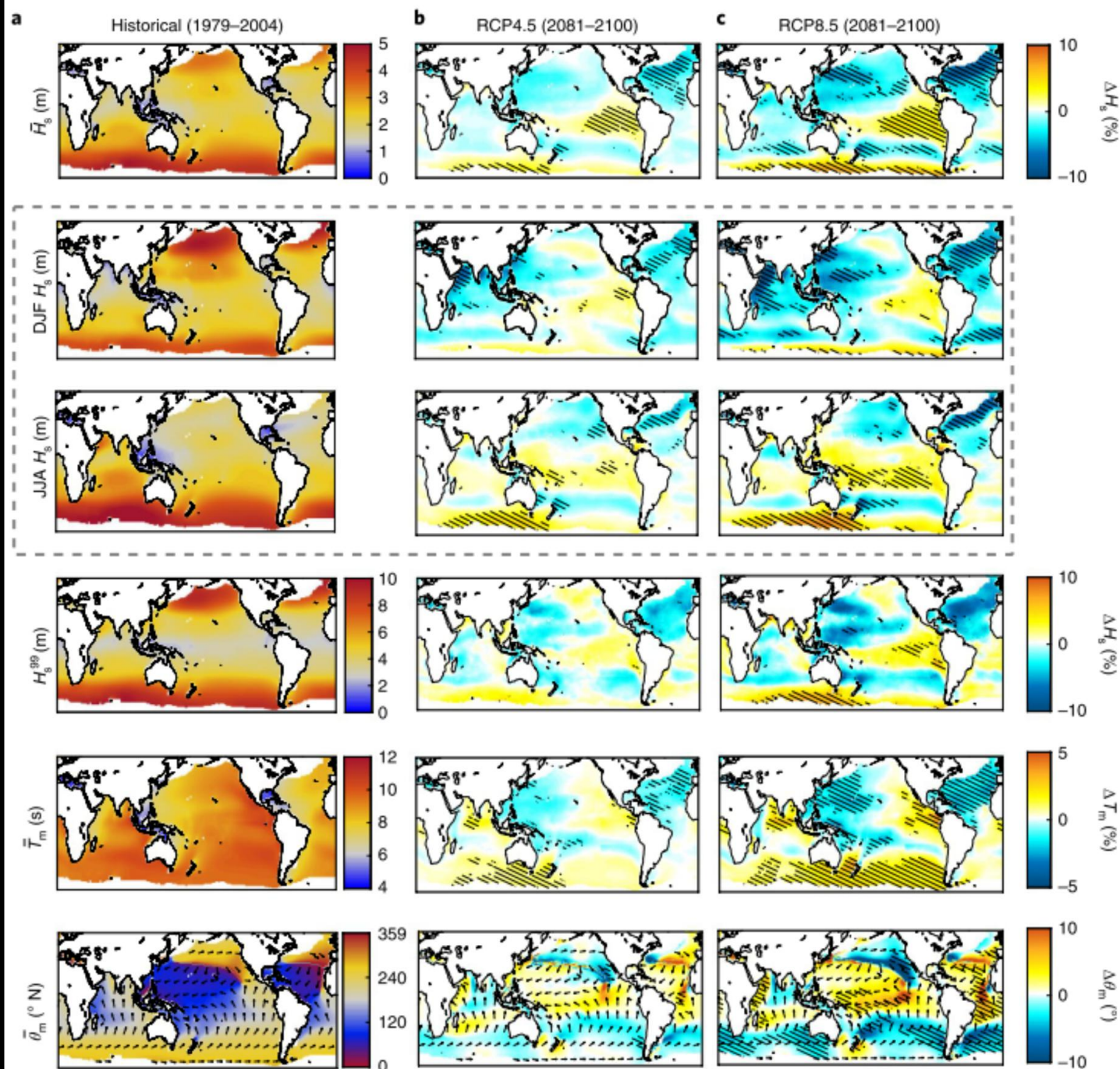
Morim, J., Hemer, M., Wang, X. L., Cartwright, N., Trenham, C., Semedo, A., et al. (2019). Robustness and uncertainties in global multivariate wind-wave climate projections. Nature Climate Change, 9(9), 711–718. doi.org/10.1038/s41558-019-0542-5

Reanalysis
NCEP/ERA5/MERRA

GCMs

- **GFDL CM3**
- **HADGEM2-ES**
- **MIROC5**
- **IPSL-CM5A-LR**
- **MPI-ESM-MR**
- **CCSM-v4**

Synthetic tropical cyclone tracks

Present climate

Future climate

Methodology

Bathymetry/Mesh

Wind fields
(NCEP, GCMS Present + SSP5 8.5)

Synthetic TCs database

Present climate:
3 Reanalysis + 6 GCMs (GFDL CM3, HADGEM2-ES, MIROC5, IPSL-CM5A-LR, MPI-ESM-MR, CCSM-v4)
Future climate:
6 GCMs – SSP5 8.5

wave modeling...

Source: NASA

MIKE 21 SW

Maximum envelopes (Hs, Tp) and Hs associated values (Tp, Dir)

Recommendations for wave design parameters

Potencia de oleaje máxima.   Evento 0489
Potencia de oleaje máxima.   Evento 0498
Potencia de oleaje máxima.   Evento 0505
Potencia de oleaje máxima.   Evento 0510
Potencia de oleaje máxima.   Evento 0517

Latitud en grados
Longitud en grados
(kW/m)

Period	Type	Model	GoM
Present climate	Reanalysis	NCEP	4207
		ERA5	5082
		MERRA2	4139
		CERA20C	4797
	GCM	HADGEM6	3557
		GFDL6	4354
		IPSL6	2587
		MIROC6	4640
		MPI6	6279
		CESM2	4306
Future climate SSP585	GCM	HADGEM6	2015
		GFDL6	4032
		IPSL6	1674
		MIROC6	4149
		MPI6	6019
		CESM2	3360
Total events			65197
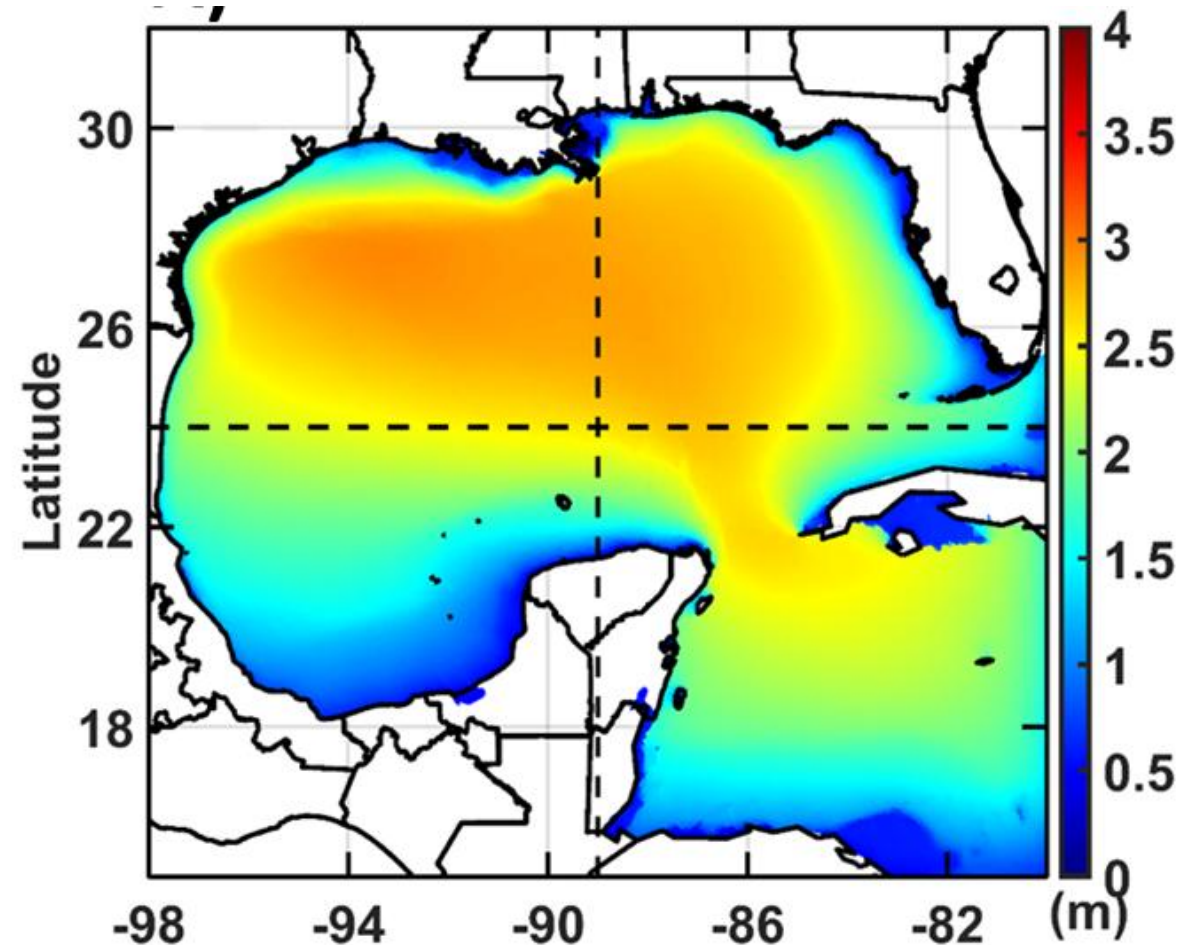
~65000 simulations in 5 days

Methodology
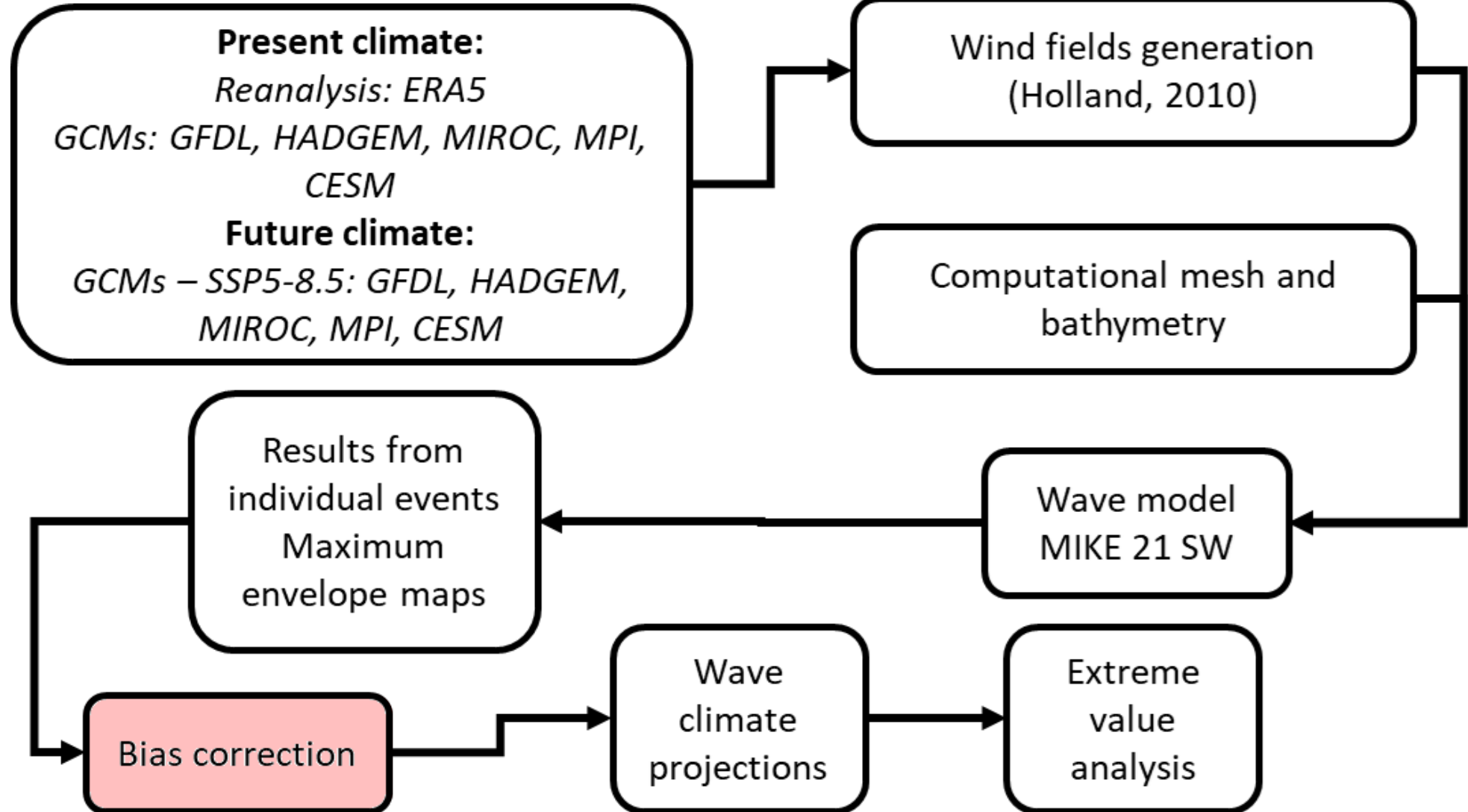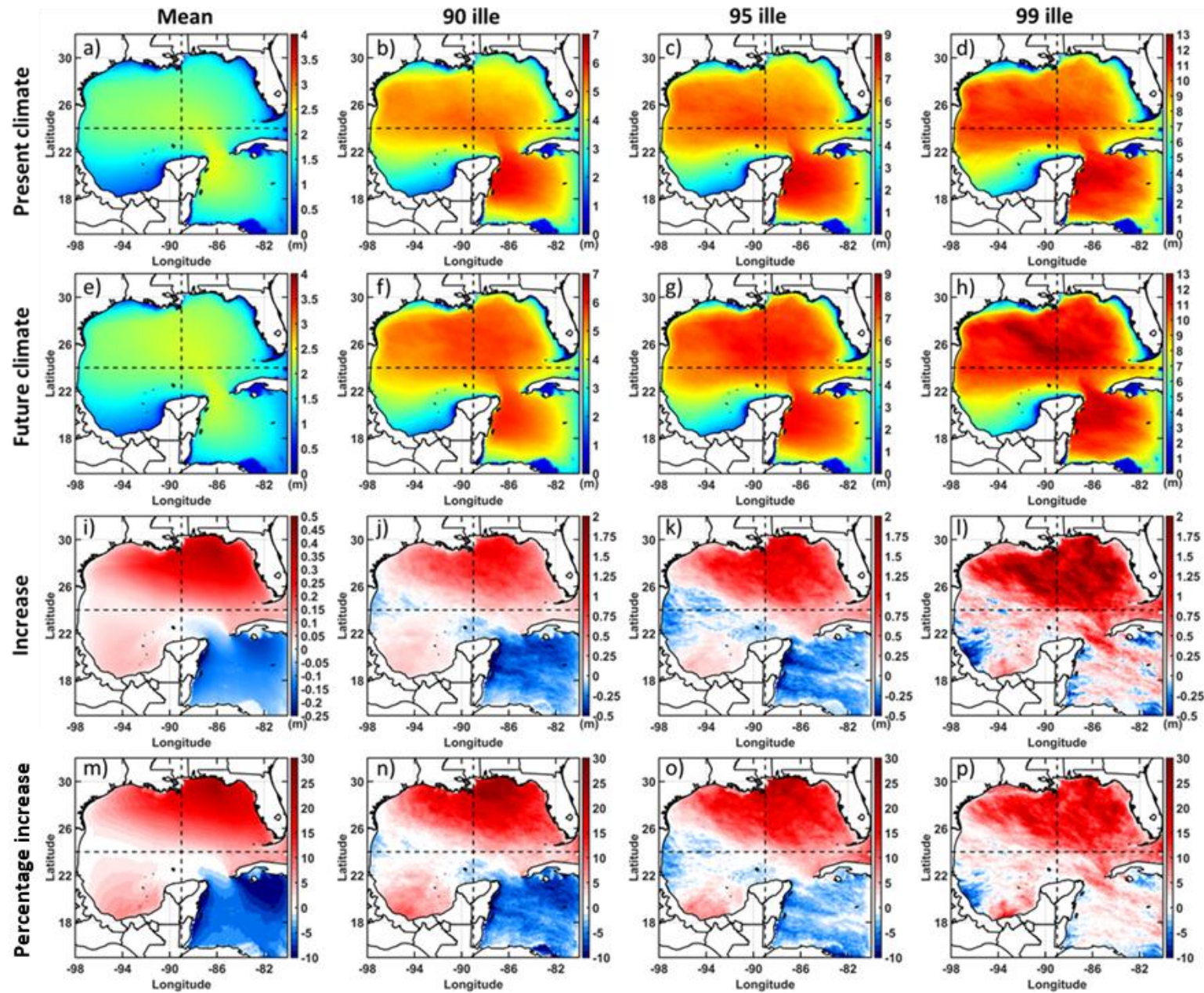
Hs for different return periods
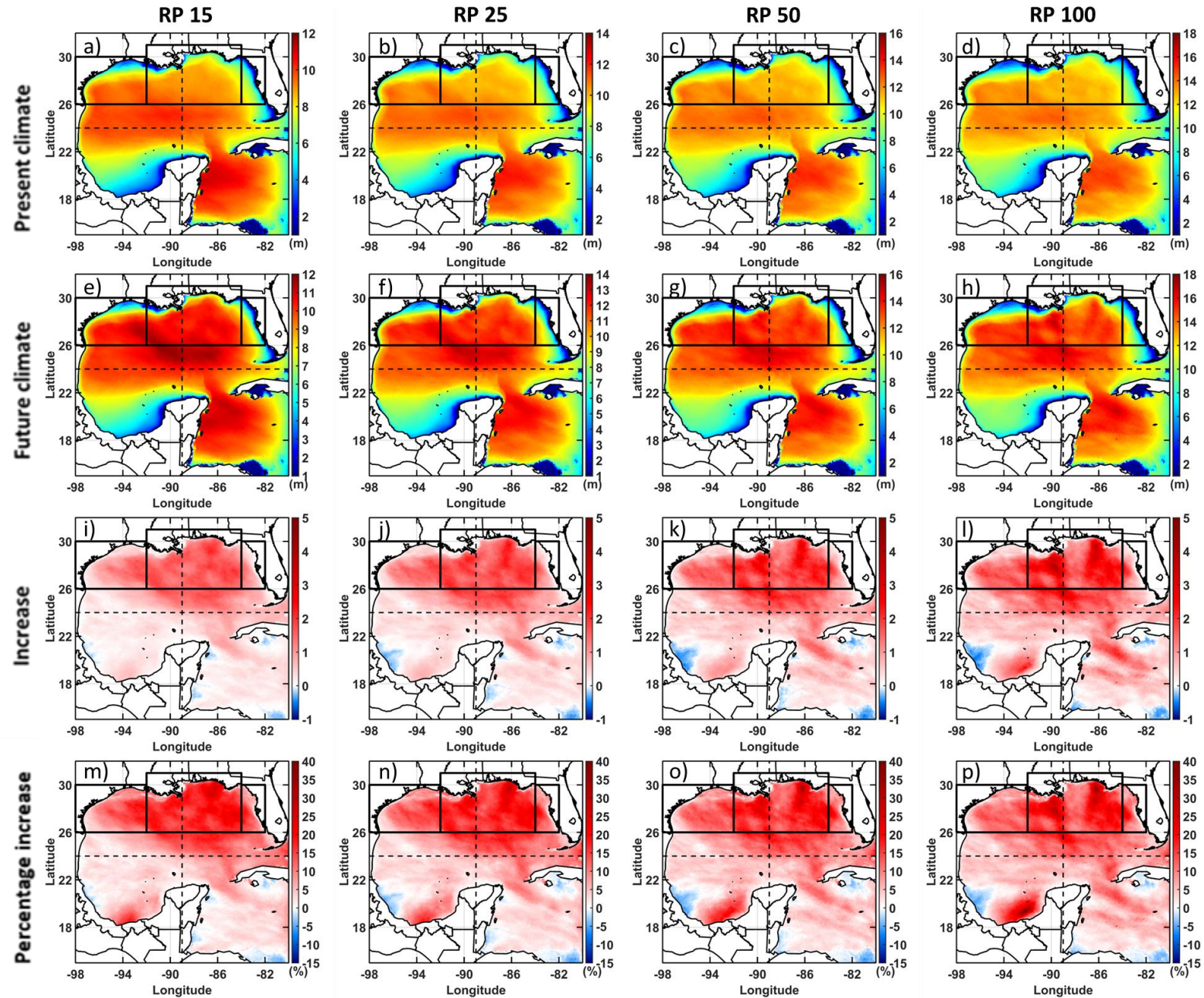
100 Years return period significant wave height – CMIP6

**Present climate
(1975 – 2005)**

**Future climate CMIP6 – SSP5 8.5
(2070 – 2100)**

CMIP5 - RCP 8.5

A) West US

B) Central US

C) East US

West   Central   East
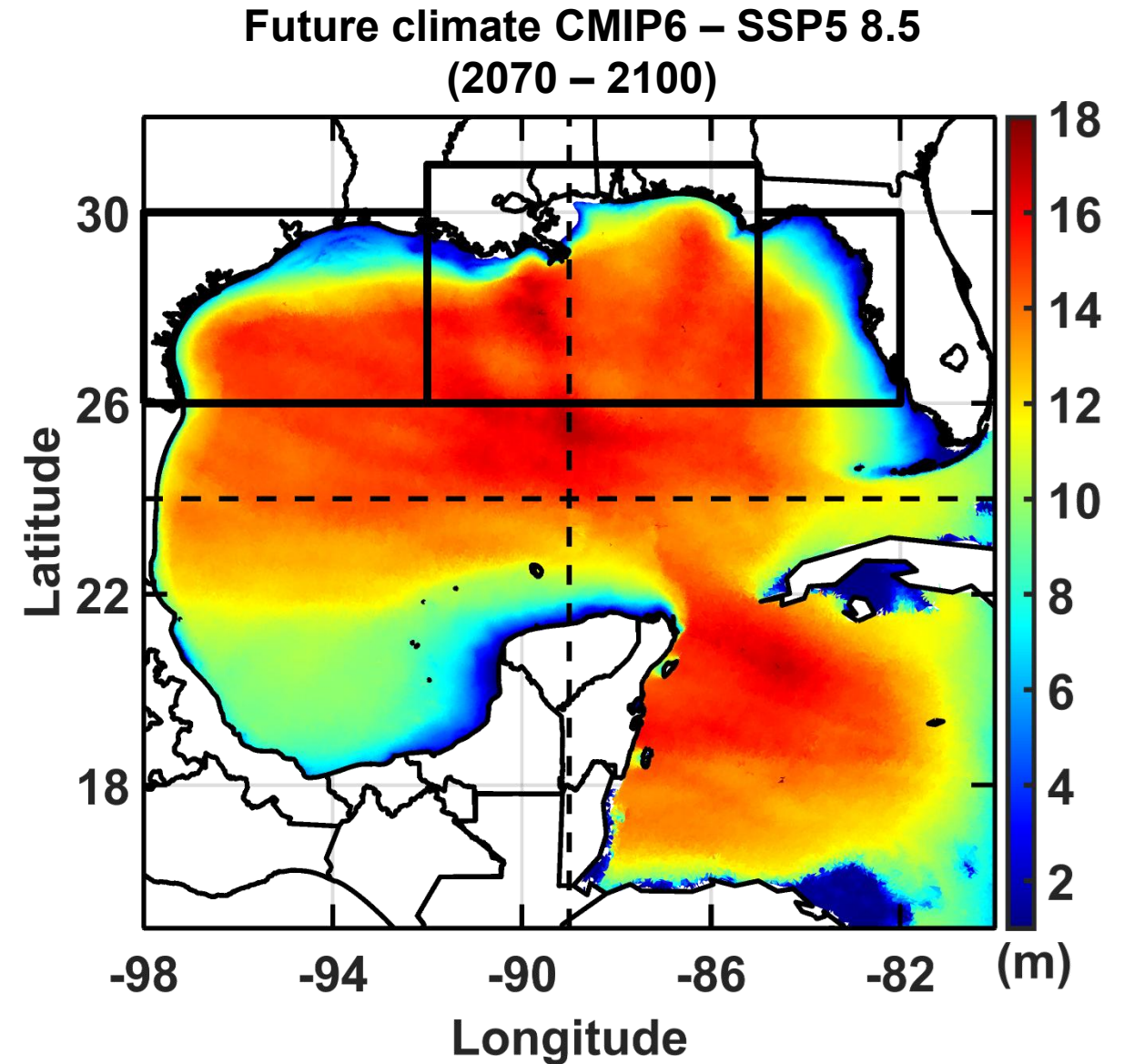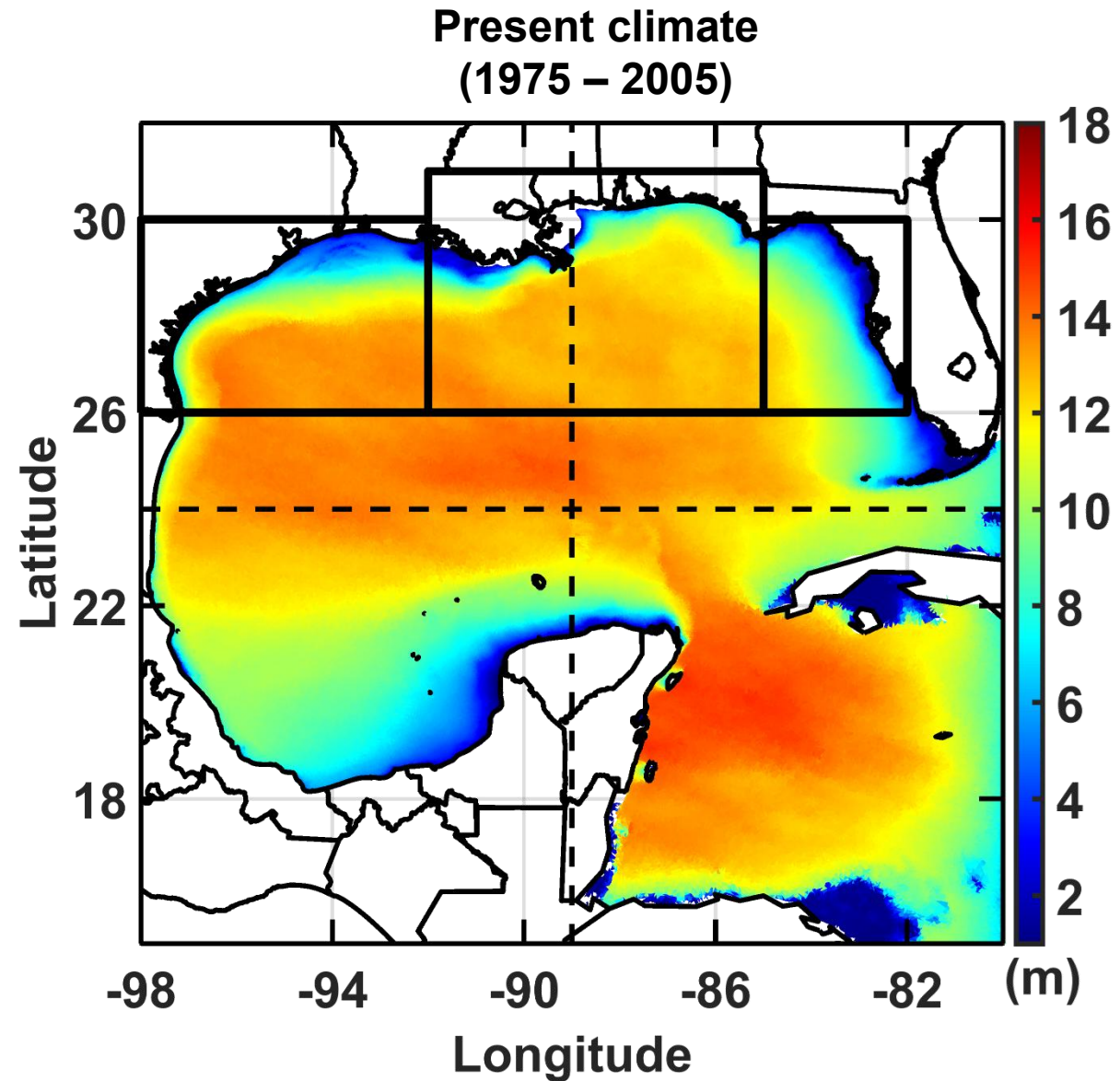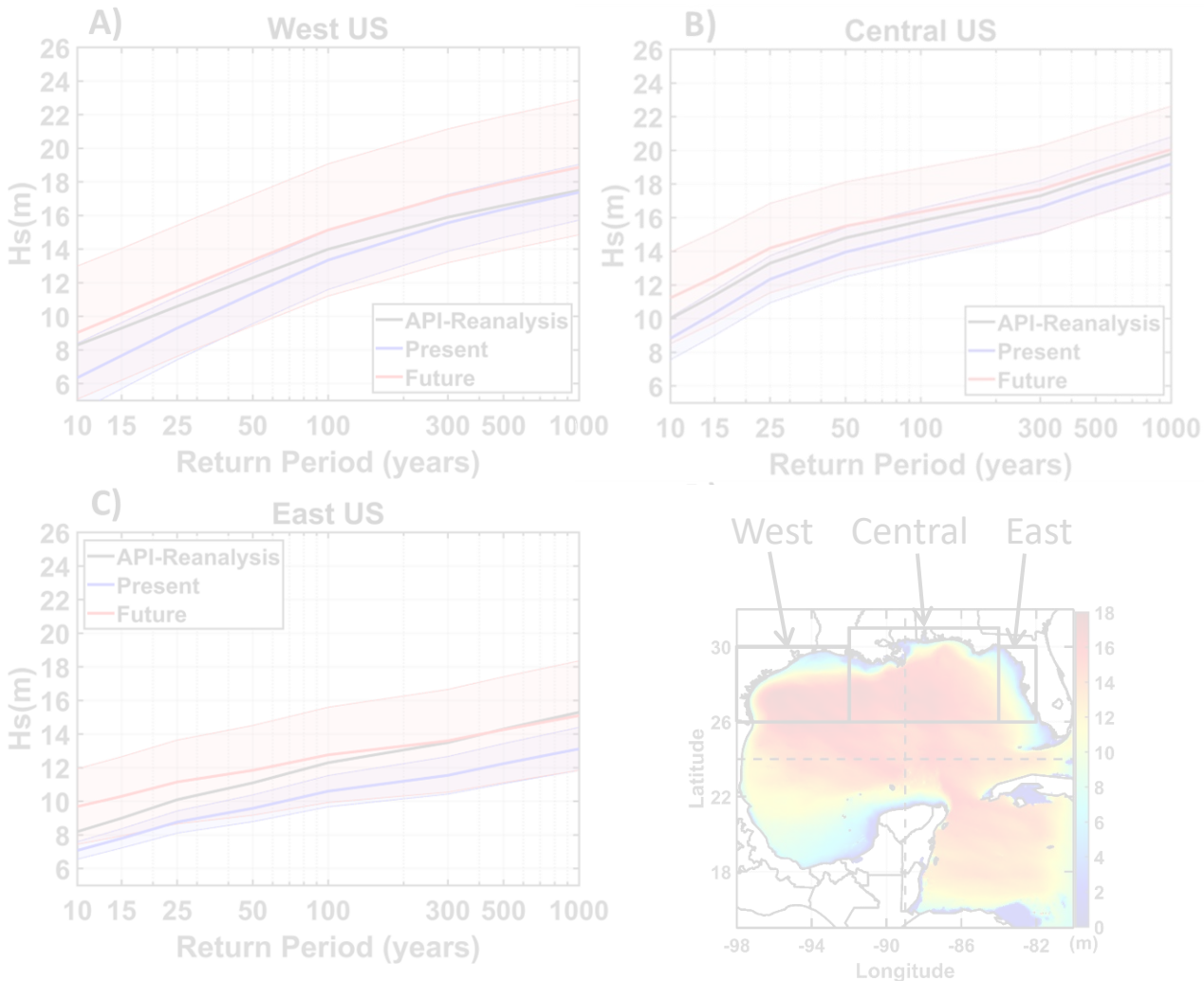
Change in design parameters due to CC – failure implications
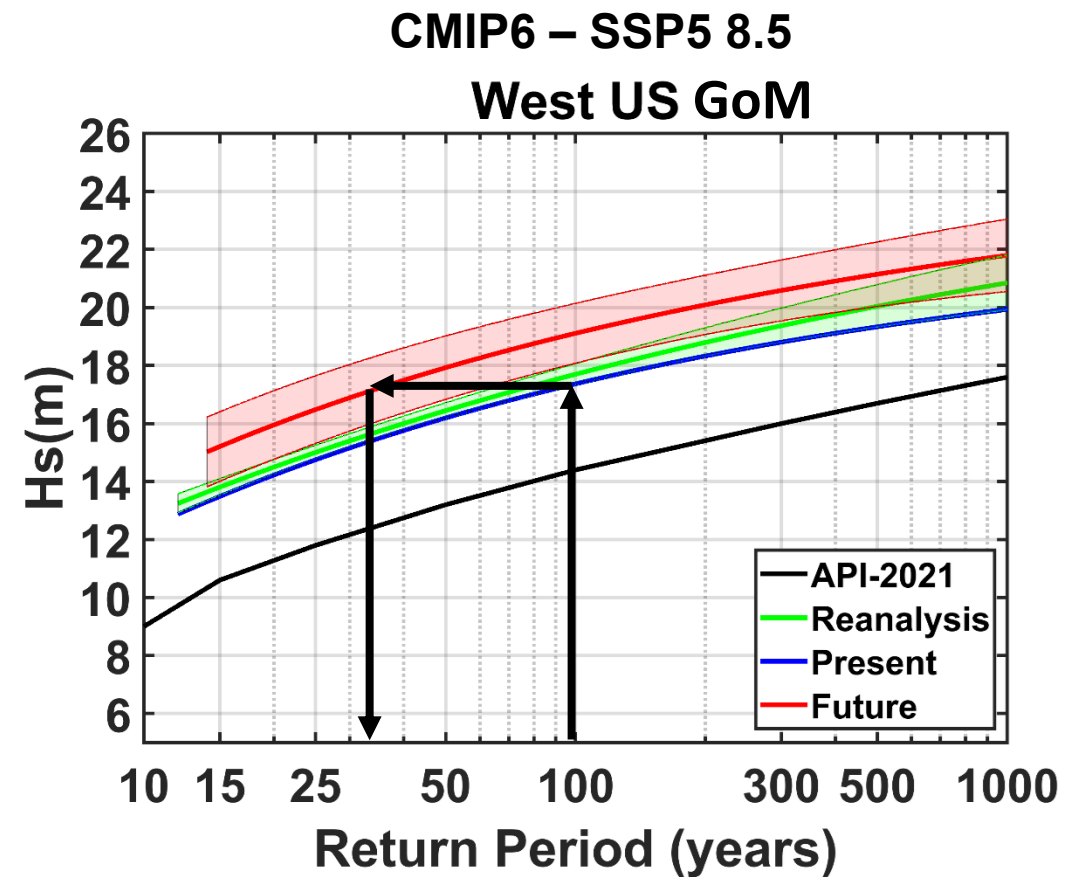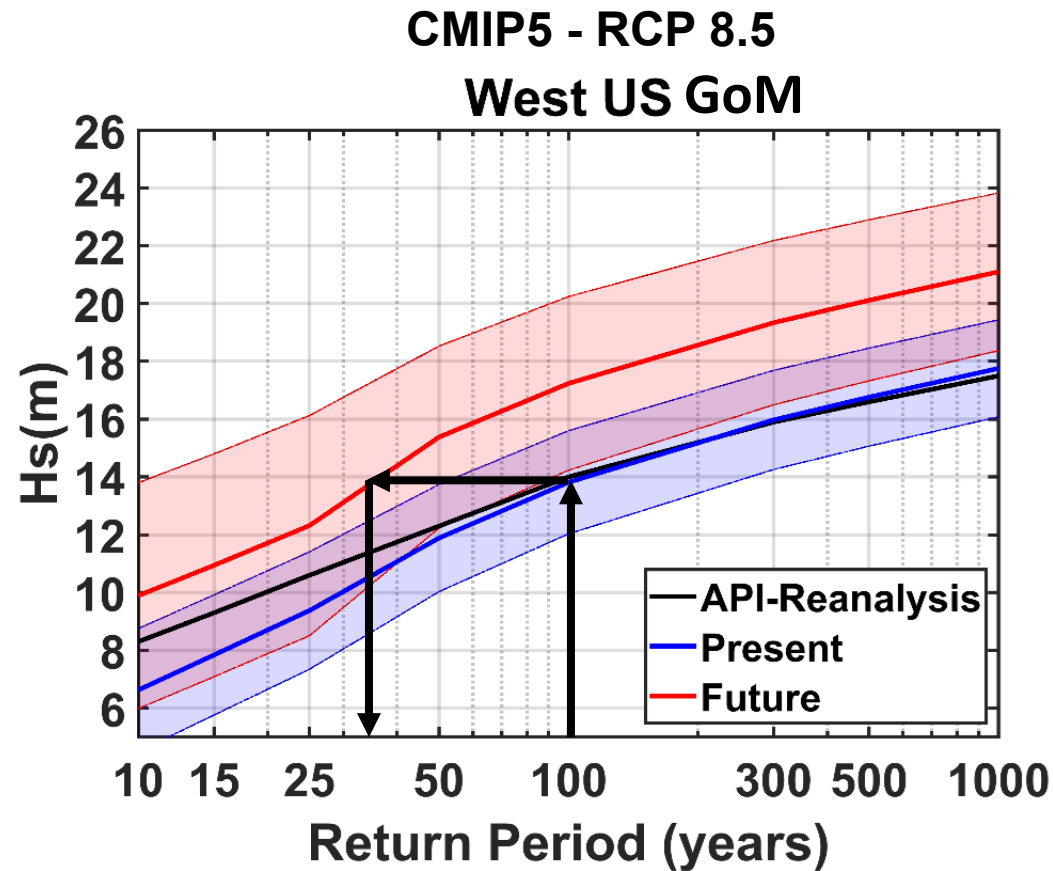
... for both cases (CMIP5 & CMIP6) the **100 year return period** in the **present climate** corresponds to **~30 year return period** in the **future climate**. Based on that, the probability of the design event to ocurr during the lifetime of a structure a increases from **26%** to **64%**

Conclusions

Estimates of extreme wave heights using historical tropical cyclone events are imprecise due to the limited time of available information.

The use of synthetic tropical cyclone events allows for a robust statistical characterization of the extreme wave climate.

Using non-stationary wave climates is essential to reduce the probability of failure in maritime structures.

Synthetic tropical cyclones enable the characterization of future climate to determine design conditions for different return periods, including non-stationary climates.

Research paper

Redefining design wave conditions in the Gulf of Mexico under a changing climate

Christian M. Appendini [a,b,*], Pablo Ruiz-Salcines [a,c], Rodrigo Duran [d,e], Reza Marsooli [f], ASM Alauddin Al Azad [f], Kerry Emanuel [g]

Check for updates

Assessment of synthetic tropical cyclones in the North Atlantic Basin

David Romero [a], Christian M. Appendini [b,c,*], Kerry Emanuel [d], Chia-Ying Lee [e], Kees Nederhoff [f], Nadia Bloemendaal [g,h], Pablo Ruiz-Salcines [b,i], Jonathan Vigh [j], Christian Domínguez [k]

Bias Correction

Node 600