Wave Climate Projections in the Indian Ocean Using CMIP6 Models

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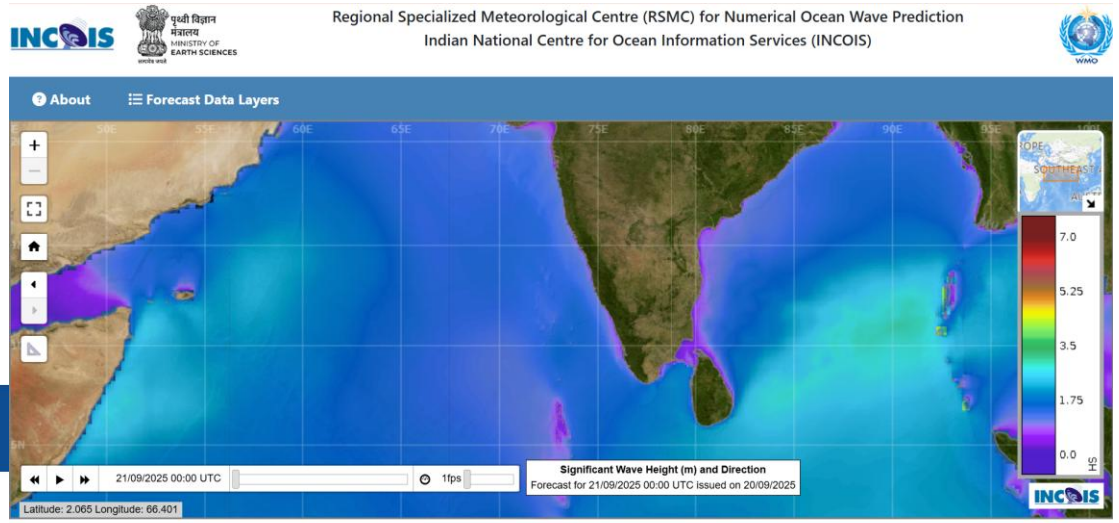
www.incois.gov.in

https://incois.gov.in/oceanservices/rsmc_waves.jsp



ECO-SYSTEM | MULTI HAZARD | FORECAST / NOWCAST | CLIMATE | INTERNATIONAL

Disclaimer

MULTI HAZARD SERVICES


Tsunami Early Warning


Storm Surge Warning

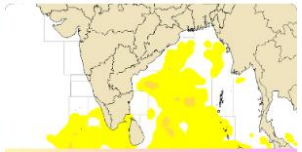

High Wave Alerts


Oil Spill Advisory

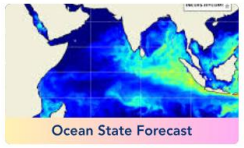

INCOIS -IMD Joint Bulletin


Small Vessel Advisory Services (SVAS)

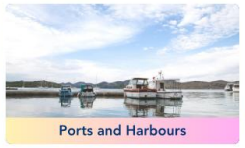

Search And Rescue Aid Tool (SARAT)


Marine Heatwave Advisory Services

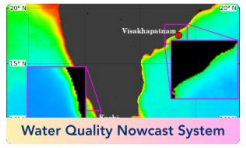
FORECAST / NOWCAST SERVICES


Ocean State Forecast

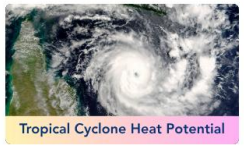

Predicted Astronomical Tide


Ports and Harbours

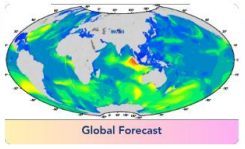

Forecast along ship routes

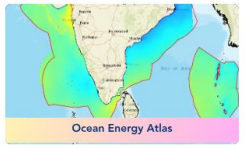


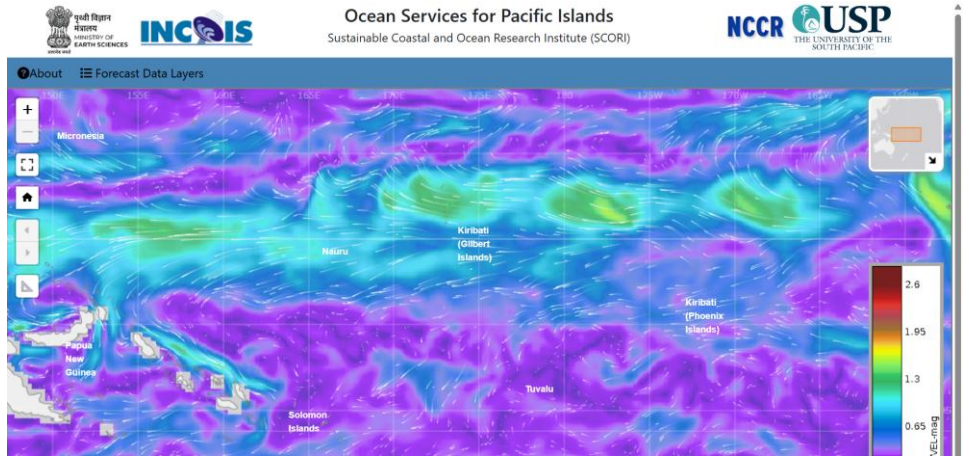
Water Quality Nowcast System

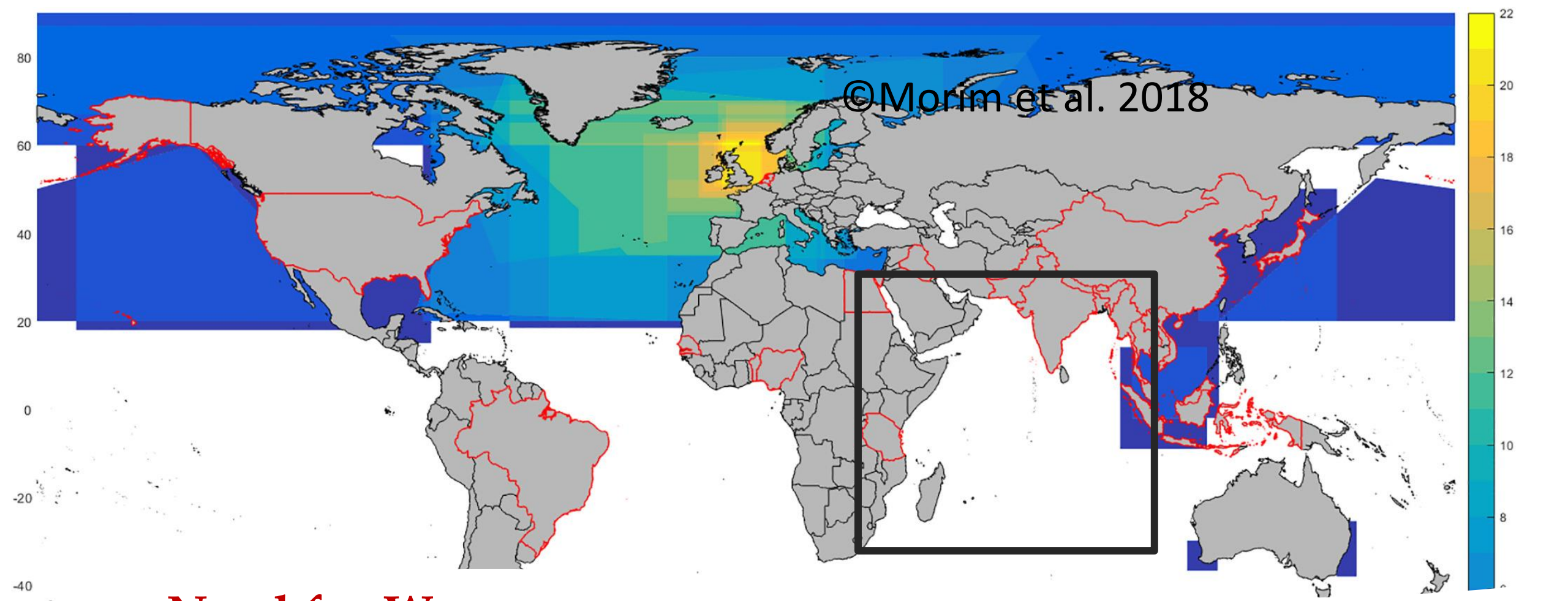

Tropical Cyclone Heat Potential


Location Specific Forecast


Global Forecast


Ocean Energy Atlas



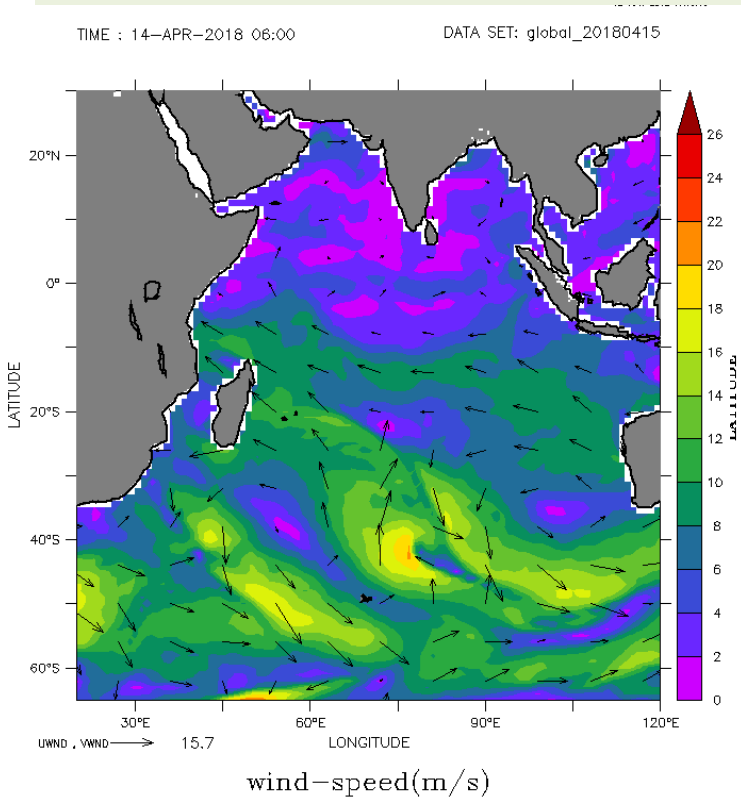


Need for Wave Climate Projections- Indian ocean

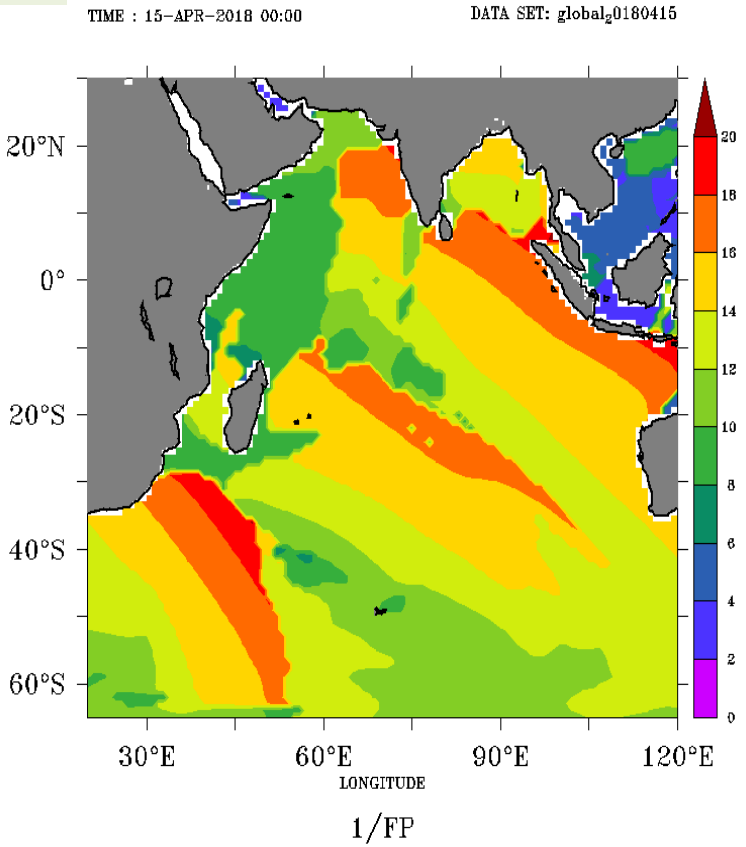
- ❑ Few studies → major knowledge gap
- ❑ Densely populated, vulnerable coasts
- ❑ Waves drive erosion & flooding risks
- ❑ Crucial for coastal planning & resilience

WAVE INDUCED COASTAL FLOODING and EROSION

Swell surge during 21-24 April 2018



Peak Wave period, Tp (s)



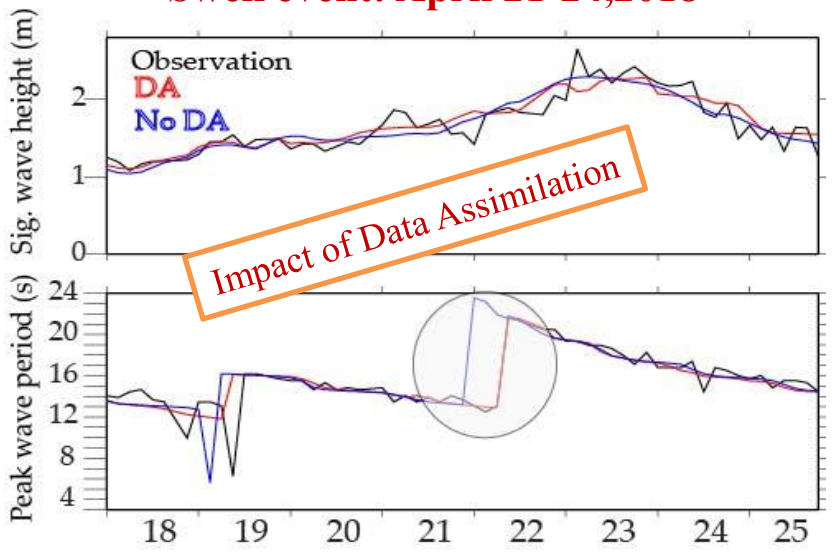
➢Kallakkadal(Sea thief)/Swell surge is a flash flooding event , caused by the long period (>17 s) southern ocean swell waves on the coasts of India

➢The intense winds associated with COLs in the Southern Ocean trigger the generation of waves, and they travel to NIO as swells.

➢The forecast of high swell events can be further improved by the data assimilation of wave data in to wave models

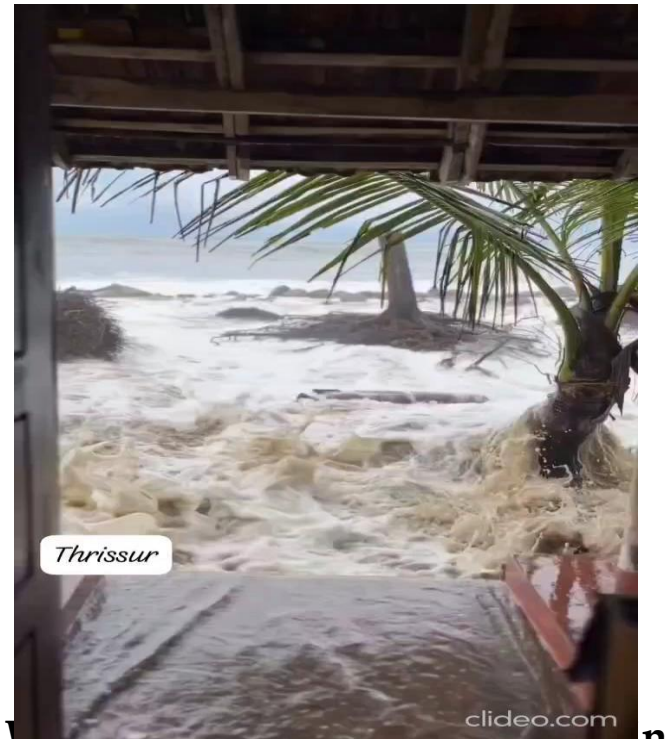
➢ These high swell events, which are occurring without any signs in the local weather, now effectively monitored and forecasted 3 days in advance using INCOIS wave forecasting system.

Swell event: April 21-24,2018



Remya P G, S Vishnu, B Praveen Kumar, T M Balakrishnan Nair, B Rohith, 2016, Tele-connection between the North Indian Ocean high swell events and Meteorological Conditions over the Southern Indian Ocean, JGR-oceans, 121, 7476–7494, doi:10.1002/2016JC011723.

Seemanth M, Remya P.G., Suchandra A Bhowmick, Rashmi Sharma, T.M. Balakrishnan Nair, Raj Kumar and Arun Chakraborty, 2021, Implementation of altimeter data assimilation on a regional wave forecasting system and its impact on wave and swell surge forecast in the Indian Ocean, Ocean Engineering .



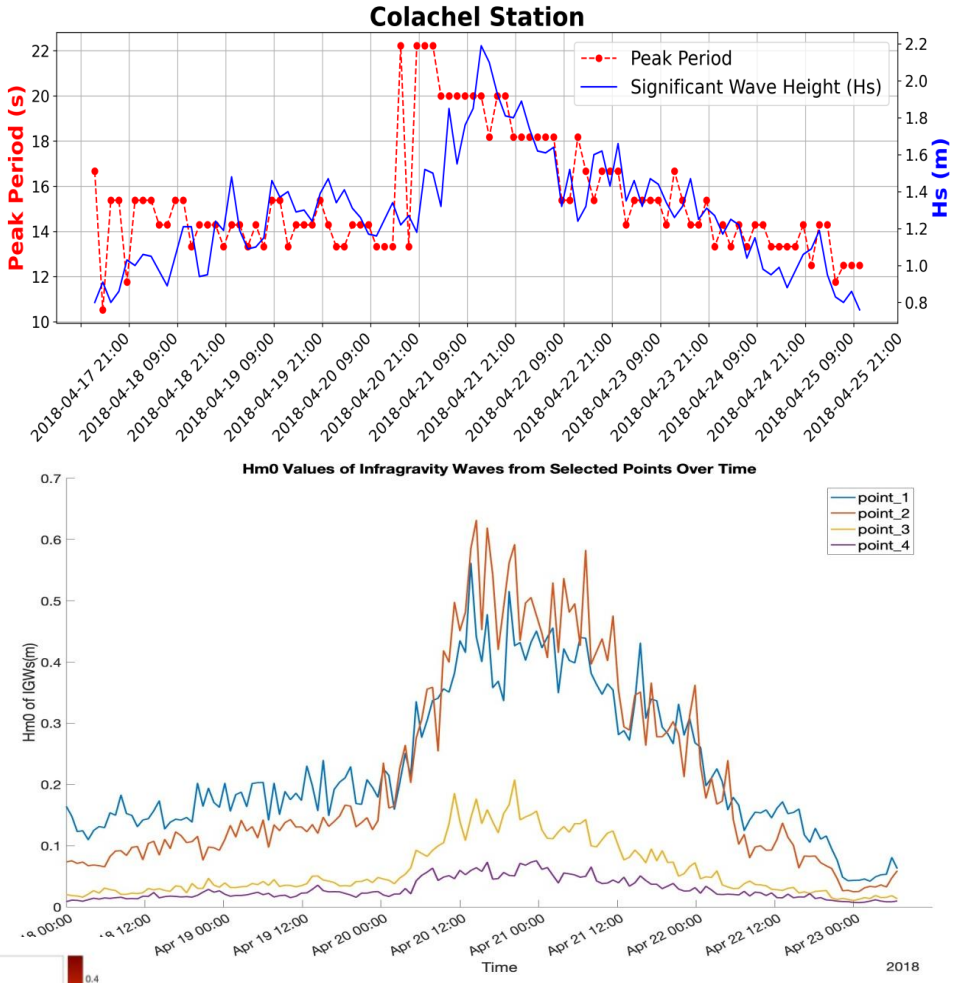
Swell surge in sea off Kanyakumari kills five medicos

Arockiaraj Johnbosco / TNN / Updated: May 6, 2024, 17:42 IST

MADURAI: Five medical college students and interns from SRM Medical College Hospital and Trichy Government Medical College Hospital vacationing in Kanyakumari district drowned in the sea off Lemur Beach on Monday due to a swell surge, a phenomenon the India

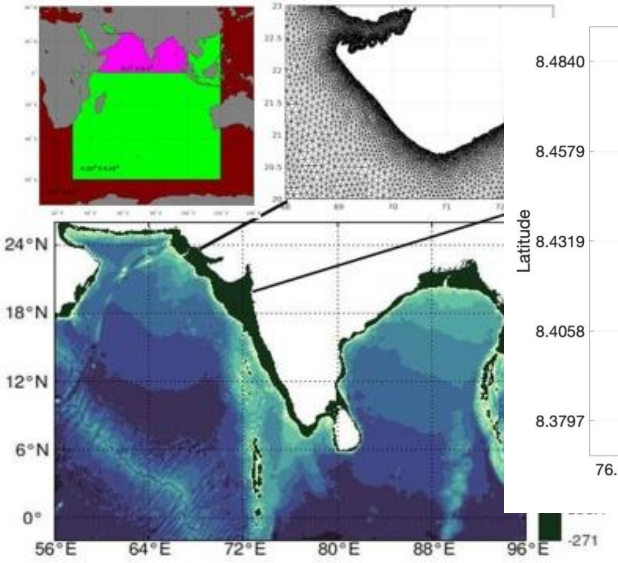
The intense event in May 2024 resulted in eight drowning deaths

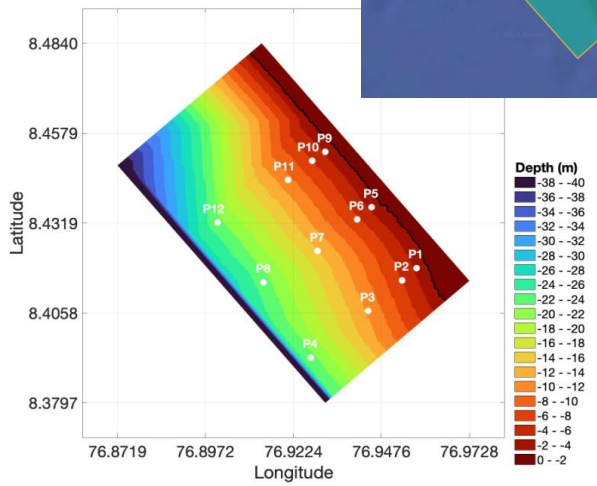
Observed short waves

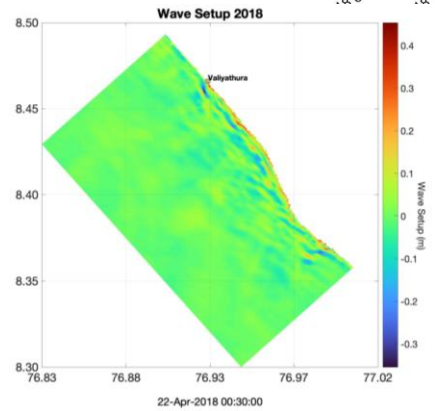


Xbeach Model Domain

WAVEWATCHIII Model Domain







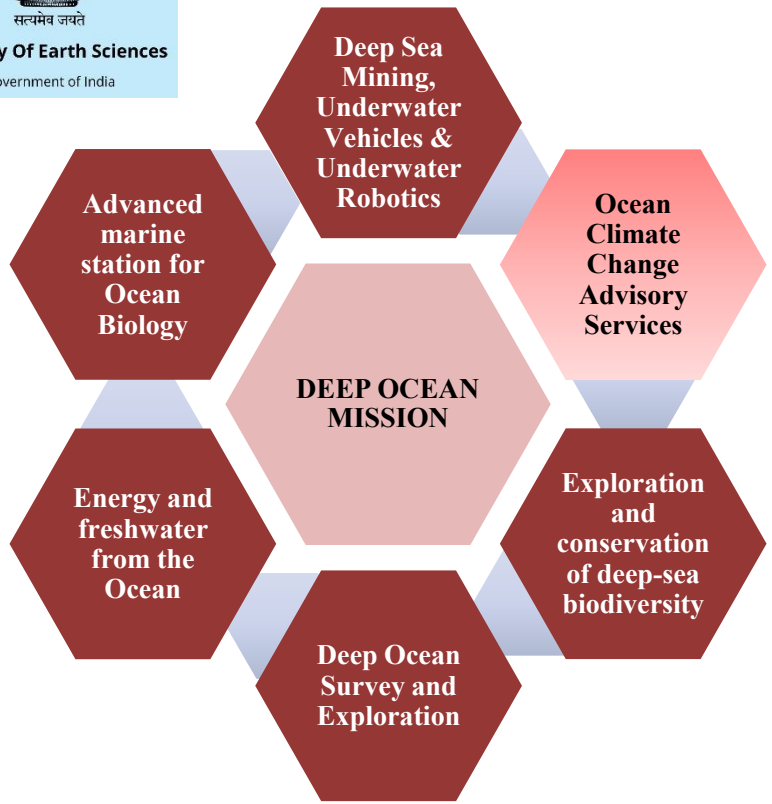
➢**The Infragravity waves and wave setup plays major roles in the inundation during swell surge events.**

Ramakrishnan, R., Remya, P.G., Mandal, A. et al. Wave induced coastal flooding along the southwest coast of India during tropical cyclone Tauktae. Sci Rep 12, 19966 (2022). https://doi.org/10.1038/s41598-022-24557-z

Deep Ocean Mission

Ministry Of Earth Sciences
Government of India

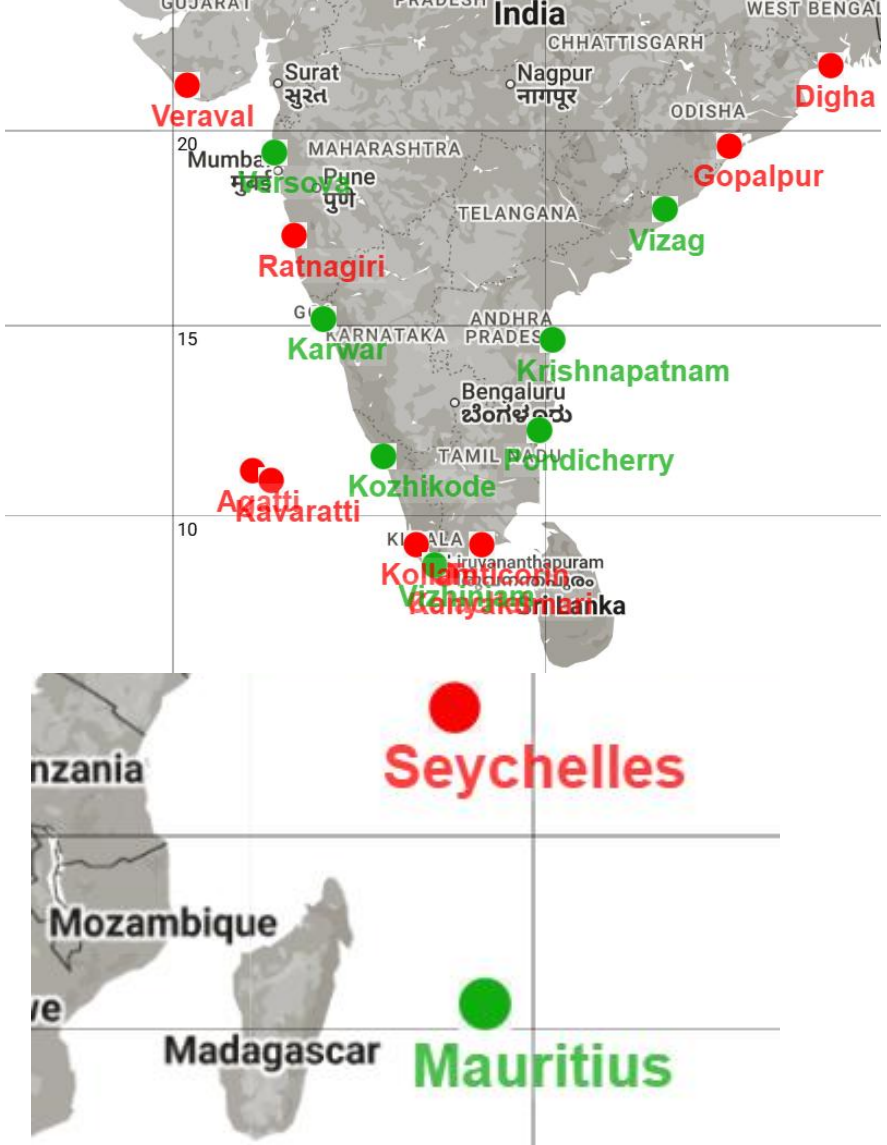
INCOIS



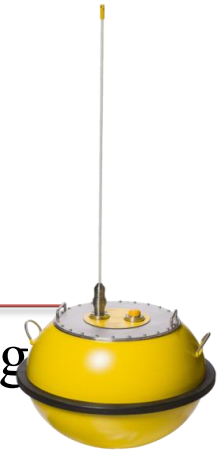
- Robust and accurate "regional" climate change assessment for the North Indian Ocean.
- Provide advisories on the future projections of important climate variables on decadal to longer time scales and associated impacts on the coastal regions of India.
- Sea Level, Cyclones, Storm Surges, Waves, Ecology
- Modelling and Deep Ocean Observing Framework.

Vertical 2: Ocean Climate Change Advisory Services

- **Advisories on the seasonal-to-decadal-to-long term projections, trends and coastal impacts:**
  - Sea level rise
  - Intensity & frequency of tropical cyclones
  - Storm surges
  - Extreme Waves and Coastal Erosion
  - Ecological impacts and harmful algal blooms
- **Multi-hazard Vulnerability Maps for the coastal regions of India**
- **Modelling and Deep Ocean Observations**



WAMAN Network



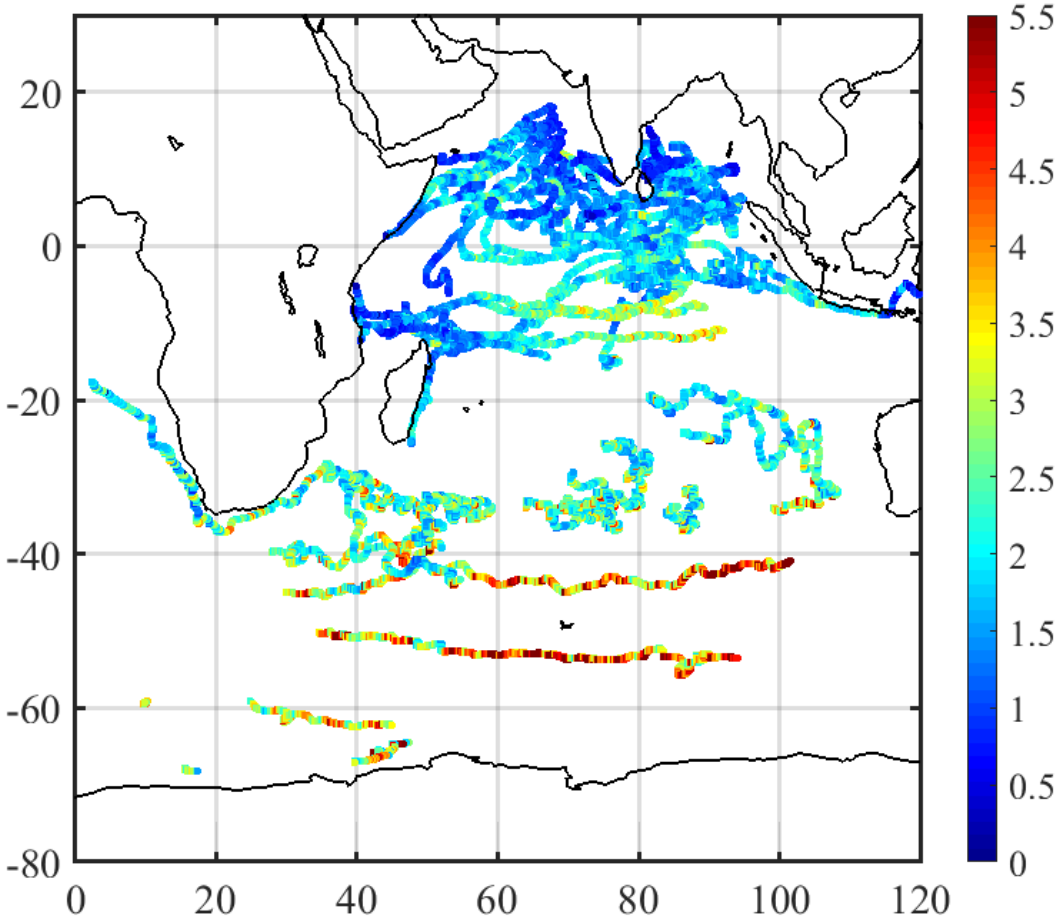
- WAve Monitoring Along Nearshore (WAMAN) Network

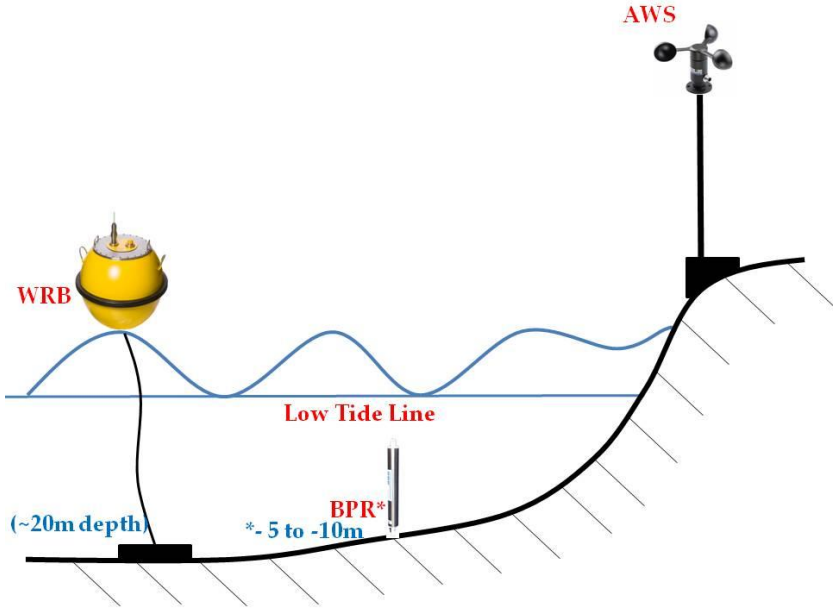
- 18 operational buoys across India and Seychelles and Mouritiuos

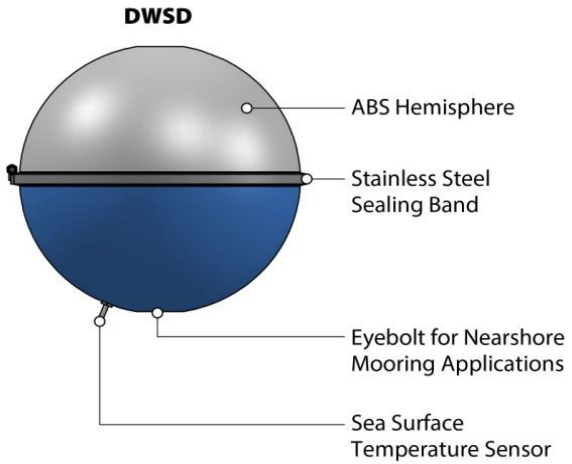
- Real-time data transmission integrated with INSAT satellites

Balakrishnan, N. T. M., and Coauthors, 2025: WAve Monitoring Along Nearshore (WAMAN) Buoy Network: Best Practices and Applications in Sea State monitoring and forecasting for the Indian Ocean. *Bull. Amer. Meteor. Soc.*, , BAMS-D-23-0263.1, https://doi.org/10.1175/BAMS-D-23-0263.1, in press.

7 Met-Ocean buoys, 64 surface wave drifters

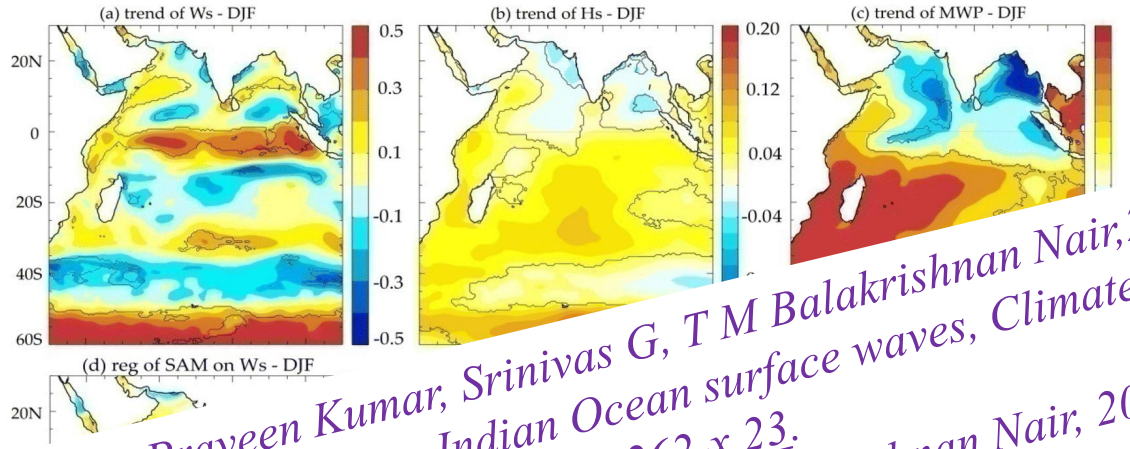






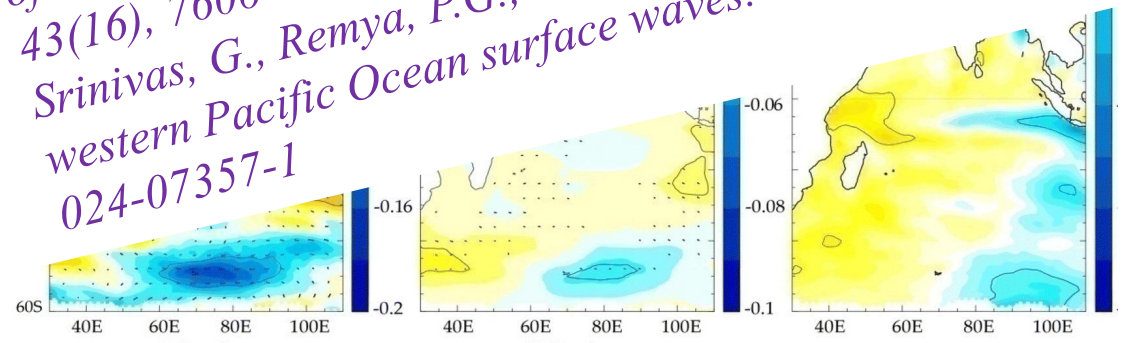
Coastal Flood Monitoring system(CFMS)
Wave buoy-20 m
Bottom pressure recorder- 5-10 m
Tide gauge and AWS

Remya P G et al., 2025, Preliminary analysis and applications of Indian ocean wave drifter program, Frontiers in Marine Science(Final review)



Impact of Climate Variabili

1. Remya P G, B Praveen Kumar, Srinivas G, T M Balakrishnan Nair,2020, Tropical and extratropical climate variability impact on Indian Ocean surface waves, Climate Dynamics, https://doi.org/10.1007/s00382-020-05262-x 23.
2. G. Srinivas, Remya P.G., S. Malavika, T.M. Balakrishnan Nair, 2020, The influence of boreal summer intra-seasonal oscillations on Indo-Western Pacific Ocean surface waves. Nature Scientific Reports , https://doi.org/10.1038/s41598-020-69496-9
3. Srinivas G, Remya P G, B Praveen Kumar, Anuradha Modi, T M Balakrishnan Nair 2020, The impact of Indian Ocean Dipole on tropical Indian Ocean surface Waves in ERA5 and CMIP5 models, International Journal of Climatology, https://doi.org/10.1002/joc.6900
4. Sreejith, M., Remya, P. G., Praveen Kumar, B., Srinivas, G., & Balakrishnan Nair, T. M. (2023). Impact of southern annular mode on the Indian Ocean surface waves. International Journal of Climatology, 43(16), 7606–7617. https://doi.org/10.1002/joc.8282
5. Srinivas, G., Remya, P.G., Dey, S.P. et al. Impact of the Pacific-Japan pattern on the tropical Indo-western Pacific Ocean surface waves. Clim Dyn 62, 8729–8740 (2024). https://doi.org/10.1007/s00382-024-07357-1



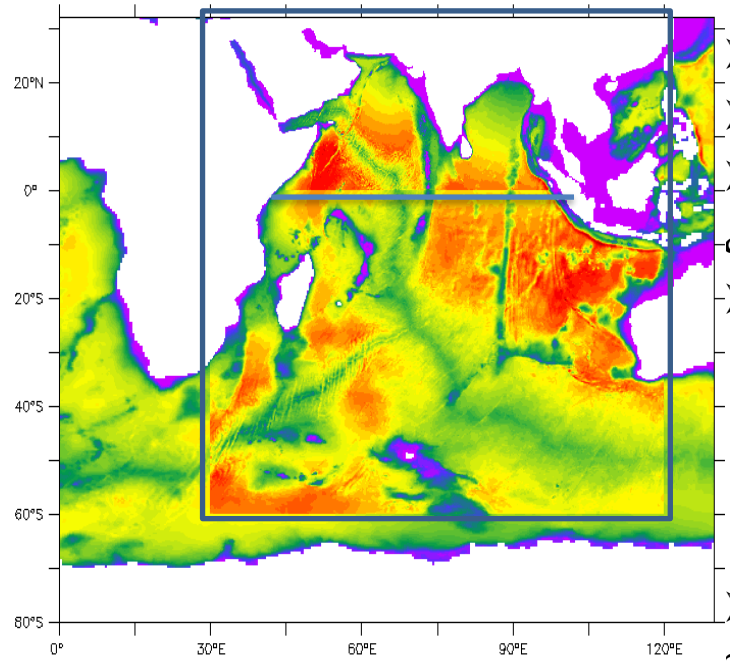
- SAM-driven SO
- but strengthens SE trade winds in ETIO → more local swells.
- **IOD Influence:**
  - Effects confined to **eastern equatorial IO**, especially in SON (Sep–Oct–Nov).

Indian Ocean wave climate shaped by both local winds and remote teleconnections.

Wave projection Setup-WAVEWATCHIII -V6.07

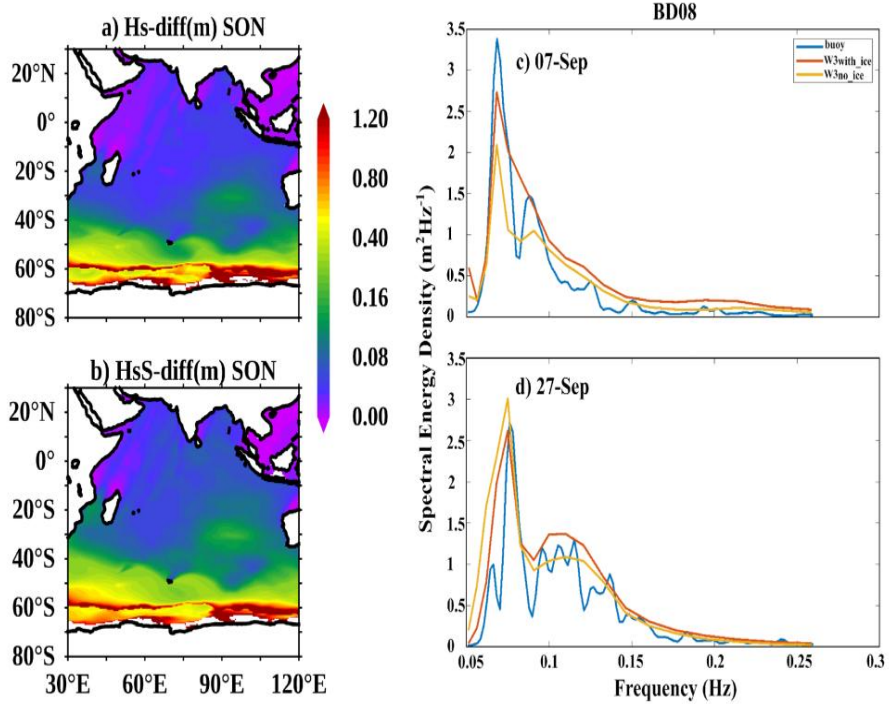
INCOIS WAVEWATCHIII Configurations

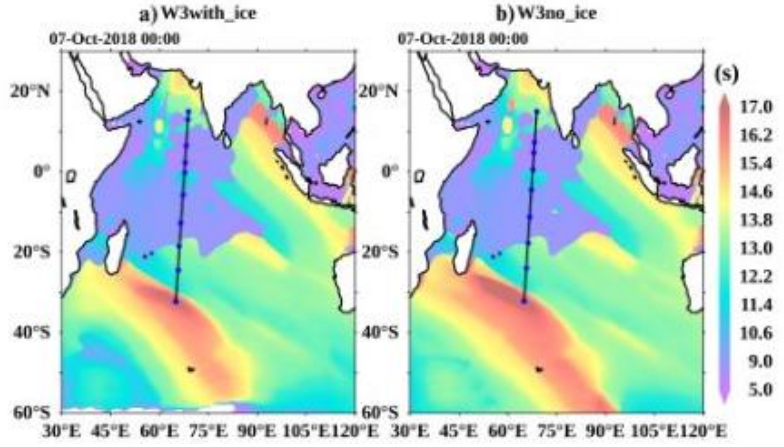
Model Domain

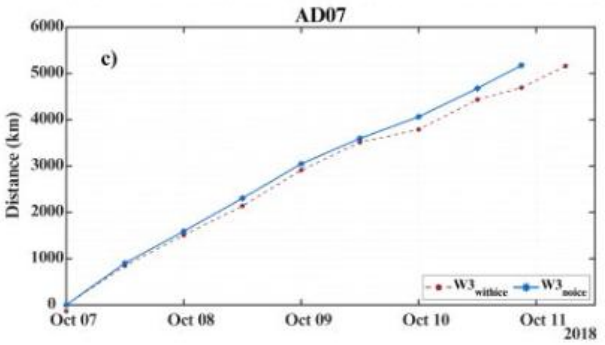


- Version-6.07
- Source term-ST4
- Bathymetry- Etopo1 & coastal - INCOIS bathy
- Spatial resolution
  - 0.5 deg Global grid
  - 0.25 deg Indian Ocean
  - 0.1 deg North Indian Ocean
- Spectral resolution
  - 29 frequencies and 36 directions

Maps showing SON averaged difference of $W3_{no\_ice}$ and $W3_{with\_ice}$ for (a) significant wave height, Hs, and (b) swell wave height, HsS.; Spectral energy density comparison of $W3_{no\_ice}$ (orange) and $W3_{with\_ice}$ (red) with BD08 data (blue) at (c) 03 UTC on 07th September 2017 and (d) 09 UTC on 27th September 2017.







~12hr difference in time taken for swell systems to reach NIO

1. *Raj, A., Kumar, B.P., Remya, P.G. et al. Assessment of the forecasting potential of WAVEWATCH III model under different Indian Ocean wave conditions. J Earth Syst Sci 132, 32 (2023).* https://doi.org/10.1007/s12040-023-02045-w
2. *Sreejith, M., P. G., Remya., Kumar, B.P. et al. Exploring the impact of southern ocean sea ice on the Indian Ocean swells. Scientific Reports(Nature), 12, 12360 (2022).* https://doi.org/10.1038/s41598-022-16634-0

A Performance evaluation of CMIP6 wind fields for robust forcing

MODEL FRAMEROWK

WAVEWATCH III

Input

- CMIP6 GCM winds

Grids

- Global [0.5° x 0.5°] [0-360°; 80°S-80°N]
- Indian [0.25° x 0.25°] [30°-120°E; 60°S-30°N]
- NIO* [0.1° x 0.1°] [45°-90°E; 5°N-25°N]

*North Indian Ocean

Output

- Significant wave height (Hs)
- Swell Wave height
- Mean wave period
- Wind-sea height

Validation

- NIOT moored buoys in NIO
- ERA5 wind & wave data

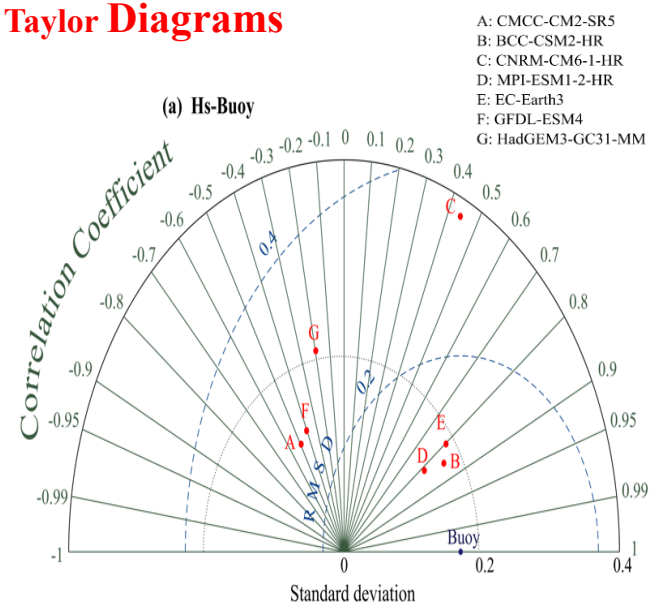
CMIP6 GCM winds

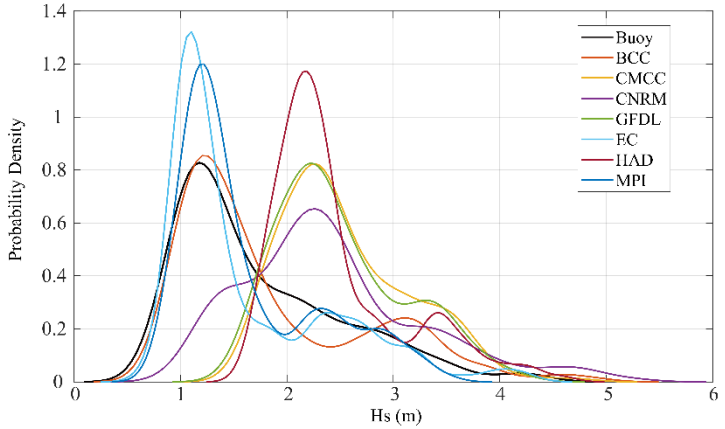
Model	Nominal Resolution	Frequency	Years available	Variables
GFDL-ESM4	100km	3 Hr	1980-2014	u,v
CNRM-CM6-1-HR	50 Km	3 Hr	1980-2014	u,v
CMCC-CM2-SR5	100 Km	3 Hr	1980-2014	u,v
HadGEM3-GC31-MM	100 Km	3 Hr	1980-2014	u,v
EC-Earth3	100 Km	3 Hr	1980-2014	u,v
BCC-CSM2-MR	100 Km	3 Hr	1980-2014	u,v
MPI-ESM1-2-HR	100 Km	3 Hr	1980-2014	u,v

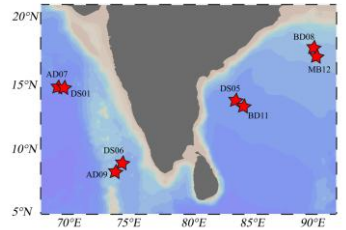
CMIP- Coupled Model Intercomparison Project | GCM- Global Climate Model

35-year (1980-2014) wind-wave climate simulation of the Indian Ocean (IO) WAVEWATCH-III (WW3), forced with seven CMIP6 Global Climate Models

Taylor Diagrams

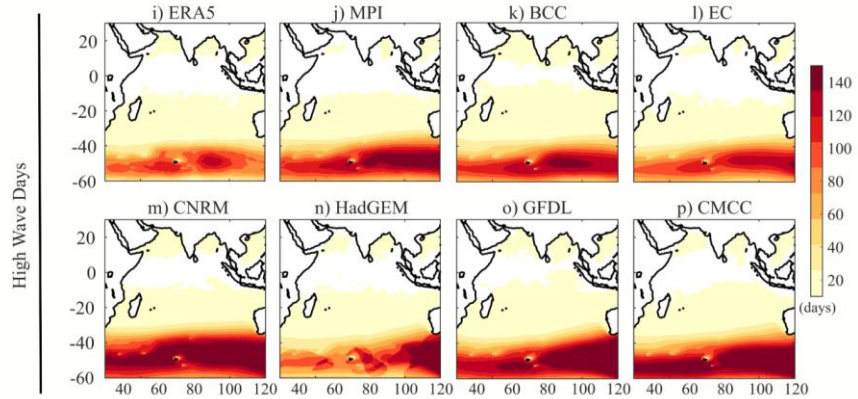






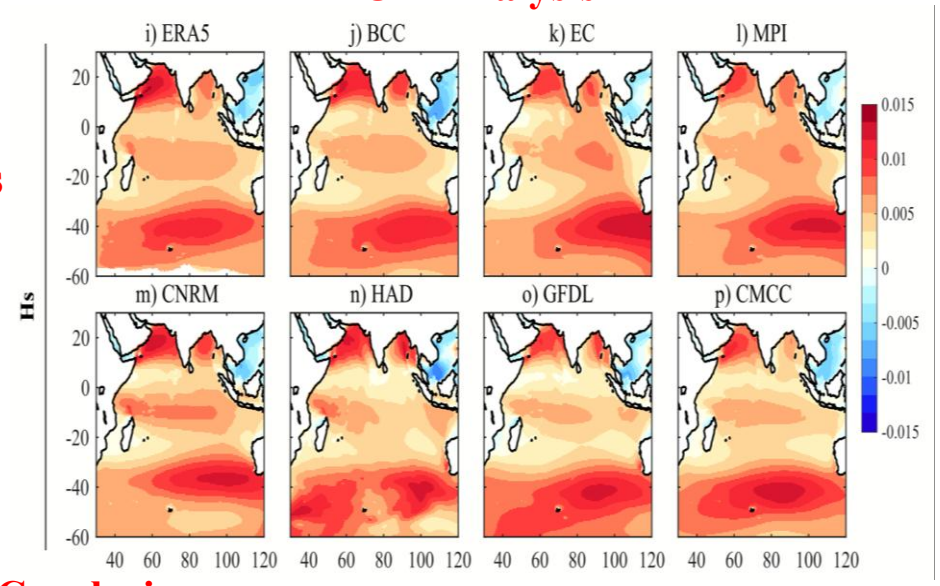
Extreme wave analysis using the ETCCDI indices

The joint CCI/WCRP-CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI)



High Wave Days: Annual count of days when the daily Hs maximum is greater than 6m.

EOF Analysis



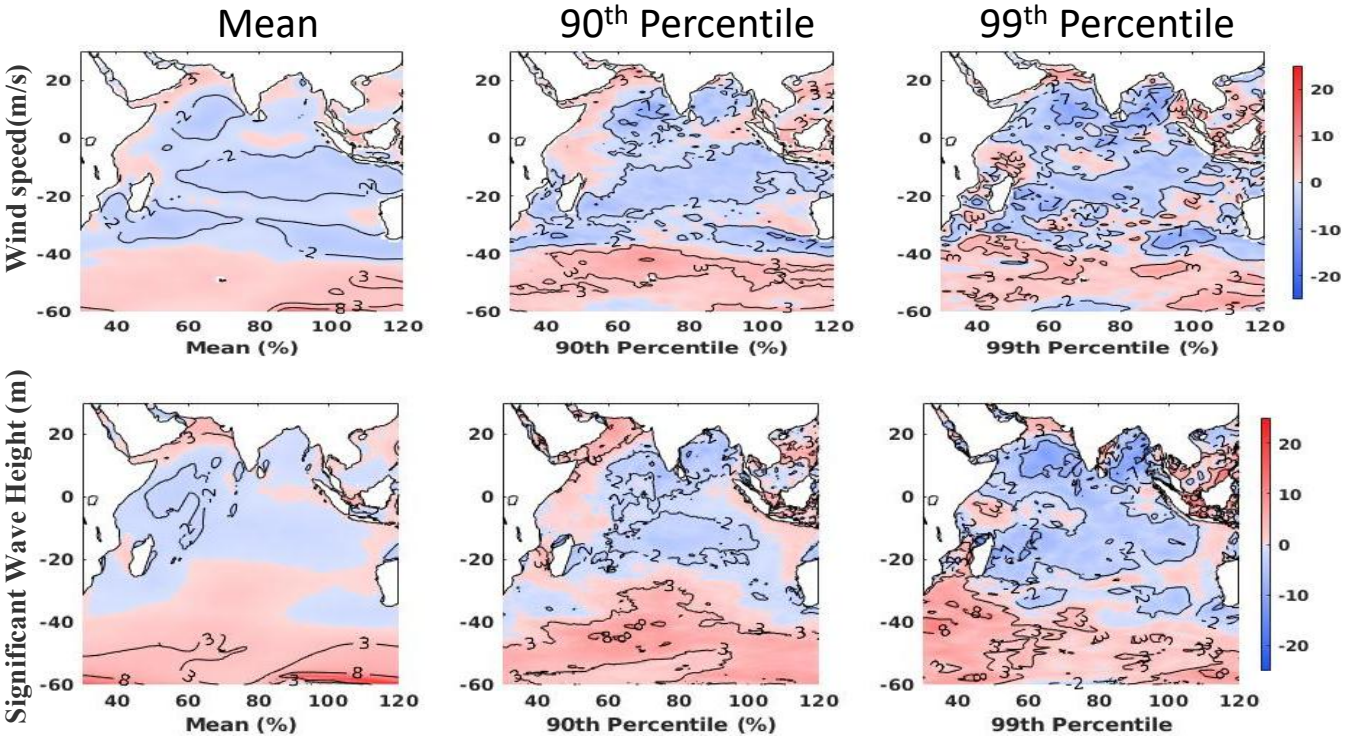
Conclusion:

The rigorous statistical analysis shows that BCC, EC and MPI outperform the other four models, demonstrating their ability to simulate both mean and extreme wave heights in the IO region.

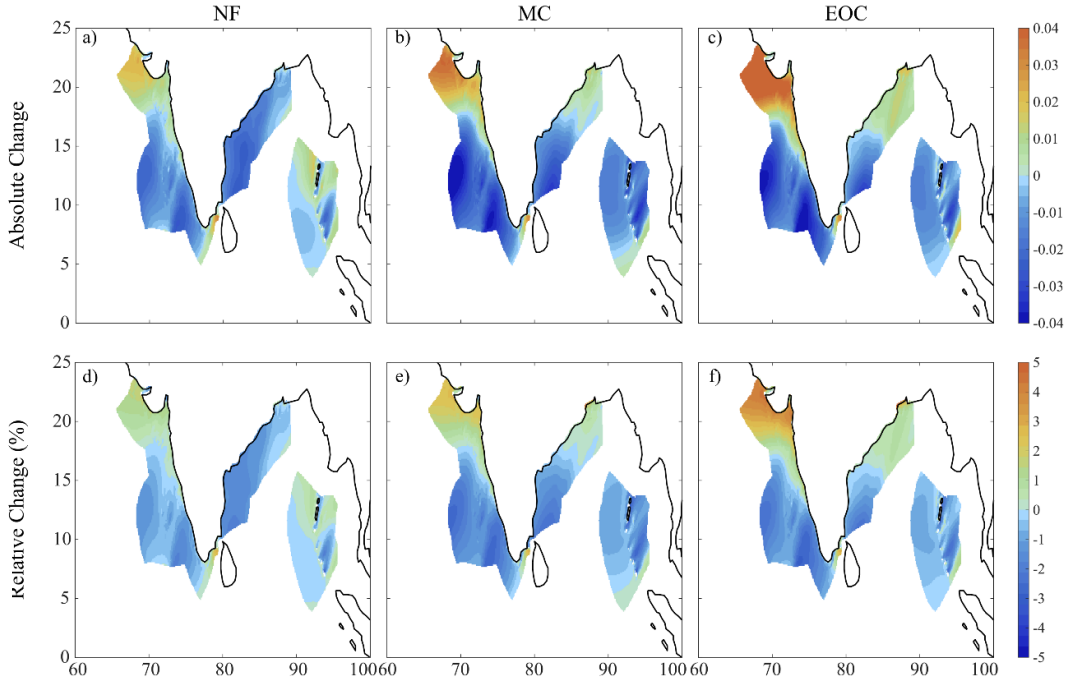
Wave Projection- SSP245 & SSP 585

WAVE model Forcing	Nominal Resolution	Frequency	Hindcast-Years available	Projection-Years available SSP245 & SSP 585	Variables
BCC-CSM2-MR	50km,25km,10km	3 Hr	1980-2014	2015-2100	Main wave parameters
EC-Earth3	50km,25km,10km	3 Hr	1980-2014	2015-2100	Main wave parameters
MPI-ESM1-2-HR	50km,25km,10km	3 Hr	1980-2014	2015-2100	Main wave parameters
CNRM-CM6-1-HR	50km,25km,10km	3 Hr	1980-2014	2015-2100	Main wave parameters
GFDL-ESM4	50km,25km,10km	3 Hr	1980-2014	Not ready	Main wave parameters
CMCC-CM2-SR5	50km,25km,10km	3 Hr	1980-2014	Not ready	Main wave parameters
HadGEM3-GC31-MM	50km,25km,10km	3 Hr	1980-2014	Not ready	Main wave parameters

- Emission scenario: SSP2-4.5
- Time slices:
  - NF- Near future- 2015-2044
  - MC- Mid century- 2045-2070
  - EOC- End of century- 2071-2100



End of century- 2071-2100

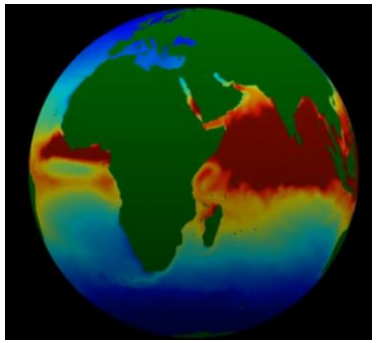


Absolute change= Projection – Historical

Relative change (%)= $(\frac{absolute\ change}{historical})$x100

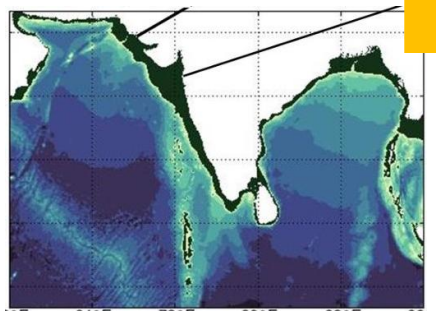
National Climate Portal

Global Scale



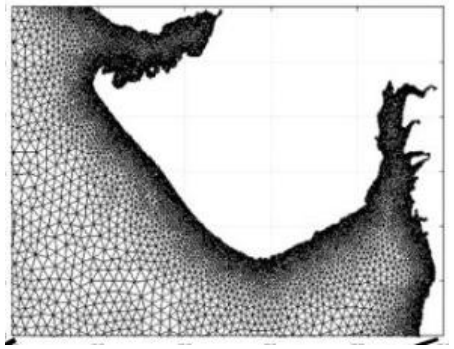
Large-scale circulation, sea ice, and waves under the influence of climate change.

Regional Scale



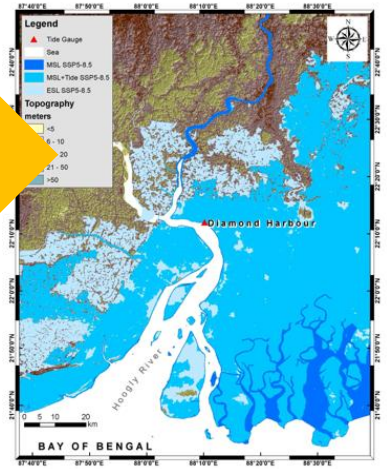
Swell propagation, wave generation, storm surge, astronomical tides and near –shore circulation

Local Scale

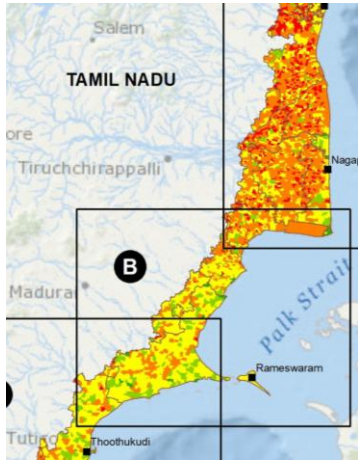


Wave setup, tides, storm surge, coastal erosion, fluvial discharge

Wave-based GIS Application



Flood Maps



Socioeconomic impacts

A national climate portal on our website, which will provide the overall picture of climate change in the Indian Ocean, including sea level, waves, storm surge, cyclone ,erosion, etc.

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On the need of bias correction methods for wave climate projections

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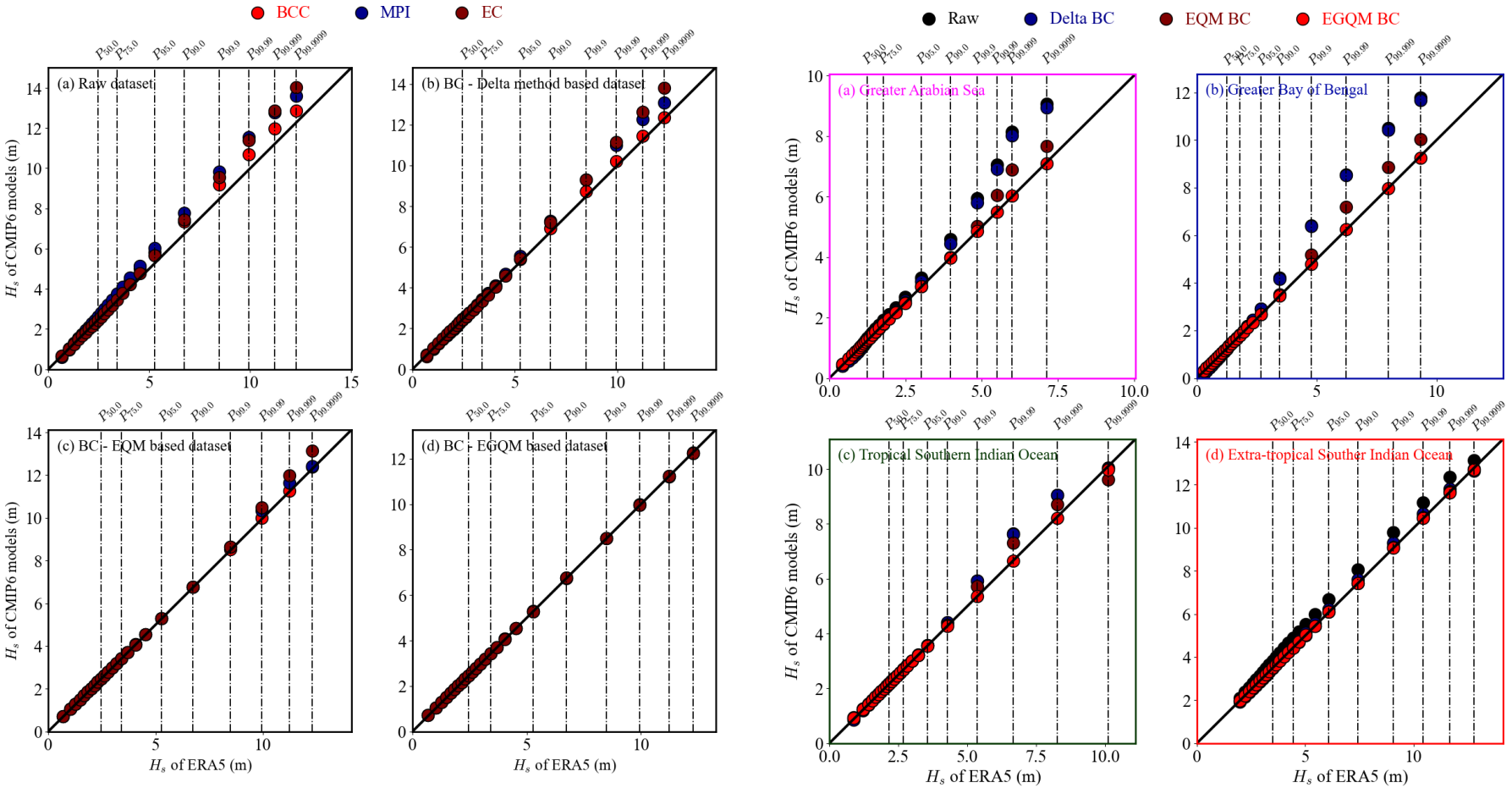
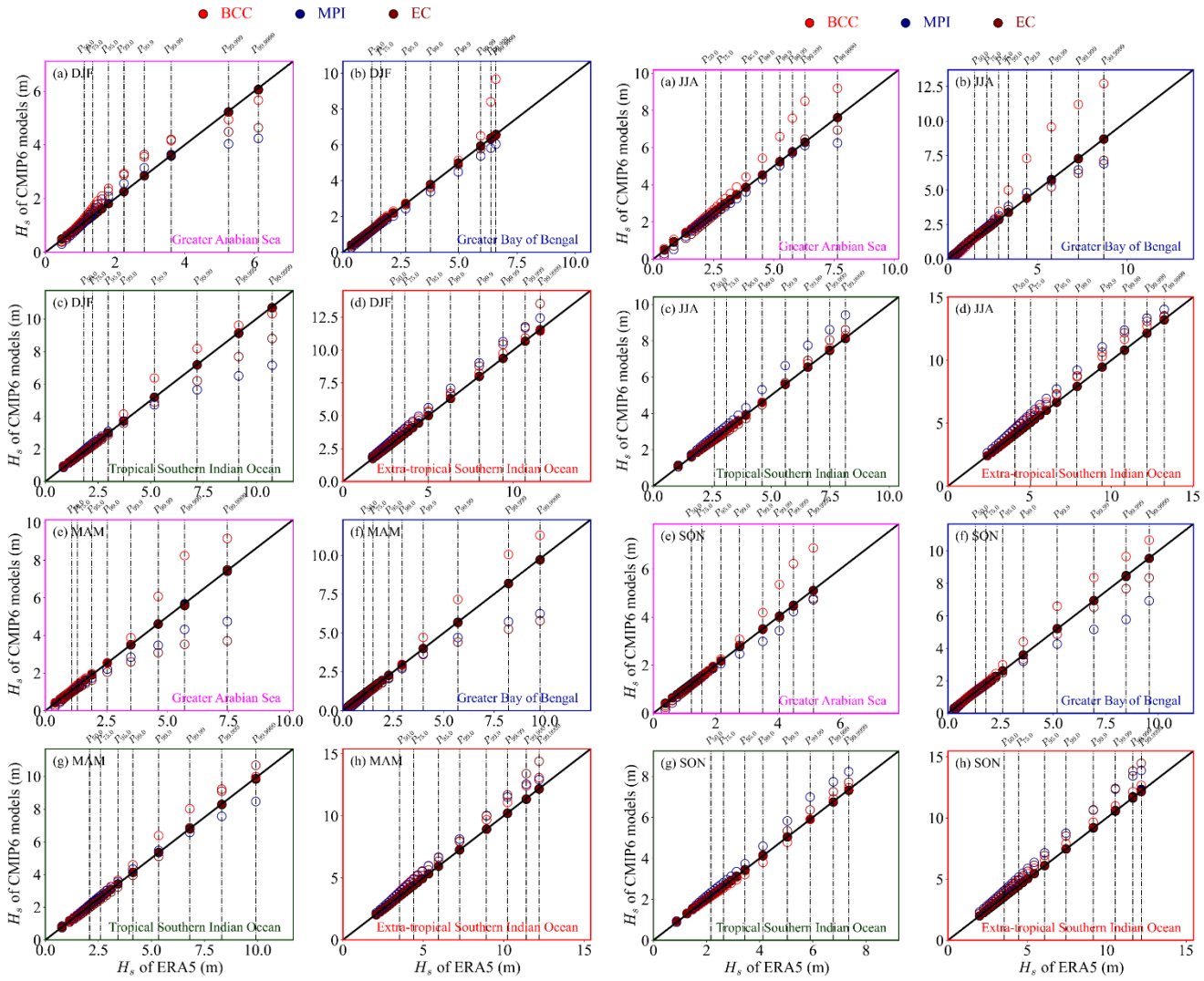
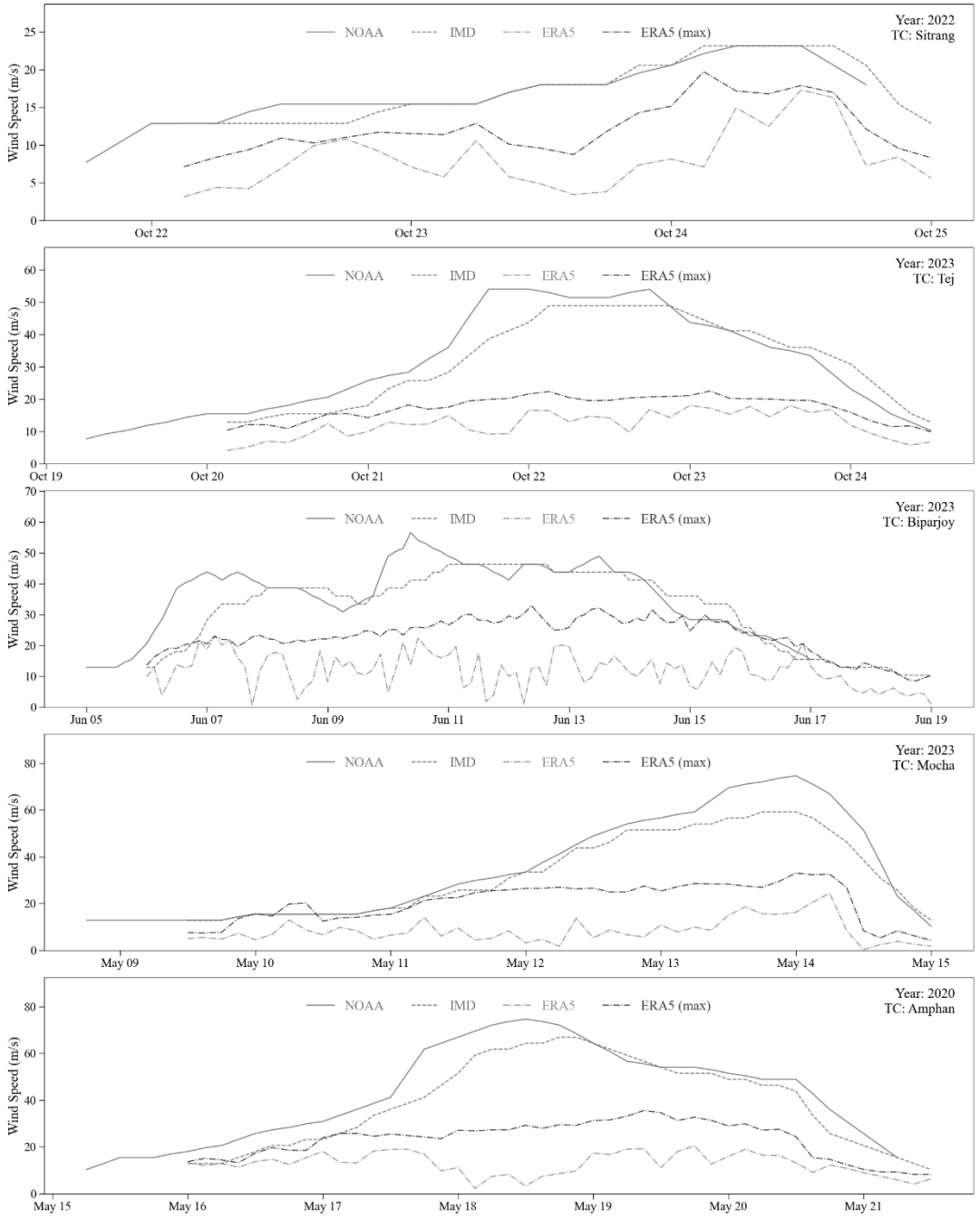
How the raw datasets perform?



BCC (representative)



- Temporal approach (seasonally grouped) based EGQM able to capture the unattended bias pretty well across regions and seasons and demonstrate the need of seasonal correction for a domain like IO, where seasonality is significant.
- The question of overfitting in EGQM, particularly when seasonal grouping is used, remains a concern if applied to future climate.



Is bias correction a need for projections?

ERA5 largely underestimates extremes, which makes bias correction questionable when using ERA5 as the reference.

We are also trying to transfer the corrections calculated using historical data — but how valid will that be for future projection datasets?

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Questions?