Indian Ocean acidification and its driving mechanisms over the last four decades (1980–2019)

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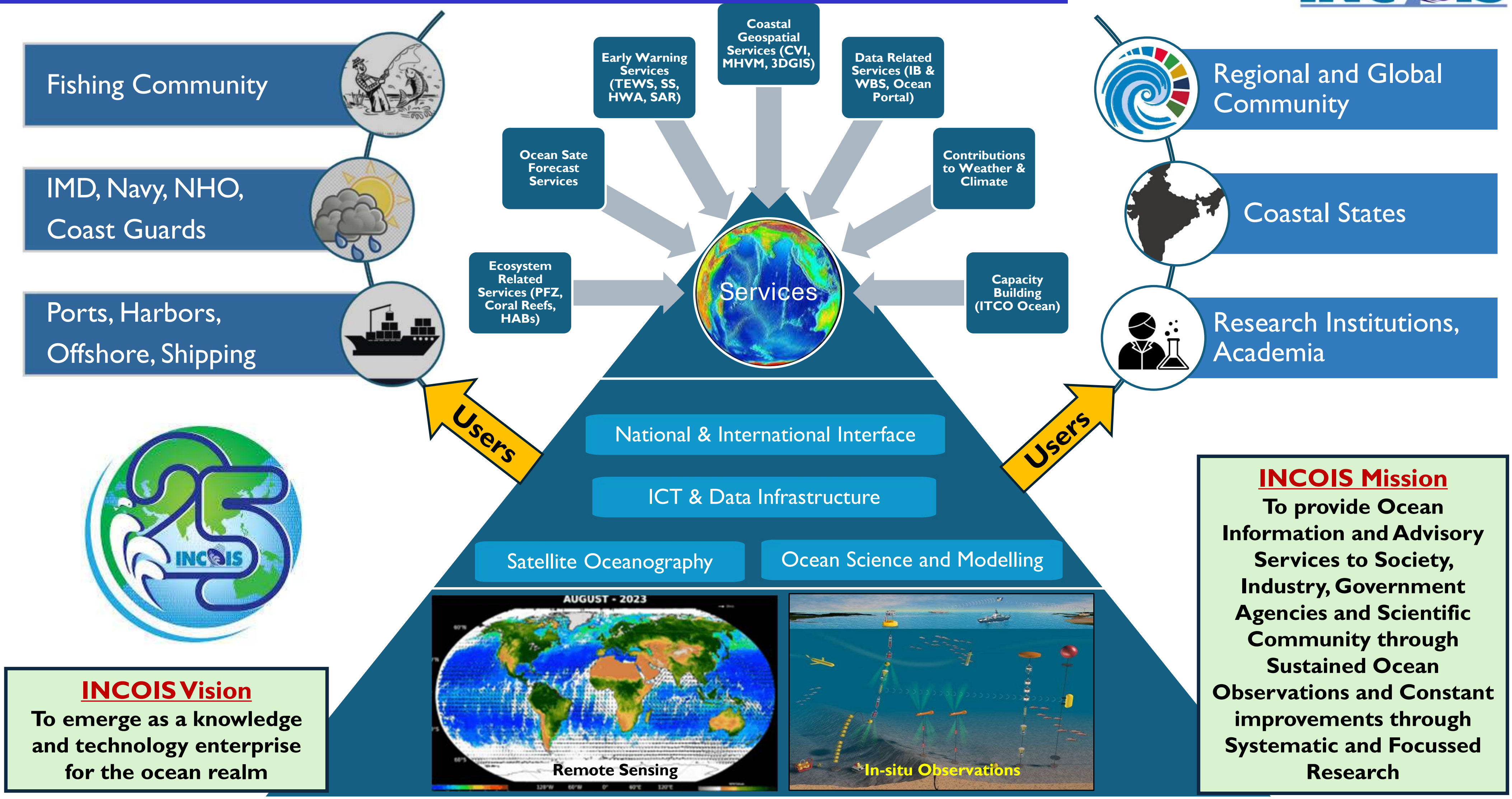
OceanPredict's Marine Ecosystem Analysis and Prediction Task Team Meeting
November 06, 2024 (on line)

Outline of the Presentation

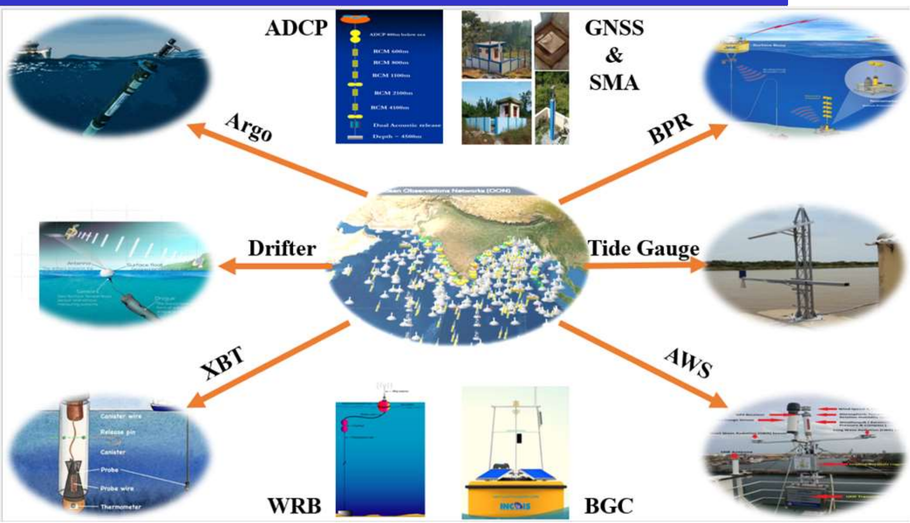
- ✓ Brief introduction to INCOIS
- ✓ Indian Ocean Acidification: What we know
  - Present status
- ✓ REgional Carbon Cycle Assessment and Processes Phase 2 (RECCAPv2)
  - Regional Ocean Models
- ✓ Ocean-Ecosystem Modeling System developed at INCOIS
  - Evaluation
- ✓ Analysis of Indian Ocean Acidification in different sub-regions
  - Trends
  - Driving Mechanisms
- ✓ El Nino and positive IOD & Indian Ocean Acidification
- ✓ Summary and Conclusions

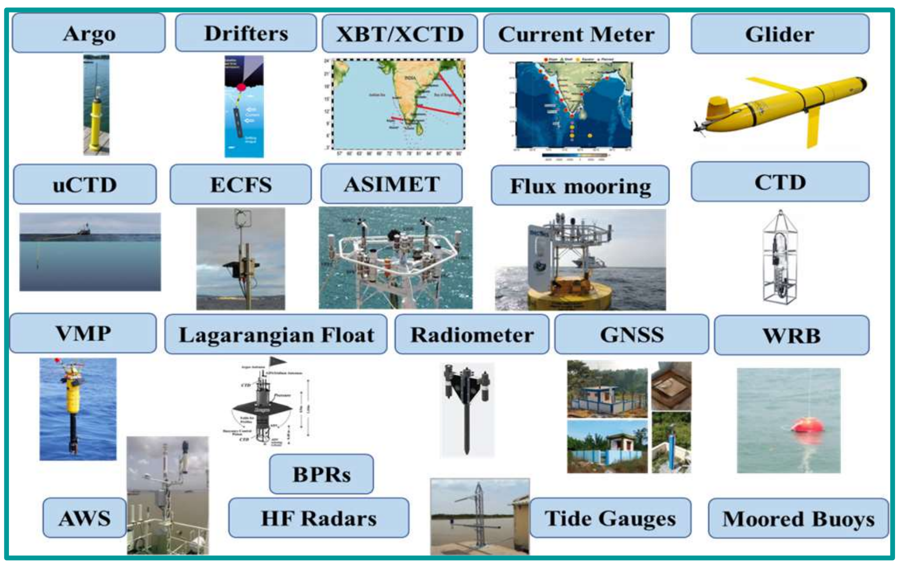
Indian National Centre for Ocean Information Services

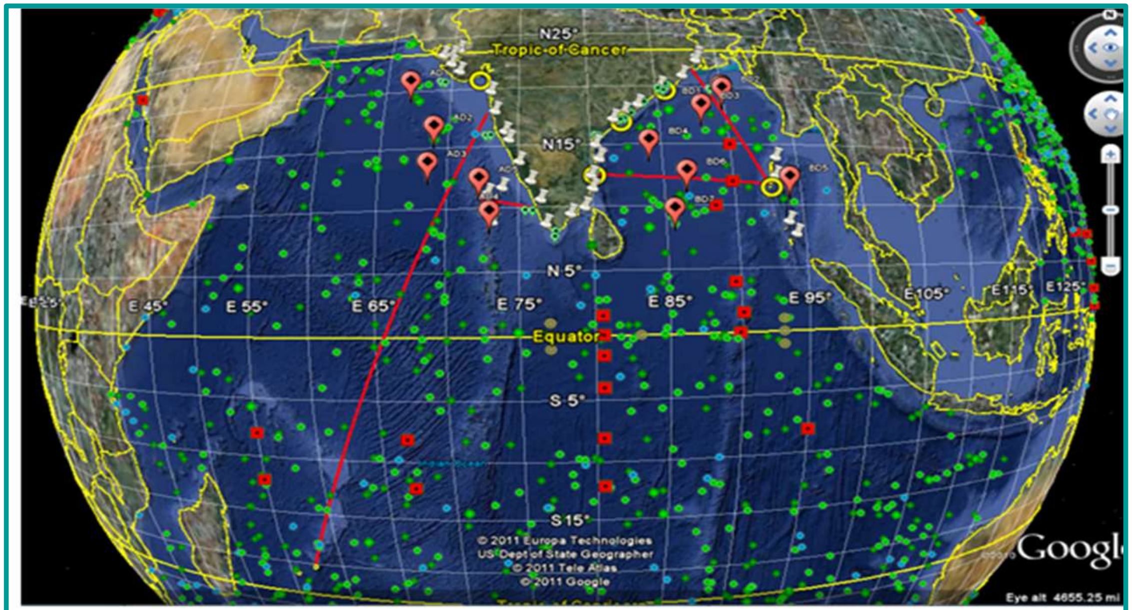


Ocean Observation Network

INCOIS







Green – Argo, Red line – XBT, Blue – Drifters, Red square – RAMA, Yellow- CODAR, green oval- ADCP, Red oval – Moorings, white mark - TG

Global Design (GOOS) -> Regional Implementation (IndOOS) -> National Contributions (INCOIS & NIOT OOS, IMD Weather Watch)

Themes: Climate, Operational Ocean Services, and Ocean Health

Essential Ocean Variables: Physics, BGC, Biology & Ecosystems, Atmosphere

CLIVAR GOOS IndOOS-2

A roadmap to sustained observations of the Indian Ocean for 2020-2030

WMO

United Nations Educational, Scientific and Cultural Organization

Intergovernmental Oceanographic Commission

IOGOOS GLOBAL OCEAN OBSERVING SYSTEM FOR INDIAN OCEAN

Operational Remote sensing data reception and services

INCOIS established 3 Groundstation's to meet the in-house operational advisory services.

Acquiring AVHRR (Metop-1, Metop-2, NOAA-18 & NOAA-19), VIIRS (Soumi-NPP), MODIS (AQUA & TERRA)&OCM(Oceansat-2).

Ocean Products

- Sea Surface Temperature –SST (AVHRR, VIIRS & MODIS)
- Chlorophyll-a (OCM , VIIRS & MODIS)
- Attenuation coefficient -Kd-490 (OCM, , VIIRS & MODIS)
- Total suspended matter (OCM)
- Water leaving radiances –nLw (VIIRS &MODIS)
- Brightness temperature's (AVHRR, VIIRS & MODIS)
- Calcite (MODIS)
- chlorophyll fluorescence efficiency-CFE (MODIS)
- particulate organic carbon (VIIRS & MODIS)

Data Users

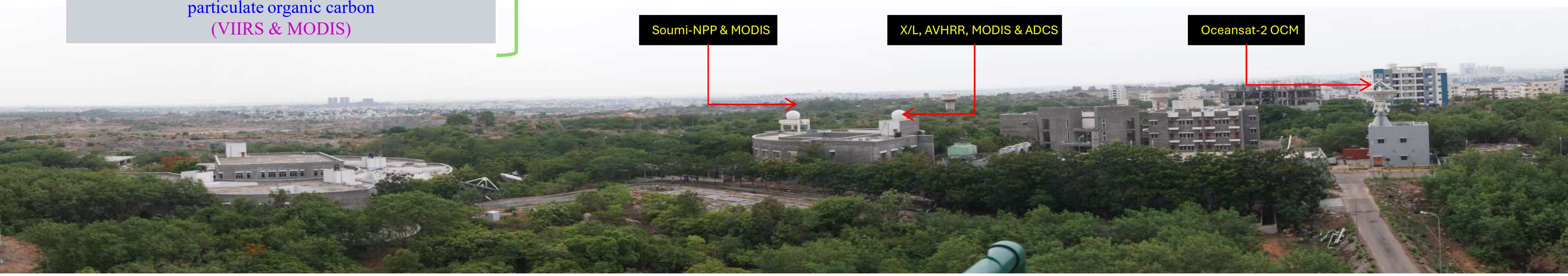
- Potential Fishing Zones
- Coral Bleaching Alerts
- Ocean state forecast
- Storm surge warning
- Assimilation Studies (RAIN)
- R&D activities by Academic & Research institutions

Atmosphere products

- FOG (AVHRR, VIIRS & MODIS)
- AOD (OCM, , VIIRS & MODIS)
- Cloud top Temperatures (AVHRR, VIIRS & MODIS)
- Water vapor (AVHRR,& MODIS)
- Lifted Index (MODIS)

Land products

- Land Surface Temperature –LST (MODIS)
- Enhanced vegetation Indices-EVI (MODIS)
- NDVI (AVHRR, , VIIRS & MODIS)
- Surface reflectance (VIIRS & MODIS)

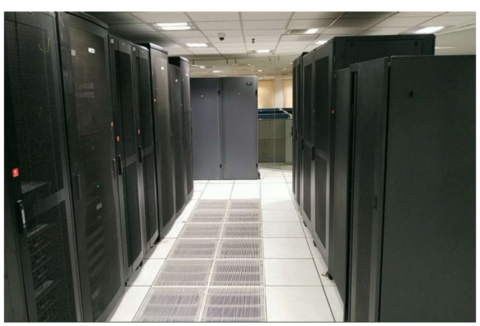


Ocean Prediction Systems

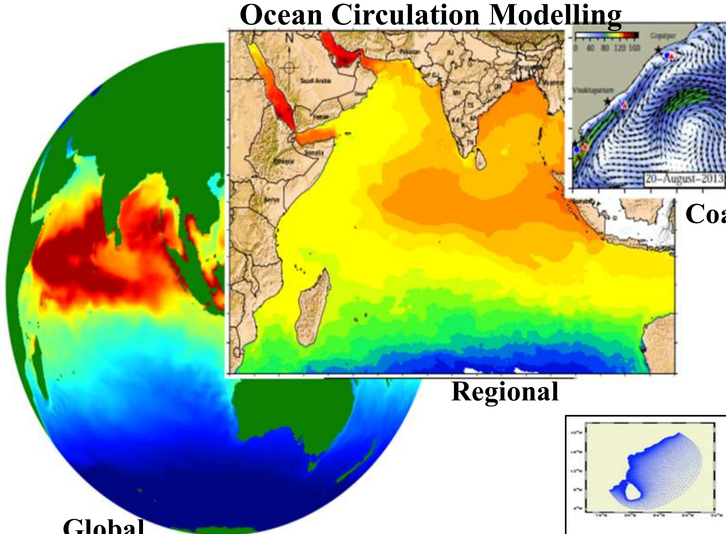
INCOIS Ocean Modeling and Data Assimilation Activities

- Ocean Modeling Mission
- Deep Ocean Mission
- Monsoon Mission
- Coastal Water Quality Monitoring and Forecast Program

Ocean Predict (GODAE Ocean View)



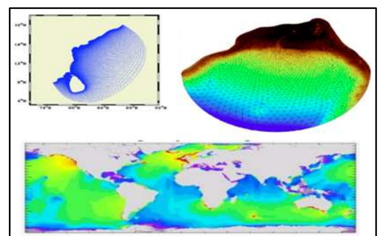
Ocean Circulation Modelling



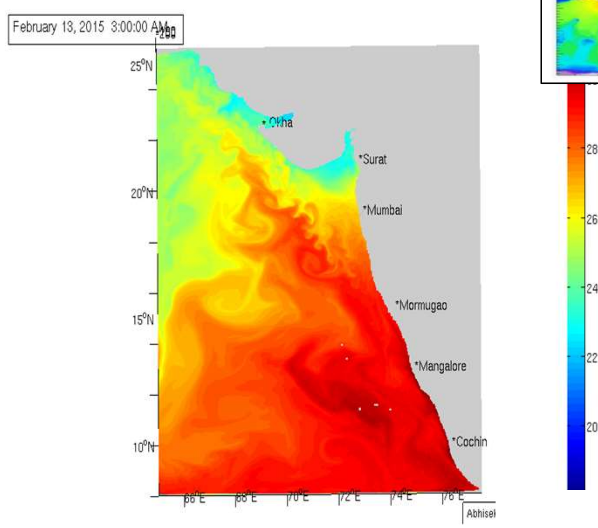
Coastal

Regional

Global



Wave, Tsunami and Storm Surge Modeling



Model simulated variability of Temperature

Ocean Analysis (GODAS)
- Monsoon Forecast (CFS model)
- Tropical Cyclone Heat Potential
- Cyclone Prediction
- Climate Indices

Data Assimilation (LETKF, 3DVAR, OI)

Circulation Models (ROMS, MOM, HYCOM)
- Regional Analysis
- Regional and Coastal Forecasts
- Value Added Services (OOSA, SARAT)

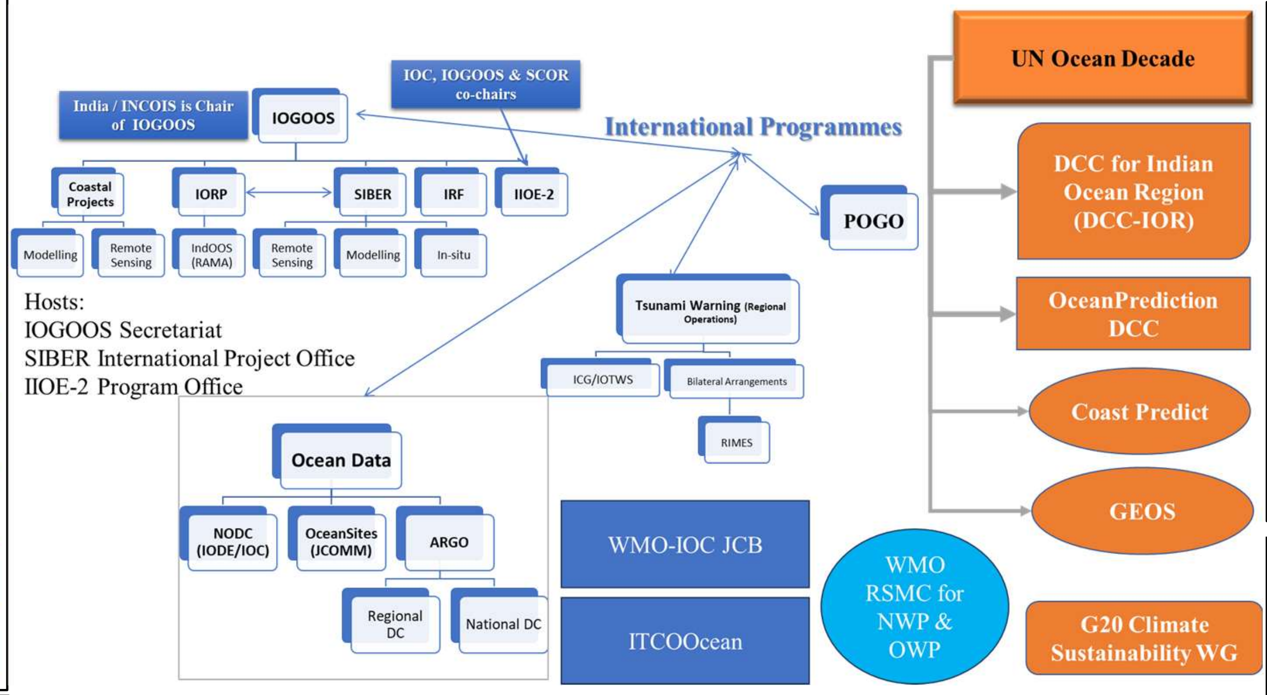
Wave, Tsunami, Cyclone, Storm Surge (Wavewatch III ADCIRC, SWAN, HWRF+HYCOM)
- Forecast and Advisory services

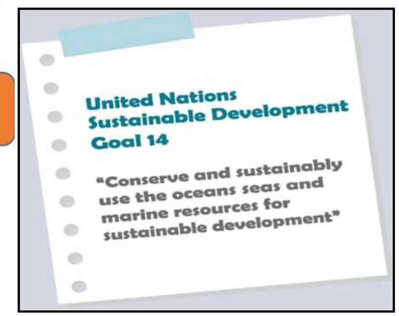
International Interface

- Pollutants
- Ecosystems
- Food from the Ocean
- Ocean economy
- Ocean-climate nexus
- Ocean-related risks
- Ocean observing system
- Ocean digital representation
- Capacity development
- Behaviour change

Ocean Decade Outcomes

- Clean Ocean
- Healthy and resilient Ocean
- Productive Ocean
- Predicted Ocean
- Safe Ocean
- Accessible Ocean
- Inspiring and engaging Ocean





ISPRS, RIMES

IOC-UNESCO EC & VC
UN Decade 2021-30 - NDCC
DCC for Indian Ocean Region

The Blue Economy

Indian Ocean acidification and its driving mechanisms

Ocean Acidification

- **The ocean plays a vital role in mitigating global climate change by sequestering ~30% of anthropogenically emitted CO_2 per year (2.4 ± 0.5 $GtCyr^{-1}$; Le- Quéré et al., 2018).**

- **The tropical Indian Ocean (IO) alone contributed to storing 16.6 ± 5.1 petagrams anthropogenic carbon, amounting a 16% of the global total ocean sink (Sabine et al., 2004).**

- **The significant uptake of anthropogenic atmospheric CO_2 into oceans leads to a reduction in pH referred to as Ocean Acidification (OA) which affects the marine organisms adversely.**

- **Several studies have projected a decline of upper ocean pH by 0.3–0.4 units by the end of 21st century (Feely et al., 2009; Kwiatkowski and Orr, 2018), which has the potential to reduce oceanic biological production in the ocean (Lovejoy and Hannah, 2005).**

Indian Ocean Acidification: What we know

- The trends of the western Indian Ocean acidity is quite alarming (0.07 pH units in last 50 years (1960-2010); Sreeush et al., 2019).

- For the period 1991-2011, Lauvset et al. (2015) suggested that the pH trend would be up to -0.027/decade in the Indian Ocean, but this is subject to uncertainty (based on a few data).

- In a recent study, Chau et al. (2024) reported a lower rate of decrease of the IO pH by -0.017 ± 0.001/decade for the period 1985-2019.

- Interestingly, in another study, Ma et al. (2023) estimated a further lower rate of decrease in the IO surface manuscript submitted to Global Biogeochemical Cycles pH for the period 1982-2021 (-0.0155 ± 0.0009 /decade) compared to Lauvset et al. (2015).

- The errors in the reconstruction of pH among the global products are globally not uniform. We must acknowledge the errors in observations-based global products due to mapping methods, particularly in higher latitudes (Burger & Fr¨olicher, 2023)

- Sarma et al. (2023) demonstrated that the spatial and temporal variability of CO_2 fluxes is better captured by regional than global models (RECCAPv2).

RECCAPv2 – Indian Ocean

INCOIS

- **The international carbon cycle research community recently concluded the largest, most comprehensive assessment it has ever undertaken: the REgional Carbon Cycle Assessment and Processes Phase 2 (RECCAPv2).**

- **Within the ocean-specific part of RECCAPv2, a global consortium of partners aimed to better quantify and understand the CO2 fluxes into and out of the ocean, the associated changes in ocean carbon storage beneath the sea surface, as well as the role of the ocean's biological pump.**

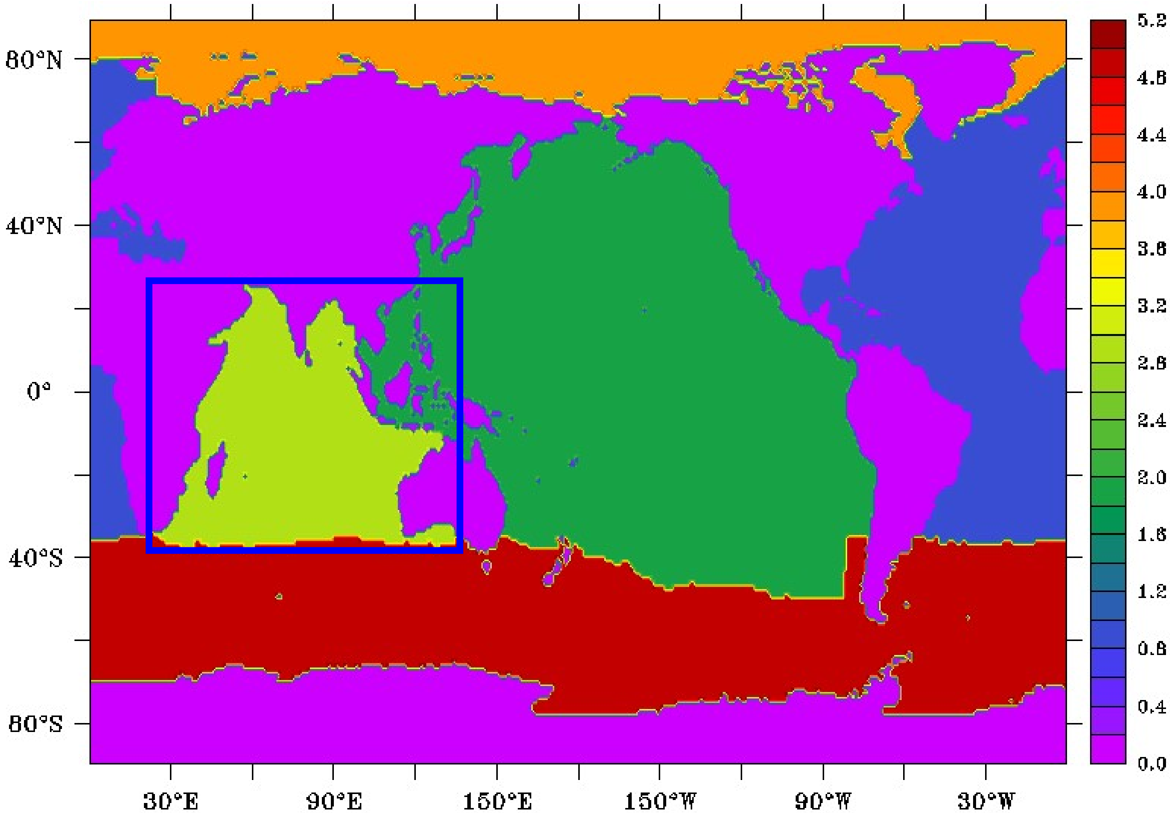
- **It was concluded within the ocean-specific part of RECCAPv1 that none of the global models capable of simulating Indian Ocean carbon cycle (Sarma et al., 2013).**

- **Under the scope of RECCAPv2, regional models were also included along with global models.**

- **A regional high-resolution, coupled ocean-ecosystem model configured at INCOIS had been participated in RECCAPv2.**

- **It was demonstrated that the spatial and temporal variability of CO2 fluxes is better captured by the high-resolution regional models than global models (Sarma et al., 2023).**

INCOIS BIO Modeling System based on ROMS



- Other Data Sets used for Analysis
  - BOBOA RAMA mooring at 15° N, 90° E (Sutton et al., 2014)
  - SOCAT (Baker et al., 2022)
  - Ocean SODA-ETHZv2023 (SODA) (Ma et al., 2023)
  - CMEMS-LSCE-FFNN (CMEMS) (Chau et al., 2022)

Model Configuration

- **Resolution**

  Horizontal : $1/12^0$ (~ 9.5 km), Vertical: 40 sigma levels.

- **Initial Condition**

  Physical state variables - GFDL's ECDA system simulated reanalysis data.

  Biological state variables (NO3, Chlorophyll-a, O2, etc.) - Cimatological state of January generated from the climatological run of the model.

  The model state of the carbon state variables - Global Ocean Data Product (GLODAP; Lauvset et al., 2019).

- **Boundary Condition**

  An ensemble coupled data assimilation (ECDA) system simulated reanalysis data.

- **River Forcing**

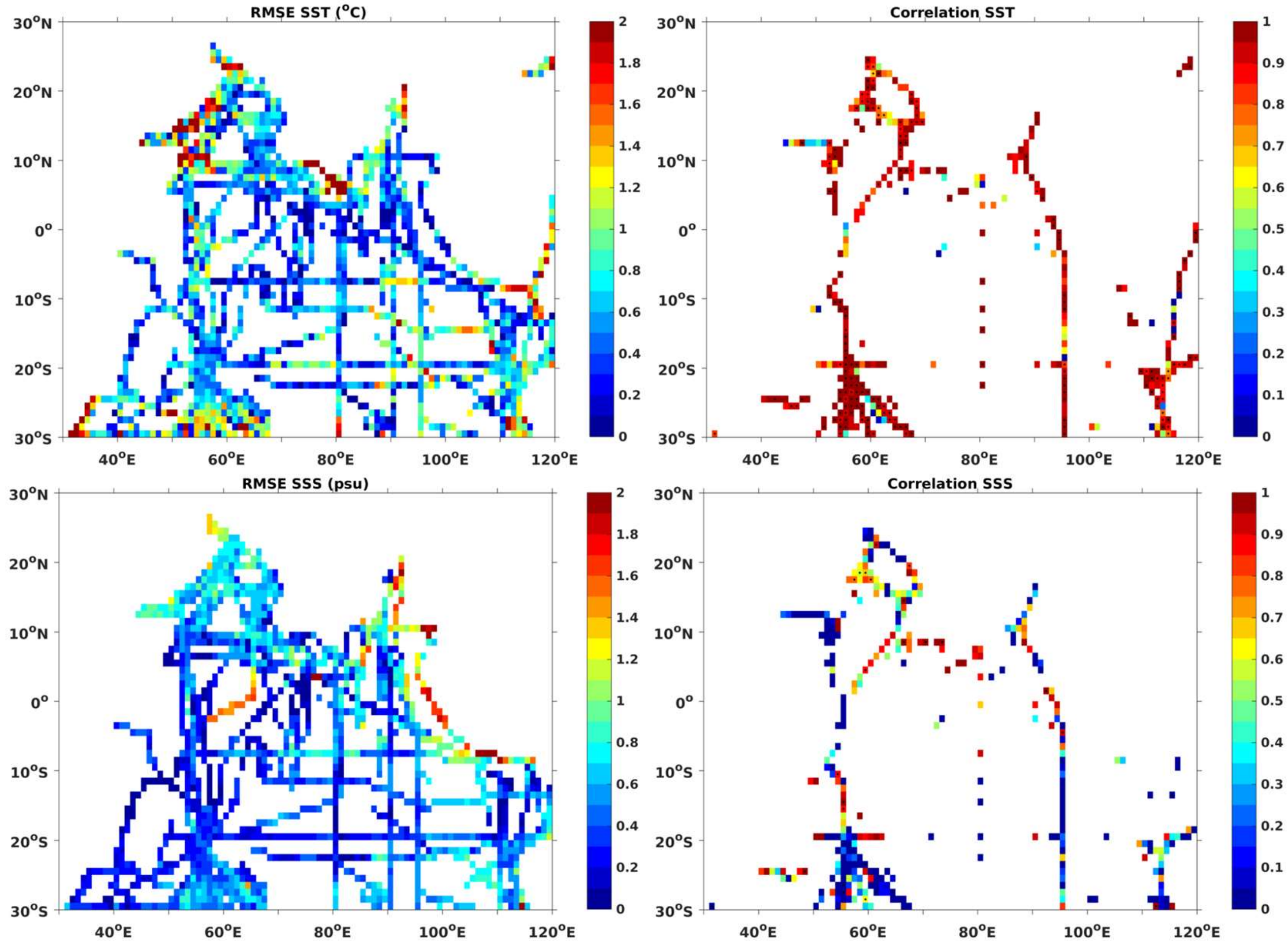
The monthly river discharge has been implemented as a freshwater flux from the JRA55-do forcing dataset.

- **Atmospheric Forcing**

  Reanalysis product JRA55-do (Tsujino et al., 2018)

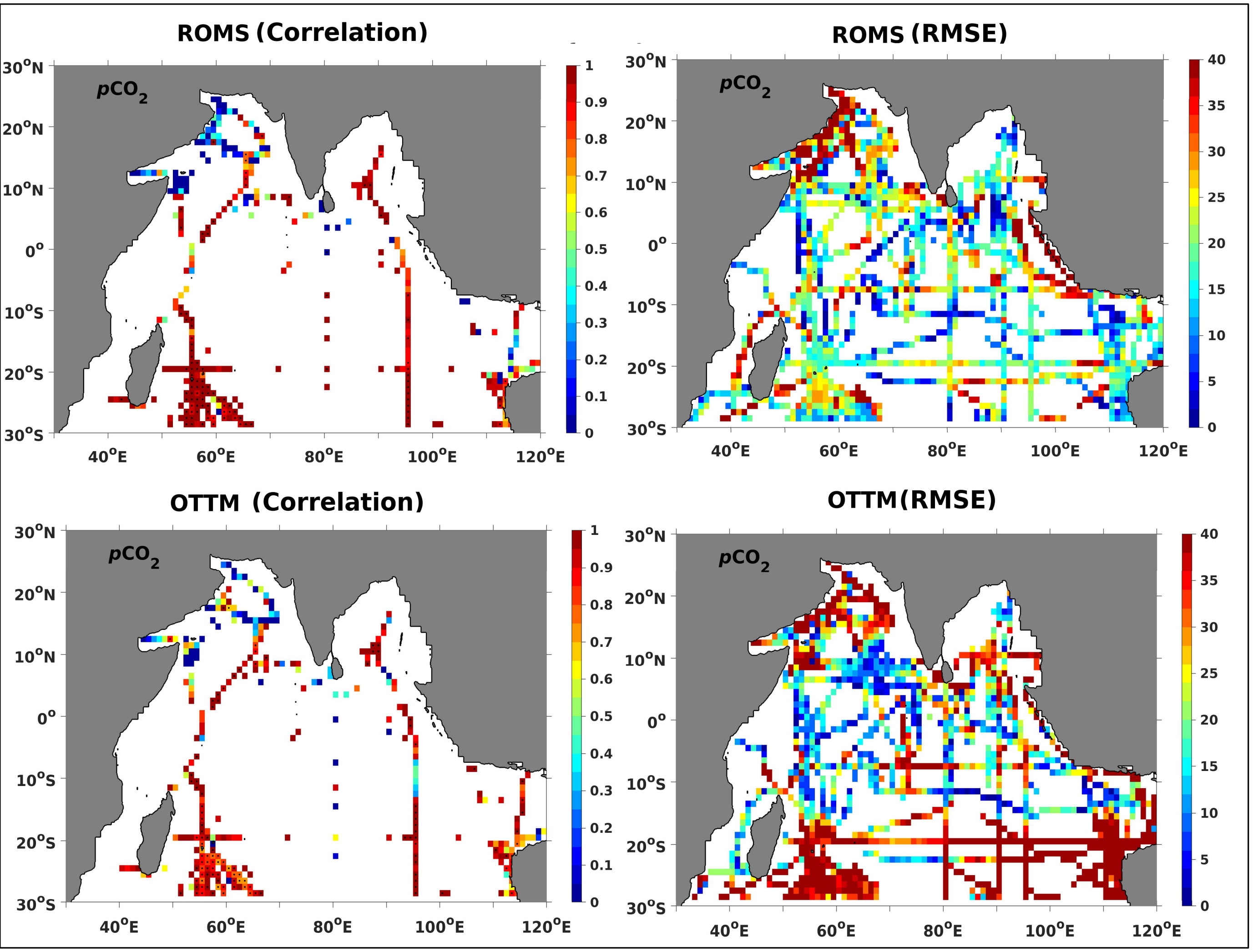
OTTM Global model simulated outputs are also analyzed.

SOCAT Measurements & ROMS Simulation



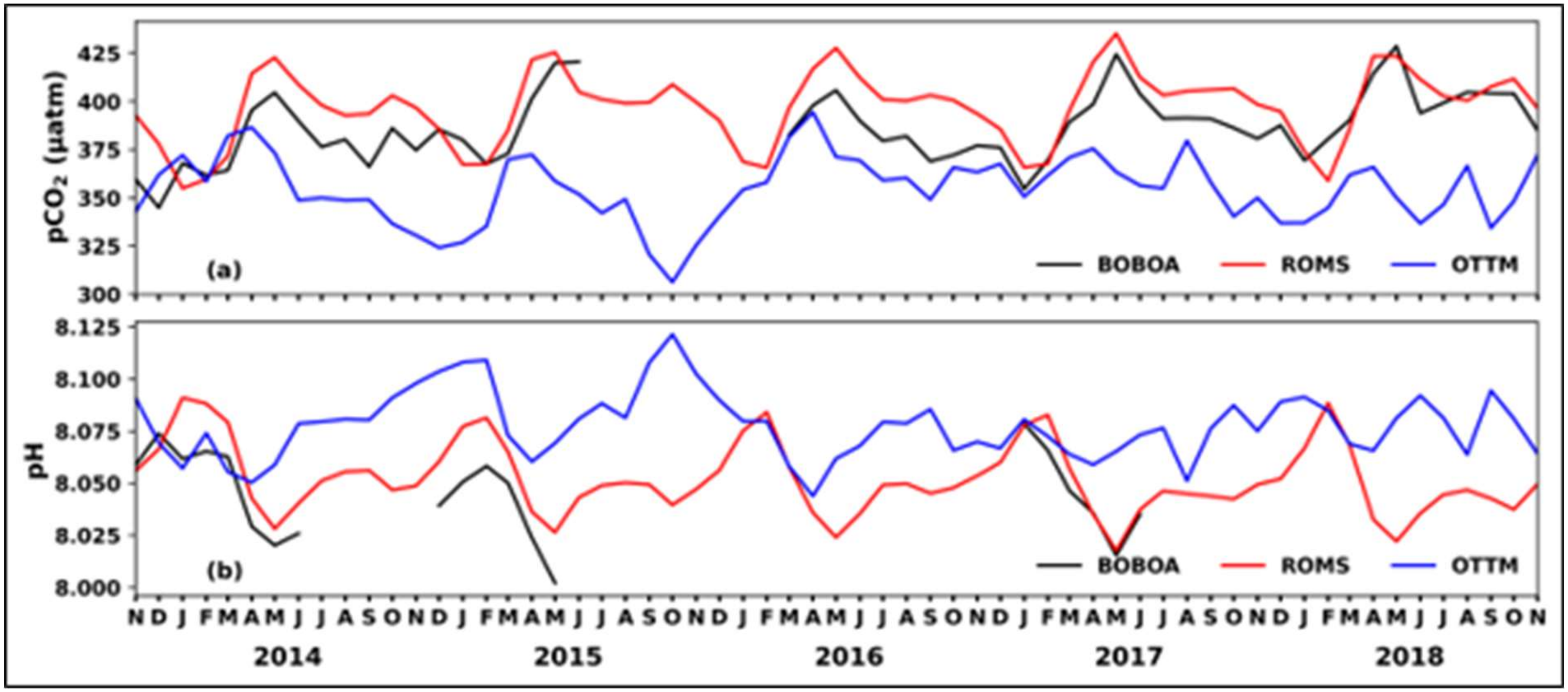
SOCAT & ROMS	
Correlation	
SST	0.94
SSS	0.80
RMSE	
SST	0.89 °C
SSS	0.64

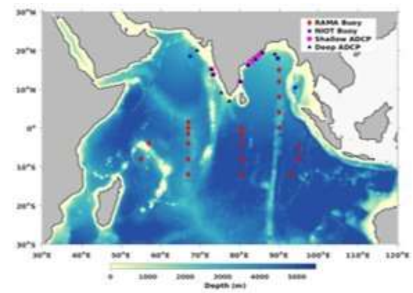
Model Evaluation



	SOCAT & ROMS	SOCAT & OTTM
Correlation		
pCO2	0.63	0.44
RMSE		
pCO2	30.02	37.65

Model Evaluation





Bay of Bengal Ocean Acidification Buoy (15°N, 90°E; Chakraborty et al. (2021)

pCO2	BOBOA & ROMS	BOBOA & OTTM
Correlation	0.79	0.19
RMSE	16.6	36.44
Mean bias	11.21	-29.13

pH	BOBOA & ROMS	BOBOA & OTTM
Correlation	0.88	0.38
RMSE	0.016	0.035
Mean bias	0.01	0.03

Decomposition analysis

INCOIS

The spatial and temporal variability of pH are primarily governed by the changes in DIC, ALK, SST, and SSS.

The component form of total variability of surface ocean pCO2 can be expressed in the following form (Sarmiento & Gruber, 2006; Takahashi et al., 2014)

$$\frac{dX}{dt} = \frac{\partial X}{\partial DIC}\frac{dDIC}{dt} + \frac{\partial X}{\partial ALK}\frac{dALK}{dt} + \frac{\partial X}{\partial SST}\frac{dSST}{dt} + \frac{\partial X}{\partial SSS}\frac{dSSS}{dt} + (other\_minor\_ions)$$

- The left-hand side of the equation shows the temporal variation of pH.
- The right side of the equation corresponds to the changes in X due to the changes in each of the drivers.
- The reconstructed pH is denoted as CTRL. We use the abiotic pump routines of OCMIP-II to reconstruct the pH using model-simulated DIC, SST, SSS, and ALK.
- To find the contribution of SST in the total pH, the abiotic pump routines of OCMIP-II are run by detrending the SST (of each model grid) while keeping all other inputs in CTRL referred to as SEN(SST).
- Subtraction of the resulting pH of SEN(SST) from CTRL gives SST's quantification in the total pH variability.

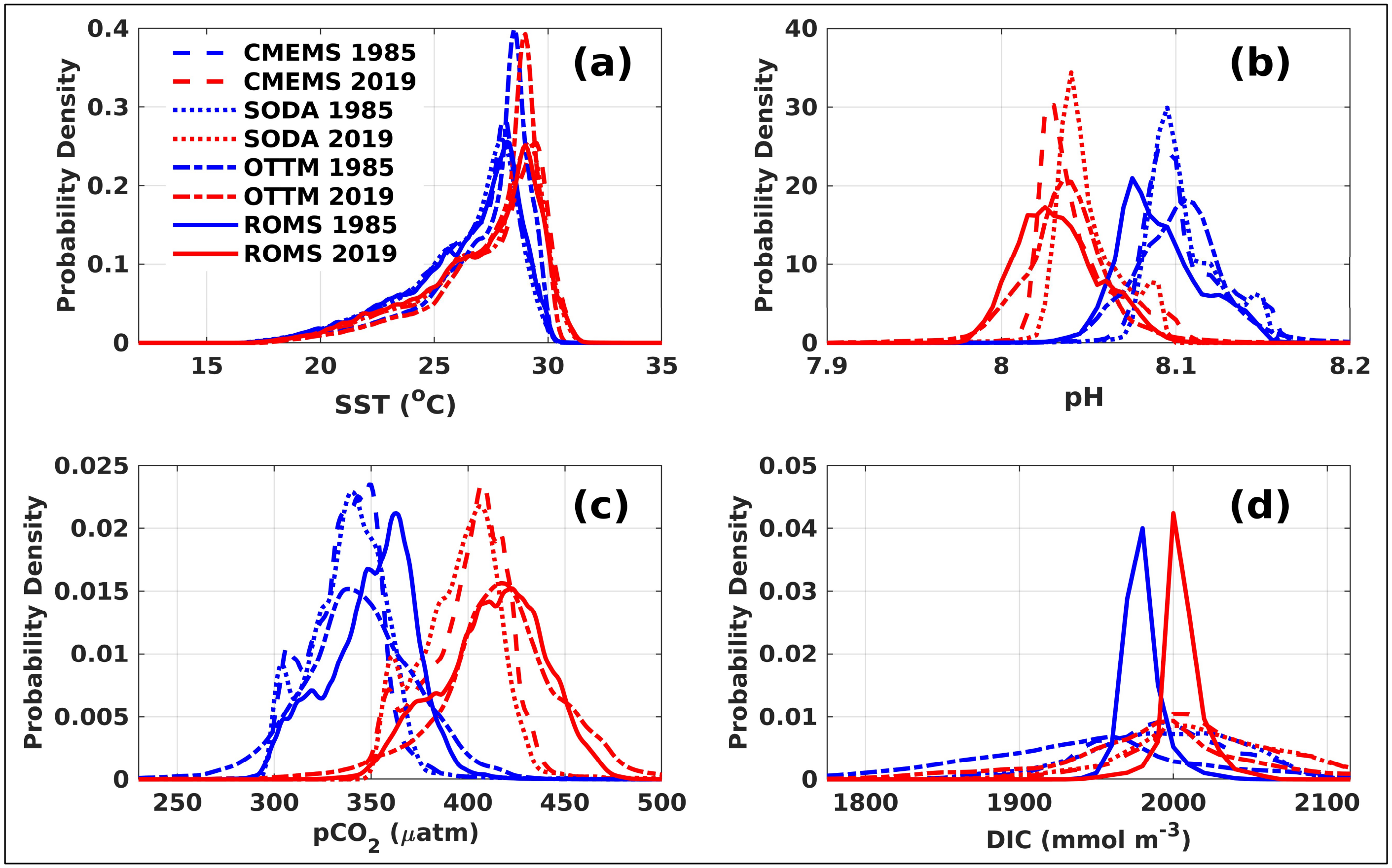
Decomposition Analysis

Arabian Sea	pH	
Model	trend/yr	contribution(%)
Overall pH trend (/year)	-0.0014±0.002	
pH_T	-0.002±0.001	14.79%
pH_ALK	-0.0001±0.001	5.00%
pH_DIC	-0.012±0.002	79.97%
pH_S	-0.000±0.001	-0.28%
Not explained(%)	0.52%	

Bay of Bengal	pH	
Model	trend/yr	contribution(%)
Overall pH trend(/year)	-0.0014±0.001	
pH_T	-0.002±0.001	13.38%
pH_ALK	-0.0001±0.001	-5.42%
pH_DIC	-0.014±0.001	94.54%
pH_S	-0.000±0.00	-2.12%
Not explained(%)	-0.39%	

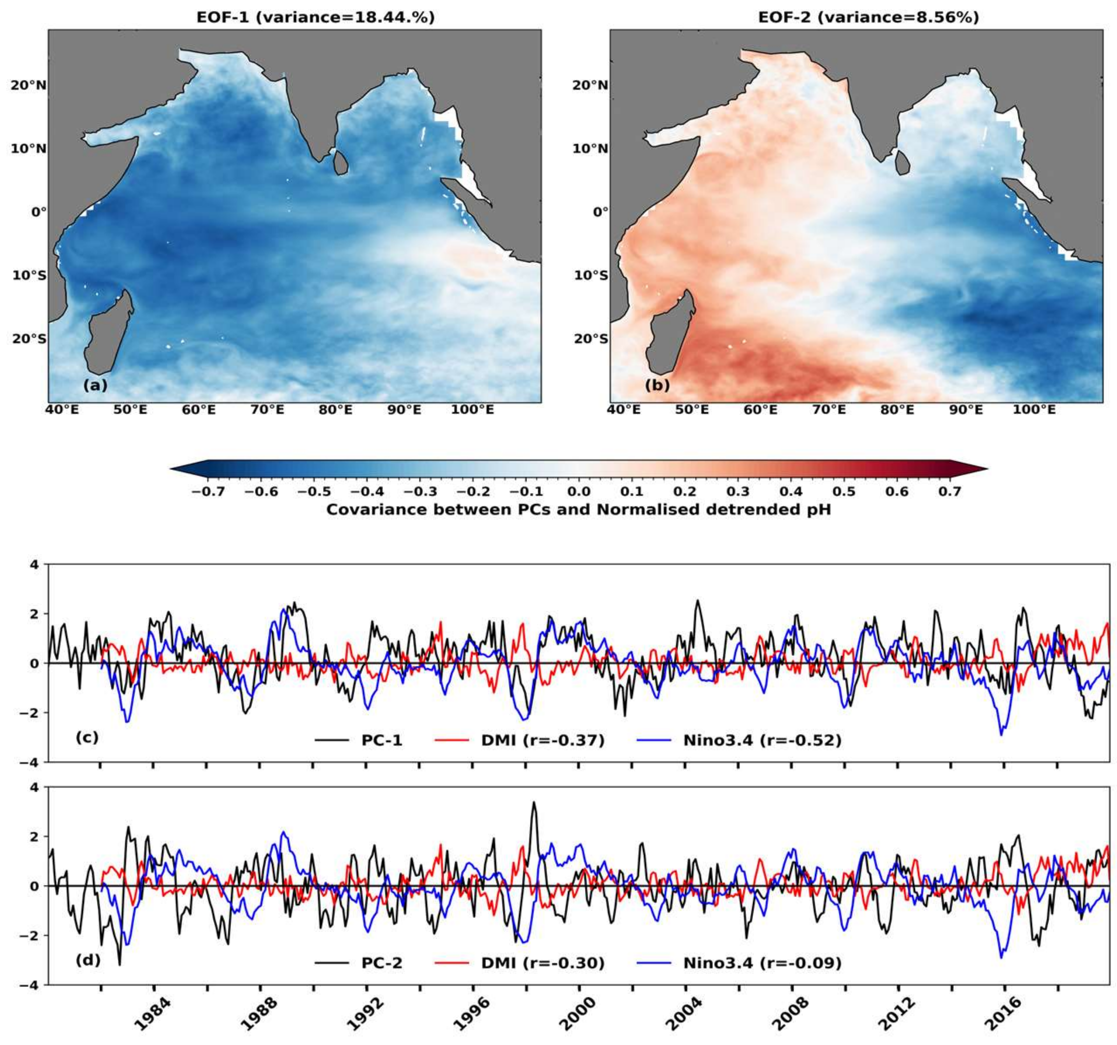
ROMS & Observations-based Data Products

INCOIS



- A right shift in the peak of SST in 2019 from 1985 is seen in both ROMS and OTTM as well as in CMEMS-LSCE-FFNN and OceanSODA data products
- CMEMS-LSCE-FFNN and ROMS suggest a drop in mean sea-surface pH value between 1985 and 2019 by 0.06, whereas a drop by 0.05 is seen from OceanSODA and OTTM.
- Interestingly, the rise in sea-surface pCO_2 seen from ROMS, OceanSODA, and CMEMS-LSCE-FFNN is almost equal to the atmospheric CO_2 rise (as seen from Mauna Loa station) in the same period (~ 64 ppm).
- A similar increase in sea-surface DIC is observed from ROMS and the observation-based reconstructed data products of the order of 25-30 mmol m-3 (50 mmol m-3 for OTTM).

El Nino and positive IOD & Indian Ocean Acidification



- Left Fig. shows a negative spatial pattern of pH anomalies, but right Fig. shows a negative spatial pattern of pH anomalies in the east and a positive in the west.
- The corresponding PC-1 shows an inverse correlation (-0.52 with 99% significance) between the pH anomalies and the Nino3.4 index, whereas PC-1 shows a moderate inverse correlation (-0.37 with 99% significance) with the DMI index.
- The first mode is found to explain 18.44% of the variance.
- Therefore, it is evident from EOF-1 mode and associated PC-1 that ENSO dominantly influences the IO pH variability.
- The basin-wide warming during the El Nino increases the free H+ ions and pCO2, shifting towards lower pH values.
- However, the moderate correlation of PC-1 with DMI indicates the combined influence of ENSO and IOD on ocean acidification.
- PC-2 correlates poorly (for pH anomalies) with Nino3.4, indicating no influence of ENSO on the second mode.
- The second mode explains 8.56% of the total variance.
- From EOF-1 mode, ENSO dominance on the IO pH variability is evident, however, the influence of IOD are spread across EOF-1 & 2 modes.

Indian Ocean Acidification and its driving mechanisms

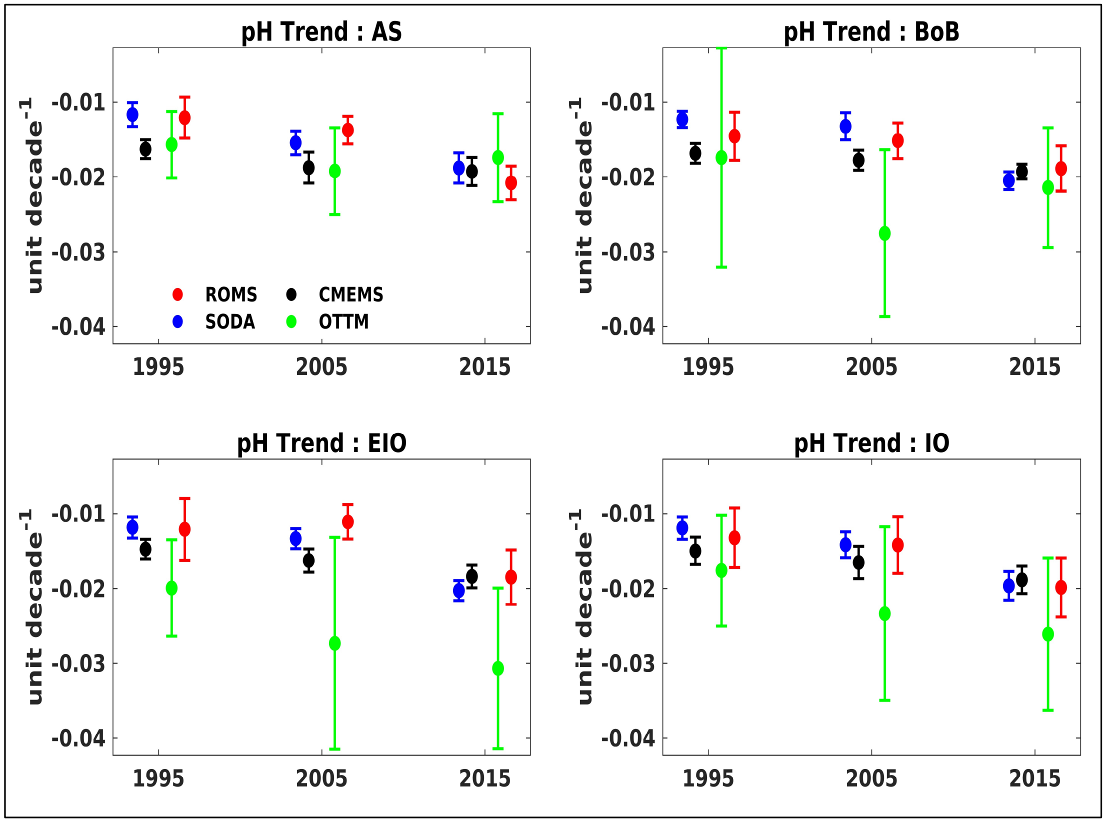


Figure 5: Decadal trend of pH in AS, BoB, EIO, and IO regions.

- Indian Ocean pH is decreasing at an average rate of 0.015 dec^{-1} from 1980-2019.
- El Nino and positive Indian Ocean Dipole events lead to an enhancement of Indian Ocean acidification.

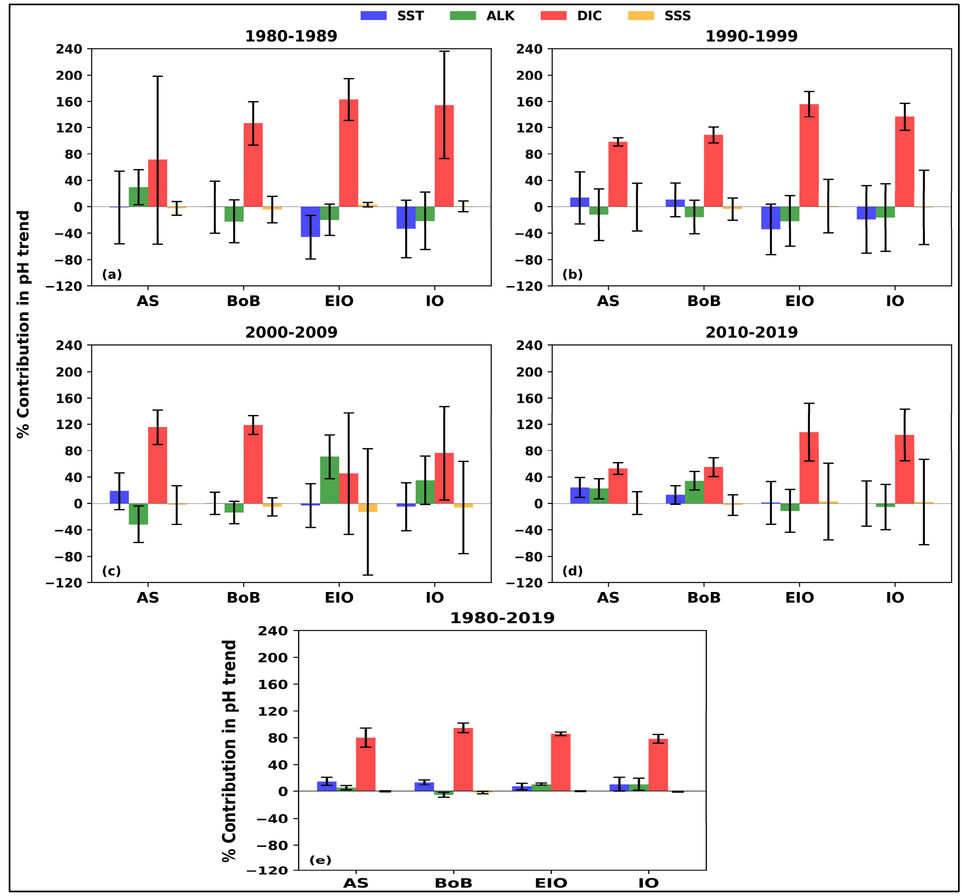


Figure 6: Percentage contribution of each driver (with standard deviation shown by error bars) on the trend of pH.

- The trend of dissolved inorganic carbon primarily drives an increasing ocean acidification trend in the Indian Ocean.

Summary & Conclusions

- The analysis indicates that the rate of change of declining pH in the Arabian Sea (Bay of Bengal) is -0.014 ± 0.002 (-0.014 ± 0.001) unit/decade.

- The trend of dissolved inorganic carbon primarily drives an increasing ocean acidification trend in the Indian Ocean.

- The increasing anthropogenic CO_2 uptake by the ocean dominantly controls 80% (94.5%) of pH trends in AS (BoB) whereas ocean warming controls 14.4% (13.4%) of pH trends in AS (BoB).

- The changes in TA contribute to enhancing the pH trend of the AS by 5%. In contrast, it has a buffering effect which results in suppressing the pH trend of BoB by -5.4%.

- El Nino and positive Indian Ocean Dipole events lead to an enhancement of the Indian Ocean acidification.

Publication Details

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RESEARCH ARTICLE

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Indian Ocean Acidification and Its Driving Mechanisms Over the Last Four Decades (1980–2019)

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Key Points:

- The Indian Ocean pH is decreasing at an average rate of 0.015 dec^{-1} from 1980 to 2019
- The trend of dissolved inorganic carbon primarily drives an increasing ocean acidification trend in the Indian Ocean
- El Ninõ and positive Indian Ocean Dipole events lead to an enhancement of the Indian Ocean acidification

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract This paper aims to study the changes in the Indian Ocean seawater pH in response to the changes in sea-surface temperature, sea-surface salinity, dissolved inorganic carbon (DIC), and total alkalinity (ALK) over the period 1980–2019 and its driving mechanisms using a high-resolution regional model outputs. The analysis indicates that the rate of change of declining pH in the Arabian Sea (AS), the Bay of Bengal (BoB), and the Equatorial Indian Ocean (EIO) is -0.014 ± 0.002, -0.014 ± 0.001, and -0.015 ± 0.001 unit dec^{-1}, respectively. Both in AS and BoB (EIO), the highest (lowest) decadal DIC trend is found during 2000–2009.

Acknowledgement

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Open Research

- **BOBOA mooring data is available at https://www.nodc.noaa.gov/ocads/oceans/Moorings/BOBOA.html.**

- **The SOCAT data is obtained from https://www.socat.info/index.php/data-access/**

- **The OceanSODA data could be obtained from https://www .ncei .noaa .gov/data/oceans/ncei/ocads/data/0220059/.**

- **CMEMS-LSCE-FFNN data can be obtained from https://essd.copernicus.org/preprints/essd-2023-146/essd-2023-146.pdf**

- **ROMS model-simulated data presented in this paper are archived at the central data repository of https://incois.gov.in/ and can be obtained by contacting kunal.c@incois.gov.in.**

Thank You for your attention!