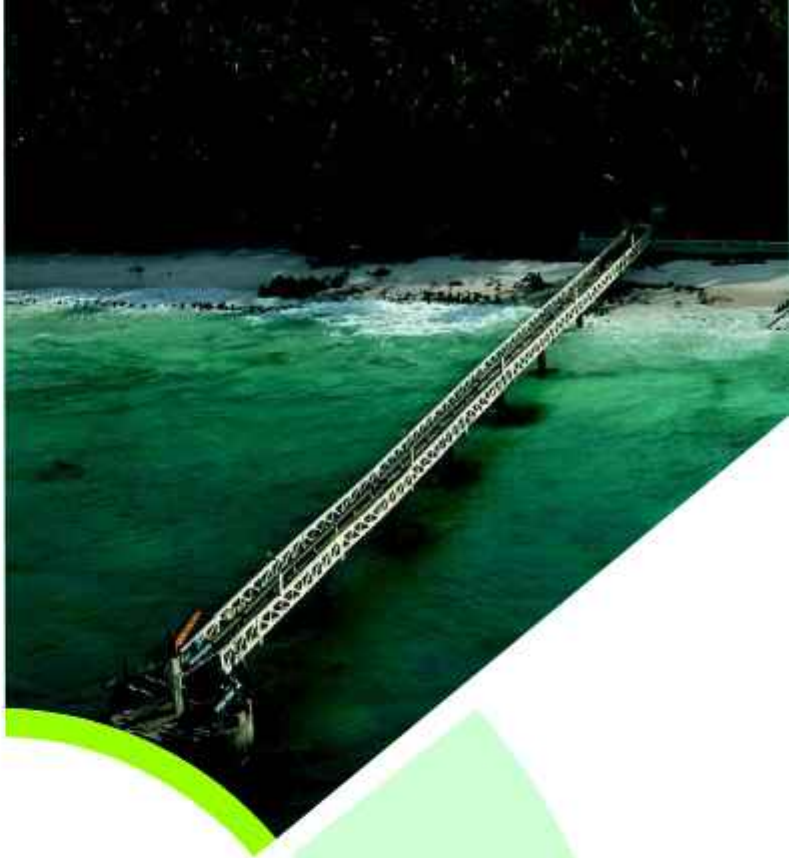
MINISTRY OF
EARTH SCIENCES



2025-2026
ANNUAL REPORT

सत्यमेव जयते

GOVERNMENT OF INDIA

Matsya-6000, India's first indigenous deep-sea submersible

Low-Temperature Thermal Desalination plant at Kavaratti island, Lakshadweep

Borehole Geophysics Research Laboratory, Karad

Doppler Weather Radar at Raipur, Chattisgarh

ANNUAL REPORT

2025-2026

Government of India
Ministry of Earth Sciences

CONTENTS

FOREWORD

It gives me great pleasure to present the annual report of the Ministry of Earth Sciences (MoES) for the year 2025-26. This report serves as a comprehensive chronicle of our ministry's steadfast commitment to advancing scientific understanding and delivering societal benefits through excellence in Earth System Sciences.

The Ministry of Earth Sciences remains at the forefront of monitoring and predicting the complexities of our planet's atmosphere, ocean, geosphere and cryosphere. Over the past year, our institutions have achieved remarkable milestones in enhancing the accuracy of weather, climate, and ocean state forecasts. These advancements are not merely scientific feats; they are critical lifelines that support disaster risk reduction, empower our farming communities, and bolster national resilience.

The thematic integration of research, technology development, and operational services is a hallmark of this year's progress. From the deployment of sophisticated observational networks to the application of high performance computing and Artificial Intelligence in modelling and forecasting, the ministry continued to expand its scientific and technological capabilities.

The achievements highlighted in this report are the result of the dedication and collaborative spirit of our scientists, engineers, and administrative personnel. I would like to express my sincere appreciation to the Directors of all MoES institutes and the personnel of the Ministry for effectively steering the scientific and research initiatives and for the sustained contributions to the Ministry's mandate.

I am confident that the insights shared in this report will inspire continued excellence and foster new partnerships as we strive to serve the nation through the power of Earth sciences

Dr. M. RAVICHANDRAN

Secretary, Ministry of Earth Sciences
Government of India

Chapter–1
Overview

Earth System Sciences encompass the study of the five vital components of our planet, the Atmosphere, Hydrosphere, Cryosphere, Lithosphere, and Biosphere, and their complex interdependencies. The Ministry of Earth Sciences (MoES) is mandated to advance Earth system science research and deliver critical services including meteorological forecasting, climate assessment, ocean state monitoring, hydrological services, and seismological surveillance. Ministry's operational remit also extends to the exploration of marine living and non-living resources, strategic research across the Earth's poles (Arctic and Antarctic) and the Himalayan region.

MoES plays a central role in national safety and economic well-being, providing timely and accurate forecasts and warnings for natural hazards such as tropical cyclones, storm surges, floods, heatwaves, lightning events, and tsunamis, while continuously monitoring seismic activity. Its services support disaster risk reduction, agricultural planning, water resource management, aviation safety, and Urban-Coastal resilience.

The fiscal year 2025-26 has been a transformative period for MoES, marked by the transition from advanced scientific blueprints into operational national assets and the establishment of new scientific platforms. From the commissioning of indigenous high-resolution forecasting systems to achievements in deep-sea exploration and oceanographic technology, MoES has consolidated India's global leadership in Earth system sciences.

Significant milestones include:

Mission Mausam

- Mission Mausam, launched on 14 January 2025 on IMD's 150th Foundation Day by the Hon'ble Prime Minister, set forth an ambitious agenda to make India weather ready and climate smart by strengthening forecasting, climate resilience, and early warning services through cutting-edge technology and high-resolution models.
- Observational infrastructure strengthened nationwide with expanded Doppler Weather Radar (DWR) and Automatic Weather Station (AWS) networks, through commissioning of C-Band DWRs at Raipur and Mangaluru, and a high-resolution X-Band dual-polarised DWR at HACPL, Mahabaleshwar, enhancing real-time data coverage, nowcasting, and monitoring of severe weather across India.
- The Indian Institute of Tropical Meteorology (IITM) developed 3D-printed indigenous AWS units to cost-effectively densify the weather observing network and improve hyper-local forecasting and data availability across urban and remote regions.
- The Bharat Forecast System (BFS), an indigenously developed, high-resolution numerical weather prediction model with a 6km grid scale, was operationalised to enable precise, localized forecasts of extreme weather events such as monsoon dynamics and cyclones, thereby strengthening climate services for agriculture, disaster management, and public safety.
- The Mithuna Forecast System (Mithuna-FS) a land–ocean–atmosphere–sea-ice coupled model was operationalized at 12 km resolution, which reduces biases in key weather variables and supports sharper medium-range forecasts by integrating multiple Earth system components.
- An AI proof-of-concept system was developed to automate weather map interpretation and briefing preparation, and AI/ML-based forecast tools were integrated with traditional numerical weather models to enhance forecasts through data-driven bias correction, downscaling, and nowcasting as part of efforts to improve weather prediction accuracy and delivery.
- The IITM-ESMv3 global Earth System Model was developed to provide control simulations and contribute to the Coupled Model Intercomparison Project (CMIP) efforts in support of the IPCC Seventh Assessment Report (AR7), advancing India's climate modelling

capabilities for global and regional climate projections. High-resolution (~27km) climate projections were generated to assess future atmospheric scenarios and support improved climate impact assessment.

- IMD has significantly enhanced its predictive capabilities over the past decade, with forecast accuracy for severe weather events improving by around 40% in recent years compared to the previous period.
- Severe weather forecast skill continued to advance in 2025, with 24-hour heavy rainfall warnings achieving about 85% accuracy, improvements in cyclone intensity and track guidance, and the Block-Wise Rainfall Monitoring Scheme (BRMS) operationalised on 27th July 2025 to deliver high-resolution real-time rainfall data at the block level, enhancing granularity beyond traditional district reporting.
- The "Mausamgram" platform was launched to provide hyperlocal weather forecasts at the village and PIN-code level, offering hourly updates for 36 hours and extended multi-day forecasts to support citizen preparedness.
- The indigenous Multi-Hazard Early Warning Decision Support System (DSS) developed by IMD enhanced self-reliance and was honoured with the National Award for e-Governance 2025 for its impact on technology-driven forecasting and public service delivery.
- In collaboration with the NDMA and state governments, IMD developed Heat Action Plans (HAPs), early warning and preparedness strategies for extreme heat events to reduce mortality and morbidity in vulnerable regions.
- Aviation weather safety was enhanced with a substantial increase in Runway Visual Range (RVR) systems and Digital Current Weather Indicating Systems (DCWIS) across airports, strengthening weather support for flight operations.
- High-density urban weather monitoring networks were deployed, including the Delhi Urban Mesonet and Testbed, providing real-time data on aerosols, clouds, and winds for improved forecasting and hazard assessment; similar observation and research testbeds have been initiated in Chennai and Visakhapatnam to strengthen urban weather monitoring capabilities.
- Cloud seeding protocols were formulated for precipitation enhancement in rain-shadow regions through warm-base cloud seeding, with significant scientific understanding of aerosol-cloud-precipitation processes unraveled through CAIPEEX observations and numerical simulations.

PRITHVI O–SMART (O-SMART – Ocean Services, Modelling, Application, Resources, and Technology)

- Three eco-friendly Low-Temperature Thermal Desalination (LTTD) plants were commissioned in the Lakshadweep archipelago to provide sustainable drinking water, including a 1.5 lakh liters-per-day plant at Chetlat inaugurated on 17th January 2025, significantly improving potable water availability for island communities.
- Under the 'Make in India' initiative, two indigenous coastal research vessels, Sagar Tara and Sagar Anveshika, were built domestically and added to the national research fleet to support oceanographic research, shallow water operations, and marine environmental monitoring along India's coastline.
- The construction of a new state-of-the-art Ocean Research Vessel (ORV) was initiated under a contract worth approximately Rs.840 crore with Garden Reach Shipbuilders & Engineers Ltd. (GRSE), marking a major enhancement of India's oceanographic research capabilities.
- A custom dual-quadcopter drone weighing ~85kg, capable of carrying up to 25 kg of oceanographic sensors, was developed and successfully field-tested at Nellore, enabling advanced in-situ coastal data collection.
- The Wave Atlas for the North Indian Ocean Version 2.0 was released by the NIOT as a ready-

to-use database of wave characteristics to support maritime operations and coastal engineering. NIOT also completed shallow water bathymetry surveys along the East Coast of India, producing seafloor tracing charts that enhance coastal and oceanographic forecasting and marine resource management.

- Operationalisation of the Hilsa Fishery Advisory Service (HiFA) promoted sustainable fisheries through machine-learning-based spatial forecasts.
- A 10 m open-sea submerged cage with AI/ML-based fish biomass monitoring was deployed in the Andaman Islands to advance deep-sea aquaculture research.
- CMLRE conducted comprehensive deep-sea surveys, documenting new species and geographic records, mapping spawning grounds of ~25 economically important fish species in the eastern Arabian Sea, identifying a major low-oxygen dead zone in the northwestern Bay of Bengal, and generating a reference library of species with detailed taxonomy and DNA barcodes; the potential fishery yield for the Indian EEZ was revalidated at 5.78 million tonnes.
- Integrated advances in biodiversity monitoring included upgrading the TAXOBot platform for real-time, multi-taxa AI-based species identification, developing self-supervised foundation models like DINOv3 and SimCLR for plankton classification, and creating standardized DNA extraction protocols for deep-sea sediments to enhance environmental DNA (eDNA) analyses.
- The Urban Environment-Science to Society (UES2S) platform was launched on 15th December 2025 to provide an integrated high-resolution framework for monitoring air quality and urban flood dynamics.
- Coastal water quality is continuously monitored at 50 locations around the Indian coastline by the NCCR, with validated data shared with NITI Aayog to support national priorities and India's SDG 14 commitments.

PRITHVI – PACER (Polar Science and Cryosphere Research)

- In July–August 2025, the NCPOR dispatched a nine-member Indian scientific team aboard RV Skagerak for a multidisciplinary expedition to the East Greenland Sea and adjacent Arctic waters, collecting oceanographic, atmospheric, biological, and biogeochemical data over ~700km, representing India's first deep-water Arctic oceanographic expedition.
- The indigenously developed Eye ROV was deployed in Antarctica to monitor under-ice ecosystems using YOLOv8 AI models for benthic species detection, demonstrating integration of AI in field research.
- Strategic collaborations were formed with GEOMAR and AWI to study solid Earth dynamics; India assumed the Chairmanship of the Asian Forum on Polar Sciences (AFoPS, 2024–2026).
- Three major facilities, Polar Bhavan, Sagar Bhavan, and a Science on a Sphere (SOS) facility, were inaugurated at the NCPOR, Goa; an MoU with HPCL was signed to develop sustainable fuels for Antarctic stations, supporting decarbonization.
- In the Himalayas, glacial surveys of Khangri Glacier and Rani Lake were carried out using drones to enhance early-warning systems for Glacial Lake Outburst Floods (GLOFS).
- Studies on Himalayan glaciers included modelling the impact of black carbon aerosols deposited in the upper snow layers, showing that such deposition reduces snow albedo and accelerates snow and ice melt, as part of climate-chemistry model development and sensitivity experiments under IITM.

PRITHVI – SAGE (Seismology and Geosciences)

- Tsunami and seismic hazard monitoring remained robust in 2025 with the Tsunami Early Warning Centre operating 24X7; indigenous tsunami buoy systems in the Bay of Bengal contributed to real-time threat detection and alerting.

- Seismic network expansion (Seoni - MP, Saiya Dera and Patna - Bihar) and microzonation advanced national earthquake monitoring and risk planning, with Seismic Microzonation Reports for Bhubaneswar, Chennai, Coimbatore, and Mangalore released in July 2025 to support disaster-resilient urban planning.

PRITHVI – REACHOUT (Research, Education, Training, and Outreach)

- MoES conducted the IISF 2025 at Panchkula (6–9 Dec), coordinated by the IITM, Pune, and organized jointly with other national scientific ministries. The festival, themed "Vigyan Se Samruddhi: For Aatmanirbhar Bharat", brought together over 10,000 participants including students, educators, scientists, and innovators through interactive exhibits, science villages, panel discussions, and hands-on activities, showcasing Earth system science advancements and promoting scientific temper and innovation nationwide.
- The Earth System Science Olympiad (ESSO) 2025–26 was conducted to engage students across India in Earth science learning and competitions, preparing them for the 18th International Earth Science Olympiad (IESO, Jining, China, 8–16 Aug 2025). The Indian team won multiple medals and a 3rd prize in the International Geoscience Youth Reporter category, highlighting strong youth talent development in Earth system sciences.
- The International Training Centre for Operational Oceanography (ITCOOcean) trained hundreds of ocean science professionals, including participants from Indian Ocean Rim Association (IORA) countries.
- Thirty new extramural projects were sanctioned across Atmospheric Sciences, Geosciences and Seismology, Ocean Sciences & Resources, Hydrology & Cryosphere, and Earth System Science Technology.
- Widespread engagement of students and researchers with the new Science on a Sphere (SOS) facility at the NCPOR enhanced outreach and scientific understanding across disciplines.
- International Coastal Cleanup Day 2025 mobilized over 26,000 volunteers across coastal States and Union Territories, coordinated by the Indian Coast Guard, to remove marine litter, raise awareness, and foster community participation in protecting marine ecosystems.

Deep Ocean Mission

- The indigenous human-occupied submersible Matsya-6000, designed to carry three people to 6,000 m, depth completed its design, integration and successful wet harbour trials at the L&T Shipbuilding facility in Kattupalli, Chennai in early 2025, and Indian (NIOT) aquanauts gained operational experience to depths of up to 5,000m aboard the French Nautile submersible in August 2025.
- India established a global benchmark in deep-sea technology by successfully testing an indigenous seabed mining system at 5,270 m depth in the Central Indian Ocean Basin, the first operation of a tethered mining machine at such extreme depths, demonstrating advanced capabilities in sustainable deep-ocean resource technology.
- An indigenously developed underwater acoustic communication system was successfully tested at Idukki Lake over a 5.5 km horizontal range, demonstrating long-range signal transmission to support deep-sea submersible operations.
- A total of 25 seamounts were surveyed, leading to the discovery of nearly 39 species potentially new to the Indian EEZ, now undergoing genomic analysis for potential applications. Autonomous Underwater Vehicles (AUVs) identified 2 active and 2 inactive hydrothermal vents in mineral rich deep ocean zones.
- Integrated advances in biodiversity monitoring include upgrading the TAXOBot platform for real-time, multi-taxa AI-based species identification, developing self-supervised foundation models like DINOv3 and SimCLR for plankton classification, and creating

standardized DNA extraction protocols for deep-sea sediments to enhance the reliability of environmental DNA (eDNA) analyses.

Budget Allocation and Expenditure

The total outlay for the Ministry for the year 2025-26 was Rs. 3648.08 crores, which was reduced to Rs. 3388.27 crores at the RE stage. The expenditure profile for the past years of MoES (Fig. 1.1).

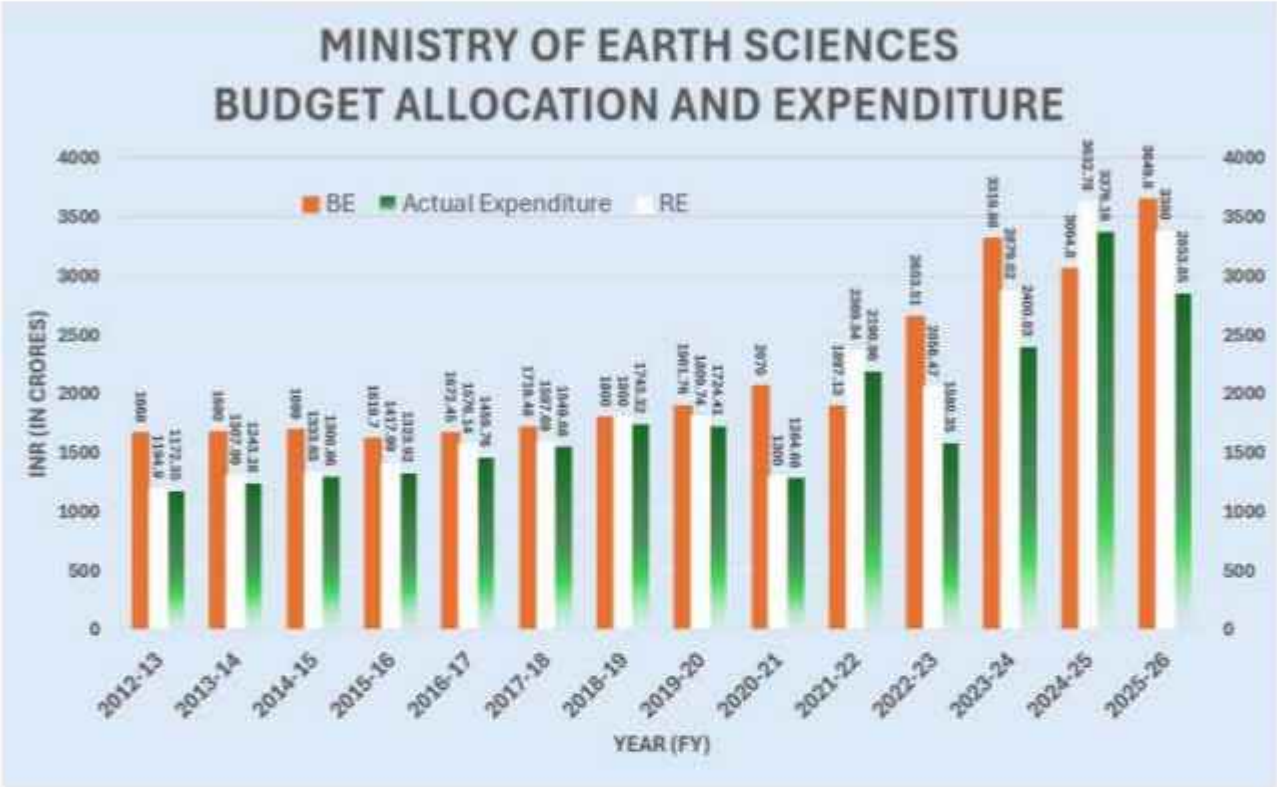


Fig. : 1.1: Budget allocation (BE and RE) and actual expenditure from 2012-2026. (Expenditure 2025-26 is as on 31 December 2025)

Chapter-2

PRITHVI Vigyan (PRITHVI) Scheme

The Union Cabinet approved the overarching scheme "Prithvi Vigyan (PRITHVI)" of the Ministry of Earth Sciences on 5th January 2024 for implementation during the period from 2021-26 at an overall cost of Rs. 4,797 crores. The scheme encompasses five MoES sub-schemes, namely:

- Ocean Services, Modelling Application, Resources and Technology (O-SMART)
- Polar Science and Cryosphere Research (PACER)
- Seismology and Geosciences (SAGE)
- Research, Education, Training and Outreach (REACHOUT)

The research and development and operational (services) activities under the PRITHVI scheme shall be carried out in an integrated manner through combined efforts of the concerned Institutes under MoES.

The major objectives of the overarching PRITHVI Scheme are as follows:

- Augmentation and sustenance of long-term observations of the atmosphere, ocean, geosphere, cryosphere and solid earth to record the vital signs of the Earth System and change.
- Development of modelling systems for understanding and predicting weather, ocean and climate hazards, and the science of climate change.
- Exploration of polar and high seas regions of the Earth towards the discovery of new phenomena and resources.
- Development of technology for exploration and sustainable harnessing of oceanic resources for societal applications.
- Translation of knowledge and insights from Earth systems science into services for societal, environmental and economic benefit.

Chapter 2.1

Ocean Services, Modelling, Applications, Resources, and Technology (O-SMART)

The Ministry's oceanographic services, research, and technology development are implemented under the O-SMART sub-scheme of PRITHVI, aimed at providing reliable ocean forecasts, advancing modelling and observational capabilities, developing indigenous technologies, and supporting sustainable utilisation of living and non-living ocean resources. Under O-SMART, activities are implemented through: Ocean Observations, Modelling and Advisory Services (OOMAS) by INCOIS; Ocean Technology and Observation (OTOO) by NIOT; Ocean Non-Living Resources led by NCPOR; Marine Living Resources and Coastal Research (MLR & CR) led by CMLRE and NCCR; and Operation and Maintenance of Research Vessels, supporting the Ministry's fleet for surveys, observations, and technology demonstrations in the ocean

2.1.1 Modelling and Advisory Services

INCOIS continued to deliver critical oceanographic services through an integrated framework of sustained observations, advanced numerical modelling, and user-focused advisories. These services support disaster risk reduction, marine safety, fisheries, coastal management, climate applications, and the blue economy at national and regional scales.

2.1.1.1 Tsunami Early Warnings

The Indian Tsunami Early Warning Centre (ITEWC) monitored 32 earthquakes of magnitude 6.5 and above during the reporting period, including one event in the Indian Ocean (Fig. 2.1.1). In all cases, ITEWC assessed and declared no tsunami threat to India. As the designated Tsunami Service Provider (TSP) for the Indian Ocean, ITEWC also disseminated the necessary bulletins to 26 Indian Ocean Rim Countries (IORA) and the Intergovernmental Oceanographic Commission (IOC) through email, Global Telecommunication System (GTS), fax, and SMS.

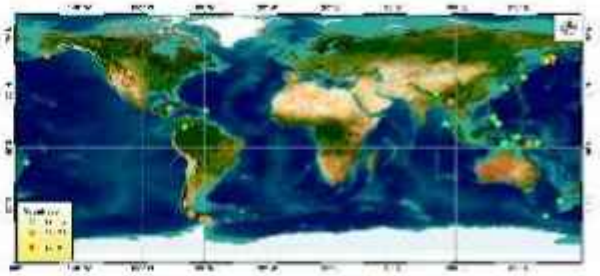


Fig. 2.1.1: Global distribution of earthquakes with magnitude 6.5 Mw monitored by the ITEWC in 2025.

The Coral Bleaching Alert System (CBAS) issued 110 advisories between January and November 2025, based on bi-weekly assessments of Hot Spots (HS) and Degree Heating Weeks (DHWs) derived from satellite-based sea surface temperature anomalies. During this period, seven warning alerts and 78 watch alerts were generated across five coral reef regions, Andaman, Nicobar, Gulf of Kutch, Gulf of Mannar, and Lakshadweep, supporting reef monitoring, and conservation planning.

2.1.1.3 Algal Bloom Information Services

The INCOIS Algal Bloom Information Services (ABIS) utilises MODIS-Aqua derived ocean colour data to provide the near real-time status of algal blooms in the North Indian Ocean waters on a daily basis. Based on the historical frequency of bloom occurrences, four algal bloom hotspot regions (the north-eastern Arabian Sea, Kerala Coast, Gulf of Mannar, and Gopalpur Coast) have been identified and are continuously monitored using ABIS. During the reporting period, ABIS products were generated for 330 days, of which alerts were issued on 15 days.

2.1.1.4 Potential Fishing Zones (PFZ) and Tuna PFZ Advisories

INCOIS provided PFZ advisories generated using satellite-derived Sea Surface Temperature (SST), chlorophyll concentration, water clarity, and sea level data. These advisories were disseminated daily through smart maps and text messages, except during the fishing-ban period and adverse sea-state

Fig. 2.1.2: Number of PFZ and Tuna PFZ advisories issued during January-November 2025.

conditions. From January to November 2025, multilingual PFZ advisories were issued on 296 days, while Yellowfin Tuna advisories were provided on 137 days (Fig. 2.1.2).

2.1.1.5 Ocean State Forecast (OSF) Services

Daily Ocean State Forecasts (OSF) are issued covering waves, winds, currents, tides, Sea Surface Temperature (SST), Mixed Layer Depth (MLD), and the depth of the 20°C isotherm (D20) across regional and coastal domains. In addition, INCOIS monitored cyclone and depression conditions, issued joint INCOIS-IMD bulletins, and disseminated warnings through multiple communication channels to reach user communities. Multi-hazard early warning services were provided to a wide range of stakeholders, including disaster management authorities, fishermen, ports and harbours, vessels operating at sea, offshore industries, and defence authorities. During the period, a total of 6,672 alerts and warnings related to high waves, swell surges, and ocean currents were issued (Fig. 2.1.3).

Fig. 2.1.3: High-wave, swell-surge, and ocean-current warnings and alerts issued.

INCOIS also provided weekly Ocean State Forecast briefings to the South Asia Hydromet Forum (SAHF) and extended ocean advisory services to the WMO Regional Specialised Meteorological Centre (RSMC), Pacific Island countries, RIMES member states, and the Colombo Security Conclave.

2.1.1.6 Support During Extreme Weather Events

INCOIS continuously monitored waves, winds, sea level, and ocean currents in both nearshore and offshore regions during extreme weather events, using a combination of numerical models, in-situ measurements, and satellite observations. Joint INCOIS-IMD bulletins were issued for all significant events affecting the Indian coast.

During the period, 29,602 emails and 82 joint INCOIS-IMD bulletins were disseminated. INCOIS successfully monitored Severe Cyclonic Storm Montha (28-29 October 2025) and issued 15 storm surge and coastal inundation advisories through IMD, demonstrating the robustness and reliability of operational forecasting systems (Fig. 2.1.4).

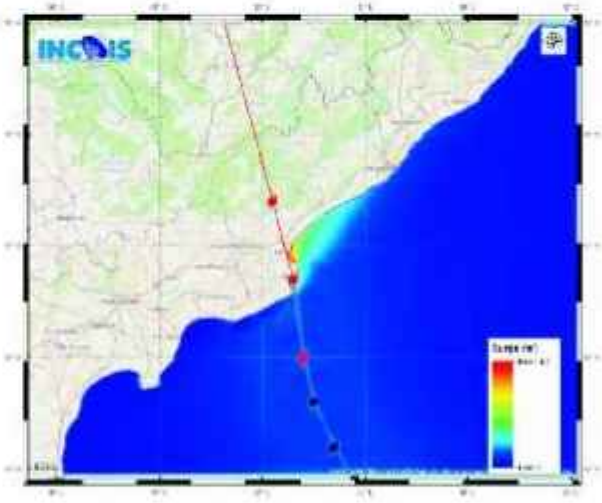


Fig. 2.1.4: Storm surge forecast issued for Severe Cyclonic Storm Montha (October 2025).

2.1.1.7 Search and Rescue and Oil Spill Advisory Services

INCOIS responded to major maritime incidents using the Search and Rescue Aid Tool (SARAT) and the Oil Spill and Object Search Application (OOSA). These services provided rapid drift trajectory forecasts and EIAs, supporting emergency response and mitigation efforts. Detailed case studies are presented under applied research activities.

2.1.1.8 New Initiatives and Services

The SOP for Volcanic-Induced Tsunamis, along with the system for dissemination of tsunami bulletins to NAVAREA stakeholders, was inaugurated by Dr. Jitendra Singh, Hon'ble Minister of Earth Sciences, and Dr. M. Ravichandran, Secretary, MoES. Subsequently, two new services, (i) the Hilsa Fishery Advisory Service (HiFA) and (ii) INCOIS Global Ocean Reanalysis Version-1 (IGORA-1), were launched on 3 February 2025 by Dr. N. Kalaiselvi, Director General, CSIR, and Dr. M. Ravichandran, Secretary, MoES (Fig. 2.1.5).

Fig. 2.1.5: Inauguration of SOP for Volcanic-Induced Tsunamis and NAVAREA bulletin dissemination services services (top), and launch of Hilsa Fishery Advisory Service (HiFA) and INCOIS Global Ocean Reanalysis Version-1 (IGORA-1); (bottom).

2.1.1.9 Consultancy and Commercial Services

INCOIS continued operational oceanographic and marine meteorological consultancy projects. Provided Commercial Ocean State Forecast Services to (i) Adani Vizhinjam Port Pvt Ltd, (ii) Vishwasamudra, Hyderabad, (iii) Directorate General of Shipping, Mumbai, (iv) NPCIL, Mumbai, (v) Captain of Ports Departments, Goa, (vi) Nautilus Shipping India Pvt Ltd, Chennai, (vii) McDermott, Kakinada, (viii) Andhra Pradesh Maritime Board and (ix) AFCONS Pvt Ltd and location specific OSF services upon request.

2.1.1.10 Information, Communication and Technology (ICT) Infrastructure

INCOIS completed the migration of 100% of its operational modelling suite to the TARANG High-Performance Computing System, enabling 24×7 uninterrupted operations following acceptance testing and shadow runs. An AI/ML GPU cluster was integrated with central storage to support advanced research. The INCOIS website and service portals were migrated to in-house, open-source infrastructure with GIS-based visualisation and OGC-compliant (WMS/WFS) services. To enhance operational reliability, 5 indigenous INSAT-enabled drifters were deployed at 22 locations in the Andaman region, 13 observatories were provided with new AC power connections, and 36 tide gauge stations were maintained to ensure continuous real-time data flow.

2.1.2 Applied Research and Ocean Observations

2.1.2.1 Automated Data Processing and Operational Services

The Automated Data Processing Chain (ADPC) provided near-real-time ocean-colour products from MODIS-Aqua and VIIRS-SNPP, supporting operational services such as PFZ, Tuna advisories, ABIS, WQNS, ChloroGIN, and in-house R&D. ABIS, operational since 2022, issued daily alerts for 4 primary and 2 secondary hotspots in the north Indian Ocean, now integrated with WQNS, enabling timely decision-making for marine ecosystem management.

2.1.2.2 Indian Ocean Land Atmosphere (IOLA) Coupled Prediction System

The Indian Ocean Land Atmosphere (IOLA) coupled prediction system simulates ocean-atmosphere interactions at convective scales to mesoscales, targeting cyclones, monsoon systems, and coastal hazards. For Severe Cyclonic Storm Dana (19-26 Oct 2024), IOLA accurately reproduced cyclone position, wind stress, and surface currents, outperforming low-resolution HYCOM systems. The model captured enhanced circulation and ocean responses, supporting storm surge forecasting and coastal hazard assessment (Fig. 2.1.6).

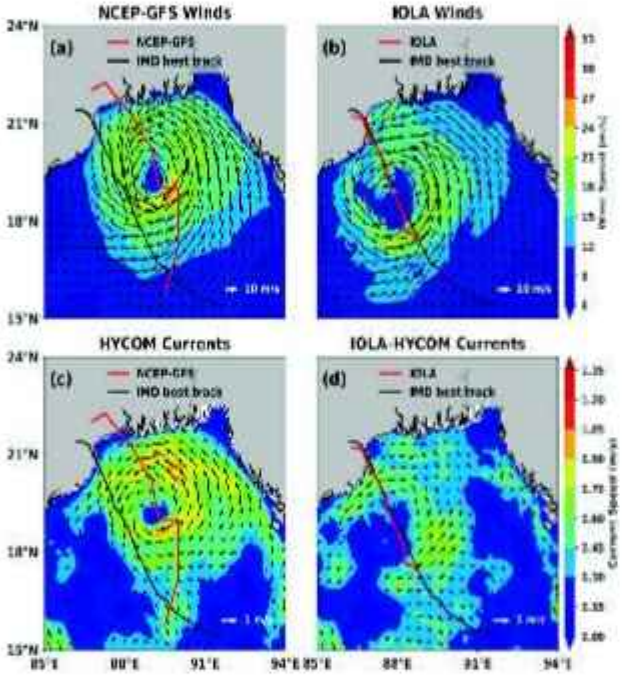


Fig. 2.1.6: Simulated wind fields (shaded) and wind vectors associated with Cyclone Dana, valid at 00 UTC on 24 October 2024, from (a) the NCEP-GFS model & (b) the IOLA coupled model, both initiated at 12 UTC on 23 October 2024. Corresponding surface ocean currents (shaded) and vectors for the same time are shown from (c) the HYCOM model forced with NCEP-GFS data & (d) the IOLA-HYCOM coupled model. The black line denotes the observed cyclone track from the IMD best-track data, while the red line the track predicted by respective models.

2.1.2.3 Maritime Incident Response and SARAT

During 24-29 May 2025, following the wreck of the Liberian container ship MSC ELSA 3 (75.7667°E, 9.5000°N), nurdle drift advisories were issued and teams were deployed for field observations along Kerala's coast (Fig. 2.1.7). Observations near Kollam and Thiruvananthapuram validated simulated drift patterns. A comparative study with MV X-Press Pearl (2021) drift showed 0% windage best matched actual observations. Estimated ecosystem impacts included 663 ha of coral reefs and 1,292 ha of mangroves.

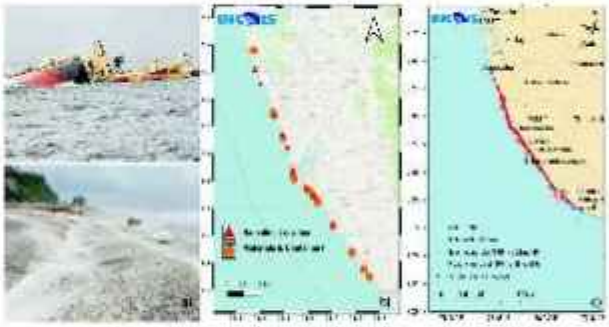


Fig. 2.1.7: (a) Wreckage of container ship MSC ELSA 3, (b) field sampling along the Kerala coast, and (c) validation of simulated plastic nurdle drift patterns.

On 09 June 2025, the Singapore-flagged vessel WAN HAI 503 caught fire, spilling containers and plastic nurdles. INCOIS deployed the Search and Rescue Aid Tool (SARAT) and Oil Spill and Object Search Application (OOSA) to generate probable drift trajectories and dispersion scenarios for both incidents.

SARAT predictions accurately identified beaching locations of drifting containers carrying hazardous materials along Alappuzha and Kollam coasts, confirmed through field surveys and reports, demonstrating its effectiveness in search and rescue operations and coastal hazard management.

2.1.2.4 High-Resolution Topography and Bathymetry

INCOIS developed a 250 m resolution topography and bathymetry dataset for the northern Indian

Ocean. Topography sources included Airborne Lidar Terrain Mapping (ALTM), Cartosat-1 DTM, and Copernicus, while bathymetry was compiled from NCPOR, NIOT, NHO, GSI, and GEBCO. These datasets were integrated into a seamless land-sea elevation model covering the Indian coastline and northern Indian Ocean. This high-resolution product underpins ocean circulation modelling, coastal inundation studies, and enhanced forecasting and risk assessment for marine and coastal environments.

2.1.3 Ocean Observation Network

2.1.3.1 In-Situ Observation Systems

INCOIS sustained and expanded its in-situ observation network across the Indian Ocean, deploying 31 Argo floats (temperature and salinity), 1 biogeochemical float, and 5 satellite-tracked drifters in the Arabian Sea. In collaboration with NIO-Goa, 17 coastal ADCPs and 3 equatorial current meter moorings were maintained, along with 3 Bay of Bengal XBT transects. The tide-gauge network was enhanced with 14 new stations and 15 co-located GNSS receivers, and a coastal water-quality mooring at Kochi remained operational. Plans are underway to install 25 upgraded AWS onboard vessels in 2025.

2.1.3.2 Wave-Rider Buoys and Geodetic Stations

As a new initiative, INCOIS deployed a wave-rider buoy in Mauritius to monitor Southern Ocean swells, increasing the operational wave-rider network to 17 platforms. INCOIS also established a network of 35 GNSS and Strong Motion Accelerometer (SMA) stations across the Andaman and Nicobar Islands. A new GNSS station was commissioned at East Island, bringing the total to 33 GNSS and 33 SMA stations currently installed and delivering real-time data.

2.1.3.3 Deployment of Gliders and Wave Drifters

Under the Deep Ocean Observing System (DOOS), 3 wave drifters were deployed near Antarctica (61.83°S, 0.96°E) during the 44th Indian Scientific Expedition to monitor Southern Ocean swells. A Slocum glider (Serial 1126) completed a two-month, 1,200 km mission at 66.53°S, 24.75°E down to 1,000 m, advancing India's polar observational capabilities.

2.1.3.4 Coastal Flood Monitoring Pilot

To improve forecasting of Kallakkadal flash floods, a pilot coastal flood monitoring system was established at Azhimala, Kerala, comprising 4 pressure sensors (3.5-9 m depth), a shore-based AWS, and a digital tide gauge. Meteorological and water-level data collected from March to May 2025 supports timely warnings, improves model accuracy, and aids risk mitigation for vulnerable coastal communities.

2.1.4 Ocean Modelling and Reanalysis

INCOIS advanced ocean modelling in the North Indian Ocean through machine learning and reanalysis-based products. An LSTM-based model forecasts daily averaged sea level anomaly (SLA) up to three days ahead across the North Indian Ocean. These SLA predictions derive surface geostrophic currents, augmented by Ekman components from NCMRWF wind forecasts, outperforming GLORYS hindcasts when validated against OSCAR products, OMNI moorings, and HF-RADAR data.

The INCOIS_TA product, generated using four decades of ship observations and reanalysis data, maps surface total alkalinity (TA) at 1/12° resolution, supporting biogeochemical model evaluation, identifying sub-regions of long-term TA changes driven by salinity, stratification, ENSO, and IOD, and enabling CMIP bias correction.

2.1.5 Ocean Technology

Ocean Technology related activities are mainly carried out by NIOT, Chennai.

2.1.5.1 Energy and Freshwater Technologies

The Ocean Thermal Energy Conversion (OTEC) powered desalination plant at Kavaratti, Lakshadweep has accomplished fabrication of major process equipment, including the flash chamber and condenser. The turbine rotor is dynamically balanced as per ISO 21940-11

standards, and civil works up to +11.8 m elevation are completed (Fig. 2.1.8). Architectural drawings for the OTEC plant building are prepared, and the Factory Acceptance Test (FAT) of electrical systems is successfully completed. Detailed simulation studies for the 3.8 km cold water pipeline installation have also been carried out.

Fig. 2.1.8: Dynamic balancing of the open cycle OTEC turbine rotor at Kavaratti, Lakshadweep.

NIOT has successfully deployed a customized wave-powered fairway buoy, funded by Kamarajar Port Ltd. (KPL), Chennai, enhancing navigation safety and enabling real-time environmental monitoring. The buoy collects oceanographic data (wave height, period, direction) and transmits it via IoT-based systems.

The Low Temperature Thermal Desalination (LTTD) Plant of 1.5 lakh Liters per day capacity at Chetlat Island UT Lakshadweep was inaugurated on 17th January 2025 (Fig. 2.1.9). The LTTD plant work is in progress at Androth Island.

Fig. 2.1.9 LTTD plant at Chetlat Island, UT Lakshadweep.

To harness renewable wind energy and to assess wind resources in the Lakshadweep Islands, A LiDAR-based offshore wind data collection instrument has been installed at Kadamat Island, and preliminary data analysis shows promising wind potential, especially during the monsoon season.

2.1.5.2 Coastal and Environmental Engineering

Shoreline Response Evaluation System (ShoRES) to predict shoreline evolution and plan shore protection schemes has been developed and a case study of Goa's coastline (excluding hilly terrain) showed 44.8 km eroding and 23.6 km accreting.

The Wave Atlas Version-2 has been released, utilizing 30 years of high-resolution wind data to simulate wind-generated waves in the North Indian Ocean, including islands. The numerical model studies has been completed for the sustainable river mouth opening of Puthuponnani river inlet, Kerala, recommending dredging of the mouth with post-implementation monitoring.

2.1.5.3 Marine Biotechnology

Large-scale culture of marine spirulina for production of C-phycocyanin was standardized and the technology was successfully transferred to M/s Varre Corporate Solutions, Andhra Pradesh. Completed pilot scale cultivation of Gracilaria edulis by tube net method and achieved maximum growth of 6.83 times with daily growth rate of 3.84% in 45-days (Fig. 2.1.10). Conducted 45 days hands on training on seaweed cultivation to Self Help Group (SHG) in A&N islands.

Fig. 2.1.10: Seaweed cultivation in open sea at Andaman and Nicobar Islands.

Technology for the production of dermo-pharmaceutically important Ectoine from bacteria, Bacillus clausii through recombinant technology was developed and transferred to Varee Ayustruct Ventures Pvt. Ltd., Vishakhapatnam, through NRDC. Nursery rearing of Asian seabass in open sea cages recorded a rapid increase in body weight from 0.3 g to 31.04 g over 90 days with 79.42% survival rate. Submersible cage and automated feeder were successfully deployed and tested at North Bay.

For ballast water testing as per IMO G8 guidelines, the required density of marine organism 10 to 50µm phytoplankton and zooplankton 50 µm *(Tetraselmis sp., Oscillatoria Skeletonemacostatum, Chaetoceros spp., Pseudonitzschia sp., Protoperidinium and Pseudodiaptomus annandalei, Apocyclopsdengizicus, Brachionusplicatilis and Onychocamptus bengalensis) are being cultured in Pamanji BWTT facility*

The design of the high-pressure retainable water sampler system (HPWS) consists of four 500 ml (600 bar pressure rated) high-pressure retainable bottles fitted in the conventional CTD carousel with eight Niskin water bottles for simultaneous collection of large volume pressurised and non-pressurised sample from the deep sea.

2.1.5.4 Marine Sensor Systems and Ocean Electronics

Indigenous Deep Sea Argo (DAUPD) floats for 2000 m and 4000 m profiles have been developed (Fig. 2.1.11) and tested, with sea-trial deployments planned shortly. Additionally, a wave-powered vertical Profiler has been completed, with laboratory tests finished and field trials scheduled off Chennai.

Fig. 2.1.11: Deep Sea Autonomous Underwater Profiling Float (DAUPD - 2000/4000 m).

2.1.5.5 Ocean Acoustics

An indigenous Underwater Acoustic Telephone (UAT) (Fig. 2.1.12 a) for manned submersibles, has been successfully demonstrated in open ocean up to 500 m depth and has undergone horizontal range testing up to 5500 m at Idukki Lake. The UAT will be integrated as part of the manned submersible in the forthcoming sea trials.

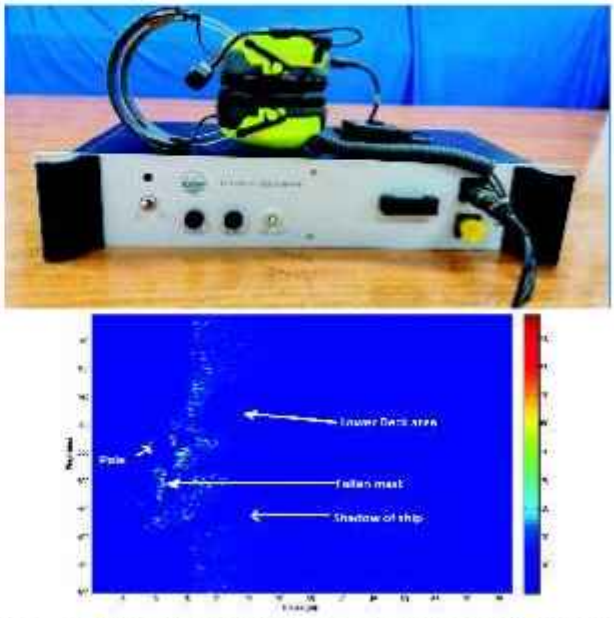


Fig. 2.1.12: (a) Underwater Acoustic Telephone (UAT); (b) Underwater Side Scan Sonar image of a shipwreck.

As part of the Side Scan Sonar development for 2D imaging of the seabed and submerged objects, 2D image of a shipwreck was captured (Fig. 2.1.12b) during sea trials, thereby fostering indigenous capabilities in oceanographic surveys.

Deep-Water Ambient Noise Measurement System (DANMS), accrued data from the Laccadive Sea has revealed changes in underwater soundscape during the pandemic period, highlighting the impact of reduced shipping traffic on marine life. As part of the International Arctic Expedition 2025, one month field experiment for sea ice monitoring in an Arctic Fjord, Svalbard towards acoustic based estimation (Fig. 2.1.13) of sea ice and glacier in the proximity of a marine terminating glacier was carried out during July 2025 to capture the melting and calving activities during summer season. The Vector Sensor Array system is being enhanced for coastal surveillance, with successful experiments demonstrating its effectiveness in tracking ship movement.

Fig. 2.1.13: Acoustic measurements at the Arctic Fjord region, Svalbard, during the International Arctic Expedition 2025.

2.1.5.6 Ocean Observation System and Research Vessels

The array of moored buoys network that continuously capture essential ocean-atmosphere parameters, including during severe cyclonic conditions is maintained. The network comprises 12 deep-ocean OMNI buoys, 3 coastal buoys, 1 CAL-VAL buoy, and 4 Tsunami buoys, all transmitting data to INCOIS in near real time.

These buoys have successfully recorded critical observations during recent severe cyclonic storms, including (Cyclones Montha and Shakti), providing valuable inputs for weather forecasting, ocean state prediction, and disaster management.

The Indigenous Tsunami buoy systems (TB09, TB06 and TB05) successfully triggered the alarm mode for the recent earthquake that occurred in Myanmar on 28th March 2025.

Indian Coastal Ocean Radar Network (ICORN) comprising of 10 HF radars are maintained. As part of upgradation, Telemetry upgrades via V-SAT have been successfully completed at the Kalpakkam and Cuddalore sites and Radial Suite from R22 to R23 was also completed for four sites including NIOT central sites.

The Ministry's six research vessels-Sagar Nidhi, Sagar Manjusha, Sagar Tara, Sagar Anveshika, Sagar Sampada, and Sagar Kanya-were operated and maintained for scientific cruises.

2.1.6 Ocean Surveys and Mineral Resources

2.1.6.1 Geoscientific Studies

A brainstorming session on Marine Geological Studies in the Indian Exclusive Economic Zone (EEZ) was conducted at NCPOR on August 14, 2025, to explore and establish collaborative initiatives aimed at fostering advanced scientific research, thereby maximizing the utility of archived sediment samples and strengthening future research directions. A report was prepared for the first time, the identification of a large-scale submarine landslide complex off Quilon, Kerala, using high-resolution bathymetric data. Twelve proposals for naming the undersea features (identified within the Indian EEZ) were submitted to NHO for further action and submission to the SCUFN committee (Fig. 2.1.14). Analysis of bathymetric data from the Andaman fore-arc region was carried out to understand the characteristics and regional variations of the accretionary prism. Identified and analysed the morphology of a seamount in the eastern Arabian Sea. Isostasy of the seamount was studied using high-resolution bathymetry and satellite free-air anomaly data. The presence of one of the world's largest deeply carved submarine channel-levee systems and its detailed geomorphological features present in the Indus River watershed of the Arabian sea has been revealed.

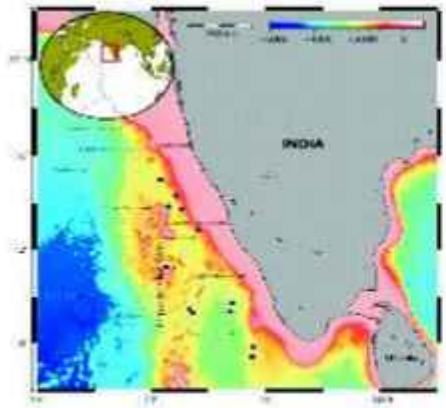


Fig. 2.1.14: GEBCO bathymetric map of the western continental margin showing the locations of undersea features proposed for SCUFN naming.

2.1.6.2 Polymetallic Nodules Program

Two close-grid nodule sampling expeditions were undertaken at 6.25 km grid intervals in the Revised First Generation Minesite (RFGM) of the Indian Contract area in the Central Indian Ocean basin covering 62 stations. The abundance and richness of nodules was calculated in the sampled areas and RFGM. A sampling expedition also was conducted from September to November, 2025, onboard the CSIR-NIO research vessel, RV Sindhu Sadhana for characterising seafloor habitat and nodule-associated living forms, alongside concurrent observations of key environmental attributes (water-column and near-bottom conditions).

The reductive acid leaching process was finalised following the establishment of iron removal process and manganese separation through solvent extraction to minimise the loss of targeted metal values. The finalized process was tested at bench scale (Fig. 2.1.15) to validate the recoveries and minimize the metal losses below 3% while achieving metal product purity of 99.9% Cu, Ni, or Co. Subsequently, the pilot scale validation of the finalized reductive acid leaching process is being focused. Another process based on gaseous reduction-melting route was developed and the Cu-Ni-Co-Fe alloy generated with an average metallization of 90% or higher was converted to matte for its subsequent downstream processing to recover Cu, Ni and Co.

Fig. 2.1.15: Processing of polymetallic nodules for the recovery of Cu, Ni, Co, and Mn at CSIR-IMMT, Bhubaneswar.

2.1.7 Marine Living Resources (CMLRE)

Under O-SMART, the study and sustainable management of marine living resources and coastal ecosystems are undertaken jointly by CMLRE and NCCR. These activities support India's Blue Economy, contribute to the UN SDG-14 (Life Below Water), and provide scientific inputs for marine spatial planning, ecosystem conservation, fisheries management, and coastal resilience.

2.1.7.1 FORV Sagar Sampada: Platform for Integrated Research

The FORV Sagar Sampada continued to be a cornerstone for multidisciplinary research in 2025, supporting eight cruises spanning 183 days across the Arabian Sea and Bay of Bengal. These cruises enabled:

- Studies on ocean acidification from CO_2 absorption and submarine groundwater discharge (SS413, in collaboration with NIO-RC Visakhapatnam)

- Hydrographic characterisation of Wadge Bank, influencing plankton productivity and food webs
- Mesopelagic plankton and fish assessments and EK-80 echosounder calibration
- Ocean Bottom Seismometer retrieval from the central Indian Ocean
- Biodiversity mapping of Lakshadweep Sea seamounts

Notably, SS420 (August-September 2025) engaged nine national institutes, yielding key observations such as fish eggs and larvae in the western Bay of Bengal, demonstrating CMLRE's leadership in integrated ecosystem research (Fig. 2.1.16).

Fig. 2.1.16. Highlights from Cruise 420: (a) Participants from CMLRE, NIOT, and various universities; (b) Pre-cruise briefing with Head of CMLRE, Chief Scientist, and Ship Captain; (c) Scientist demonstrating benthic organism sorting from deep-sea sediments; (d) Celebration of Onam festival onboard during sampling activities.

2.1.7.2 Microzooplankton and Biodiversity Insights

Time-series monitoring in the Eastern Arabian Sea revealed novel insights into microzooplankton diversity, including the first Indian Ocean record of the *tintinnid ciliate Codonaria cistellula,* previously reported only from the Mediterranean, Atlantic, and western tropical Pacific. Two distinct morphotypes were observed in the northeastern region, exhibiting lorica polymorphism despite consistent lorica opening diameters, highlighting the need for genetic validation.

The study also documented the poorly known species *Wangiella dicollaria* and *Stenosemella parvicollis* from neritic waters. Scanning Electron Microscopy (SEM) revealed lorica features suggesting that *S. parvicollis* may belong to the genus Wangiella. These findings extend the biogeographic ranges of tintinnids and underscore the importance of integrated morphological, cytological, and molecular approaches to resolve the diversity of these ecologically significant microorganisms (Fig. 2.1.17).

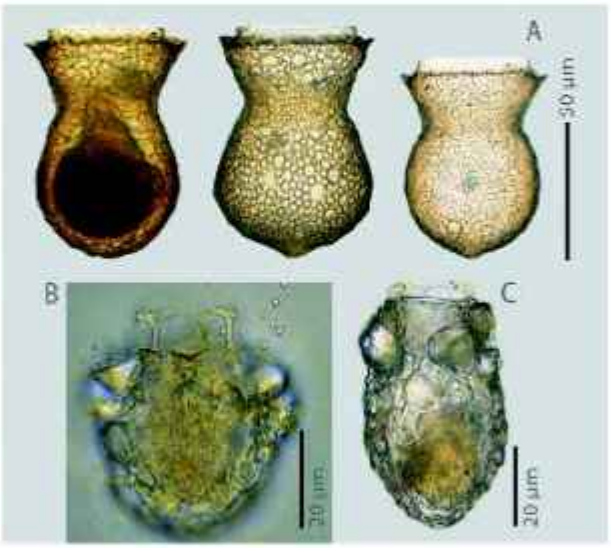


Fig. 2.1.17: Microzooplankton observed in the Eastern Arabian Sea: *(a) Codonaria cistellula; (b) Wangiella dicollaria; (c) Stenosemella parvicollis.*

2.1.7.3 Biodiversity Documentation, Taxonomy, and Repository Development

In 2024, CMLRE released the Compendium of New Marine Faunal Discoveries (2012-2024) in the Indian EEZ and High Seas, documenting 47 new species and 93 new geographical records of deep-sea organisms. The compendium, featuring high-resolution images and distribution maps, provides a critical reference for species identification and

regional biodiversity assessments. Complementing this, the Deep-sea Anguilliformes of Indian EEZ: An Identification Guide details 49 deep-sea eel species, including diagnostic morphological features, taxonomic keys, and distribution data, serving as a valuable resource for researchers and marine resource managers.

CMLRE has further advanced marine taxonomy through the development of approximately 100 integrated species profiles, combining classical morphological taxonomy with DNA barcoding to establish a comprehensive reference library for biodiversity and ecological research. Recognising these efforts, the National Biodiversity Authority provisionally approved CMLRE's Referral Centre as a Designated National Repository for deep-sea organisms. Named 'Bhavasagara', the repository currently houses around 4,000 voucher specimens from the Indian EEZ and adjacent high seas, including rare and unique deep-sea species, supporting both scientific research and outreach initiatives (Fig. 2.1.18).

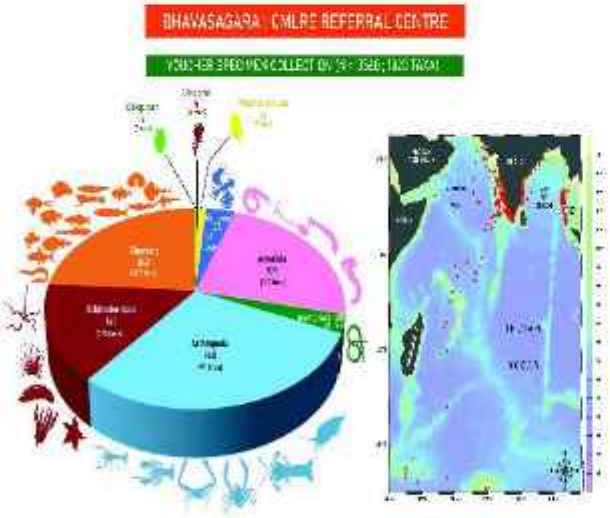


Fig. 2.1.18: Distribution of voucher specimen collection from various regions across the Indian Ocean.

2.1.7.4 Species Discovery, Spawning Dynamics, and Otolith-Based Modelling

Unexplored biodiversity in the Arabian Sea continues to yield significant discoveries. Scientists from the Fisheries Resources and Habitat Assessment (FRHA) team at CMLRE confirmed the first record of *Parascorpaena mcadamsi* in this region. Integrating morphological characterisation and mitochondrial COI gene analysis, the species identity was validated, extending its known distribution from the Indo-West Pacific to the northern Indian Ocean (Fig. 2.1.19).

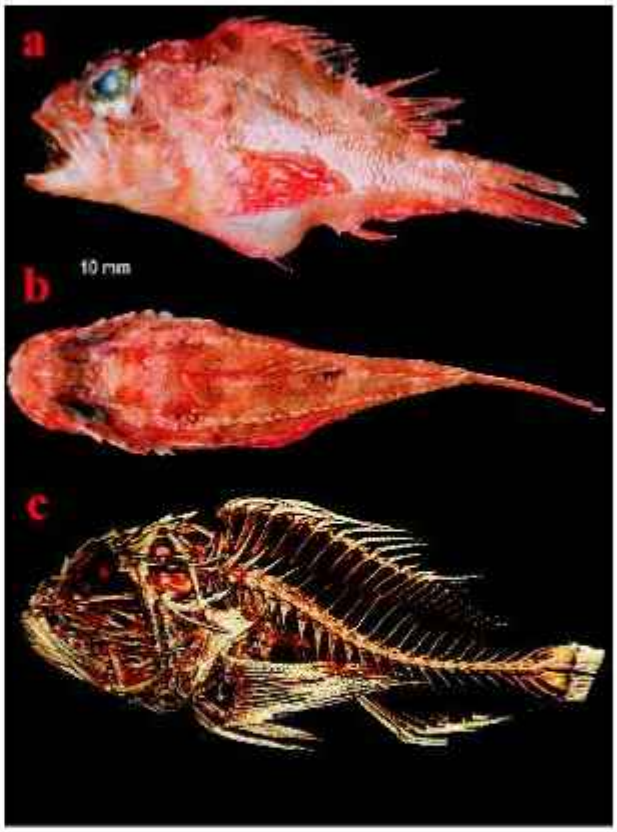


Fig. 2.1.19: *Parascorpaena mcadamsi* from the Arabian Sea: (a) lateral view of freshly caught specimen, (b) dorsal view, (c) micro-CT scan highlighting internal morphology.

Species-specific numerical models were developed to establish relationships between otolith morphometrics and fish size for ten deep-sea scorpaenoid and dactylopterid species. Analysis of 567 right sagittal otoliths from commercial deep-sea shrimp trawl bycatch showed strong correlations (r^2 = 0.96), demonstrating reliable fish size estimation from otoliths, valuable for dietary, paleoecological, and population assessments (Fig. 2.1.20).

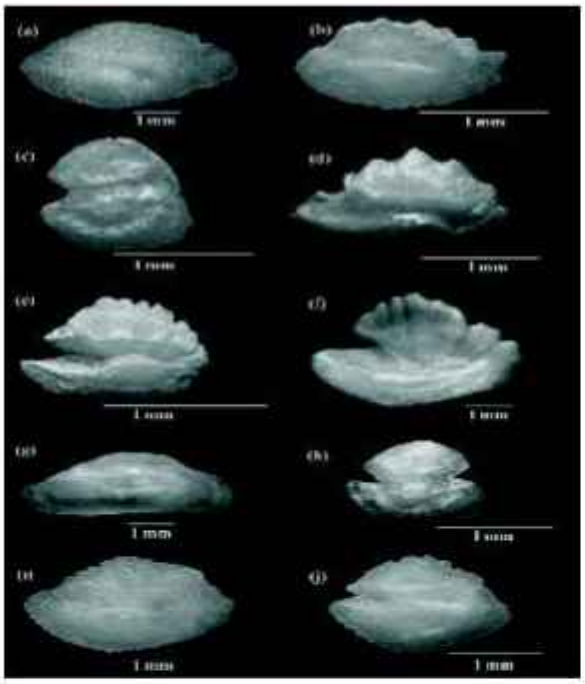


Fig. 2.1.20. Representative otoliths of deep-sea scorpaenoid and dactylopterid fishes from the southeastern Arabian Sea: (a) Snyderina guentheri, (b) *Minous inermis*, (c) *Pterygotrigla arabica*, (d) *Dactyloptena orientalis*, (e) *Dactyloptena papilio*, (f) *Setarches guentheri*, (g) *Grammoplites suppositus*, (h) *Pterygotrigla macrorhynchus*, (i) *Neomerinthe erostris*.

Year-round ichthyoplankton studies revealed that fish eggs and larvae are present throughout the year, with spatial and temporal shifts in spawning grounds linked to monsoon cycles, upwelling, and ocean mixing. Over 100 fish species' spawning grounds were mapped using combined morphological and DNA-based techniques, providing crucial information for ecosystem protection and sustainable fisheries management.

2.1.7.5 Population and Biomass Assessment Using Acoustic Methods

Advanced sound-based instruments were deployed to map the abundance and distribution of marine organisms in the eastern Arabian Sea. Ship-mounted acoustic measurements, combined with direct plankton sampling, allowed accurate estimation of living biomass, particularly of near-surface fish larvae. Observed *diel vertical migration* patterns showed organisms rising at dusk and sinking at dawn.

Deep scattering layers were quantified using specialized echosounders and mid-water nets during surveys aboard FORV Sagar Sampada, covering multiple stations across the eastern Arabian Sea. Biomass was found to vary substantially with seasonal and local oceanographic conditions, providing insights into ecosystem structure and dynamics (Fig. 2.1.21). These integrated acoustic and sampling approaches strengthen ecosystem monitoring capabilities, support fisheries assessment, and inform spatial management of marine resources.

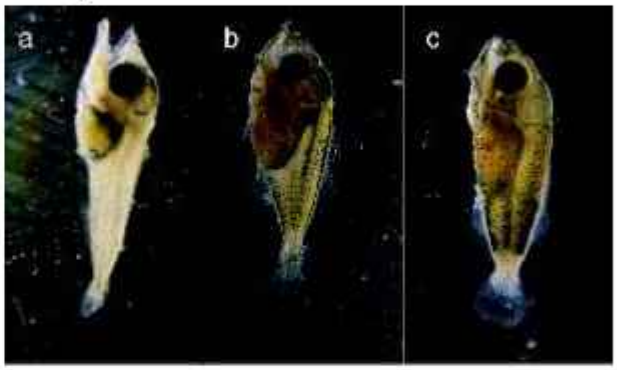


Fig. 2.1.21: Fish larvae of some economically important fishes in the eastern Arabian Sea: (a) *Decapterus russelli*, (b) *Scomberoides* tol, (c) *Thunnus albacares*.

2.1.7.6 Fishery Yield Assessment

Scientists have reassessed the fishery potential of India's vast Exclusive Economic Zone (EEZ), which covers about 2.03 million square kilometres of ocean. The updated estimate combines production from open-ocean (pelagic) ecosystems and the seafloor (benthic) environment, using well-established food-web relationships to understand how energy moves from microscopic plants to fish. India's EEZ potential fishery yield integrated pelagic production (5.13 mt primary, 4.14 mt secondary) and benthic inputs (1.08 mt) using trophic efficiencies (5.7-29.5% primary-secondary; 1-10% secondary-tertiary).

Based on this integrated approach, the study estimates that India's seas can sustainably support a fish harvest of about 5.72 million tonnes per year. A large share of this potential comes from deep-sea fishes, especially lanternfishes (myctophids), which alone account for around 4.2 million tonnes of biomass. The findings provide a more realistic and ecosystem-based picture of India's marine fishery resources and was submitted to the Ministry of Fisheries to support long-term, sustainable management of ocean resources.

2.1.7.7 Marine Ornamental Fish Propagation

As part of efforts to support coastal communities and promote sustainable livelihoods, CMLRE established a pilot Recirculating Aquaculture System (RAS) in Kochi to breed high-value ornamental clownfish in a controlled, eco-friendly environment. The facility uses synthetic seawater with regulated temperature and water conditions, complemented by an algae laboratory producing live feed for larvae. The system ensures continuous breeding while reducing dependence on wild fish populations.

Breeding stock sourced from Lakshadweep and the Gulf of Mannar demonstrated regular spawning, and scientists developed reliable methods for egg hatching, larval rearing, and productivity monitoring. Innovative tools, such as a light-based larval trap and AI-assisted egg counting, improved efficiency and reduced manual effort. On 15 August 2025, the first batch of hatchery-reared clownfish was distributed during a beneficiary induction programme, accompanied by hands-on training for coastal communities (Fig. 2.1.22).

Early estimates indicate that a facility producing one million juvenile fish annually could support approximately 400 families, each earning around Rs.2.5 lakh per year. Looking ahead, plans include establishing a centralised production hub, expanding live-feed culture, incorporating greater automation, and diversifying into additional ornamental fish species. These efforts aim to position India as a sustainable supplier in the global marine ornamental fish trade, while protecting ocean ecosystems and strengthening coastal livelihoods.

Fig. 2.1.22: Marine ornamental fish propagation facility and clownfish breeding activities at CMLRE, Kochi.

2.1.8 Coastal Research and Management (NCCR)

The National Centre for Coastal Research (NCCR) conducts multi-disciplinary research on marine and coastal pollution, coastal processes and hazards, and coastal habitats and ecosystems. It provides scientific and technical support for sustainable management of coastal areas and contributes to global and national initiatives such as the UN SDG-14, the UN Decade of Ocean Science for Sustainable Development (2021-2030), and the Sendai Framework for Disaster Risk Reduction (2015-2030). As part of India's Blue Economy strategy, NCCR plays a pivotal role in Marine Spatial Planning (MSP) under the Indo-Norway International Ocean Management and Research Initiative, providing expertise to optimise coastal and marine resource utilisation.

2.1.8.1 Coastal Pollution: Monitoring, Modelling, and Mitigation (CoP: 3M)

The Seawater Quality Monitoring (SWQM) programme tracks water quality at 50 locations along the Indian coastline, generating multi-parameter datasets that support national initiatives, including the SDG-14 Index by NITI Aayog and MoSPI. Pollution surveillance was strengthened using sewage- and wastewater-derived chemical markers, especially quaternary ammonium compounds (QACs). An action plan for coastal pollution mitigation was prepared for the Puducherry Pollution Control Committee. Notably, a rare mass swarming of *Loimia medusa* was observed after 58 years, linked to productivity enhancement by mesoscale cold-core eddies (Fig. 2.1.23A).

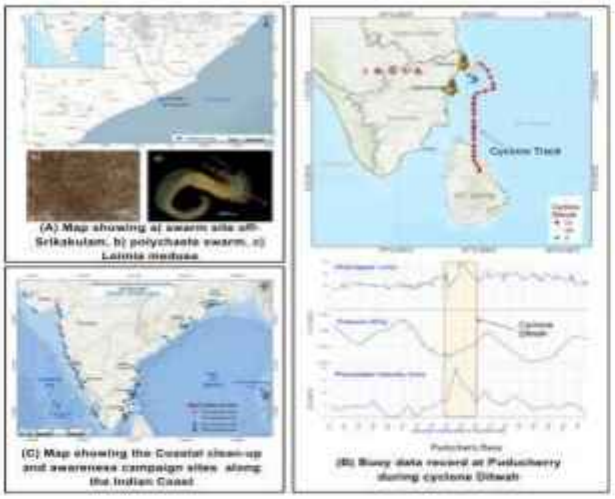


Fig. 2.1.23: Maps showing various activities carried out under the CoP:3M Programme.

Three automated water quality buoys along the east coast, integrated with numerical models, remained operational for over 320 days. During Cyclone Ditwah, the Puducherry and Chennai buoys recorded extreme winds (56-66 km/h), rainfall (138-143 mm), and short-term variability in temperature and salinity (Fig. 2.1.23B).

Ecological and human health risk assessments in the Netravati and Cochin estuaries and Vembanad Lake identified cadmium and zinc as priority contaminants, supported by sediment toxicity bioassays and Adverse Outcome Pathway (AOP) modelling. National marine litter and microplastics monitoring were enhanced through systematic surveys, source-pathway-sink analyses, and rapid-response investigations. Since 2018, over 250 coastal cleanup events, including 46 beaches in 2025, removed more than 150 tonnes of litter, generating harmonised datasets that informed the National Marine Litter Policy (Fig. 2.1.23C).

2.1.8.2 Coastal Processes and Hazards

Comprehensive Shoreline Management Plans (SMPs) were prepared for Tamil Nadu, Kerala, Puducherry, and Andhra Pradesh, integrating scientific analyses, socio-economic considerations, and stakeholder inputs. NCCR continues to provide technical support to multiple coastal states for shoreline monitoring, erosion assessment, and coastal protection planning (Fig. 2.1.24). Detailed sea-level rise impact assessments and resilience recommendations were provided for Willingdon Island, Kochi. A baseline report on Rehabilitation of Coastal Bio-shields and a 1:25,000-scale Atlas of Coastal Puducherry Bio-shields (ABC-P) were submitted to the Government of Puducherry.

The real-time flood early warning system (IFLOWS) was operational in Chennai, Mumbai, and Kolkata, providing high-resolution inundation forecasts during Cyclone Ditwah and other major rainfall events. Chennai's coverage area expanded from 426 sq. km to 8,045 sq. km, enhancing urban flood preparedness.

Fig. 2.1.24: Coastal erosion assessment study carried out at Eden Beach, Puducherry.

2.1.8.3 Coastal Habitats and Ecosystem

Field studies assessed reef and seagrass habitats across Lakshadweep, Andaman Islands, Palk Bay, and the Gulf of Kachchh, documenting the impacts of the Global Coral Reef Bleaching Event (2024-25). Observations included bleaching extent, coral recovery, reef and seagrass biodiversity, lunar-linked spawning behaviour, and ecosystem resilience. Advanced remote sensing, in-situ experiments, and long-term monitoring revealed spatial variations in reef health, successful restoration outcomes, and changes in seagrass density.

A comprehensive ecosystem services and ocean accounting assessment of Coringa mangroves, using CICES and SEEA frameworks, established it as a national pilot site. The study quantified livelihoods, blue carbon stocks, biodiversity, and nursery functions, demonstrating enhanced carbon and nutrient accumulation following restoration and highlighting mangroves' role in coastal protection and fisheries support.

2.1.8.4 Marine Spatial Planning

The India-Norway Collaboration on Marine Spatial

Planning (MSP) achieved significant progress through coordinated scientific, technical, and outreach activities. A dedicated side event at the third UN Ocean Conference (UNOC-3) in Nice, France, attended by Hon'ble Minister of Earth Sciences and the Crown Prince of Norway, enhanced the international visibility of India's MSP initiatives and partnership outcomes (Fig. 2.1.25).

A week-long community interaction in Palk Bay, conducted in collaboration with NIVA and the OMCAR Foundation, supported the development of guidelines for seagrass restoration, incorporating fisher community inputs on restoration methods, site selection, and monitoring frameworks for integration into MSP.

Additionally, a three-day workshop on Benthic Habitat Mapping and Modelling held in Chennai, in collaboration with IMR, Norway, strengthened capacity in seafloor mapping, habitat classification, and predictive modelling, enhancing scientific support for MSP implementation.

Fig. 2.1.25: Glimpse of the side event on Marine Spatial Planning at UNOC-3, Nice, France.

2.1.8.5 Consultancy Projects

For the Kalpasar Project, NCCR prepared and submitted a Detailed Project Report (DPR) to the Government of Gujarat, following technical, environmental, socio-economic, and engineering assessments. The DPR proposes a 60-km sea dyke, flood regulator, transport corridor, and renewable energy facilities, supported by a web-GIS-based Decision Support System and a Digital DPR for statutory clearances (Fig. 2.1.26).

Fig. 2.1.26: Preparation of DPR for the Kalpasar Dyke project across Gulf of Khambhat, Gujarat.

2.1.8.6 Outreach and Capacity Building

The Ministry, through its institutions, continues to strengthen national and regional capacity in ocean observation, hazard preparedness, and coastal ecosystem management. Three Conclaves on Marine Multi-Hazard Services (Aug-Sep 2025) with over 500 stakeholders were conducted. The IOWave25 tsunami exercises included community-level mock drills on the West Coast and in the Andaman & Nicobar Islands. Fifteen user-interaction workshops and 20 ITCOocean training programmes trained 644 participants from India and other Indian Ocean countries, alongside on-job training for Oman officials. International workshops, including DBCP and TEMPP/TRRP, and EKAMSAT 2025 trained early-career researchers in ocean processes, data analysis, and scientific communication. INCOIS also hosted 4,813 students and supervised 109 academic projects, promoting ocean literacy and research skills.

NCCR complemented these efforts through school outreach on National Science Day and the 'Plastic Odyssey' initiative on ocean plastic pollution. These efforts collectively showcase the Ministry's commitment to capacity building, stakeholder engagement, and enhancing societal resilience for sustainable coastal and marine management.

Chapter-2.2

Polar and Cryosphere Research (PACER)

PACER sub-scheme under PRITHVI represents India's scientific endeavour to understand and monitor the Earth's polar regions and cryosphere. Implemented by the National Centre for Polar and Ocean Research (NCPOR), an autonomous R&D institution under the Ministry, PACER coordinates and executes India's Antarctic, Arctic, Southern Ocean, and Himalayan cryosphere research programmes. NCPOR maintains India's permanent research stations in Antarctica (Maitri and Bharati) and the Arctic (Himadri), and supports Himalayan cryosphere observations. This chapter highlights key achievements that reflect India's growing capacity and commitment to polar and cryosphere science.

2.2.1. Scientific Studies in Antarctica

2.2.1.1. Fieldwork Activities

A. Geophysical survey of Nivlisen Ice Shelf

"SENS- Survey of East Antarctic Nivl Ice Shelf", a collaborative project between the NCPOR and Norwegian scientists, mapped the Nivlisen Ice Shelf in Dronning Maud Land using hovercraft-based seismic and radar surveys. An active seismic system comprising a sledge-mounted airgun and a geophone array, was deployed by a three-person field team, which collected more than 580 km of radar data and approximately 130 km of seismic profiles beneath the ice shelf (Fig. 2.2.1). Field operations were coordinated with the Dronning Maud Land-RINGS-DML airborne gravity surveys.

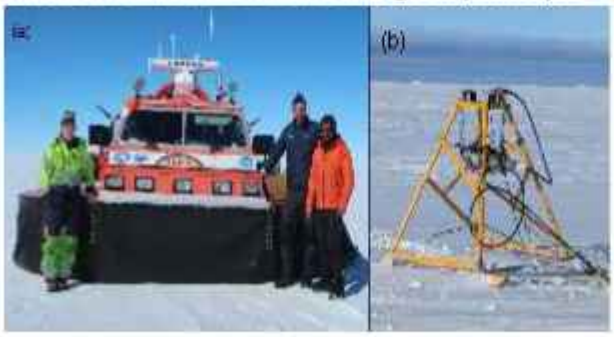


Fig. 2.2.1: (a) SENS field team in front of the hovercraft and (b) Seismic airgun-sledge setup.

B. Firn-core drilling and shallow radar survey

A research team travelled approximately 200 km inland into Princess Elizabeth Land from Bharati Station to investigate spatial variability in snow accumulation and associated climate signals. Seven firn cores, each 8-12 m deep, were recovered along a 60 km survey transect. The field campaign integrated shallow ice-penetrating radar surveys with GNSS measurements to constrain accumulation patterns and surface elevation changes (Fig. 2.2.2).

Fig. 2.2.2: Field team after a successful shallow-firn coring.

C. Environmental Impact Assessment

Extensive environmental monitoring was carried out in the vicinity of Maitri and Bharati Stations as part of ongoing EIA (Fig. 2.2.3). Soil samples from 34 sites, lake water samples from 40 lakes, along with sediment cores, permafrost samples, and moss specimens, were collected to evaluate emerging pollutants, toxic metals, and microbiological parameters. In addition, the Gas & Oil sewage treatment plant was inspected to verify operational compliance and the environmental safeguards.

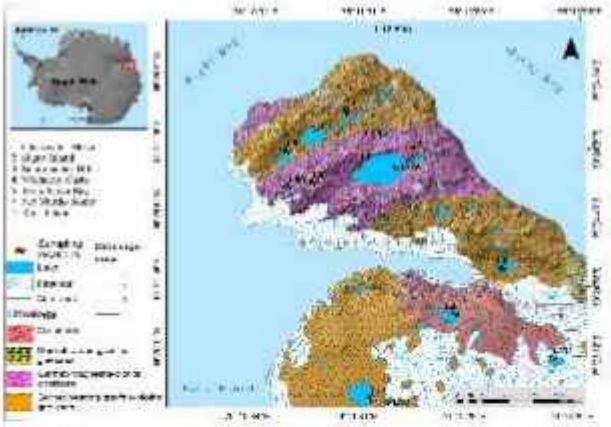


Fig. 2.2.3: EIA Sampling locations around Bharati Stations.

D. STAPLES: Spatio-Temporal Investigation of Polar Lacustrine Systems

The first international field campaign of the STAPLES (Spatio-Temporal Investigation of Polar Lacustrine Systems) project was conducted in the Larsemann Hills and comprised a 50-day expedition involving researchers from India, Belgium, and Japan. The campaign included the collection of sediment cores and water column profiles, as well as drone-based bathymetric surveys, to investigate past climate evolution and ecosystem resilience.

2.2.1.2. Dramatic rise in anthropogenic copper deposition since the mid-1980s

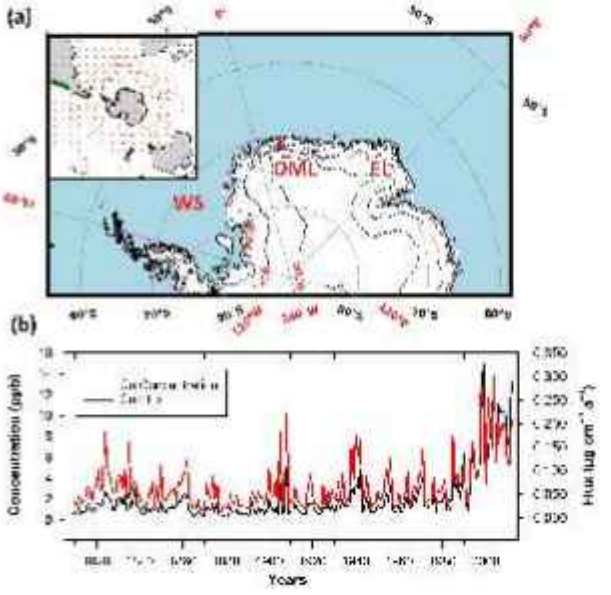


Fig. 2.2.4: (a) Study area in the central DML with ice core location marked as red star. Other regions marked as EL-Enderby Land and WS-Weddell Sea. (b) The flux of copper in the core IND33 from coastal Dronning Maud Land, East Antarctica from 1809-2012.

An ice-core record from central coastal Dronning Maud Land reveals a pronounced increase in atmospheric copper deposition beginning in the 1940s, followed by a sharp doubling after approximately 1985. This trend corresponds with increased copper production in Chile and with large-scale atmospheric circulation modes, particularly the El Niño-Southern Oscillation (ENSO) and the Southern Annular Mode (SAM), that facilitate long-range transport of aerosols to East Antarctica (Fig. 2.2.4). These findings underscore the growing influence of anthropogenic metal emissions on Antarctic environments and highlight the potential ecological risks associated with copper toxicity.

2.2.1.3. Mapping katabatic and foehn winds in Dronning Maud Land

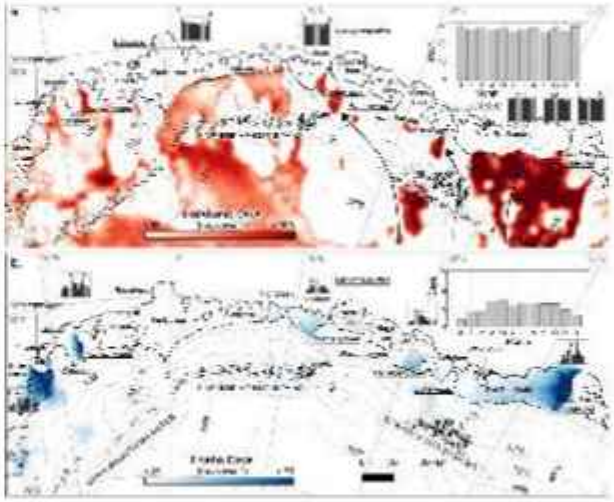


Fig. 2.2.5: Spatial and seasonal distribution of katabatic (a) and foehn (b) winds over Dronning Maud Land, expressed as days per year and derived from daily MAR model outputs (2014-2021). Insets illustrate the monthly occurrence of these wind regimes at five selected ice-shelf locations, with initials marking the two peak months; the top-right inset shows the mean annual frequency.

A high-resolution modelling study using the Modèle Atmosphérique Régional (MAR) regional climate

model, for the first time, enabled detailed mapping of the spatial and seasonal distribution of katabatic and foehn winds across Dronning Maud Land (Fig. 2.2.5). The results demonstrate that both wind regimes exert a strong control on the surface energy balance, leading to localized warming, firn densification, and enhanced surface melting. Their combined influence promotes supraglacial ponding during summer and preconditions the snow surface for increased melt in subsequent seasons.

2.2.1.4. Reconstruction of West Antarctic Ice History

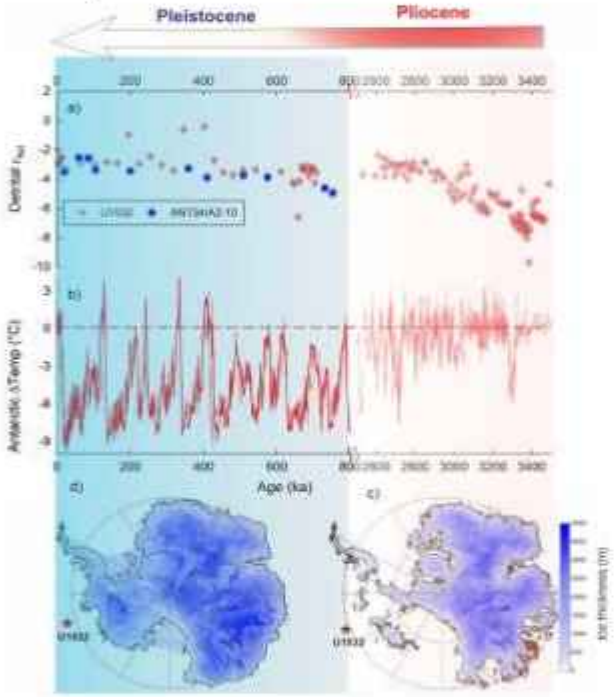


Fig. 2.2.6: Evolution of the West Antarctic Ice Sheet (WAIS) from the Pliocene to the Pleistocene based on proxy records and model simulations. (a) Detrital neodymium isotope (Nd) records from IODP Site U1532 (this study) and core ANT34/A2-10, indicating changes in sediment sources and ice-sheet drainage in the Amundsen Sea sector; (b) Antarctic temperature anomalies; and (c-d) numerical model reconstructions showing ice-sheet thickness and extent during the Pliocene (c) and Pleistocene (d), highlighting the transition from a smaller, dynamic WAIS to a thicker, more stable configuration. The red star marks the location of IODP Site U1532.

Understanding past Antarctic ice-sheet behaviour is essential for improving projections of future sea-level rise. New neodymium (Nd) isotope records from International Ocean Discovery Program (IODP) Site U1532 in the Amundsen Sea provide critical constraints on the evolution of the West Antarctic Ice Sheet (WAIS) across the late Pliocene-Pleistocene transition. The records indicate a shift from a smaller, more dynamic WAIS during the Pliocene to a larger and more stable configuration resembling its modern extent in the Pleistocene (Fig. 2.2.6). These findings identify a key tipping point in ice-sheet growth, marking the establishment of the modern WAIS during the Plio-Pleistocene transition and offering important insights into its potential stability under continued climatic warming.

2.2.1.5. Operations and Management of Indian Antarctic Stations

The 45th Indian Scientific Expedition to Antarctica (ISEA) was launched in multiple batches, with 57 of the planned 110 expedition members safely inducted to Maitri and Bharati stations via the Dronning Maud Land Air Network (DROMLAN). Fuel requirements for the expedition were secured through a collaborative agreement between NCPOR and HPCL Green R&D Centre, supporting efforts to reduce emissions and enhance the use of cleaner energy solutions. The annual resupply vessel departed Cape Town on 25 December 2025. A major operational milestone was achieved with the launch of a direct air cargo flight from Manohar International Airport, Mopa (GOX), to Antarctica, transporting 18 tonnes of essential supplies.

NCPOR continued to play a leadership role in international Antarctic logistics and governance through active participation in the Council of Managers of National Antarctic Programs (COMNAP) and DROMLAN. NCPOR also partnered with the SCAR-RINGS project. In addition, cargo and fuel support was extended to the Belgian Antarctic Programme, the DROMLAN air operator (Ultima Antarctic Logistics), and the Japanese Antarctic Research Expeditions, reinforcing India's role as a reliable partner in Antarctic operations.

2.2.2. Southern Ocean Studies

2.2.2.1. The 12th Indian Scientific Expedition to the Southern Ocean (ISESO)-2025

The 12th Indian Scientific Expedition to the Southern Ocean (ISESO-2025) was conducted aboard SA Agulhas from 12 February to 28 March 2025, sailing from and returning to Port Louis, Mauritius (Fig. 2.2.7). The expedition involved 42 participants from 12 Indian institutions, including 15 women scientists and four technical staff, and covered both coastal and open-ocean regions. Fourteen multidisciplinary stations and 13 Conductivity-Temperature-Depth (CTD) stations were occupied in coastal and frontal zones. Expendable XCTDs were deployed at ~1° intervals along the cruise track to characterise water masses and ocean fronts in the Indian sector of the Southern Ocean. Under the Indian Argo Programme, nine Argo floats were deployed, along with concurrent atmospheric observations.

Fig. 2.2.7: Scientific team of ISESO-2025

2.2.2.2. Participation in 2nd Antarctic Circumnavigation Expedition (ICCE)

Seven Indian researchers participated in the 2nd Antarctic Circumnavigation Expedition (ICCE), joining over 60 scientists from BRICS countries and South American nations (Fig. 2.2.8). The 70-day expedition aboard Akademik Tryoshnikov focused on integrated studies of Antarctic coastal biological, chemical, physical, glaciological, and atmospheric systems. Data and samples collected during the expedition will support assessments of coastal ecosystem functioning, past climate variability, and future environmental responses to climate change.

Fig. 2.2.8: Indian scientific team participating in the 2nd ICCE.

2.2.2.3. Maintenance of PRAISE Observatory

Under the PRAISE (Prydz Bay Air-Sea-Ice Exchange) winter observatory programme, the 44th ISEA winter team successfully deployed ice-tethered oceanographic moorings in Quilty Bay near Bharati Station in August 2025. The mooring system comprises five CTD sensors and four current meters spanning 150 m of the water column. In addition, a new sea-ice meteorological tower equipped with four-component radiometers and sensors for wind, temperature, pressure, humidity, and rainfall was installed. These observations strengthen long-term monitoring of air-ice-sea interactions in the landfast ice zone of Prydz Bay, East Antarctica.

2.2.2.4. Underwater Robotic Systems for Ocean Observation in the Indian Antarctic Program

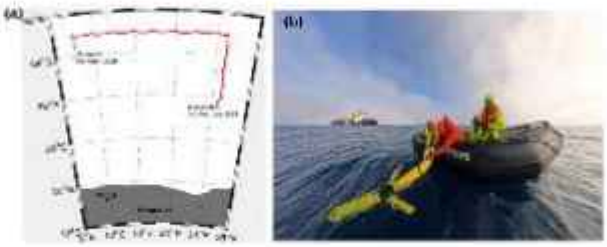


Fig. 2.2.9: (a) Glider (1126) transects during ISEA44 and (b) Glider deployment from Vasiliy Golovnin.

Underwater robotic platforms have become an important component of the Indian Antarctic Program's ocean observation capabilities. On 3 February 2025, NCPOR and INCOIS scientists deployed a Slocum G3 underwater glider (Sr. No. 1126) at 66°31.875S, 24°45.595E (Fig. 2.2.9). The

glider, equipped with sensors for temperature, conductivity, pressure, PAR, fluorescence, turbidity, dissolved oxygen, and backscatter, operated autonomously for nearly two months in challenging conditions, including strong currents and severe weather. It covered ~1,300 km and collected data to depths of 1,000 m before recovery on 7 April 2025 during the return voyage to Cape Town.

2.2.2.5. Remotely Operated Underwater Vehicle (ROV)

Fig. 2.2.10: a) ROV operations near Bharati Station and (b) the deployed ROV.

During ISEA-44, NCPOR deployed an indigenously developed Remotely Operated Vehicle (ROV) to investigate under-ice ecosystems in Antarctic coastal waters (Fig. 2.2.10). The 400 m depth-rated ROV, equipped with high-definition cameras, a Conductivity-Temperature-Depth (CTD) sensor, and navigation systems including Ultra-Short Baseline (USBL), Doppler Velocity Log (DVL), and an echo sounder, carried out three targeted dives in ice-covered coastal waters near the Bharati and Maitri stations. Underwater imagery, analyzed using a YOLOv8 deep-learning model trained on a custom Roboflow dataset, successfully detected benthic species such as sea urchins, starfish, seaweeds, and polychaete worms, revealing complex reef-like structures in sediment-dominated regions.

2.2.2.6. Assessing seasonality and extent of Antarctic Sea ice using satellite records

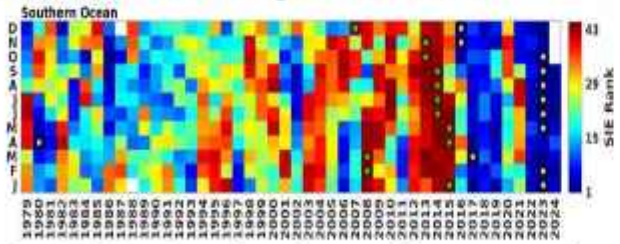


Fig. 2.2.11: Annual and monthly mean sea-ice extent (1979-2008) across Antarctic sectors, highlighting record-low (yellow) and record-high (green) periods.

Long-term satellite observations indicate that Antarctic sea-ice extent (SIE) showed modest growth until 2015, reaching record-high levels during 2013-2015, with a peak in 2014 (Fig. 2.2.11). Since 2016, SIE has declined sharply, exhibiting an overall negative trend of 0.42% per decade over 1979-2023. Record-low extents occurred frequently between 2016 and 2023, with 2023 recording historic lows for eight months. The strongest declines in 2023 were observed in the Weddell Sea, Ross Sea, and Indian Ocean sectors, while slight increases were noted in parts of the Ross and western Pacific sectors. The enhanced negative trends during winter and spring since 2016 suggest a possible transition towards a reduced Antarctic sea-ice regime.

2.2.2.7. Phytoplankton productivity measurements using FRRf in the Southern Ocean

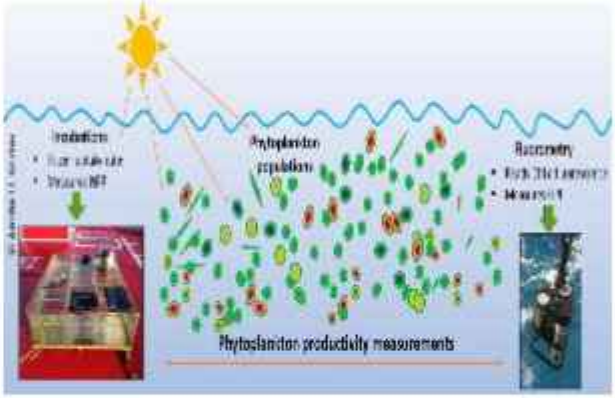


Fig. 2.2.12: Graphical abstract comparing incubation-based and fluorescence-based productivity measurements in the Southern Ocean

Conventional methods for estimating phytoplankton productivity (PP), such as carbon isotope incubations, are limited by low temporal resolution and the use of radioactive tracers. To address these constraints, Fast Repetition Rate Fluorometry (FRRf) was evaluated alongside ^{13}C and ^{1}C incubation techniques during Southern Ocean studies (Fig. 2.2.12). PP estimates derived from FRRf showed good agreement with ^{13}C measurements, with a slight overestimation (factor of 1.24), and exhibited stronger correlation with ^{1}C than with ^{13}C. These results establish FRRf as a reliable, rapid, and

safer tool for high-resolution monitoring of phytoplankton productivity, while also providing additional insights into photochemical efficiency and photo-physiology.

2.2.3. Scientific Studies in Arctic: Indian Arctic Expedition 2025-2026

For the Indian Arctic Expedition 2025-26, NCPOR issued a nationwide call for research proposals focused on the Ny-Ålesund research base in Svalbard. A total of 76 proposals were received Following peer review and evaluation by the Arctic Project Selection Committee, 36 projects were approved for implementation across thematic areas including atmospheric sciences, space science, astronomy and astrophysics, oceanography, geosciences, cryospheric studies, environmental sciences and biology.

2.2.3.1. Macroalgal-induced changes in carbon dynamics in Kongsfjorden

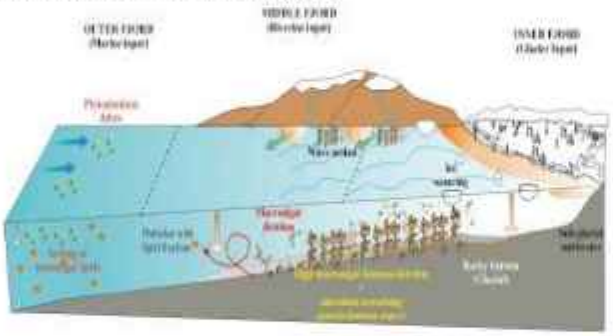


Fig. 2.2.13: Schematic illustrating the sources, transport, and fate of macroalgal detritus across fjord regions, rapid burial with terrestrial material in the inner fjord due to ice scouring and glacial melt; redeposition and microbial reworking under low-oxygen conditions in the middle fjord; and mixing of transported macroalgal and phytoplankton particles during slower settling in the outer fjord.

NCPOR scientists investigated the impact of expanding macroalgal forests on carbon dynamics in a high-Arctic fjord system using lipid biomarker and isotopic analyses (Fig. 2.2.13). Results reveal substantial macroalgal contributions to fjord sediments, accompanied by enhanced microbial degradation that promotes low-oxygen conditions. The findings suggest that continued macroalgal expansion under future warming scenarios could intensify oxygen depletion in Arctic fjords. This study provides a process-level framework for understanding the role of polar macroalgal forests in coastal carbon sequestration and associated biogeochemical feedbacks.

2.2.3.2. Diatom-Based Reconstruction of Holocene Thermal Maximum (HTM) from Arctic

This study reconstructs August sea surface temperatures (aSST) in Kongsfjorden, Svalbard, during the Holocene Thermal Maximum (10.5-7.5 ka BP) using a high-resolution diatom-based record. The results indicate moderately warm but highly variable surface conditions, with intervals of cooler temperatures and seasonal sea-ice presence. Variability appears to be driven by changes in summer insolation, glaciers and sea-ice melt, and shifts in oceanic frontal zones, while the influence of surface Atlantic Water was limited. The occurrence of diatoms only during the HTM and in modern sediments suggests notable similarities between current environmental conditions and those of the HTM.

2.2.3.3. A year-long high-resolution sampling campaign in Kongfjorden

Fig. 2.2.14: Field sampling and measurements carried out during different seasons for the high-resolution time series in Kongsfjorden.

NCPOR researchers, in collaboration with Lehigh University (USA), the Alfred Wegener Institute (Germany), and the Norwegian Polar Institute, conducted year-long, high-resolution weekly sampling at KB3 station as part of the Year-round EcoSystem Study on Svalbard (YESSS)-International

Kongsfjorden Year (IKY) project from August 2024 to July 2025 (Fig. 2.2.14). Monthly sampling was also performed at a nearby macroalgae-dominated site until October 2025 to assess its influence on microbial and biogeochemical dynamics. Preliminary results reveal significant shifts in microbial communities and organic matter composition, providing new insights into fjord processes and Arctic ecosystem functioning.

2.2.3.4. First Indian scientific cruise in the Denmark Strait

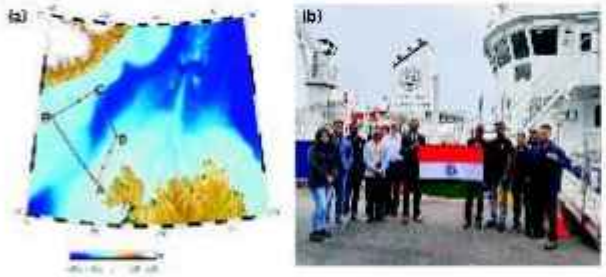


Fig. 2.2.15: (a) Sampling locations in the Denmark Strait, and (b) NCPOR researchers with the Hon'ble Indian Ambassador to Iceland flagging off the cruise.

The Denmark Strait, where cold Arctic waters meet the warm Atlantic current, is vital to the North Atlantic overturning circulation. India's first scientific expedition to the Greenland Sea and Denmark Strait was conducted over 15 days aboard the University of Gothenburg's RV Skagerak, and was flagged off in Reykjavik, Iceland (Fig. 2.2.15).

Heat and salt budgets, nutrient supply, and freshwater influences on ocean stratification and circulation was investigated. Ship-based observations were complemented by satellite data and high-resolution numerical models. Samples of phytoplankton, zooplankton, microbes, and organic matter were collected to assess ecosystem responses. The study strengthens India's Arctic research efforts by improving understanding of coupled ocean-atmosphere-ice processes and their implications for regional climate variability and global climate systems, including potential links to the South Asian monsoon.

2.2.3.5. Arctic Atmosphere-Ocean-Ice Feedback

Atmospheric warming in Svalbard and Bjørnøya has altered precipitation and local wind patterns, strongly influencing mixed-layer depth in the Greenland Sea (MOMSIS simulations, 2000-2023; Fig. 2.2.16). In Kongsfjorden, hemispheric winds and pressure anomalies drive warm Atlantic Water intrusions, enhancing nutrient supply, autumn mixing, and extending the growing season. IndARC mooring data show that winter cooling, storms, and Atlantic Water intrusions maintain nitrate levels, supporting spring phytoplankton blooms (~10-14 mg C m^3 day^1). These results highlight the rapid, coupled feedback between the atmosphere, ocean, and ice in the Arctic.

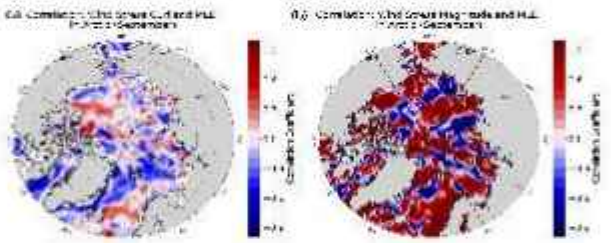


Fig. 2.2.16: Correlation of Arctic Ocean (60°N-90°N) mixed-layer depth (MLD) in September with (a) wind stress curl (WSC) and (b) wind stress magnitude (WSM), based on MOMSIS simulations for 2000-2023.

2.2.4. Himalayan Cryosphere Studies

2.2.4.1. Glaciological Field Activity

Fig. 2.2.17: (a) Snow core sampling from the accumulation zone of Samudra Tapu glacier for snow density measurement and total annual snow accumulation, and (b) AWS near Himansh station with snow-covered surface.

During summer 2025, glaciological fieldwork in the Chandra Basin combined hydrological and glaciological observations using AWS, Automatic Water Level Recorders (AWLR), and snow-core sampling. Key sites, including Tandi and Baralacha, enabled systematic upstream-downstream monitoring. Core activities included installing ablation stakes, measuring snow accumulation, and monitoring river runoff. Seven glaciers, Sutri Dhaka, Batal, Samudra Tapu, Bara Shigri, Kunzam, Gepang Gath, and Chandran, are under ongoing mass-balance monitoring. Additionally, the Khangri glacier was incorporated into the Himalayan Cryosphere Programme, where NCPOR established a hydrological site, AWS, and ablation stakes, marking the first systematic glacier studies in the eastern Himalaya (Fig. 2.2.17).

2.2.4.2. Glacier-Lake Interactions and Mass Balance at Gepang Gath, Western Himalaya, India

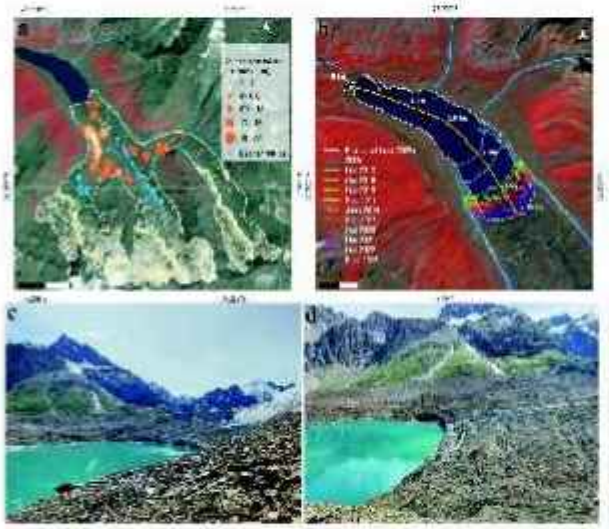


Fig. 2.2.18: (a) In-situ debris thickness measurements over the ablation area. (b) Frontal recession of the Gepang Gath glacier from Sentinel-2 MSI imagery (2014-2023). (c-d) Field photographs of the calving front and proglacial lake.

The lake-terminating Gepang Gath glacier was studied to understand its response to climate warming and interactions with its proglacial lake (Fig. 2.2.18) The lake expanded from 0.57 ± 0.20 km² (1962-2005) to 1.21 km² in 2023, nearly six-fold. Surface features, including transverse crevasses, ice cliffs, and debris tills, were observed across the ablation area, with debris thickness reaching up to 35 cm; debris-free ice extends along the central flow line to 4,250 m elevation. The glacier shows a consistently negative mass balance, averaging 0.90 ± 0.30 m w.e. a^{1} (2014/15-2022/23). Findings highlight the proglacial lake's role in accelerating ice loss via surface melt and calving. Continued mass loss is expected, emphasizing the need for high-resolution monitoring and early-warning systems to mitigate hazards such as Glacial Lake Outburst Floods (GLOFs).

2.2.5. Paleoclimate Reconstruction: MAGLEARN

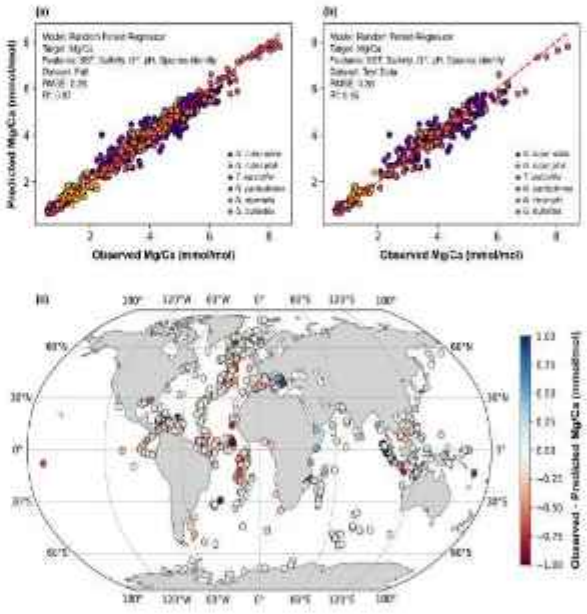


Fig. 2.2.19: Performance of the MAGLEARN paleotemperature calibration: (a-b) Comparison of predicted and observed foraminiferal Mg/Ca for the full dataset and an independent test set, accounting for temperature and key environmental controls; colours denote species. (c) Global distribution of core-top residuals (>1,100 sites), showing low and largely region-independent bias.

NCPOR developed MAGLEARN, a global machine learning-based calibration framework for Mg/Ca paleothermometry using commonly studied planktic foraminifera species. Built on over 1,100 globally distributed core-top records, MAGLEARN integrates temperature with key non-thermal controls such as salinity, pH, calcite saturation state, dissolution effects, species identity, and shell-cleaning protocols (Fig. 2.2.19). Cross-validated forward and inverse models show significantly improved accuracy and reduced regional bias compared to conventional calibrations, enhancing the reliability of past ocean temperature reconstructions across diverse marine environments.

Chapter 2.3
Seismology and Geoscience Research (SAGE)

SAGE, implemented under the Ministry of Earth Sciences, plays a pivotal role in advancing the nation's understanding of earthquake processes, geodynamic evolution, and associated natural hazards. Through a combination of nationwide seismic observations, deployment of advanced monitoring systems, and integrated geological and geophysical investigations, the programme delivers robust scientific outputs that support disaster risk reduction, infrastructure safety, and informed policy formulation.

Its activities are structured around interlinked thematic areas encompassing earthquake monitoring, understanding, and assessment; lithospheric evolution and deep earth processes, including India's participation in the International Ocean Discovery Program (IODP) and studies of the Indian Ocean Geoid Low (IOGL); geodynamics and surface processes; and institutional strengthening and capacity enhancement to support sustained operational and research capabilities.

2.3.1 Earthquake Monitoring, Understanding and Assessment

2.3.1.1 Observational Seismology, Earthquake Monitoring and Services

The National Seismological Network (NSN), comprising 169 field seismic stations, remained fully operational during 2025. The 24×7 operational activities at the National Centre of Seismology (NCS), New Delhi, ensured uninterrupted real-time monitoring of seismic activity within India and its surrounding regions. Earthquake information was rapidly processed, located, and disseminated immediately after occurrence to concerned stakeholders and the public through official bulletins and multiple social media platforms.

During the period January to 31 December 2025, a total of 1,860 earthquakes occurring within the region 0°-40° N and 60°-100° E were detected, located, and disseminated by the national network (Fig. 2.3.1). Of these, 60 events were of magnitude M 5.0. The magnitude-wise distribution of earthquakes, along with a comparison across different magnitude ranges with respect to the previous year (2024), is presented in Fig. 2.3.2.

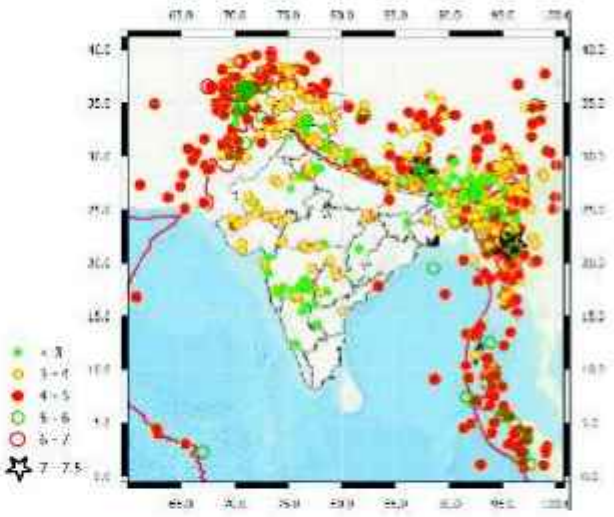


Fig. 2.3.1: Location of earthquakes disseminated by NSN during 01st January 2025 - 31 December 2025

In comparison, 1,395 earthquakes were recorded during 2024 using the same network strength of 169 seismic stations. The increase in the number of earthquakes recorded during 2025 reflects both enhanced seismic activity in the region and sustained improvements in network performance and data processing capabilities.

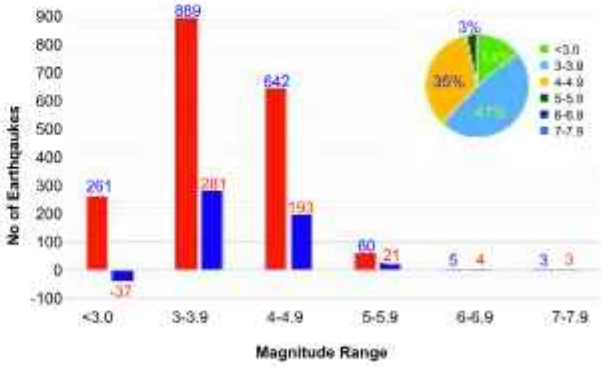


Fig. 2.3.2: Magnitude-wise distribution of earthquakes recorded during 01 January-31 December 2025, with comparison to 2024.

2.3.1.2 Significant Felt Earthquakes During 2025

Several moderate to large earthquakes occurring within and around the Indian region were widely felt during 2025 and are summarised below:

(i) Tibet Earthquake

A strong earthquake of magnitude M:7.1 occurred at 06:35:18 IST on 07 January 2025 in the Tibet Autonomous Region (TAR) at 28.86° N, 87.51° E, with a focal depth of 10 km. The epicenter was located approximately 100 km northeast of Lobuche (Nepal) and 175 km northwest of Gangtok (Sikkim). The event occurred close to the Indus-Tsangpo Suture Zone (ITSZ). Preliminary fault-plane solutions indicate normal faulting at shallow depth, with rupture along a north-south-oriented fault plane, consistent with the observed aftershock distribution.

(ii) Myanmar Earthquake

An earthquake of magnitude M:7.5 struck Mandalay, Myanmar, at 11:50:52 IST on 28 March 2025, located at 21.93° N, 96.07° E, with a focal depth of 35 km. The epicenter lay approximately 220 km north of Naypyidaw, 395 km southeast of Aizawl, and 430 km northwest of Chiang Mai (Thailand). This event was followed by a strong aftershock of M:7.0, occurring about 10 minutes later, south of the mainshock epicenter. Both events occurred in the vicinity of the Sagaing Fault, a major seismically active strike-slip fault system. Waveform inversion and fault-plane solutions confirm strike-slip faulting mechanisms for both earthquakes.

(iii) Afghanistan Earthquake

A deep-focus earthquake of magnitude M:6.3 occurred at 19:17:41 UTC on 31 August 2025 in Afghanistan, at 34.50° N, 70.81° E, with a focal depth of 160 km. The epicenter was located approximately 88 km northwest of Peshawar (Pakistan), 140 km east of Kabul, and 370 km west of Srinagar (India). Moment tensor inversion suggests thrust faulting, and the earthquake was widely felt across parts of north-western India.

(iv) Assam Earthquake

An earthquake of magnitude M:5.8 occurred at 16:41:50 IST on 14 September 2025 near Udalguri, Assam, at 26.78° N, 92.33° E, with a shallow focal depth of 5 km. The epicenter was located approximately 48 km west-northwest of Tezpur, 60 km northwest of Nagaon, and 188 km west of Jorhat. Preliminary moment tensor solutions indicate strike-slip faulting. The event occurred near the Kopili Fault zone and close to the source region of the 28 April 2021 M:6.4 Sonitpur earthquake. A sequence of nine aftershocks with magnitudes ranging from M:2.4 to 3.1 was recorded within 24 hours of the mainshock.

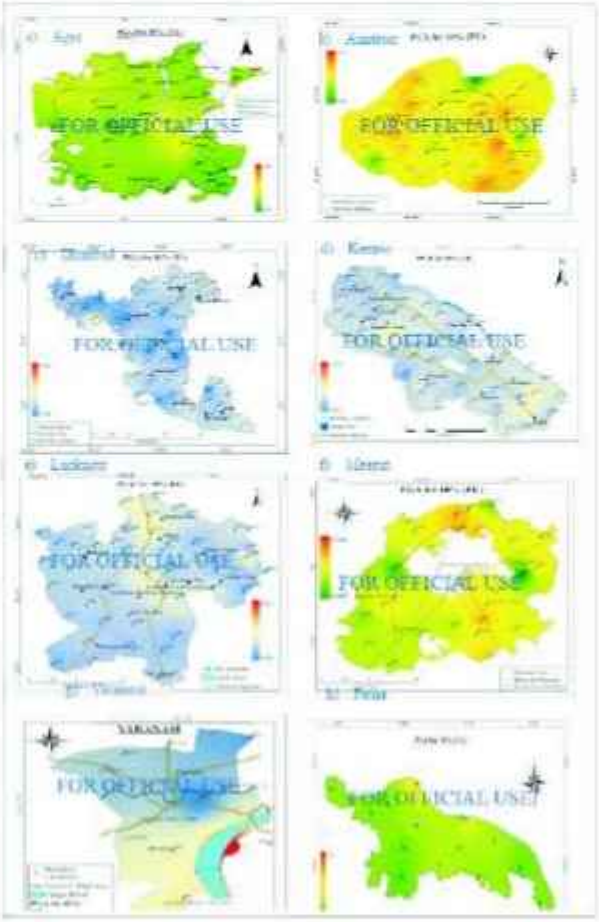


Fig. 2.3.3 Variation of Peak Ground Acceleration (PGA) for 10% probability of exceedance (EL) in eight cities under the NCS-MoES Seismic Microzonation programme.

2.3.1.3 Seismic Hazard and Risk Assessment studies

A comprehensive report on seismic hazard and risk microzonation was published for four selected cities, namely Bhubaneswar, Chennai, Coimbatore, and Mangalore. In addition, seismic microzonation studies were undertaken for eight more cities, Agra, Kanpur, Patna, Amritsar, Dhanbad, Varanasi, Lucknow, and Meerut, as part of the flagship programme on Seismic Microzonation of 30 Cities in India.

For these eight cities, field investigations and laboratory testing were completed, covering multi-parametric geophysical and geotechnical characterisation of soils. The reports for the 8 cities are currently under review. The spatial variation of Peak Ground Acceleration (PGA) for 10% probability of exceedance (PE) corresponding to the design earthquake level (EL) for these eight cities is shown in Fig. 2.3.3.

2.3.1.4 Setting up of Earthquake Early Warning (EEW) network

A total of ten P-Alert earthquake early warning (EEW) instruments, received from the National Science and Technology Center for Disaster Reduction (NCDR), Taiwan, were deployed in Himachal Pradesh and integrated with the newly established Data Receiving Centre at the National Centre of Seismology (NCS) using Earthworm software. These instruments provide real-time ground-motion data for rapid P-wave detection, enabling the earliest possible identification of earthquake onset. The network also supports preliminary event location using high-frequency triggers from multiple stations.

This configuration allows NCS to test, evaluate, and refine EEW algorithms under real field conditions, including source characterisation, threshold optimisation, and alert-generation logic. In parallel, NCS is developing a national-scale EEW system to substantially enhance early warning capability across seismically active regions of the country. The planned system is for the installation of approximately 100 dedicated EEW instruments at 10-15 km spacing, ensuring dense coverage and improved detection speed and warning reliability.

2.3.2 Scientific Deep Drilling in the Koyna Region

2.3.2.1 Seismological Monitoring in the Koyna Seismic Zone

The Koyna-Warna region of western Maharashtra constitutes a globally important natural laboratory for the study of reservoir-triggered seismicity (RTS). Seismic activity has remained confined to a limited area of approximately 20 km × 30 km for more than six decades following the impoundment of the Sivajisagar (Koyna) Reservoir, offering a rare opportunity to investigate earthquake processes under sustained hydrological forcing.

To advance understanding of the causative mechanisms, a 3-km-deep scientific pilot borehole (KFD1) was drilled in 2017 by MoES-BGRL, confirming the presence of buried faults. To support high-resolution monitoring in the vicinity of the borehole, a local broadband seismic network comprising five stations within a 5 km radius of KFD1 was established in 2022 and further strengthened with the installation of four additional stations in January 2025.

By July 2025, the expanded network had recorded approximately 4,000 local earthquakes in the magnitude range M 0.0-3.7, occurring at depths between 2 and 10 km. Improved event location using a region-specific velocity model and double-difference relocation techniques significantly enhanced hypocentral accuracy, enabling identification of four distinct sub-zones of seismic activity within the Donichawadi Fault Zone.

Seismological modelling further refined the geometry of the Donichawadi Fault, the causative structure of the 1967 M 6.3 Koyna earthquake. Fault-plane solutions indicate dips between 60° and 80°, with a ~70° west-northwest dipping plane providing the best agreement with observed seismicity. Modelling results demonstrate that a vertical borehole drilled to ~6 km depth at the KFD1 site would optimally intersect the active fault plane (Fig. 2.3.4).

These results provide a robust scientific basis for drilling the Koyna Main Borehole to an optimal depth of approximately 6 km. Installation of downhole instrumentation in the 5-6 km depth interval will enable near-field monitoring of physical, chemical, and mechanical processes associated with earthquake nucleation and fault slip. Direct access to the active fault zone at seismogenic depths will significantly enhance national capabilities in earthquake science, hazard assessment, and disaster risk reduction.

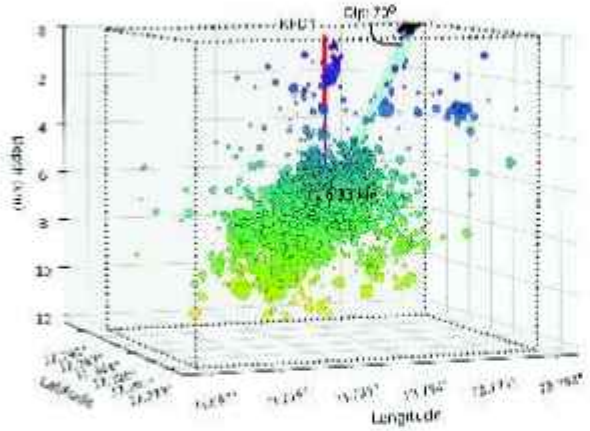


Fig. 2.3.4: 3D depth distribution of earthquake hypocentres in the Koyna region, with symbol size proportional to magnitude. The vertical red line indicates the trajectory of the KFD1 borehole, while the light-blue plane represents the inferred Donichawadi fault surface dipping at ~70°. The dashed blue line shows the projected depth at which the borehole is expected to intersect the fault plane.

2.3.2.2 In-situ Stress, Permeability and Recurrent Seismicity in the Koyna Region

In-situ stress measurements conducted in the Koyna pilot borehole indicate that the region is critically stressed and characterised by a transition from strike-slip to normal faulting regimes. Estimates of the normal and shear stresses resolved on the Donichawadi Fault, the causative structure of the 1967 M 6.3 Koyna earthquake, indicate a relatively low frictional strength of the fault (Fig. 2.3.5). As most earthquake hypocentres in the region are aligned along the strike of this fault, the results suggest the presence of mechanically weak fault gouge materials that facilitate fault slip under comparatively low shear stress conditions.

A strong temporal correlation between reservoir water-level fluctuations and seismic activity further underscores the role of subsurface hydrological processes in modulating seismicity. Diffusion modelling demonstrates that surface water can migrate to depths of approximately 6 km over timescales ranging from a few months to several decades, depending on bulk permeability values of the order of 10^{-1}-10^{-1} m^2 (Fig. 2.3.6). The observed peak in seismicity during the post-monsoon period (2-6 months after peak rainfall), together with the depth range of earthquake occurrence (2-10 km), is consistent with pore-pressure diffusion driven by monsoon-related hydrological loading.

These findings indicate that permeability-controlled fluid diffusion, coupled with a critically stressed and mechanically weak fault system, plays a key role in triggering recurrent reservoir-induced seismicity in the Koyna region.

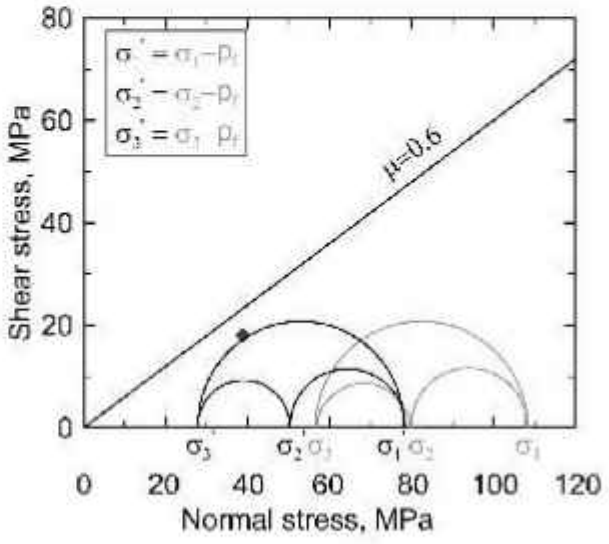


Fig. 2.3.5: 3D Mohr's circle representation of principal stress magnitudes. The purple diamond denotes the resolved normal and shear stress on the Donichawadi Fault.

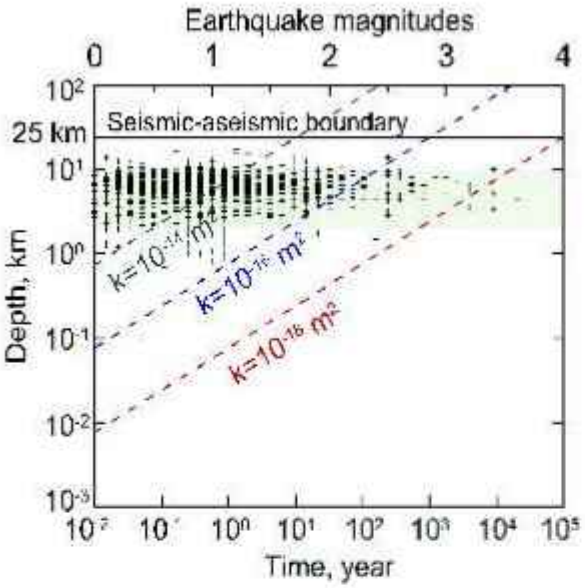


Fig. 2.3.6: Diffusion times for surface water to reach different depths under varying bulk permeability values. The solid line at 25 km depth denotes the thermal seismic-aseismic boundary. Also shown is the magnitude-depth distribution of earthquakes (2022-2024) recorded by BGRL's local broadband seismic network in the Koyna region.

2.3.2.3 Fault zone rocks associated with RTS in Koyna region

Microstructural, isotopic, and geochemical analyses of fault zone rocks recovered from depths up to 1.5 km in the crystalline basement across multiple wells reveal a multi-stage deformation history. These rocks, including breccias and cataclasites, feature sub-vertical fractures, often open, indicating a high density of permeable faults. Hydrothermal minerals such as epidote and chlorite form matrices or vein infill, evidencing repeated reactivation in the brittle regime (Fig. 2.3.7).

Two chlorite groups formed at 155-304°C (Group I) and 76-213°C (Group II), with the lowest-temperature chlorite (average 129 ± 41°C) lining steeply dipping faults alongside calcite veins from meteoric fluids. These mark the most recent brittle deformation.

Hypocenters cluster at 3-10 km depth, corresponding to temperatures of 68-84°C and 145-180°C based on heat flow data. Recurrent seismicity likely reflects monsoon-modulated reactivation of these steep faults at 70-170°C ambient conditions. These results support the objective of using deep borehole investigations in Koyna-Warna to understand the physical controls on RTS and to improve future assessment of seismic hazard in reservoir-influenced regions.

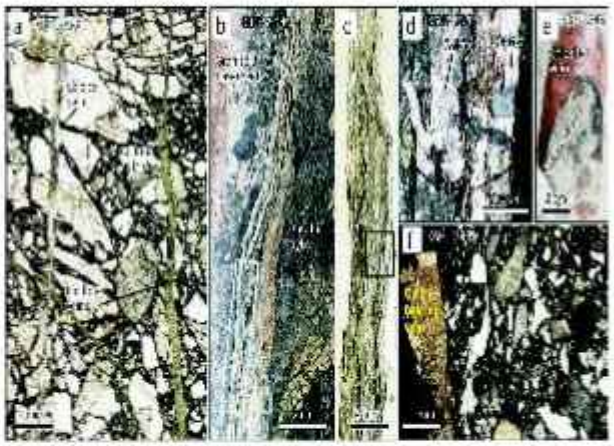


Fig. 2.3.7: Borehole cores and fault rocks, Koyna-Warna region. (a) Epidote-matrix cataclasite with sub-vertical epidote-calcite veins (calcite latest). (b) Chlorite-calcite fault at Deccan dyke (right)-Neoarchean granitoid (left) contact. (c) Growth fibers in chlorite-calcite vein (calcite latest). (d) Calcite vein cross-cutting chlorite-quartz vein. (e-f) Calcite veins in chlorite-matrix cataclasite.

2.3.3 Geological and Geophysical studies

2.3.3.1. Plume-lithospheric interaction revealed by IOGL- OBS array

The Indian Ocean Geoid Low (IOGL), Earth's most significant gravitational anomaly, presents a major geodynamic puzzle. Building on investigations of the large negative geoid anomaly in the Indian Ocean, NCPOR analyses surface wave data from the Central Indian Ocean Basin (CIOB). Their findings reveal a pronounced low-velocity zone (LVZ) in the shallow asthenosphere, most significant beneath the Capricorn Plate, a feature previously overlooked. They interpret this extensive LVZ as evidence of mantle plume upwelling from the Réunion hotspot, west of the Central Indian Ridge. Furthermore, it is proposed that the rapid northward drift of the

Indian Plate inhibits complete melt extraction, leaving residual melt fractions in the uppermost mantle that amplify the velocity reduction. This plume-lithosphere interaction provides a unified mechanism for the observed seismic structure and the geoid anomaly (Fig. 2.3.8)

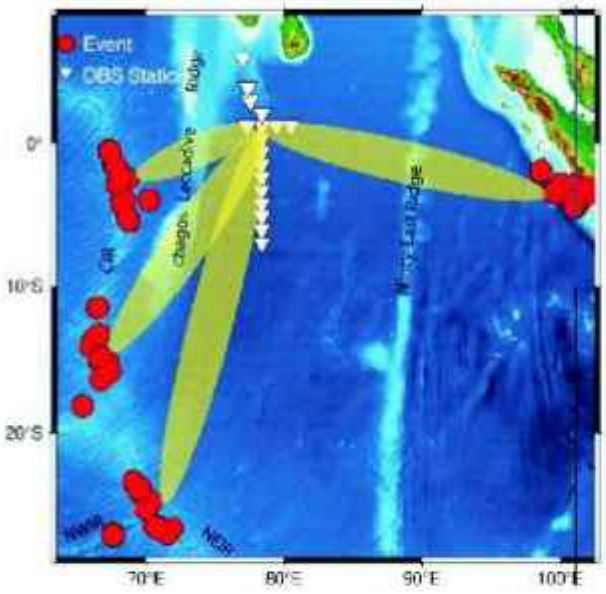


Fig. 2.3.8: Regions of investigation between earthquake epicentres and OBS stations, with yellow shading showing source-receiver path coverage for observed surface wave group velocities. Solid red circles mark earthquakes of magnitude 4.5; CIR - Central Indian Ridge; NWIR - North-West Indian Ridge; NEIR - North-East Indian Ridge.

2.3.3.2. Mantle deformation beneath the Indian Ocean Geoid Low region

A study by NCPOR in the IOGL region provides the first direct constraints on upper mantle flow within the IOGL through shear-wave splitting analysis from ocean-bottom seismometers (OBS). Using shear-wave splitting analysis from ocean-bottom seismometers (OBS), researchers identified a complex two-layer anisotropic structure: Lithospheric Layer (~100 km): Exhibits north-south anisotropy, preserving fossilized spreading fabric. Asthenospheric Layer (~300 km): Shows northeast-southwest anisotropy, indicating active mantle flow.

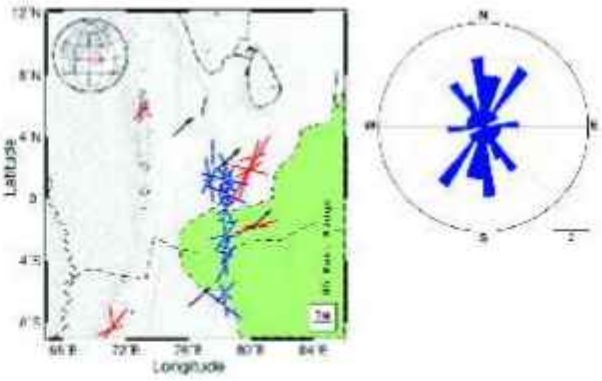


Fig. 2.3.9: (L) Map of shear-wave splitting measurements in the IOGL region. Blue and red bars represent new and previous measurements, respectively; bar orientation indicates the fast polarization direction and length denotes delay time. Green shading marks diffuse lithospheric deformation, and black arrows show Absolute Plate Motion (NUVEL1A). (R) Rose diagram illustrating dominant splitting directions from the composite dataset.

The findings suggest that material from the African Large Low Shear Velocity Province is channelled via the Kenya plume and Mascarene Basin into the Central Indian Ocean. This provides the first observational link between deep mantle structures and the large-scale circulation shaping the world's most significant geoid anomaly, resolving a long-standing geodynamic mystery (Fig. 2.3.9).

2.3.3.3 Dominance of coastal microseism in the Indian Ocean

NCPOR research using ocean-bottom seismometers (OBS) challenges the theory that Indian Ocean microseisms originate solely from Southern Ocean wave activity. By integrating Rayleigh wave polarization and numerical wave modeling, the study reveals that coastal reflections are the primary drivers of peak seismic noise. This is evidenced by heightened signals during simultaneous bi-hemispheric cyclones and storm surges driven by Southern Ocean "Cut-off Lows" impacting Indian coastlines. These findings necessitate a revised framework for quantifying seismic noise in closed ocean systems. (Fig. 2.3.10).

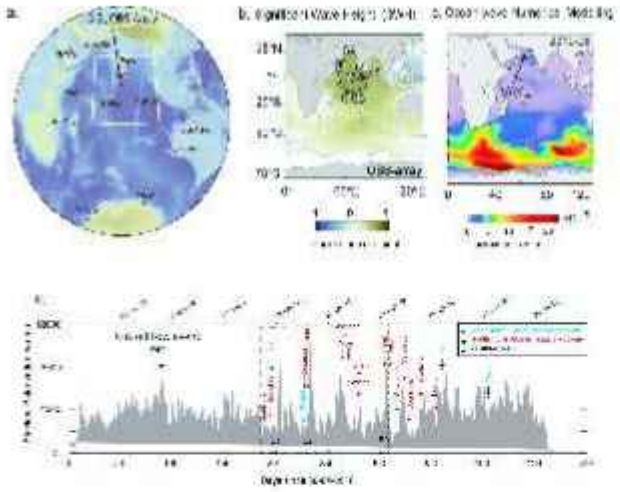


Fig. 2.3.10: (a) Seismic station locations; (b) Microseism source locations via cross-correlation; (c) Numerical wave modelling; and (d) Correlation of noise anomalies with tropical cyclones.

2.3.3.4 Phase-II OBS-TREE: Mantle Dynamics and Intraplate Deformation

In April 2025, NCPOR successfully concluded a year-long seismic monitoring mission in the IOGL. All 18 broadband Ocean Bottom Seismometers (OBSs) from the OBS-TREE array were retrieved via FORV Sagar Sampada, achieving a 100% recovery rate with high data quality. This unprecedented 3D dataset provides the essential constraints needed to elucidate the origin of the world's largest geoid anomaly and the mechanisms driving Indian Ocean intraplate deformation. (Fig. 2.3.11.)

Fig. 2.3.11: (L) Retrieval of OBS unit SN-189 onboard FORV Sagar Sampada. (R) The onboard scientific and engineering team responsible for the successful deployment and recovery.

2.3.3.5 Metamorphic Evolution of South Indian Granulites

The Precambrian Southern Granulite Terrane (SGT) of south India is well known for the preservation of high to ultrahigh-temperature granulite facies metamorphic rocks, with their formation linked to the assembly of the East Gondwana supercontinent. Although the timing and duration of this Himalayan-scale collisional orogeny are well characterised, the peak-to-post-peak evolutionary history of these granulitic rocks is poorly understood. This study aims to characterise the peak-to-post-peak metamorphic evolutionary history of south Indian granulites using in-situ accessory mineral geochronology and isotopic fingerprinting of a metapyroxenite sample collected from the central part of the SGT. U-Pb dating of zircon and monazite from the sample constrains the timing of peak metamorphism at 560-550 Ma, while the timing of fluid activity and cooling was characterised using titanite (557 ± 2 Ma) and apatite (410 ± 3 Ma) dating. U-Pb ages recovered from available accessory phases, together with temperature estimates from trace element thermometry and closure temperature estimates, suggest variable and slow cooling rates for the studied granulite. On the other hand, Hf-Nd isotopic fingerprinting of zircon and titanite points to the involvement of slab-derived materials during peak metamorphism, providing new evidence for melt/fluid-assisted metamorphism in the area (Fig. 2.3.12).

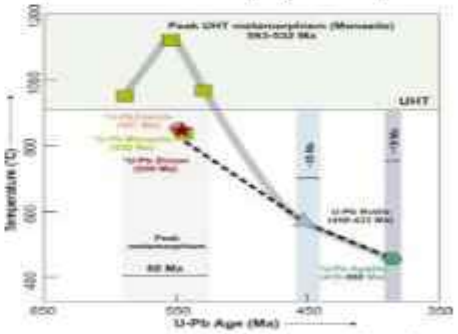


Fig. 2.3.12: Time-temperature (T-t) diagram comparing the cooling pattern of the studied metapyroxenite (dashed lines) with the generalized T-t path for the Madurai block (continuous line).

2.3.3.6 A 3D Shear Wave Velocity Structure of the Indian Ocean

The structure of the lithosphere-asthenosphere system beneath the Indian Ocean remains one of the most enigmatic and complex frameworks among the world's oceans due to relatively limited seismic data coverage and intricate tectonic settings. This study presents the regional tomography model (INDOVsv24), which provides a 3D shear-wave velocity structure for the entire Indian Ocean with a lateral resolution of 200-600 km, down to a depth of 300 km. In this model, NCESS inverted the regionalised local group velocities, obtained from ~32,000 high-quality dispersion data spanning a period range of 18-180s using a trans-dimensional inversion approach. This model shows excellent correlation with surface tectonics and accurately delineates significant features such as mid-oceanic ridges, Sunda subduction zone (SSZ), and low-velocity zones in the eastern and western sides of the Indian Ocean (Fig. 2.3.13). Intriguingly, the present model and tectonic regionalisation results identify a distinct low-velocity anomaly oriented in the SW-NE direction with a localised strong low-velocity anomaly/reservoir in the north-eastern side within the Indo-Australian diffusion plate boundary (IADPB) zone. This observation concurs with seafloor age data, suggesting a relatively younger age (~40 Ma) in this region compared to its surroundings. The strong low-velocity anomaly/reservoir within the IADPB zone on the western side of the SSZ could be due to the accumulation of asthenospheric material from ridges, which are ultimately fed by superplumes along with upwellings from the deep-seated sources beneath the region. These seismological findings strongly suggest ongoing active dynamics in study region.

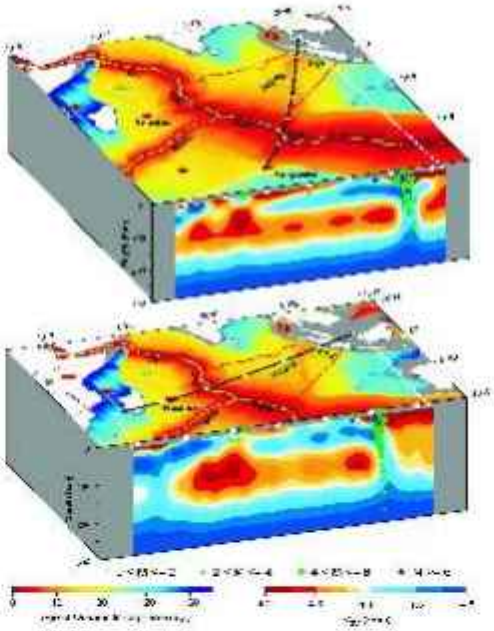


Fig. 2.3.13: Schematic of the INDOVsv24 model. Horizontal planes show seafloor lithospheric age with plate boundaries (yellow-red/dashed red lines) and hotspots (red-black circles). Black lines denote tomographic depth profiles, with white circles marking grid points and green circles showing earthquake distribution. L1 identifies the prominent low-velocity anomaly within the IADPB zone.

2.3.3.7 Pressure-Temperature-time (P-T-t) evolution of pelitic granulites from the Larsemann Hills, East Antarctica: Insights from accessory mineral geochronology and phase equilibria modelling

Pelitic granulites from the Larsemann Hills, Prydz Bay, East Antarctica, preserve a complex polymetamorphic history associated with the supercontinent assembly. This study integrates mineral chemistry, geothermobarometry, phase equilibria modelling, and accessory mineral petrochronology to reconstruct the pressure-temperature-time (P-T-t) evolution of these rocks. Peak metamorphic conditions of 950 °C at 8.5 kbar were followed by retrogression along a clockwise P-T path marked by a near-isothermal decompression and a near-isobaric cooling. In situ U-Pb dating of zircon and monazite constrains the timing of peak

metamorphism to 565 Ma, while apatite U-Pb ages of 526 Ma records the subsequent cooling. Older Neoproterozoic ages (822-862 Ma) preserved in zircon and monazite indicate an earlier metamorphic episode, reflecting a protracted tectonothermal evolution (Fig. 2.3.14). Rare earth element (REE) partitioning supports garnet growth during the Ediacaran-Cambrian orogeny. The ~50 Myr duration of metamorphism and slow cooling rates link Prydz Bay to contemporaneous high-grade terranes in South India, Sri Lanka, and Madagascar during the final assembly of East Gondwana.

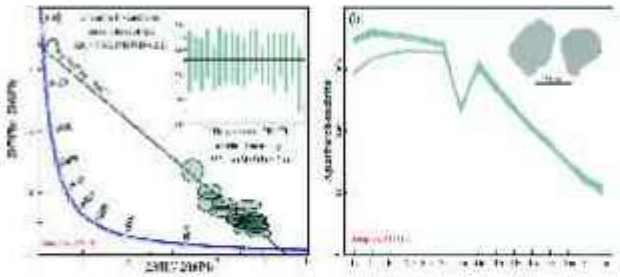


Fig. 2.3.14: (a) U-Pb data of apatites from the melanosome sample (ANT105) presented in the Terra-Wasserburg diagram. The inset shows weighted average 207Pb-corrected 206Pb/238U ages. (b) Chondrite-normalised REE patterns of apatites. The inset shows the BSE image of apatites.

2.3.3.8 Effects of climate and sea level change on the growth of the Bengal Fan during the late Quaternary

The Bengal Fan is a vast repository of clastic sediments from the Himalayas, Peninsular India and the Indo-Burman ranges. Many ancient submarine channels through which the turbidity currents operated in the Bay of Bengal are currently inactive. These defunct channels provide some of the best sediment records of continental weathering and climate. Results of a sedimentological, geochemical, and Sr-Nd isotopic study done by NCESS on a well-dated sediment core (27-1.5 kyrs BP) collected from the now-defunct submarine channel in the eastern Bay of Bengal to examine the roles of various environmental factors on the growth of the fan. The results suggest that active fan progradation at the eastern margin of the Bengal Basin continued until approximately 12,000 years before present (kyr BP), with the rapid deposition of coarse-grained terrigenous flux. Deposition of sediments from Indo-Burman-Arakan (IBA) ranges and Ganga-Brahmaputra rivers through channel E7 was active during 27 to 12 kyrs. Subsequently, hemipelagic sedimentation from the Irrawaddy increased. Unlike other major fans, the Bengal Fan had a very active coarse-grained terrigenous flux during the Last Glacial Maximum and subsequent deglacial period. The post-12 kyr BP cessation of coarse-grained terrigenous deposition despite significant sediment influx from the Himalaya/Indo-Burman-Arakan Ranges was likely a result of the inland retreat of river mouths due to sea level rise and the subsequent detachment of the submarine channels from the coast. The present study also suggests that the sedimentation in the Bengal Fan is less sensitive to the variations in the rainfall associated with the Indian Summer Monsoon than to the sea level changes (Fig. 2.3.15). These findings underscore the complex interplay between the climate and coastal geomorphology in shaping the Bengal Fan.

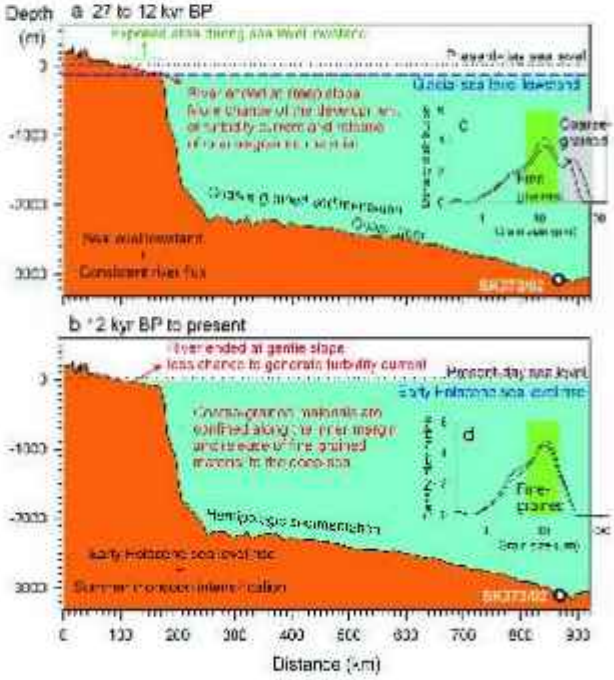


Fig. 2.3.15: A schematic diagram of the land-sea interface in northern BoB between 27000 yr BP and the present (a: 27 to 12 kyr BP; b: 12 kyr BP to present).

2.3.3.9 Radon (222Rn) as a geochemical tracer for submarine groundwater discharge (SGD)

A comprehensive review of 222Rn isotope techniques to refine the estimation of Submarine Groundwater Discharge (SGD) fluxes was conducted. Due to its inert nature and significant enrichment in groundwater compared to seawater, 222Rn serves as a critical tracer for quantifying freshwater inputs into coastal zones. The study outlines the evolution of SGD research over the last 30 years, detailing the application of RAD7 time-series measurements and the development of mass balance conceptual models. By clarifying box model boundaries and identifying previously neglected factors in pore-water exchange, the review provides a standardized framework for managing coastal ecosystems, particularly in regulating the transport of nutrients and pollutants (Fig. 2.3.16).

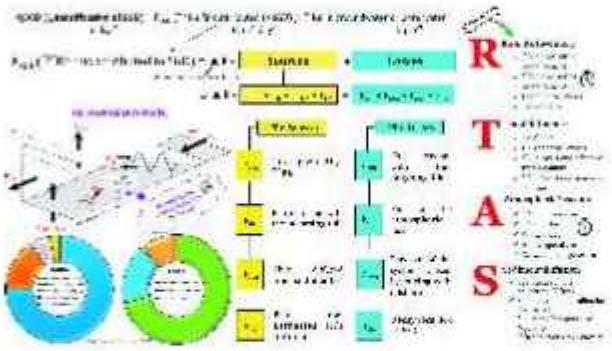


Fig. 2.3.16: Conceptual investigation of 222Rn mass balance model.

2.3.3.10 Seasonal Dynamics and Health Risks of Heavy Metals in the Western Ghats

Monsoon-driven hydrological variability and anthropogenic pressures in tropical critical zones pose significant threats to water quality and public health. Hydrogeochemical variability and public health risks of trace metals at the Munnar Critical Zone Observatory was investigated the study identified pronounced seasonal contrasts: monsoon rains trigger a two-to-threefold increase in Al, Fe, Pb, and Zn in surface waters due to enhanced weathering of hornblende-biotite gneiss and agrochemical runoff from tea and eucalyptus plantations. Groundwater chemistry reflects aquifer lithology, while Cd and Pb enrichment during monsoon recharge is significantly influenced by anthropogenic sources. Multivariate statistical analyses attribute (PCA, HCA) 60-75% of metal variability to geogenic weathering (PC1: Al, Fe, Ti) and 15-25% to anthropogenic sources (PC3: Cd, Pb from agrochemicals). Pollution indices (WPI, HPI, HEI) classify contamination as low-to-moderate overall, yet Fe exceeds thresholds in rivulets during monsoon (notably at S1 and S6). Health risk assessments prioritise Co, Mn, and Pb as non-carcinogenic threats (HI<1), while Cr and Cd pose significant carcinogenic risks, with children's ingestion risk 3-4 times higher than adults. Concentration-discharge relationships indicate consistent chemodynamic metal transport in river systems, contrasting with seasonally variable behaviour in rivulets, where chemostasis occurs for specific elements during pre-monsoon. These findings emphasize the necessity of regulating agrochemicals and monitoring Cr and Cd in climate-sensitive tropical landscapes.

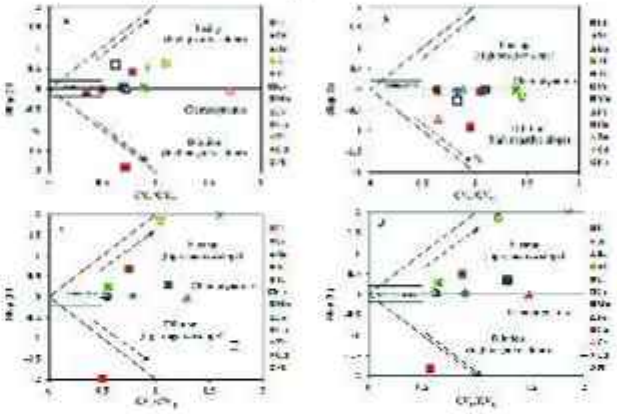


Fig. 2.3.17: C-Q plots for rivulets during a) PRM and b) MON periods, and for the river during c) PRM and d) MON periods.

2.3.3.11 Nutrient Fluxes in Rivers Across the Southern Western Ghats

The Western Ghats of southern India, a biodiversity hotspot and major water source, host several rivers influenced by diverse climatic, geological, and land-use settings. This study investigates the spatiotemporal dynamics of Dissolved Inorganic Nitrogen (DIN), Dissolved Inorganic Phosphate

(DIP), and Dissolved Silica (DSi) in two small rivers, the Bhavani and the Thuthapuzha. A total of 150 water samples were collected across seasons and zones to assess nutrient fluxes and their controlling factors. The Bhavani River exhibited significantly higher nutrient levels, particularly during the monsoon, with mean DIN reaching 1432.14 µg/l compared to 306.90 µg/l in the Thuthapuzha. In the semi-arid Bhavani catchment, nutrient enrichment increased downstream due to intensive agriculture and domestic wastewater. In the humid Thuthapuzha catchment, higher nutrient loads were restricted to areas of high land-use intensity. Elevated DSi levels (up to 8.73 mg/l) across both rivers were linked to accelerated silicate weathering and soil erosion in cultivated zones.

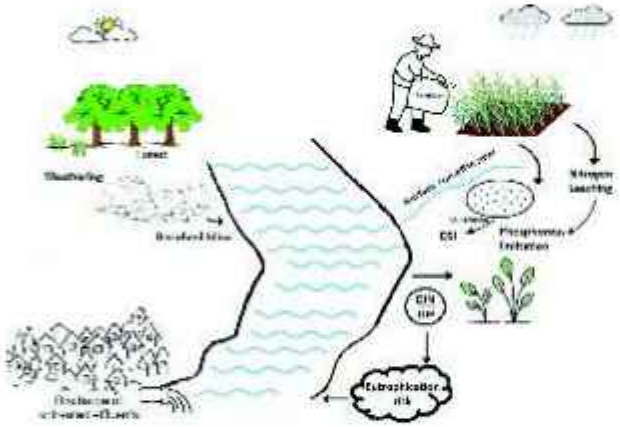


Fig. 2.3.18: Schematic diagram representing the sources and pathways of nutrient inputs into river systems.

The study concludes that seasonal monsoonal runoff and increased fertilizer use are the primary drivers of nutrient flux, highlighting the urgent need for integrated watershed management in these rapidly transforming tropical catchments (Fig. 2.3.18).

Chapter-2.4

Research, Education, Training, and Outreach (REACHOUT)

REACHOUT programme under the PRITHVI scheme of MoES is aimed at strengthening India's national capacity in Earth system sciences through research support, human resource development, international cooperation, and large-scale public outreach. The programme plays a critical role in ensuring that scientific knowledge generated by the Ministry reaches policymakers, students, institutions, and the wider public, thereby enhancing awareness, preparedness, and informed decision-making in matters related to weather, climate, oceans, and natural hazards.

REACHOUT activities during FY 2025-26 focused on expanding scientific engagement at the national level, nurturing young scientific talent, strengthening regional and international collaboration, and promoting environmental awareness and responsible citizen participation.

The REACHOUT programme is implemented through the following six sub-programmes:

i. Research and Development in Earth System Science (RDESS);

ii. Outreach and Awareness;

iii. BIMSTEC Centre for Weather and Climate (BCWC);

iv. International Training Centre for Operational Oceanography (ITCOOcean);

v. Development of Skilled Manpower in Earth System Sciences (DESK); and

vi. Knowledge Resource Centre Network (KRCNET).

2.4.1 Research and Development in Earth System Science (RDESS)

RDESS supports research proposals from universities, institutes, and organisations to strengthen scientific and technological capacity in earth system sciences.

In FY 2025-26, 44 new research projects were sanctioned across key thematic areas (Table 2.4.1).

Table 2.4.1: New Projects Sanctioned during 2025-26.

Atmospheric Science	Ocean Science	Geosciences and Seismology	Hydrology & Cryosphere	Technical Research Board (TRB)	Total
17	06	06	11	04	44

Several ongoing and completed projects during the year delivered significant scientific, technological, and capacity-building outcomes.

2.4.1.1 Atmospheric Science

Thunderstorm Understanding and Experimental Real-time Prediction (THUNDER) - CUSAT, Kochi

This project enhanced the understanding and prediction of severe thunderstorms over the south-west India, where convective weather frequently results in loss of life, damage to infrastructure, and disruption of services. By integrating high-resolution radar-based (205 MHz VHF radar) wind observations with advanced numerical weather modelling, the study improved the representation of mesoscale convective systems relevant for operational forecasting.

Key outcomes include the development of an improved convective index for thunderstorm nowcasting, refinement of wind retrieval techniques, and improved estimation of boundary layer height, parameters critical for early warning of severe convection. The optimised modelling framework demonstrated reliable simulation of convective events ranging from moderate storms to cloudbursts and lightning, supporting its potential application in real-time forecasting and disaster preparedness. The project also contributed to human resource development through training, national workshops, and scientific publications.

Land-Atmosphere Interaction during Thunder storms over Major Urban Areas - NIT, Rourkela

This project addressed the growing challenge of urban-induced modification of weather by

examining pre-monsoon thunderstorm activity across eight major Indian cities: Delhi, Mumbai, Kolkata, Chennai, Hyderabad, Bengaluru, Pune, and Ahmedabad. High-resolution land-use and land-cover (LULC) data, remote sensing, GIS, and advanced AI/ML techniques were employed to assess how urbanisation influences rainfall, lightning, and storm intensity. Coupled WRF-based numerical simulations quantified urban effects on convective storm development and rainfall patterns.

The study produced high-resolution urban LULC maps, urban growth projections, and improved scientific understanding of urban-climate interactions during extreme weather. Eight research papers were published, and two personnel were trained during the project tenure.

Probabilistic Forecasting of Lightning over India - BHU

This project developed an advanced framework for probabilistic forecasting of thunderstorms and lightning across India by integrating high-resolution numerical weather simulations with statistical modelling. A key output, the Lightning Potential Index (LPI), quantifies lightning probability based on atmospheric dynamics, enabling region-specific forecasts over thunderstorm-prone areas.

The study also analysed long-term trends in pre-monsoon thunderstorms, lightning, and hail, identifying eight regional hotspots and revealing increasing lightning activity over eastern, north-eastern, east-central, west-central, and southern India, while hail activity declined in northern and northwestern regions.

The framework enhances operational forecasting and early warning capabilities, supporting hazard mitigation and disaster preparedness. Two personnel were trained as part of capacity-building efforts.

2.4.1.2 Hydrology & Cryosphere

Estimation of Hydraulic Properties of Soil Macropores - IIT Kanpur

This initiative enhanced understanding of soil macroporosity and hydraulic behaviour through integrated modelling and field experiments. A 1-D inverse modelling framework supported by a genetic algorithm was developed to estimate key soil parameters, demonstrating strong agreement with field observations and literature values. Validation using multi-scale field data and SMAP-based soil moisture observations confirmed the approach's applicability for operational hydrological studies. The project also supported capacity building by training two personnel and resulted in five publications.

Sustainable Wastewater Reclamation for Water Security - GB Pant University of Agriculture & Technology

This project advanced sustainable wastewater utilisation in agriculture through long-term evaluation of vegetation filter systems with bioenergy plantations and biochar-amended soils. The study demonstrated effective treatment of domestic wastewater, enabling reuse for irrigation, enhancing biomass productivity, improving soil health, supporting carbon sequestration, and reducing pollutant discharge. A full-scale treatment system has been implemented on campus to treat domestic wastewater before release into rivers. Initiated patenting of the in-situ treatment process.

Hyper-resolution Soil Moisture Modelling - IIT Bombay

This project aims to develop a 30 m hyper-resolution hydrological modelling framework for simulating surface and rootzone soil moisture using satellite data assimilation, demonstrated in the Upper Bhima basin. Adaptation of the HydroBlocks model to Indian watershed conditions, incorporating soil heterogeneity and lateral connectivity, has shown high agreement with in-situ observations and improved performance over existing products. Integration with WRF and dynamic MODIS-based Leaf Area Index enhances simulation realism. The framework is expected to support drought assessment, irrigation planning, and land-atmosphere studies.

DeepINDRA: Street-scale Urban Flood Forecasting - IIT Delhi.

This initiative is developing an open-source urban flood forecasting system that couples hyper-resolution physical models with AI/ML to provide street-scale inundation forecasts. Focused on Guwahati and Hyderabad, the system integrates EF5 with TRITON hydrodynamic modelling, with baseline simulations completed for Guwahati. Street-level flood simulations using 1 m DEM data for Rukminigaon and 10 m LiDAR for greater Guwahati have demonstrated the model's potential to strengthen real-time flood forecasting.

21st Century Evolution of Small Himalayan Glaciers - IIT Roorkee.

This project examines the status, evolution, and hydrological role of small Himalayan glaciers (<2-5 km^2) using field campaigns, satellite observations, and high-resolution modelling. A workflow for generating high-resolution glacier topography from Cartosat-1/ASTER has been standardised, and field campaigns in the Chandra Basin provided validation datasets. The regional glacier evolution model (GloGEM) has been coupled with the Raven hydrological model, tested in Swiss catchments, and is being applied to the Himalayas. Outcomes are expected to improve understanding of glacier dynamics, streamflow response, and support community-level climate resilience.

2.4.1.3 Geosciences & Seismology

GNSS Observations (Delhi-Aravalli Fold Belt & NW Himalaya) - NGRI, Hyderabad

Continuous GNSS measurements since December 2022 have provided over two years of data on crustal displacement, seasonal deformation, plate motion, and preliminary geodetic strain rates. In western Delhi, the data indicate active compression, consistent with observed seismicity, while seasonal deformation due to mass and atmospheric loading has also been quantified. In the NW Himalaya, processed GNSS data, including two new stations in western Jammu, have enabled updated strain rate and coupling maps, revealing low coupling in the Kashmir Valley. These observations provide critical input for seismic hazard assessment and the development of potential earthquake scenarios.

Active Fault, Paleoseismic, and Crustal Deformation Studies- IIT Kanpur

The Active Fault Mapping programme has identified several new active faults and produced a high-resolution (1:25,000) Active Fault Atlas. Paleoseismic trenching revealed surface-rupturing earthquakes from the 15th to 20th centuries. GNSS data from 14 stations indicate convergence rates of ~16.5 ± 1 mm/yr and arc-parallel shearing, highlighting elevated seismic hazard and potential activity of the Main Boundary Thrust. These findings inform regional earthquake risk assessment and disaster preparedness.

Pranmati Basin Himalayan Critical Zone Observatory - Delhi University

At the Pranmati Basin Himalayan Critical Zone Observatory, dense RTK-GNSS measurements have quantified soil creep and hillslope deformation, complemented by electrical resistivity surveys that characterise subsurface structure. Machine-learning-based enhancement of land surface temperature from satellite data has been achieved, while hydrological modelling with data assimilation has improved runoff estimation in data-scarce regions. Cosmogenic nuclide analysis (^{10}Be) reveals spatial variability in erosion and soil production rates, enabling modelling of soil thickness and its validation through field observations.

2.4.1.4 Ocean Sciences

Benthic and Pelagic Biodiversity in Arabian Sea Seamounts - NIO, Goa

This study investigated deep-sea seamounts off Mangalore (12°-14° N, 72°-74° E), focusing on interactions with the oxygen minimum zone (OMZ) at 340-440 m depth. Sediment analyses revealed elevated metals (Fe, Mn, Ni, V, Cr, Zn) and predominantly refractory organic matter. Environmental DNA (eDNA) analyses showed benthic communities dominated by annelids, arthropods, and cnidarians adapted to low-oxygen, high-metal environments, while pelagic eDNA identified crustacean, cnidarian, and chordate

communities with significant spatial variability. The study highlights the ecological importance of OMZ-seamount interactions and demonstrates the effectiveness of eDNA for exploring deep-sea biodiversity.

Metal-Ligand Interactions in Tropical Estuarine Systems - IIT Kharagpur

Investigating Vembanad Lake, Kerala, the study assessed trace and toxic metal cycling, speciation, and ecological risks. Fe and Mn oxyhydroxides and organic matter strongly influenced metal partitioning, while northern sectors exhibited persistent contamination from industrial effluents. Pollution Load Index (PLI) analyses indicated chronic sediment stress, particularly for Cd, Pb, and Hg. The findings provide insights to guide monitoring, remediation, and policy actions to safeguard estuarine ecosystems.

Late Quaternary Changes in Indian Ocean OMZs - NIO, Goa

This study examined temporal variability in oxygen minimum zones off Goa and in the Bay of Bengal using water column profiles (2019-2023) and multi-proxy sediment analyses (up to 51 ka BP). Results show shoaling of the OMZ lower boundary from ~1100 m in 2019 to ~400-800 m by 2023 and increased dissolved oxygen levels, driven by enhanced oxygen supply from Red Sea Water and South Indian Central Water. Sediment core analyses revealed historical OMZ intensification during 37-23 ka BP and oxygenated phases between 13-10 ka BP. These findings enhance understanding of OMZ dynamics, influencing marine biodiversity, biogeochemical cycles, and climate modelling

2.4.2 Awareness and Outreach Programme

2.4.2.1 Earth Day 2025

The Earth Day 2025 was celebrated on 22nd April 2025 under the theme "Our Power, Our Planet", highlighting the transition to renewable energy and sustainable living. Over 85 institutions participated across multiple states, including collaborations with IMD, New Delhi, and IITM, Pune. Activities included rallies, plantation drives, art and slogan competitions, and renewable energy-focused science projects. Thousands of students and community members actively participated, raising awareness about environmental conservation and sustainable practices. (Fig. 2.1)

Fig. 2.1: Celebration of Earth Day 2025 at various organisations/institutions.

2.4.2.2 International Earth Science Olympiad (IESO) 2025

The Ministry supported the 18th International Earth Science Olympiad (IESO 2025), held in Jining, China (8-16 August 2025). Following a national selection process coordinated by the Geological Survey of India (GSI), four student delegates represented India after a three-week residential training program with mentorship from subject experts. The team secured seven medals (1 Gold, 4 Silver, 2 Bronze) and a special award in the I-GYM Reporter category. Students were felicitated by the Hon'ble Minister of Earth Sciences, Dr. Jitendra Singh. The achievement highlights MoES's commitment to nurturing young Earth science talent and promoting STEM education at the school level.

2.4.2.3 Swachh Sagar, Surakshit Sagar

The Swachh Sagar, Surakshit Sagar (SSSS) campaign, led by the Ministry and conducted from 15-20

September 2025, aligned with International Coastal Cleanup Day, actively engaged citizens, educational institutions, NGOs, and volunteers in coastal and marine conservation initiatives. Cleanup drives were carried out at over 800 locations, including more than 75 beaches across key coastal states and Union Territories. Activities included collection and proper disposal of plastic and other waste, awareness workshops on marine pollution, community rallies, and educational outreach highlighting the importance of sustainable coastal management. Thousands of participants, including students, local communities, and partner organisations, contributed to improving marine and coastal health, fostering environmental responsibility, and promoting long-term stewardship of India's shoreline. (Fig. 2.2)

Fig. 2.2: Coastal and marine cleanup activities under the SSSS 2025 campaign.

2.4.2.4 India International Science Festival (IISF) 2025

The IISF 2025, held at Panchkula, Haryana (6-9 December 2025) under the theme "Vigyan Se Samruddhi: for Aatmanirbhar Bharat", showcased India's scientific achievements and innovation. The festival was inaugurated by Hon'ble Minister for Earth Sciences, and attended by dignitaries including the Governor and Chief Minister of Haryana (Fig. 2.3). It brought together scientists, students, startups, industry representatives, and policymakers, featuring 15+ thematic sessions, exhibitions, panel discussions, and outreach activities. Over 1 lakh participants attended, supported by more than 160 curtain-raiser programmes across the country.

Fig. 2.3: IISF 2025 Conducted at Panchkula, Haryana.

2.4.2.5 MoES Foundation Day

MoES celebrated its 19th Foundation Day on 27th July 2025 through a month-long campaign "19 Saal - Vigyan, Sankalp aur Seva", with HMoES as Chief Guest. The campaign highlighted the Ministry's contributions from cyclone forecasting and early warnings to ocean exploration and climate research, showcasing its role in decision support, disaster preparedness, and innovation.

2.4.2.6 Seminars, Workshops, Conferences, Exhibitions & Fairs

During FY 2025-26, financial support was provided for over 200 seminars, workshops, conferences, exhibitions, and fairs, promoting public awareness in Earth Sciences (Table 2.4.2).

Table 2.4.2. MoES Outreach activities during 2025.

Outreach initiatives	
Earth Day Celebration	82 Places
Ozone Day Celebration	02 Places
INESO/IESO	07 Medals
Seminars/Workshops/Conferences	132
Swachh Sagar, Surakshit Sagar	80 Beaches
Exhibitions	12

2.4.3 BIMSTEC Centre for Weather and Climate (BCWC)

NCMRWF/BCWC hosted the BIMSTEC 'Youth-Led Action on Climate Change' organised by Bharat Scouts and Guides (BSG), inaugurated by Dr. M. Ravichandran, Secretary, MoES (Fig. 2.4). Over 100 scouts and guides from BIMSTEC member countries attended sessions on weather and climate forecasting, engaged in interactive discussions with scientists, and toured the NCMRWF HPC facility. Participants were also informed about opportunities for R&D collaboration across BIMSTEC countries.

Fig. 2.4: BIMSTEC youth conference at NCMRWF with student-scientist interactions.

2.4.4 International Training Centre for Operational Oceanography (ITCOOcean)

ITCOOcean conducted 20 training programmes, training 644 participants (India: 570; Other Indian Ocean Rim Countries: 74). 3rd short-term training course, spanning 4 months, was successfully conducted for officers from the School of Naval Oceanology and Meteorology (SNOM), Cochin.

Notable Training Programmes:

- TEMPP Training on Tsunami Evacuation Maps, Plans, and Procedures (15-23 April 2025, INCOIS, Hyderabad): 45 participants from various Indian states attended. (Fig. 2.5)
- DBCP-INCOIS Training Workshop on Ocean Observations (5-7 August 2025, INCOIS, Hyderabad): Focused on operational services in the Indian Ocean. (Fig. 2.6)
- On-job Training for Oman Officials (24-28 November 2025): 8 officials trained in tsunami early warning systems at National Multi Hazard Early Warning System, DGMAN, Oman.

Fig. 2.5: TEMPP Training on Tsunami Evacuation Maps, Plans, and Procedures at INCOIS, Hyderabad (15-23 April 2025).

Fig. 2.6: DBCP-INCOIS Training Workshop on Ocean Observations for Operational Services, INCOIS, Hyderabad (5-7 August 2025).

2.4.5 Development of Skilled Manpower in Earth System Sciences (DESK)

DESK conducted ab-initio training for 25 MRFP JRFs (Batch VI) hosted across nine MoES institutes:

NCESS (4), NCCR (2), NCMRWF (3), IMD (2), CMLRE (5), INCOIS (3), NCPOR (2), NIOT (3), and BGRL (1). The programme included first-semester coursework for IITM and AcSIR JRFs and annual progress reviews for Batches II and IV. In addition, DESK organized over 15 training events, workshops, and conferences in 2025-26, covering topics such as Weather Radar, ARKA HPC, Scientific Writing, AI in Science, GIS & ENVI, Stable Isotopes, Meteorology, and Karmayogi training, with participants from MoES institutes, Navy/IAF officers, and external stakeholders.

2.4.6 MoES Knowledge Resource Centre Network (KRCNET)

The KRCNet & Library programme continued to strengthen MoES's digital knowledge infrastructure facilitating seamless access to scientific information and research outputs across all its institutes. Key achievements include joining the Prime Minister's One Nation One Subscription (PM-ONOS) initiative via INFLIBNET, enabling access to e-resources and peer-reviewed journals from 30 national and international publishers through a unified platform. Additionally, a MoU with CSIR-NIScPR under the NKRC consortium expanded e-resource availability to all MoES scientists and staff.

Chapter-3

Deep Ocean Mission (DOM)

Oceans are central to climate regulation, biodiversity conservation, food security, and global economic systems. Despite covering more than 70 per cent of the Earth's surface, large parts of the deep ocean remain unexplored. For India, a major maritime nation with a coastline of about 11,098 km and a vast EEZ, the deep ocean represents a strategic national resource with significant potential for minerals, energy, biodiversity, and scientific knowledge.

The sustainable exploration and utilisation of deep-ocean resources require advanced technologies, long-term observations, and interdisciplinary research, particularly given the extreme conditions prevailing at great depths. Strengthening indigenous capabilities in deep-ocean science and technology is therefore essential for national resource security, climate resilience, and informed ocean governance.

Against this backdrop, the Ministry launched the Deep Ocean Mission (DOM) in September 2021 as a mission-mode, multi-institutional programme under the Blue Economy framework. The Mission aims to develop technologies for deep-ocean exploration, generate scientific knowledge on ocean processes, and enable the sustainable use of living and non-living marine resources. The Mission also contributes to India's commitments under the SDG 14 on the conservation and sustainable use of oceans.

The Mission is implemented through six thematic verticals:

1. Development of Technologies for Deep Sea Mining, Manned Submersible and Underwater Robotics.
2. Development of Ocean Climate Change Advisory Services.
3. Technological innovations for exploration and conservation of deep-sea biodiversity.
4. Deep Ocean Survey and Exploration.
5. Energy and Freshwater from the Ocean.
6. Advanced Marine Station for Ocean Biology.

The Mission has an approved total outlay of Rs. 4,077 crore, to be implemented in a phased manner over five years. The estimated cost of Phase I (2021-2024) was Rs. 2,823.4 crore, and a no cost extension of Phase I has been approved by the Department of Expenditure to facilitate completion of key technology development, trials, and infrastructure creation.

The Mission is coordinated by MoES through its implementing institutes, National Institute of Ocean Technology (NIOT), Indian National Centre for Ocean Information Services (INCOIS), Centre for Marine Living Resources and Ecology (CMLRE), and National Centre for Polar and Ocean Research (NCPOR), in collaboration with national research organisations, academic institutions, industry partners, and international agencies. During 2025, substantive progress was achieved across all Mission verticals.

3.1. DEVELOPMENT OF TECHNOLOGIES FOR DEEP SEA MINING, MANNED SUBMERSIBLE AND UNDERWATER ROBOTICS.

The development of indigenous technologies for deep-sea exploration and resource utilisation is a core component of the Deep Ocean Mission. This vertical focuses on building national capability in human-occupied submersibles, autonomous and remotely operated underwater vehicles, and environmentally responsible deep-sea mining systems, which are critical for scientific exploration, mineral resource assessment, and meeting India's obligations under international seabed regimes.

3.1.1. Human Submersible MATSYA-6000 and Underwater Robotics

Underwater vehicles are being developed under the Deep Ocean Mission to support scientific exploration and the harnessing of deep-ocean resources. The deep-water human submersible MATSYA-6000 is being designed and developed indigenously at NIOT, Chennai, for scientific exploration up to a water depth of 6,000 m (Fig.3.1

(a). The battery-powered submersible is designed to accommodate three personnel for a mission duration of up to 12 hours, with life-support provision for up to 96 hours in emergency conditions.

Detailed system engineering of MATSYA-6000 was completed in accordance with DNV rules applicable to human-rated underwater vehicles. [Fig. 3.1(a)]. Major subsystems and equipment have been realised and tested independently prior to system-level integration. A key component of the submersible is the 2.1 m diameter, 6,000 m depth-rated titanium alloy personnel sphere. Its realisation is underway through coordinated efforts involving NIOT, the Vikram Sarabhai Space Centre, and the Liquid Propulsion Systems Centre of ISRO. Forgings for the viewport and hatch flanges have been completed, while fabrication of the intermediate rings and bottom dome for the first article has been completed at the L&T facility at Hazira, along with fabrication of associated sub-assemblies.

A 500 m depth-rated, DNV-certified main ballast system has been realised and functionally tested at NIOT. Parallely, a 6,000 m depth-rated, DNV-certified titanium alloy exo-structure and pressure-rated enclosures have been developed to house mechanical, electrical, and electronic subsystems. Assembly and integration of the MATSYA-6000 submersible for wet testing were completed, incorporating all major subsystems and equipment [Fig. 3.1(d)]. Control and monitoring software for the submersible and the associated mission control centre were developed, and integrated dry testing was successfully carried out.

Integrated wet tests, both unmanned and manned, of the human-occupied submersible were successfully conducted for a three-hour endurance at a depth of 8 m at L&T Kattupalli Port during January-February 2025 [Fig. 3.1(d)]. These trials validated the performance of critical systems, including power, control, flotation, stability, life-support, acoustic data telemetry, and maneuverability.

As part of international collaboration and capacity building, five scientists from NIOT participated in an Indo-French deep-sea expedition using the 6,000 m depth-rated human submersible NAUTILE in the North Atlantic Ocean (off Portugal) during August 2025. Two aquanauts from the MATSYA-6000 team undertook dives to water depths of 4,025 m and 5,002 m, respectively [Fig. 3.1(b)]. The expedition provided hands-on operational experience in human submersible missions, including dive preparation, piloting, intervention tasks, deployment, and retrieval. With the operationalisation of MATSYA-6000, India will join a select group of nations possessing human submersible capability to 6,000 m water depth, with approximately 70 per cent indigenous content and complete system assembly [Fig.3.1.(a)].

The scientific exploration trials using the deep-water Autonomous Underwater Vehicle (AUV) OMe-6000 were completed at hydrothermal sulphide sites along the Southwest Indian Ridge and the Central Indian Ridge. High-resolution bathymetric data and imagery of hydrothermal vents on the seafloor were acquired, including at active vent sites [Fig. 3.1(e) & (f)].

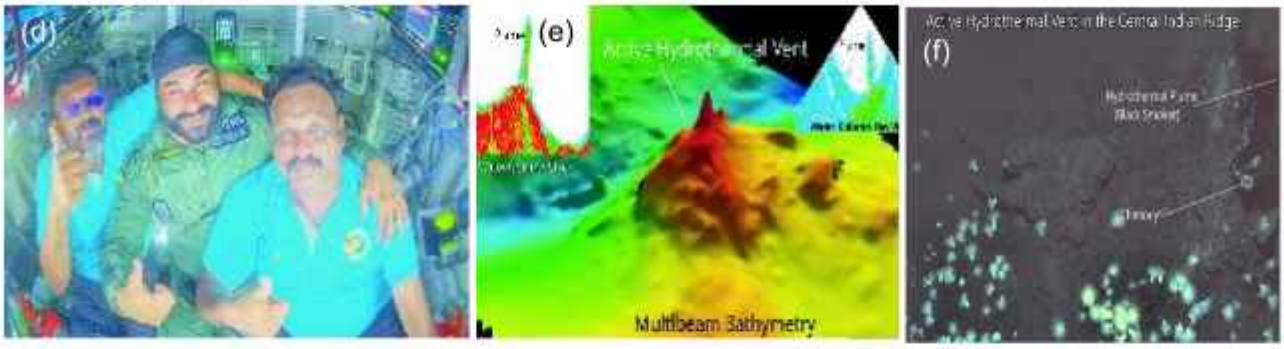


Fig. 3.1.1: The integrated view of MATSYA-6000 (a), NIOT scientists in the NAUTILE expedition (b), the Mission Control Centre c), the wet testing of MATSYA-6000 (d), multibeam bathmetry of an active hydrothermal vent in the Central Indian Ridge (e-f).

3.1.2. Deep-Sea Mining Technology

Technological development for deep-sea mining under the Deep Ocean Mission has progressed significantly, emphasizing environmentally responsible and sustainable practices. Mining machines are being developed and tested to enable India to relinquish its ISA-allocated contract area in the Central Indian Ocean, ultimately retaining only the most promising and commercially viable zones for potential exploitation. The seabed mining system was upgraded by integrating a rake-type nodule collector, which minimizes disturbance to the seabed while enhancing the efficiency of nodule collection. A subsea alternator is being incorporated to provide a reliable power supply for the control and instrumentation systems, ensuring uninterrupted operation during deep-sea mining activities. An end-to-end mining system is under development, capable of collecting, sizing, pumping, and dewatering polymetallic nodules at the surface [Fig. 3.2(a)].

Parallel efforts are underway to upgrade the research vessel Sagar Nidhi with heavy-lift and heavy-compensated systems, enabling it to operate efficiently in open-sea conditions. To complement these efforts, a scoping study has been initiated to develop scalable deep-sea mining technology suitable for the exploration of polymetallic nodules. Additionally, the Deep Ocean Simulator (DOS-1500), designed to replicate extreme deep-sea conditions at 1,500 bar pressure and 3-4°C, is expected to be delivered and installed by mid-2026.

Environmental impact assessments form a key component of this vertical. Detailed studies are being conducted to evaluate seabed plume transport, subsea noise propagation, and appropriate mitigation measures, highlighting India's commitment to developing sustainable and environmentally responsible deep-sea mining technologies. A nodule crushing system has been developed and successfully tested, capable of handling hard rocks and gravel pieces efficiently [Fig. 3.2(b)]. Complementing this, a ship-based slurry dewatering and separation system is under development to separate collected nodules from seawater slurry, ensuring that the extraction process minimizes ecological impact [Fig. 3.2(c)].

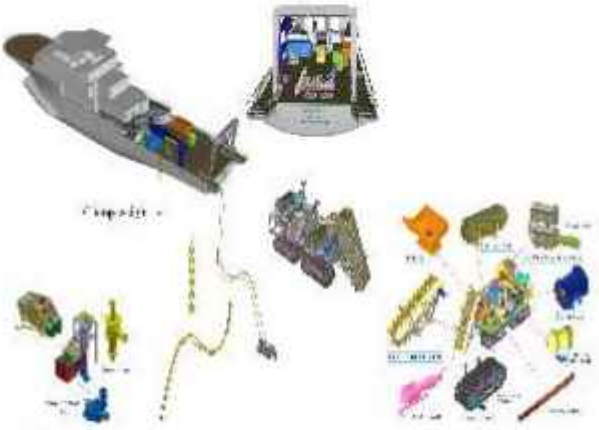


Fig. 3.2a: Schematic of the seabed mining system showing enhanced nodule collection, crushing, slurry pumping, and surface dewatering /separation.

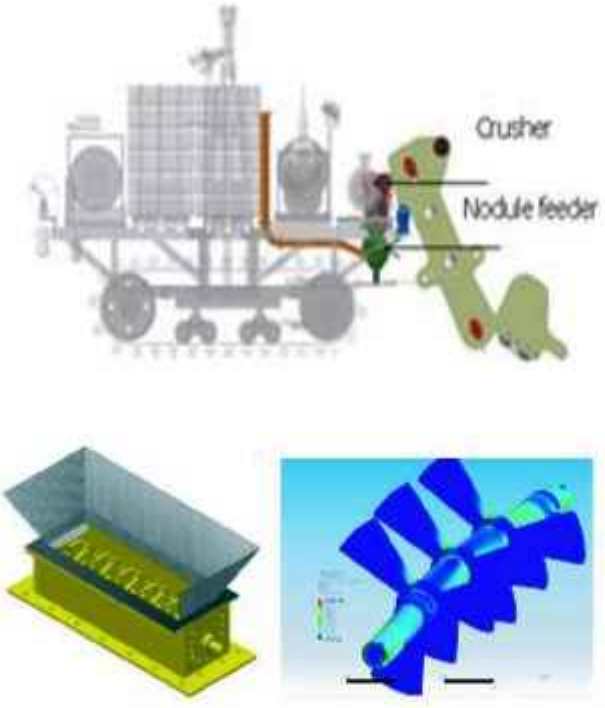


Fig. 3.2b: Schematic of the subsea nodule crusher.

Fig. 3.2c: Schematic of the ship-based slurry dewatering and separation system for recovery of nodules from seawater slurry.

3.2. DEVELOPMENT OF OCEAN CLIMATE CHANGE ADVISORY SERVICES

The Ocean Climate Change Advisory Services (OCCAS) focuses on assessing changes in sea level, cyclone intensity, storm surges, and wave dynamics, along with their impacts on coastal erosion and inundation under projected climate scenarios. In addition, OCCAS evaluates the effects of climate change on the coastal marine ecosystem and generates advisories on the likelihood, intensity, and spread of Harmful Algal Blooms (HABs), which can influence the migration of fishing zones and contribute to the marine-driven economy along India's extensive coastline. The outcomes of these assessments are disseminated through interactive GIS-based mapping applications to facilitate informed decision-making for coastal zone management and policy planning.

3.2.1. Sea Level Projections

The sea level projections module provides downscaled assessments of Mean Sea Level (MSL) along the Indian coast under various climate scenarios. The downscaling is based on a high-resolution Indian Ocean regional model nested within a global model and forced using selected CMIP6 atmospheric datasets. A global model using the Modular Ocean Model (MOM6) with a horizontal resolution of 1/12° (~9 km) and 41 hybrid vertical layers has been developed and integrated for 30 years of hindcast data. Simultaneously, a very high-resolution Indian Ocean regional model at 1/36° (~3 km), nested within the global configuration, has been developed to simulate complex coastal processes. Both models have undergone validation to ensure accuracy, and atmospheric forcings from selected CMIP6 models were bias-corrected for robust downscaling.

Coastal vulnerability maps at 1:25,000 scale have been prepared. While downscaled global model simulations are ongoing, probabilistic 100-year return Extreme Sea Level (ESL) estimates along the Indian coastline, including select island stations, have been computed using available global datasets. These assessments were carried out under SSP2-4.5 (medium challenges to mitigation /adaptation, radiative forcing 4.5 W/m^2) and SSP5-8.5 (fossil-fuel-based high emission scenario, radiative forcing 8.5 W/m^2).

The wave climate analysis of the Indian Ocean has been conducted using the WAVEWATCH-III v6.0.7. A 35-year simulation (1980-2014) forced with seven

CMIP6 Global Climate Models (BCC-CSM2-HR, EC-Earth3, CMCC-CM2-SR, GFDL-ESM4, CNRM-CM6-1-HR, HadGEM3-GC31-MM, and MPI-ESM1-2-HR) was generated and validated against in-situ buoy observations and ERA5 reanalysis data. Statistical analyses indicate that MPI, BCC, and EC models most accurately represent wave characteristics in the Indian Ocean and effectively capture inter-annual variability.

Storm surge projections along the east coast of India were evaluated using the ADCIRC model with synthetic cyclone tracks generated for a 100-year period. For assessing future cyclone activity, a new Genesis Potential Index (GPI) was developed for the Bay of Bengal during the post-monsoon season, demonstrating higher skill than existing GPIs. The median ESLs for baseline and projected scenarios, along with 1-sigma uncertainties, are shown in Fig. 3.3 Coastal vulnerability maps for SSP5-8.5 along Mumbai and cochin are presented in Fig. 3.4.

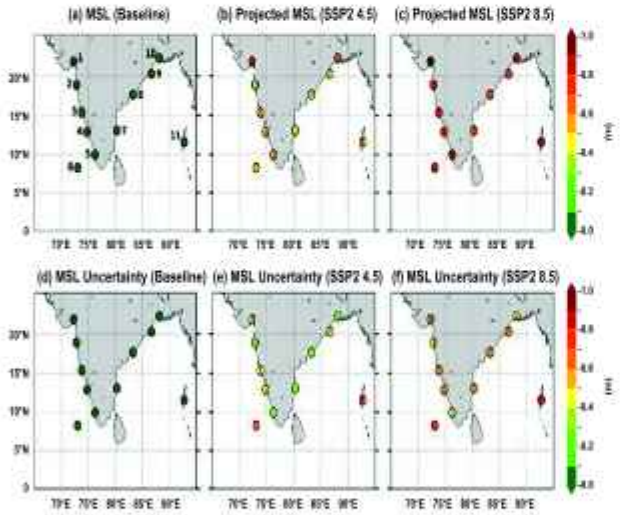


Fig. 3.3: Median Extreme Sea Levels (ESLs) along the Indian coast for the present-day baseline (1980-2014) and future projections under SSP2-4.5 and SSP5-8.5 scenarios for 2100. Panels (a), (b), and (c) show the median ESLs for the baseline, SSP2-4.5, and SSP5-8.5 scenarios, respectively, while panels (d), (e), and (f) display the corresponding 1-sigma uncertainties. Units are in meters.

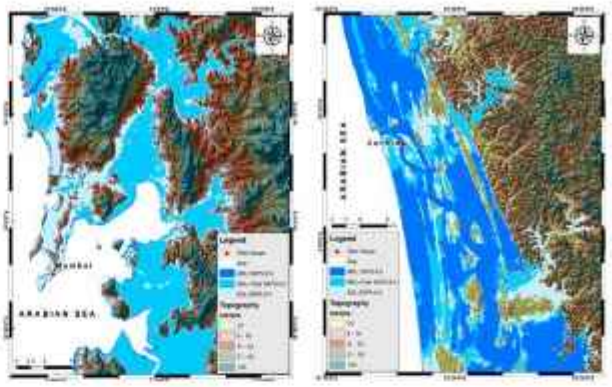


Fig. 3.4: Coastal vulnerability to sea level rise and extreme events under the SSP5-8.5 scenario along Mumbai (left) and cochin (right).

3.2.2. Impact on the Marine ecosystem

The effects of increasing global warming and climate change on the marine ecosystem of the Indian Ocean are becoming increasingly evident, with declining primary productivity and rising ocean acidification disrupting ecosystem balance. To investigate potential future changes, a regional high-resolution coupled ocean-ecosystem model is being used to simulate the Indian Ocean's marine ecosystem for the period 1980-2100. Atmospheric forcings, initial conditions, and boundary conditions for these simulations were prepared using data from three bias-corrected CMIP6 global climate model outputs (GFDL, UKESM, and CNRM).

Biases in atmospheric forcings from the CMIP6 models were corrected using the time-varying delta (TVD) method, with ERA5 reanalysis data as the reference. Physical ocean state variables were bias-corrected against the ECDS reanalysis, while biogeochemical variables were adjusted using appropriate reanalysis datasets. Simulations for the historical period (1980-2014) have been completed, and those for the future period (2015-2100) are currently underway.

3.2.3. Deep Ocean Observations

To support climate advisories INCOIS has deployed 11 Deep Sea Slocum Gliders (SG) in the Bay of Bengal, along with 60 drifters and 92 physical and biogeochemical Argo floats. Both glider tracks in the Arabian Sea and the Bay of Bengal are fully

operational, and to date, 11 glider missions have been successfully completed These missions provide continuous, high-resolution data on oceanographic and biogeochemical parameters essential for climate impact assessments and marine ecosystem monitoring.

The Deep Ocean Observation System (DOOS) incorporates a deep-ocean cable-based multiparameter observatory installed at a depth of 2,000 m. This observatory is designed to monitor deep-ocean physical and biogeochemical parameters in the northern Indian Ocean, study the temporal and spatial variability of the Oxygen Minimum Zone (OMZ), and track water mass properties and ventilation processes in the North Indian Ocean. Complementing this, deep-sea gliders, deep Argo floats, wave drifters, and cable-based ocean bottom observatories collectively provide a comprehensive monitoring network, enhancing India's capacity for climate assessments, early warning systems, and informed ocean governance.

3.3. TECHNOLOGICAL INNOVATIONS FOR EXPLORATION AND CONSERVATION OF DEEP-SEA BIODIVERSITY

Under the Deep Ocean Mission, NIOT and CMLRE are spearheading initiatives to explore, document, and conserve deep-sea biodiversity. Key objectives include the systematic inventorisation and archival of deep-sea organisms, development of a DNA bank and biological repository, and advancement of technologies for isolating piezo-tolerant and piezophilic microbes. Complementary efforts focus on screening for novel biomolecules using both culture-based and metagenomic approaches.

3.3.1. Inventorisation and Archival of Deep-Sea Biodiversity

CMLRE conducted extensive surveys across 25 seamounts, recognized as biodiversity hotspots, during six cruises aboard Sagar Nidhi, Sagar Manjusha, and Sagar Sampada. These surveys yielded over 1,062 samples of deep-sea fauna and flora, along with 1,062 DNA sub-samples from Arabian Sea seamounts. The samples represent approximately 195 species, of which around 39 appear to be previously undescribed, potentially new to science. To standardize collection and documentation procedures, a comprehensive manual, "Building a Baseline: Comprehensive Survey Methods for the Collection, Preservation and Documentation of Marine Biodiversity", was published and released by the Hon'ble Minister of State for Earth Sciences during the 19th Foundation Day of MoES (Fig. 3.5). A germplasm resources facility for deep-sea organisms has also been established at CMLRE, Kochi. The IndOBIS portal (https://indobis.in/) and the OceanEyes mobile application have been updated to include new records and species, thereby enhancing citizen science contributions to marine biodiversity documentation.

Fig. 3.5: Release of the manual "Building a Baseline: Comprehensive Survey Methods for the Collection, Preservation and Documentation of Marine Biodiversity" on the 19th Foundation Day of MoES.

NIOT conducted nine cruises aboard Sagar Manjusha, Sagar Nidhi, and Sagar Sampada, collecting 142 deep-sea water and 33 sediment samples from the Arabian Sea, Indian Ocean, and Bay of Bengal. Analyses of these samples identified 940 distinct heterotrophic bacteria, 360 actinobacteria, 323 fungi, 222 yeasts, and 35 myxobacteria. A significant rediscovery was made with the deep-sea molluscan species *Nassarius subsimilis* (E.A. Smith, 1906), recorded from the Lakshadweep seamount ecosystem at 341-345 m depth, marking its first observation in over a century (Fig. 3.6).

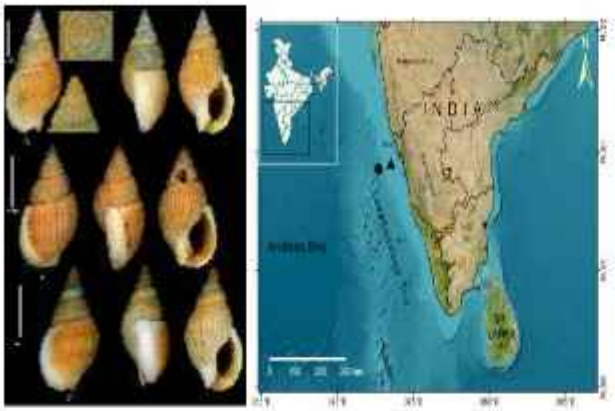


Fig. 3.6: Deep-sea molluscan species *Nassarius subsimilis* (E.A. Smith, 1906) recorded from the Lakshadweep seamount ecosystem after 119 years (left) and its collection site (right).

Protocols for DNA extraction from deep-sea sediment samples have been standardized to improve the yield, purity, and integrity of environmental DNA (eDNA). Nearly 30 distinct copepod genera have been documented, and a novel cell culture system has been developed from the caudal fin tissue of *Amphiprion percula*. Microbial profiling of water and sediment samples from the Northern Indian Ocean revealed microbial counts ranging from 3.08×10^3 to 5.01×10- CFU/mL in water and 7.63×10^3 to 9.58×10- CFU/g in sediments.

Analyses of deep-sea microbes for functional biomolecules demonstrated promising capabilities. A filamentous fungus, *Trichoderma sp.*, was found to produce surface-active hydrophobin (HFB) with a molecular weight of 7.8 kDa. The deep-sea yeast *Hortaea werneckii* NIOT129A8 exhibited potential as a high-yield melanin producer (15 g/L). Furthermore, the hydrocarbonoclastic bacterium *Bacillus tequilensis* G6 degraded 94% of pyrene at 10 MPa, compared to 86.5% under atmospheric pressure, indicating enhanced activity under high-pressure conditions. A representative deep-sea microbe isolated from the Northern Indian Ocean is shown in Fig. 3.7.

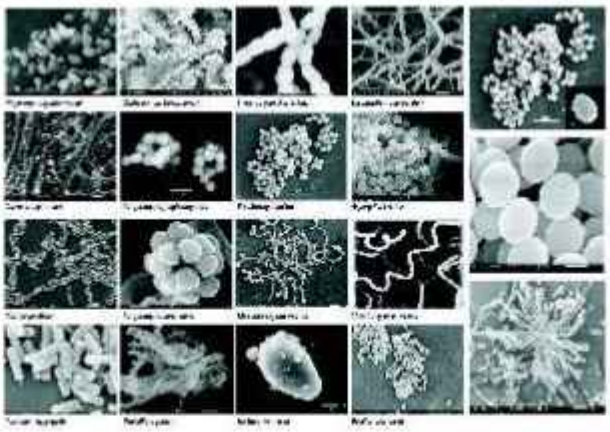


Fig. 3.7: Representative deep-sea microbe isolated from the Northern Indian Ocean.

3.3.3. Developing technologies for isolating deep-sea piezo-tolerant and piezophilic microbes

Under the Deep Ocean Mission, significant progress has been made in developing technologies for the collection and cultivation of deep-sea piezo-tolerant and piezophilic microbes. The high-pressure retainable water sampler system (HPWS), designed to collect large volumes of both pressurised and non-pressurised deep-sea samples, has been fully designed and is in the realization phase. Complementing this, a high-pressure microbial culture system (Fig. 3.8) rated to 600 bar with precise temperature and hydrostatic controls has been designed to support the cultivation of piezophilic microbes. Furthermore, the civil infrastructure and overall design for the upcoming Marine Microbial Repository at NIOT Chittedu have been finalized, and construction work is underway through CPWD .

Fig. 3.8: Design of the high pressure retainable water sampler (left) and the high pressure microbial culture system (right).

3.3.4. Screening for Novel Biomolecules Using Culture-Based and Metagenomic Approaches

A comprehensive program of culture-based and metagenomic screening has been undertaken to explore novel biomolecules from deep-sea microbial communities. From sediment and water samples collected across the Arabian Sea, Indian Ocean, and Bay of Bengal, 22,577 and 1,248 metagenomic clones were constructed, respectively. Subsequent analyses generated 1,402 metagenome-assembled genomes (MAGs) and 150 deep-sea single-cell genomes (SAGs), revealing rare microbial groups including *Omnitrophota, Patescibacteria, Candidatus Sifixiota, Candidatus Asafiota, Candidatus Cuxufiota,* and *Armatinmonadota.*

FACS-based screening of 8,640 fosmid clones identified eight clones with high production of polyhydroxyalkanoates (PHAs), naturally occurring biodegradable polymers. These clones exhibited a maximum PHA content of 71% and thermal stability up to 482°C. Additionally, LC-MS/MS exometabolomics analyses revealed 88 metabolite classes distributed across 42 superclasses, including N-acyl amines, fatty alcohols, dipeptides, amino acids, and various alkaloids. These efforts underscore the potential of deep-sea microorganisms as a rich source of industrially and pharmaceutically relevant biomolecules.

3.4. DEEP OCEAN SURVEY AND EXPLORATION

3.4.1. Exploration of Hydrothermal Deposits

In September 2016, the Government of India signed a 15-year contract with the International Seabed Authority (ISA) for the exploration of polymetallic sulphides over a 10,000 km² area along the Central Indian Ridge (CIR) and Southwest Indian Ridge (SWIR) in the Indian Ocean. NCPOR has conducted extensive multidisciplinary shipboard surveys in these license areas to identify potential mineralization zones and hydrothermal vent sites. The datasets include physical oceanographic (turbidity, temperature, redox), chemical oceanographic (Mn, CH, He, Fe concentrations), geophysical (multibeam bathymetry, gravity), and geological (mineral deposits and sediments) data.

Analysis revealed evidence of hydrothermal plumes in the water column, marked by elevated turbidity, trace metals, and dissolved gases, predominantly located within rift valleys and intra-rift highs in both CIR and SWIR. Sulphide mineral deposits were sampled at multiple sites, and integrated data analysis highlighted 26 promising locations for hydrothermal vents or mineral-rich zones.

From these, 13 locations were selected for high-resolution near-seabed geophysical surveys using the Autonomous Underwater Vehicle (AUV) (Fig.3.9). The surveys, conducted between March and June 2024 at approximately 55 m above the seabed, utilized a suite of sensors including multibeam echosounder, synthetic aperture sonar, electric self-potential sensors, magnetometers, CTD, turbidity, methane, ORP, DO, and pH sensors, as well as a sub-bottom profiler. These surveys confirmed four active hydrothermal vent fields and identified sulphide deposits at two CIR locations. Follow-up AUV surveys in December 2024 provided visual confirmation of active venting, capturing imagery of hydrothermal chimneys, plumes, and associated ecosystems (Fig.3.9).

The next stage involves detailed surveys using a Remotely Operated Vehicle (ROV) to collect mineral and rock samples, sediments, and biological specimens, and record high-resolution videos to support India's claim over 2,500 km² of the seabed.

Fig. 3.9: Deployment of the AUV from ORV Sagar Nidhi for hydrothermal vent exploration.

3.4.2. Acquisition of Research Vessel

Under this vertical of the Deep Ocean Mission, a new multi-purpose research vessel is being acquired to enhance India's oceanographic research capabilities and safeguard strategic interests in the Indian Ocean. The vessel is being constructed by M/s Garden Reach Shipbuilders and Engineers Ltd. (GRSE), Kolkata, at a cost of Rs.839.55 crore.

Fig. 3.10: Sequential stages of vessel block assembly at GRSE dry dock, Kolkata.

Following the steel-cutting ceremony, block fabrication for the vessel commenced at the GRSE premises. Fabricated blocks undergo inspections and testing before being assembled at the dry dock. Block fabrication and erection activities are presently underway (Fig. 3.10). GRSE has placed orders for major long-lead items. Model studies and detailed drawings of the vessel have been completed. Steel cutting for fabrication began in November 2024, and to date, 50% of the blocks have been assembled. The vessel is scheduled for completion and delivery by January 2028.

3.5. ENERGY AND FRESH WATER FROM THE OCEAN

This initiative aims to harness renewable energy from the ocean by using India's tropical ocean conditions, where surface temperatures range between 27°C and 32°C, and temperatures at 1000 m depth are around 7°C. This temperature difference creates a constant thermal gradient that can be used for energy generation through Ocean Thermal Energy Conversion (OTEC). Detailed studies and engineering designs are underway for a large offshore OTEC-powered desalination plant. The plant will have two modules of 2.5 million litres per day (MLD) desalination capacity using open-cycle OTEC and two 5 MW power generation modules using closed-cycle OTEC. The design of critical process equipment, such as heat exchangers, and the layout on the offshore spar-shaped platform (Fig. 3.11) have been finalized. A Detailed Project Report is nearing completion in collaboration with M/s Oceanergy.

To demonstrate this technology on a smaller scale, a pilot offshore OTEC platform is planned to generate both electricity and fresh water. The pilot plant will feature a 100 kW closed-cycle OTEC unit and a 1 lakh litres per day open-cycle desalination module, designed for deployment on a floating platform in waters over 1 km deep. Proposals from four consortia have been received, and preliminary designs and layouts have been developed.

Additionally, a 1 MW hybrid renewable power plant is proposed for the Lakshadweep. This plant will integrate floating solar panels, offshore wind, OTEC, and ocean currents to provide reliable power to these remote islands. The project has a budget allocation of Rs.200 crore.

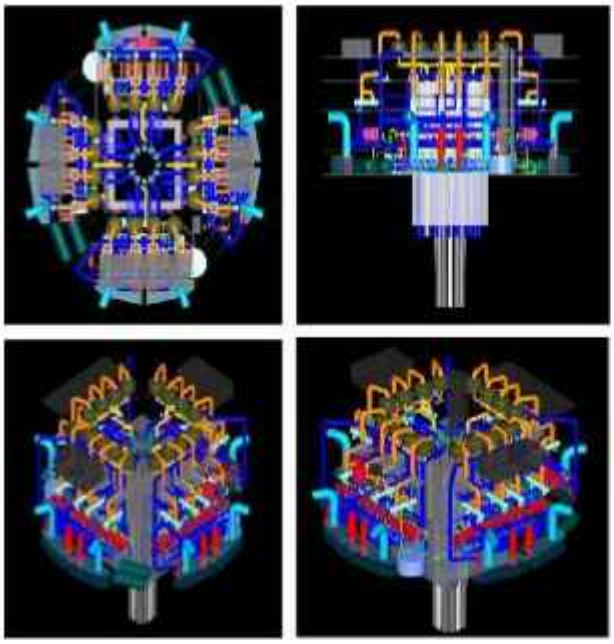


Fig. 3.11: Layout of process equipment on the spar-shaped offshore OTEC platform for electricity and desalinated water generation.

3.6. ADVANCED MARINE STATION FOR OCEAN BIOLOGY (AMSOB)

An Advanced Marine Station for Ocean Biology (AMSOB) is being established to strengthen human capacity and enterprise in ocean biology. AMSOB will expand basic and applied research in marine biology, ecology, and related marine technology and engineering, translating research into industrial applications and product development through on-site business incubators.

AMSOB aims to fuel the Government of India's blue economy vision through knowledge sharing, student and scientist exchange programs, translational and interdisciplinary research, research-to-product development, and support for incubation centres. As part of capacity-building initiatives, the MSc Marine Biology course with Pondicherry University was launched in April 2025 by the Secretary, MoES (Fig. 3.12), marking the first academic program under AMSOB.

Fig. 3.12: Launch of the MSc Marine Biology course with Pondicherry University in April 2025 by the Secretary, MoES.

AMSOB will provide the necessary infrastructure and facilities to support a wide range of ocean-biology activities. It is planned to include state-of-the-art in-house research laboratories, classrooms, administrative offices, conference hall, meeting rooms, hostels, and specialised facilities equipped with cutting-edge research equipment, instrumentation, and technology to support advanced research and educational programs in various areas of marine science. AMSOB will also provide accommodation facilities for researchers and students who may visit the main centre for short or extended periods, ensuring a conducive environment for focused research and outreach programs.

The objectives include building national and international capacity, fostering collaborative education and research, and enabling translational and industry-oriented research. A 4.99-acre coastal land for AMSOB has been procured in Nemmeli, Tamil Nadu. Preliminary layouts and architectural designs are being finalized.

The hub-and-spokes model for AMSOB has been initiated with DOM spokes at MoES institutes in Goa (NCPOR), Kochi (CMLRE), Chennai, Andaman, and Chittedu in Nellore (NIOT). Scientific project manpower has been recruited, and approximately 140 collaborative research projects are ongoing with over 50 national institutions. Academic programs include MSc courses with Pondicherry University, Vikrama Simhapuri University, and

Bhavnagar University; conference programs with IIT Madras and Sathyabama University; joint PhD fellowships with CSIR; postdoctoral programs; and international collaborations with institutions in France (Roscoff Marine Station, Sorbonne University, CNRS, Institute of Biological Sciences, Institute of Ecology and Environment, IFREMER) and Germany (DSMZ), along with incubation support through TIFR/NCBS.

A dedicated website (https://www.amsob.in/NIOT/HomePage) has been developed with CDAC Noida, hosting comprehensive information about AMSOB's research, collaborations, and programs, including a module for announcing postdoctoral opportunities, ensuring accessibility for students, researchers, and collaborators.

Chapter - 4
Mission Mausam

4.1 Introduction

Mission Mausam is a flagship initiative of the Ministry aimed at making India weather ready and climate smart by enhancing observational, modelling, forecasting, and dissemination capabilities. Approved by the Union Cabinet with an outlay of ₹2,000 crore for 2024-26, the Mission aims to improve weather and climate services across temporal and spatial scales, with particular emphasis on monsoon research, climate change, severe weather, hydrometeorology, air quality, and related atmospheric and climate sciences.

Mission Mausam builds on the foundations of Atmosphere & Climate Research Modelling Observing Systems & Services (ACROSS) umbrella scheme of the Ministry. ACROSS was continued under the 15th FC cycle with an approved outlay of ₹2,135 crore for 2021-26 and, in September 2024, was subsumed into Mission Mausam to provide a unified, mission mode framework. This enables better coordination, leverages broader investments, and strengthens implementation across weather and climate forecasting, observational infrastructure, Earth system modelling, and service delivery.

At its core, Mission Mausam advances high-resolution numerical weather prediction and climate models, with a particular focus on understanding and predicting the Indian monsoon. Modernisation of observational networks and generation of impact-based forecasts aim to support decision-making across agriculture, water, energy, health, and disaster management, enhancing preparedness for extreme weather and societal resilience.

Mission integrates the expertise of all MoES institutions. IMD, IITM, and NCMRWF lead in observations, forecasting, and high-resolution modelling. INCOIS and NIOT strengthen ocean and coastal monitoring, while CMLRE improves aerosol and atmosphere-ocean interaction studies. NCESS advances Earth system and hydrometeorological research, and NCPOR, NCS, and NCCR contribute polar, seismic, coastal, and geodynamic insights. Together, these institutions strive to ensure accurate forecasts, early warnings, and climate services, supporting disaster preparedness, sustainable development, and India's vision of Viksit Bharat 2047.

Implementation of Mission Mausam through modern observational and computing infrastructure will enable high-resolution (5×5km) forecasts for severe weather, impact- and risk-based warnings, last-mile early warning delivery, and a 10-15% improvement in forecast accuracy by 2030.

To operationalise its strategic goals, nine interrelated verticals have been established under Mission Mausam, each with specific objectives and deliverables:

- OBSERVE_All: Comprehensive weather monitoring and data collection for nowcasting, data assimilation, model development, and decision support.
- DEVELOP: Development of next generation Earth System Models (ESM) for improved forecasts.
- IMPACT: High impact weather forecasting, early warning systems, and research to operations pathways.
- FRONTIER: Establishment of advanced technologies for weather observation and measurement.
- ATCOMP: Air quality monitoring and decision support systems for pollution management.
- DECIDE: Development of Decision Support Systems (DSS) for weather services across sectors.
- Weather_MOD: Protocols and technologies for weather modification strategies, including rain enhancement and fog/hail suppression.
- LEAD (Leading Effort for Advanced Decisions): Capacity building and innovation in weather information dissemination.
- NEAT (National Enterprise for Atmospheric Technology): Establishment of a unified observational approach through public-private partnerships.

Together, these verticals integrate observational expansion, scientific research, technology development, modelling and forecasting improvements, and rapid dissemination frameworks to realise Mission Mausam's vision of a safer, more resilient, and climate prepared India. Major milestones for 2025-26 include:

4.2 Observations Enhancement to monitor all weather - OBSERVE_All

4.2.1 Enhanced Doppler Radar Network: Dual-polarized Doppler Weather Radars (DWR) have been commissioned under Mission Mausam to enhance severe weather monitoring across India. State-of-the-art C-Band DWRs with solid-state power amplifiers are operational at Raipur (Chhattisgarh) and Mangaluru (Karnataka), providing a 250 km radial coverage for phenomena such as monsoon depressions, low-pressure systems, heavy rainfall, thunderstorms, lightning, squalls, turbulence, and hailstorms (Fig.4.1). Complementing these, an X-Band DWR at the High-Altitude Cloud Physics Laboratory (HACPL), Mahabaleshwar, delivers high-resolution observations of intense rainfall and detailed precipitation microphysics over the Western Ghats.

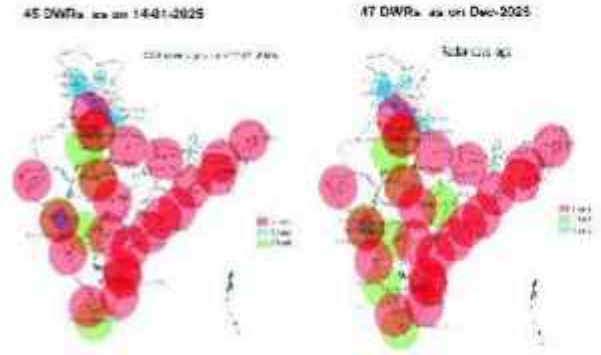


Fig. 4.1: Augmentation of the Doppler Weather Radar network across India (Jan-Dec 2025).

4.2.2 Atmospheric Research Testbeds (ART): Process Testbeds

IITM, Pune has established ARTs across India to advance the understanding of atmospheric processes in diverse environments. In the Mumbai Metropolitan Region, four X band radars at Panvel, Vasai Virar, Vile Parle and Kalyan Dombivli provide comprehensive urban coverage. The 2025 monsoon season was monitored using the Urban Radar Network and the dense Rain Gauge network (MESONET), with high resolution rainfall information made available in real time through a dedicated portal www.mumbairain.tropmet.res.in and mobile applications in Marathi, Hindi and English. Urban testbeds are also operational in Delhi, Mumbai and Chennai, while process testbeds are being established at Bhopal, Munnar and Visakhapatnam. These facilities represent distinct climatic and geographical settings, enabling detailed studies of boundary layer dynamics, cloud microphysics, precipitation processes, and urban weather impacts. Fig. 4.2 illustrates specific observational capabilities, including 3D wind retrieval over Mumbai [(Fig. 4.2(a) & (b)].

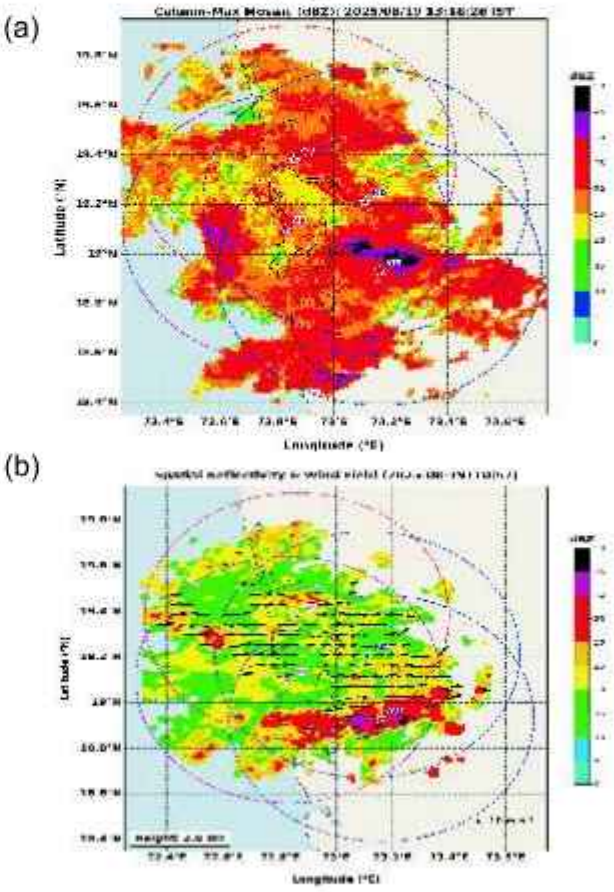


Fig. 4.2 (a) & (b) 3A robust multi-Doppler analysis algorithm has been implemented to retrieve three-dimensional wind structures over the Mumbai region, marking this the first such effort in India.

The ART is being established at Visakhapatnam, targeting the coastal and marine-influenced environment to better understand monsoon convection, extreme weather events, and aerosol-cloud interactions along India's east coast. Of the five procured ceilometers, three are installed at Visakhapatnam, while the remaining two are deployed at Mumbai and Mahabaleshwar to monitor cloud base, aerosol, and boundary layer heights. Additionally, ART at Visakhapatnam is equipped with advanced aerosol and cloud monitoring systems, including instrumentation for carbonaceous aerosol speciation, refractory black carbon characterization, and cloud condensation nuclei (CCN) measurements, supporting comprehensive studies of atmospheric composition and aerosol-cloud interactions.

The Central India ART conducted the Monsoon Observational Campaign 2025, employing high-resolution radiosonde profiles, radar, and co-located instruments to capture detailed monsoon dynamics. The facility also hosted the Balloon Experiments for Atmospheric Composition and Troposphere-Stratosphere Studies (BEATS) campaign, focusing on the upper troposphere-lower stratosphere (UT/LS), yielding valuable insights into atmospheric composition and vertical coupling processes. Collectively, these ART and Urban Testbed facilities establish a nationwide high resolution atmospheric observation network that strengthens research on monsoon dynamics, urban weather, extreme events, and aerosol-cloud interactions, thereby enhancing India's weather forecasting and climate resilience capabilities.

4.2.3 Lightning Location Network (LLN) & Thunderstorm Dynamics

The Lightning Location Network (LLN) has been established under Mission Mausam to monitor and study both cloud to ground (CG) and intra cloud (IC) lightning flashes across India, providing crucial insights into lightning characteristics, spatial distribution, and thunderstorm behavior. With recent expansion, the network now comprises 117 operational sensors integrated with the central processing system at IITM, Pune, greatly strengthening national lightning detection capability for operational use, research, and early warning services. The LLN data are processed centrally at IITM, providing location information with high spatial accuracy and supporting nowcasting and warning services shared with IMD and State Governments for use in forecast and warning dissemination at sub divisional and district levels. To support public awareness and dissemination, the Damini mobile application provides real time lightning alerts based on LLN data, notifying users of nearby lightning strikes within defined radius thresholds.

Mission Mausam has also supported the development of specialised infrastructure to study atmospheric electricity and thunderstorm dynamics. Dr. A.K. Kamra Atmospheric Electricity Observatory at IITM Pune houses instruments such as electric field mills, Gerdien apparatus, Maxwell antennas, and space charge tubes to measure potential gradients, atmospheric conductivity, electric currents, and air-earth current density over India. Complementing this, an Atmospheric Electricity Observatory has been established at Maitri Station, Antarctica (Fig. 4.3), equipped with similar instrumentation in both indoor and outdoor configurations to enable comprehensive measurements of atmospheric electricity variability and its linkages with lightning activity over the Indian subcontinent and polar environments.

Mission Mausam's LLN collaborates with regional partners including the North-Eastern Space Applications Centre (NESAC) and the Assam State Disaster Management Authority (ASDMA) to enhance lightning data use and develop public-facing alert tools. Partnerships with Krishi Vigyan Kendra (Ramanathapuram), Kamraj College (Thoothukudi), and the College of Fisheries Engineering under Dr. J. Jayalalithaa Fisheries University (Nagapattinam) strengthen regional detection and dissemination efforts. Collectively, these LLN and atmospheric electricity observation systems support critical research on thunderstorm electrification, boundary layer processes, and the influence of lightning on cloud microphysics,

advancing scientific understanding and operational forecasting under Mission Mausam.

Fig. 4.3: Atmospheric electricity observatory at Maitri station, Antarctica.

4.2.4 Disdrometer Network for Rainfall Microphysics

Managed by IITM, the Disdrometer Network is India's first national infrastructure for high-resolution, continuous monitoring of rainfall microphysics. Strategically deployed across diverse climatic zones, including tropical maritime, monsoonal, mountainous, and urban environments, the network uses Joss-Waldvogel Disdrometers (JWDs) to capture detailed rainfall characteristics such as drop size distribution (DSD), rain rate, liquid water content, and reflectivity, which are essential for understanding how regional precipitation variability is influenced by local dynamic and thermodynamic conditions (Fig. 4.4). In 2025-26, the network was expanded with new installations at Itanagar (Arunachal Pradesh) and Goa, strengthening observational coverage in the northeast and coastal western regions. Disdrometers have also been deployed in Delhi to support urban meteorology studies and integrate rainfall microphysics research with operational weather services. Currently, 20 disdrometers are part of this expanding network, which also contributes to the National Monsoon Experiment under Mission Mausam.

Fig. 4.4: Joss-Waldvogel Disdrometer (JWD) installation at NCPOR, Goa.

4.2.5 North-East India Observational Network Enhancement

Under the Northeast India Observational Network (NEION) initiative, advanced instrumentation has been installed to capture high-resolution precipitation data in the northeastern region. A Micro Rain Radar, an Impact Disdrometer, and Automatic Rain Gauges (ARGs) have been deployed at the ST Radar Facility of Gauhati University, Guwahati, Assam, with additional ARG measurements collected at multiple locations in Arunachal Pradesh. Several instruments have also been procured to support the urban meteorological testbed facility in Guwahati. This observational effort is designed to examine the impacts of rapid anthropogenic changes and shifting land use patterns on cloud properties, precipitation microphysics, and severe weather occurrences in one of the country's most vulnerable climatic regions.

4.2.6 Scintillometer Facilities, Soil Moisture Network & Ceilometer

Advanced surface and atmospheric profiling systems have been deployed to strengthen

understanding of land-atmosphere interactions and improve weather prediction. Scintillometers installed at critical zone observatories in Attappadi, Munnar, and Aduthurai provide real-time measurements of surface heat and moisture exchanges, enhancing assessments of energy balance and microclimatic variability, which support irrigation scheduling, water planning, and climate-resilient agriculture (Fig. 4.5). Soil moisture observations, a key link between the land surface and atmosphere, help reduce forecast biases and improve predictions of extreme events. NCESS is establishing a network of COsmic-ray Soil Moisture Observation System (COSMOS) and profile soil moisture stations across major climatic zones and developing operational high-resolution soil moisture datasets at broader scales (Fig. 4.6). To augment atmospheric profiling, ceilometers for continuous cloud base and aerosol measurements have been installed at the NCESS campus and the High Altitude Cloud Physics Observatory, Munnar, while Laser Precipitation Monitors (LPMs) deployed across observatories provide detailed precipitation microphysics (Fig. 4.7). Radiosondes have also been procured and launched for real-time vertical profiles. of temperature and humidity.

Fig. 4.5: Scintillometer facility established by NCESS at the Tamil Nadu Rice Research Institute (TRRI), Aduthurai Critical Zone Observatory.

Fig. 4.6: Soil moisture profiler installed at the NCESS Critical Zone Observatory in Aduthurai.

Fig. 4.7: Instrumentation at NCESS atmospheric observatories: (a) Ceilometer installed on the rooftop of the NCESS campus, (b) Laser Precipitation Monitor at the High Altitude Cloud Physics Observatory in Munnar, and (c) Radiosonde launch at the NCESS campus.

4.2.7 Hydrometeorological Observation System: Scalable Climate Monitoring with Internet of Things (IoT)

An IoT based hydro meteorological monitoring system has been developed to provide accurate, high resolution observations of soil moisture and atmospheric variables. Designed, deployed, and evaluated at the IITM-COSMOS site in Pune, the system offers real time automated measurements of soil moisture and temperature at multiple depths, along with air temperature, humidity, pressure, rainfall, and phenological data. Its modular microcontroller based design allows flexible sensor integration and scalable deployment. Using BLE, GSM/GPRS, and Wi Fi, with solar and battery backup, it ensures reliable, continuous data transmission. Multi-depth, area-averaged measurements improve representativeness, while features like sensor damage alerts enhance data quality and continuity. The system also supports training and

demonstrations, making it a cost-effective solution for climate-resilient agriculture, water management, and environmental research under Mission Mausam.

4.2.8 Direct Broadcast Network (DBNet) stations

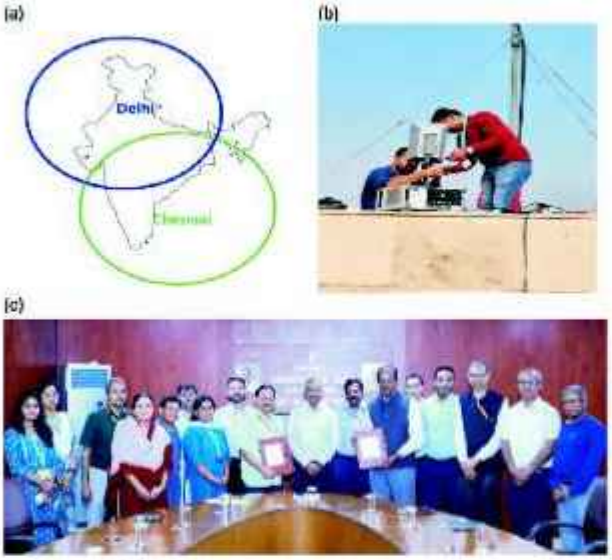


Fig. 4.8. (a) Expected DBNet data coverage over Delhi/NCR and Chennai during LEO satellite overpasses, (b) site survey of DBNet stations at NCMRWF, and (c) MoU signing between MoES and NewSpace India Limited (NSIL), DoS on 23 September 2025.

Real-time observations are crucial for generating accurate initial conditions in Numerical Weather Prediction (NWP) models, as delays can degrade forecast quality, disrupt assimilation cycles, and slow the dissemination of refined forecasts. Typically, Low Earth Orbit (LEO) satellite data reach forecasting centres with a latency of 1.5-2 hours, since observations are stored onboard and transmitted only after a full orbit pass, limiting their usefulness for time-sensitive applications, particularly during high-impact weather events. The Direct Broadcast Network (DBNet) ground station framework addresses this challenge by enabling immediate, real-time reception of satellite data during each overpass, providing timely atmospheric measurements such as temperature, humidity, cloud properties, and microwave sounding data for NWP assimilation.

To implement this capability, NCMRWF signed a MoU on 23 September 2025 with NewSpace India Limited (NSIL) to establish two state of the art DBNet stations in Delhi/NCR and Chennai. These DBNet stations will receive real time data from a wide constellation of current and future LEO satellites operated by agencies such as NASA/NOAA, ESA, ISRO, and others, capturing observations across both X band and L band frequencies with provisions for future expansion. By significantly improving data timeliness for assimilation into global and regional NWP systems, the DBNet framework is expected to enhance forecast accuracy for phenomena such as convection, cyclogenesis, fog, heavy rainfall, and other high impact weather events. The expected spatial coverage during satellite overpass is shown in Fig. 4.8.

4.2.9 Aerosol Monitoring and Sampling over the Indian Coastal Stations

Fig. 4.9: Coastal aerosol sampling network showing locations of stations established along India's east and west coasts, including the Andaman & Nicobar Islands and Lakshadweep.

A network of 18 continuous aerosol monitoring and sampling stations has been established along India's east and west coasts, including the Andaman & Nicobar Islands and Lakshadweep, to systematically observe coastal aerosol characteristics (Fig. 4.9). Developed in collaboration with national research laboratories, universities, and academic institutions, this network offers comprehensive coverage of coastal environments, supporting long term capacity building and logistical coordination. Standardised sampling protocols have been implemented at all sites to collect Total Suspended Particulates (TSP), PM_{10}, and $PM_{2.5}$ using high volume and size segregated samplers. Regular seasonal sampling, especially during pre and post monsoon periods that see significant shifts in aerosol sources and transport pathways, yields high quality data on aerosol mass, water soluble ions, organic carbon fractions, and optical properties essential for understanding coastal aerosol sources, chemistry, and their influence on atmospheric and marine processes.

Beyond routine monitoring, CMLRE has initiated experimental and process focused studies to assess the role of atmospheric aerosols in coastal environmental systems. These investigations have yielded insights into aerosol chemical composition, secondary formation pathways, and interactions with coastal waters. The progress in establishing the coastal aerosol observation network and initial scientific findings provides a strong foundation for future work to quantify aerosol deposition to oceans, examine effects on marine biogeochemistry and ecosystems, and inform national strategies on air quality, climate variability, and coastal environmental management.

4.2.10 Drone based coastal observations

NIOT is making significant contributions to Mission Mausam through the development and deployment of drone based observatories for coastal atmospheric and oceanographic measurements. Customized unmanned aerial vehicles equipped with advanced sensor payloads collect real time data on air and seawater CO_2, as well as key water quality parameters and ocean surface conditions. Drone-assisted measurements were carried out along the Tamil Nadu coast and the Swarnamukhi river-sea transect, providing high-resolution in-situ data on coastal air-sea exchanges and ecosystem health (Fig. 4.10). These drone systems enhance spatial and temporal resolution of coastal datasets, complementing fixed platform observatories.

Fig. 4.10: Drone assisted measurements of air and seawater CO_2 along the Tamil Nadu coast and Swarnamukhi river-sea transect at Pamanji-Nellore.

NIOT is advancing fixed platform coastal observatory systems, including integrated multi-parameter stations at near shore and offshore locations, to monitor atmospheric and oceanographic processes continuously. These systems supply comprehensive data on variables such as temperature, humidity, salinity, and gas fluxes, which are essential for improving models used in weather and climate prediction. NIOT also collaborates with IMD and IITM, Pune, on research initiatives such as drone based atmospheric profiling for thunderstorm and boundary layer.

4.3 Earth System Model Development - DEVELOP

4.3.1 Bharat Forecast System (BharatFS) and Extended Range Prediction (BharatFS-ERP)

India's advanced short- and medium-range weather prediction capability was significantly strengthened with the development of the Bharat Forecast System (BharatFS). The system was dedicated to the nation on 26th May 2025 at Vigyan Bhawan, New Delhi, by the Hon'ble Minister of Earth Sciences (Fig. 4.11). Developed by IITM, BharatFS is a high-resolution global numerical weather prediction system operating on a TCo grid with 6 km horizontal resolution, placing India among a select group of global leaders in real-time, ultra-high-resolution operational forecasting. The model was initially

implemented in 2022 and, after three years of rigorous testing, was handed over to IMD for operational deployment. This milestone is a landmark achievement for all institutes involved under the Ministry making India the only country currently running a global forecasting model at such high resolution in real time. The system is accessible online through the Bharat FS portal.

Fig. 4.11: Launch and Handover of Bharat Forecast System to IMD on 26th May 2025 at Vigyan Bhawan

Further extending India's forecasting capabilities, the Bharat Forecast System, Extended Range Prediction (BharatFS-ERP), a second-generation extended-range prediction system developed by IITM, was launched on 28 July 2025 during the 19th Foundation Day of MoES and handed over to IMD for operational use. BharatFS-ERP enhances the nation's ability to generate reliable forecasts over longer time horizons, supporting disaster preparedness, climate services, and socio-economic planning.

4.3.2 Monsoon Mission Climate Forecast System - Version 2 (MMCFSv2)

Complementing short- and extended-range forecasting efforts, the second-generation Monsoon Mission Climate Forecast System (MMCFSv2) has been developed to improve seasonal prediction skill. MMCFSv2 incorporates a modified GFS Semi-Lagrangian atmospheric model, the MoM6 ocean model, CICE5 sea-ice model, and the Noah land surface model. The system was evaluated using monsoon hindcasts for the period 1992-2024, initialized from February to May conditions. Results demonstrate substantial improvements over the previous version. The seasonal prediction skill for Indian Summer Monsoon Rainfall (ISMR) increased from 0.55 to 0.74, representing an improvement of approximately 32%. The system also shows a 30% improvement in extreme rainfall prediction skill, along with a marked reduction in false alarms. MMCFSv2 is now operationally utilised as part of IMD's multi-model ensemble (MME) framework.

4.3.3 Mithuna Forecasting System (Mithuna-FS)

India's weather is strongly influenced by the surrounding tropical oceans to the south, east, and west, where many weather systems originate and intensify. Recognizing that atmosphere-only models have limitations in representing complex ocean-atmosphere interactions, including tropical cyclones and monsoon depressions, NCMRWF has upgraded its global forecasting system for the medium-range time scale.

The earlier NCUM-G atmosphere-land model has been replaced by the Mithuna Forecasting System (Mithuna-FS), India's first fully coupled Ocean-Atmosphere-Land Surface-Sea Ice numerical weather prediction system. Developed under the MOMENTUM India-UK partnership, Mithuna-FS integrates all major Earth-system components within a unified modelling framework (Fig. 4.12).

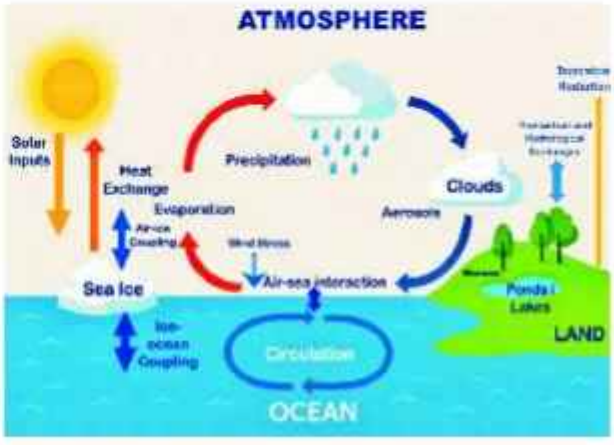


Fig. 4.12: Schematic representation of Mithuna-FS, illustrating the coupled Earth System Model components and their feedback processes at the medium-range time scale.

Operationalisation of Mithuna-FS involved refinements across the entire forecast production chain, including observation pre-processing, weakly coupled data assimilation, and optimised model integration. Operational since November 2025, the system now delivers routine short- to medium-range forecasts to IMD and other government agencies, significantly strengthening national weather monitoring and prediction capabilities. Mithuna-FS also provides initial and lateral boundary conditions for convection-permitting and regional high-resolution models, supporting a seamless modelling strategy across multiple forecasting applications.

4.3.4 IITM Earth System Model Version-3 (IITM-ESMv3)

A next-generation high-resolution global Earth System model, IITM Earth System Model version-3 (IITM-ESMv3), has been developed at the Centre for Climate Change Research (CCCR), IITM with a horizontal resolution of 67 km, to contribute to the IPCC Seventh Assessment Report (AR7) and CMIP7. IITM-ESMv3 builds upon the modelling framework and scientific advances achieved through earlier generations of IITM ESMs that contributed to CMIP-6 and IPCC AR6, while incorporating substantial enhancements in resolution and Earth-system processes. The model operates at a horizontal resolution of 67 km and employs a TCo atmospheric grid, a tropics-enhanced ocean model, river routing, updated Indian land-use/land-cover datasets from NRSC, and new three-dimensional aerosol optical property forcing, enabling improved representation of regional climate processes over South Asia.

Control simulations under CMIP-7 have been initiated, marking India's continued participation in coordinated international climate modelling efforts. The enhanced atmospheric resolution has resulted in a substantial reduction in tropical precipitation biases, particularly over South Asia, addressing limitations identified in earlier model generations. In addition, high-resolution (27 km) climate projections using the atmospheric-only configuration of IITM-ESMv3 have been generated at CCCR. These simulations extend previous high-resolution regional downscaling efforts undertaken under national climate programmes and will support the development of sector-specific climate products for applications in agriculture, water resources, health, and disaster management.

4.4 High-Impact Weather Forecasting and Services - IMPACT

4.4.1 AI-Enabled Forecasting Systems

As part of efforts to explore next-generation forecasting approaches, NCMRWF has initiated real-time experimental runs of AI/ML-based global weather prediction models. Analysis fields generated by the Mithuna coupled numerical weather prediction system, which provides a physically consistent global Earth-system state, are post-processed using the Scalable Platform for Automated Real-Time Key Weather Toolkit (SPARK). This toolkit automates data processing, standardisation, and real-time dissemination to produce gridded diagnostic variables. These gridded fields are then used as initial conditions for AI/ML models such as Pangu-Weather, GraphCast, and FourCastNet, enabling data-driven forecasts alongside conventional numerical weather prediction outputs.

In addition, the NCMRWF AI Weather Expert, an in-house AI-enabled weather analysis platform, processes high-resolution weather imagery including ensemble and combined datasets to rapidly generate insights into weather patterns, trends, and anomalies. Currently, the platform is used internally for quality verification and validation prior to wider operational deployment. An example of an AI-enabled weather report generated from a 4 km convection-permitting model is shown in Fig. 4.13.

Fig. 4.13: AI enabled Weather Analysis platform developed at NCMRWF.

4.4.2 Citizen-Centric Weather Services: Mausamgram

IMD has also developed "Mausamgram" (Har Har Mausam, Har Ghar Mausam), a citizen-centric digital platform that provides hyper-local weather forecasts down to the village level. Mausamgram delivers hourly forecasts for the next 36 hours, three-hourly forecasts for five days, and six-hourly forecasts for up to ten days.

Users can conveniently access forecasts using PIN code, location name, or through the administrative hierarchy down to the gram panchayat level, ensuring easy and timely access to location-specific weather information. This platform significantly enhances the last-mile delivery of weather services, supporting informed decision-making by citizens and local authorities. An example of a hyper-local village-level weather forecast generated through Mausamgram is shown in Fig. 4.14.

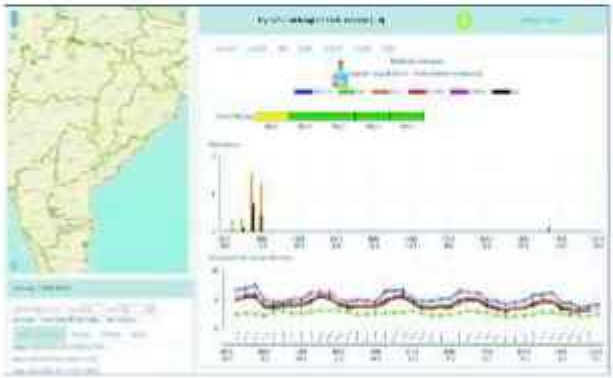


Fig. 4.14: Example of hyper-local village-level weather forecast available through the Mausamgram platform.

4.4.3 Nowcasting System for Convection

IMD's nowcasting system monitors and predicts convective activity with lead times of up to two hours, using real-time weather radar observations. The system provides critical short-term forecasts to support weather-sensitive operations and improve preparedness for mesoscale convective systems. In the next phase, the system will be further refined and enhanced using data from the upcoming urban radar network in the Delhi region, which is expected to improve spatial coverage and forecast accuracy, particularly for urban weather monitoring and forecasting.

4.4.4 Tropical Cyclone Forecasting and Early Warning Systems

IMD has achieved a significant leap in tropical cyclone forecasting accuracy during the 2021-2025 period compared to 2016-2020. Track forecast errors have been reduced by 5-10% for lead times up to 48 hours and by 20-25% for longer lead times (Fig. 4.15). Intensity forecasting has also shown substantial improvement, with a 33-35% enhancement for lead times up to 72 hours, while errors at the 96-hour lead time have decreased by 10%. The average 12-hour intensity forecast error declined from 5.4 knots during 2015-19 to 3.4 knots during 2020-24.

The most pronounced improvement has been observed in landfall prediction, which is critical for timely coastal evacuations. Landfall point errors decreased by 35-45% for 24 to 48 hours and by about 20% for other lead periods. The average 24-hour landfall point error reduced from 31.9 km during 2016-20 to 19.0 km during 2021-25, while the 48-hour landfall error declined from 61.5 km to 34.4 km.

Fig. 4.15: Improvement in tropical cyclone forecasting skill by IMD-MoES, showing average track forecast errors (km) for 2021-2025 compared with 2016-2020.

Overall, these advancements have significantly strengthened IMD's capability to protect coastal communities and support timely decision-making in disaster risk management.

4.5 Atmospheric Composition Monitoring, Modelling and Prediction - ATCOMP

4.5.1 Atmospheric Chemistry and Source Apportionment

Atmospheric Chemistry Laboratories at IITM Pune and IITM Delhi advance high-resolution source apportionment of atmospheric aerosols, providing crucial data for national air quality management and policy. IITM Pune houses offline facilities, including Ion Chromatography (IC) and Inductively Coupled Plasma-Mass Spectrometry (ICP-MS), for detailed analysis of ionic species and trace metals in particulate matter, supporting compliance monitoring under India's National Clean Air Programme (NCAP).

IITM Delhi features continuous online monitoring, including a Carbonaceous Aerosol Speciation System (CASS) and Aerosol Mass Spectrometer (AMS), delivering near-real-time measurements of organic carbon (OC), elemental carbon (EC), total carbon (TC), brown carbon, black carbon, and biomass-burning contributions. A Chemical Ionization Mass Spectrometer (CIMS) provides continuous monitoring of volatile organic compounds (VOCs), critical for ozone and secondary aerosol formation. Together, these instruments enable real-time national-scale source apportionment, identification of emission hotspots, and support evidence-based mitigation strategies. Data are regularly updated on the Air Quality Forecasting System website, providing a nationally relevant tool for air quality assessment, public health advisories, and policy decisions under NCAP and other urban air quality initiatives.

4.5.2 Plant-Atmosphere Interaction Research (PAIR) Laboratory

Established in March 2025 at IITM, the PAIR Laboratory investigates the impacts of air pollution and climate change on plant health and crop productivity. Equipped with a Portable Photosynthesis Analyzer, the laboratory measures photosynthetic gas exchange and chlorophyll fluorescence to assess plant physiological responses to atmospheric pollutants, directly linking air quality to ecosystem and agricultural outcomes.

The instrument has been uniquely modified for controlled ozone exposure, enabling direct, leaf-level quantification of ozone effects, a capability not previously implemented in India. Beyond laboratory studies, PAIR has supported field campaigns in the Pichavaram mangrove ecosystem, investigating the impacts of aerosol deposition on plant function under natural environmental conditions.

4.5.3 Advancement of High-Resolution Urban Modelling Framework Beyond Delhi

DM-Chem, a very high-resolution (330 m) city-scale composition forecast model developed at NCMRWF, has been providing air-quality guidance over the Delhi- National Capital Region (NCR) region since 2022. This urban modelling framework incorporates prognostic aerosol chemistry, advanced urban parameterizations, complex physical schemes, and city-specific processes such as anthropogenic activities, irrigation, and high-resolution surface boundary conditions, including land-use/land-cover information. The fog and particulate matter products from this model is being used routinely by IMD and other stake holders for visibility and air quality warning. This framework has also proven to be useful for simulating fog holes, which have become more frequent over Delhi in recent years, as well as for capturing the onset of fog and its evolution. In view of the rapid urbanisation occurring across several Indian metropolitan cities, it is now proposed to extend this advanced urban modelling capability to other cities in India. The same modelling framework will be applied to address city-specific weather-hazard issues such as air pollution, fog, urban heat stress and heavy rainfall. The advanced urban schemes used in this framework rely on urban morphology such as building height. Despite their importance, high-resolution urban datasets are not available on a global scale and are largely limited to a few regions, with most existing datasets available only at coarse spatial resolutions. At such scales, these datasets cannot accurately represent narrow streets, small buildings, or the contrast between single-storey and multi-storey structures. This limitation is

particularly critical in the Indian context, where urban growth is often rapid, unplanned, and highly heterogeneous. Accordingly, efforts will be made to explore the procurement of high-resolution urban morphology datasets for other Indian cities as part of the planned advancement of urban modelling activities.

4.5.4 Air Quality Warning and Integrated Decision Support System for Emissions (AIRWISE)

IITM has developed and operationalized the Air Quality Warning and Integrated Decision Support System (AIRWISE) for the Delhi NCR, providing high-resolution, near-real-time air quality forecasts. The system integrates satellite-derived aerosol optical depth (AOD), satellite-based fire data, surface observations from over 320 monitoring stations, and high-resolution emission inventories. Operating at a spatial resolution of 400 m over Delhi, AIRWISE uses a globally standardized modelling framework to deliver timely forecasts for residents, policymakers, and regulatory agencies, including IMD, MoES, CAQM, CPCB, MoEFCC, and DPCC.

AIRWISE has been enhanced with several key advancements: a computationally efficient first-order secondary organic aerosol (SOA) parameterization integrated into the MOZART-GOCART scheme, (ii) an ensemble-based probabilistic air quality forecasting system for Delhi using the WRF-CMAQ offline framework, and (iii) satellite data assimilation using VIIRS and OCM sensors to replace MODIS for improved $PM_{2.5}$ predictions. A lightweight DSS framework employing a single-tracer approach and a CAMx-based ensemble has been developed to quantify local and external pollution contributions, particularly during winter pollution episodes.

AIRWISE has been extended beyond Delhi to Jaipur, Alwar, and Bhiwadi, with Mumbai expected to come online soon. The AQEWS version 2.0 (AIRWISE) system was formally handed over to the India Meteorological Department on 27 July 2025 during the MoES Foundation Day, providing a nationally relevant tool for operational air quality forecasting, policy planning, and public health advisories.

4.5.5 Winter Fog Experiment (WIFEX): 10 Years of WIFEX (2015-2025)

Launched in winter 2015 at Indira Gandhi International Airport (IGIA), New Delhi, the Winter Fog Experiment (WiFEX) has completed a decade of sustained research on dense winter fog over northern India. Led by IITM under MoES, with support from IMD and NCMRWF, WiFEX is among the few long-term, open-field fog research programs globally dedicated exclusively to understanding this phenomenon, which frequently disrupts aviation, rail, and road transport across the Indo-Gangetic Plain.

Two depolarization ceilometers have been installed at IGI Airport, New Delhi, and Noida Airport. These instruments operate reliably, with real-time observations displayed on the WiFEX website. The datasets are extensively used for studies on boundary-layer dynamics, pollution characterization, and mixing-layer and planetary boundary layer height estimation. In the near future, these observations will support advanced research on cloud properties and fog-layer microphysical characteristics.

Daily, real-time verification of all three forecasting systems is available on the WiFEX website, covering key meteorological variables, surface visibility, and radiative flux components. These integrated observational and modelling efforts have significantly enhanced fog prediction capability, strengthening operational decision support for aviation safety, public transportation, and general public safety over northern India.

4.6 Decision Support Ecosystem Development - DECIDE

Over the past five years, IMD has significantly strengthened its decision support ecosystem, enabling impact-based forecasts and risk-informed warnings at the district level. DECIDE integrates observations, NWP systems, hazard thresholds, vulnerability information, and dissemination platforms to support timely decision-making by disaster management authorities and local administrations. This ecosystem supports

preparedness and response to a wide range of high-impact weather events, including cyclones, heavy rainfall, thunderstorms, heatwaves, and cold waves, by moving beyond event prediction to assessment of potential impacts on communities, livelihoods, and infrastructure.

A major milestone under DECIDE is the development and operationalization of IMD's in-house Decision Support System (DSS), which has resulted in an estimated cost saving of 250 crore while eliminating dependence on foreign vendors, thereby supporting the "Atmanirbhar Bharat" initiative. The DSS integrates observations, numerical weather prediction outputs, hazard thresholds, and exposure information to support real-time, impact-based decision-making.

4.6.1 Improved Forecast Skill and Early Warning Capability

Heatwave forecasting has seen substantial improvements. Five-day forecasts during 2020-25 achieved accuracy previously attained only in three-day forecasts (2015-19), effectively extending lead time by two days without compromising reliability. For example, the Probability of Detection (POD) for Day-3 forecasts (March-June, all India) rose to 77% in 2024 and 75% in 2025, compared with 28% in 2021. Day-5 forecasts improved from 8% POD in 2021 to 60% in 2024 and 46% in 2025 (Fig. 4.16), reflecting enhancements in observational networks, modelling techniques, and forecasting systems.

Fig. 4.16: Heatwave forecast verification scores (POD) for 2021-2025, showing improvement in forecasts.

4.6.2 Enhanced Spatial Coverage and Data Granularity

IMD's observational infrastructure has expanded significantly. Under the District Rainfall Monitoring Scheme (DRMS), coverage increased from 660 to 729 districts, with the number of rainfall stations rising from 4,359 to 6,727. To enable finer-scale monitoring and localized decision support, the Block-wise Rainfall Monitoring Scheme (BRMS) was launched in July 2025, complementing district-level observations for detailed hydrometeorological assessments.

Gridded daily temperature (1° x 1°) and rainfall (1° x 1° and 0.25° x 0.25°) datasets are publicly available through the IMD website, supporting research, planning, and operational decision-making. Hydrometeorological products, including the Agricultural Agrometeorological Index (AAI), Standardized Precipitation Index (SPI), and Standardized Precipitation Evapotranspiration Index (SPEI), are routinely integrated into climate-informed health bulletins. The IMD Rainfall Information System (IRaINS) further strengthens in-house capabilities for efficient analysis of rainfall statistics.

4.6.3 Sector-Specific Decision Support and Dissemination

Forecasting capacity has been strengthened through multi-model ensemble approaches for monthly and seasonal predictions. Sub-division level seasonal forecasts were introduced in 2025, enabling region-specific guidance. IMD has collaborated with ICAR institutes (IIHR, NIVEDI, NDRI, DPR, and CIFA) to deliver weather-based advisories for horticulture, livestock, poultry, and inland fisheries. Automated, crop-specific advisories are generated through the Dynamic Crop Weather Calendar for major Kharif and Rabi crops.

Dissemination mechanisms have been significantly expanded to reach rural, vulnerable, and last-mile users. Weather advisories are disseminated via WhatsApp to Panchayat members, Krishi and Pashu Sakhis, and dedicated groups, covering approximately 20 million farmers across 6,062

blocks. The Meghdoot mobile application (available in English and 12 Indian languages) and the MAUSAM app have recorded approximately 1.31 million downloads, indicating widespread adoption. Weather services are integrated with 982 Agriculture Produce and Livestock Markets (APMCs) and state platforms, reaching more than 16 million farmers, while over 10 million farmers receive SMS-based advisories through public-private partnerships.

In support of aviation and transport safety, IMD has strengthened automated weather observing infrastructure across airports and heliports. Heliport-Automatic Weather Observing Systems (H-AWOS) are operational at ten heliports, while Automated Weather Observing Systems (AWOS) (Fig. 4.17) are installed at ten airports, with expansion underway at eight additional airports. The network of Runway Visual Range (RVR) systems has increased from 170 to 183 sites across 93 airports, and the number of Digital Current Weather Instrument Systems (DCWIS) has expanded to 138 installations. Together, these systems enhance continuous, real-time surface weather monitoring, standardized reporting, and forecast accuracy for aviation operations.

Fig. 4.17: Automated Weather Observing System installed at Mumbai Airport.

4.6.4 Mobile-Based Decision Support Applications:

a. DAMINI - Lightning Alert App:

The Damini mobile application is a critical public-safety tool that provides real-time lightning alerts. A recent upgrade has integrated an interactive Leaflet Map, leveraging a widely used open-source JavaScript library to deliver fast and flexible geospatial visualizations. This enhancement allows users to receive instantaneous notifications of lightning activity in their vicinity while visualizing strike locations with high precision. The map supports smooth zooming and panning, making it easier to identify high-risk areas, and the use of open-source Leaflet technology ensures that the app remains lightweight, responsive, and efficient across a wide range of mobile devices.

b. MAUSAM - Unified Weather App:

The Unified Mobile App MAUSAM delivers accurate, reliable, and real-time weather information, with hourly forecasts up to 7 days. MAUSAM supports English and 12 Indian languages and features GIS-based interactive weather maps for easy visualization. It offers a comprehensive range of services, including weather forecasts and warnings, rain, cyclone, and lightning alerts, radar and satellite products, as well as forecasts along national highways, railways, aviation routes, and agro-meteorological advisory services. Additionally, it supports crowdsourcing, i.e., it allows users to report observed weather phenomena with an instant photo upload option. A recent transition from station-wise reporting to user location-based data sourced from Mausamgram has significantly enhanced the availability of weather data on the App. This improvement ensures more precise, localized weather information and better data availability tailored to each user's exact location. Air Quality Index from Central Pollution Control Board (CPCB) has also been integrated with MAUSAM App for real time Air quality data availability to users.

4.7 Weather Modification Research - Weather_MOD

The centre of excellence for cloud physics and weather modification research is approved by the Hon. Secretary and was announced at the WMO conference on cloud physics and weather modification held at IITM on 2nd Nov 2025. The centre will develop observational facilities and conduct field campaigns for weather modification strategy research for rain enhancement/reduction,

fog dispersal, hail suppression, and pollution dispersal, conduct numerical experiments on small-scale geoengineering studies and develop cloud chamber facility for fundamental research on cloud physics and weather modification. The effective outcome of the vertical is in the development of protocols for weather modification and weather management operations. The development of Technology and, instrumentation and testing and calibration facilities for weather modification and monitoring in collaboration with industry for innovation and fast-track development goals is planned.

4.7.1 Observational infrastructure for weather modification research

4.7.1.1 Capital Observatories for aerosol cloud precipitation studies

IITM has established an observational facility equipped with 3-dimensional wind profiling and scanning lidar at Prithvi Bhavan, MoES, New Delhi. This instrument provides high spatial and temporal resolution wind measurements over the capital, Delhi (Fig. 4.18). This system is having the capability to scan both in azimuth and elevation to map winds, aerosols, and clouds with high range and time resolutions. Direct measurements of vertical velocity is the unique feature of this system. The information on clouds and aerosols is also derived from the instrument data.

Ceilometers with Depolarization measurement capability are installed at these three stations. It profiles aerosols and clouds with high range and time resolutions. The capability to measure depolarization can be utilized to understand the shape of the aerosols (spherical or non-spherical), which will have an impact on radiative forcing and help in classifying the type of aerosols. The ceilometer in colocation with the wind lidar at MoES is providing additional information on the real-time influence of dynamics on characteristics of aerosols and clouds. Both wind lidar and ceilometers can make measurements on a continuous (24x7) basis during all weather conditions. Urban aerosol characteristics and their activation properties are measured.

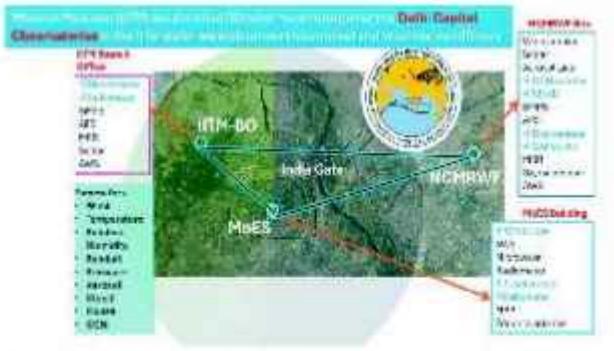


Fig. 4.18: The capital observatories give detailed information on the aerosol, cloud and precipitation properties to have a detailed hyperlocal forecast over the capital.

4.7.1.2 Urban testbeds for decision support systems

Five sites in the Delhi region (3 capital and 2 outside the city) have been equipped with advanced vertical profiling instruments for aerosols, cloud properties, winds, and temperature, complemented by multiple urban meteorological observation locations across Delhi-NCR to support high-resolution monitoring of urban atmospheric processes. The MoES HQ facility features Wind Lidar, Microwave Radiometer, Automatic Weather Stations (AWS), and Ceilometer, while NCMRWF, Noida functions as a dedicated aerosol laboratory measuring CCN number concentration, black carbon, aerosol size distribution, and vertical aerosol profiles using lidar. Additional sites at the IITM Branch Office, New Delhi and SRM, Sonipat and Galgotias University use ceilometers with depolarization capabilities, and disdrometers have been installed at all locations to characterize precipitation. With 185 AWS under installation across the region, and upcoming two X-band radars, the Delhi Urban Testbed provides a robust platform for improving nowcasting capabilities and enhancing climate resilience in one of the world's most populous urban environments. Early warning systems for high-impact weather and fine-tuning of weather forecasts through convective scale data assimilation, nowcasting tools and decision support systems will be possible with the unique data collected. This facility and the outcome of accurate

weather forecasting will be used in the decision support for weather modification experiments to develop protocols for weather management options.

4.7.1.3 Urban testbed facility at the coastal city Chennai

An Urban Testbed Facility has also been established at Sathyabama Institute of Science and Technology (SIST), Chennai, through an MoU. Inaugurated on 13 Oct 2025 by Dr. M. Ravichandran, Secretary, MoES (Fig. 4.19), the facility operates ceilometers with depolarization capability, a SODAR, and a Micro Rain Radar (MRR). It supports high-resolution observations of urban atmospheric processes, enabling research on boundary-layer dynamics, precipitation, and urban weather and climate applications.

Fig. 4.19: Mission Mausam Urban Testbed Facility at Sathyabama Institute of Science and Technology (SIST), Chennai, inaugurated on 13 October 2025 by the Secretary, MoES.

4.7.1.4 Cloud Chamber facility Development

A convection cloud chamber facility (Fig. 4.20) is being implemented at IITM to advance research on weather modification and aerosol-cloud interactions. In support of this initiative, an Aerosol-Cloud Droplet Laboratory has been established at IITM Pune to conduct pre-evaluation and process-level investigations. This laboratory focuses on examining aerosol activation into cloud droplets, detailed chemical composition analysis of aerosol particles, and chemical speciation of CCN, including CCN closure experiments. The datasets generated from these studies will be instrumental in constraining and validating aerosol-cloud interaction schemes within numerical weather and climate models, thereby enhancing predictive capabilities and improving process understanding relevant to weather modification strategies.

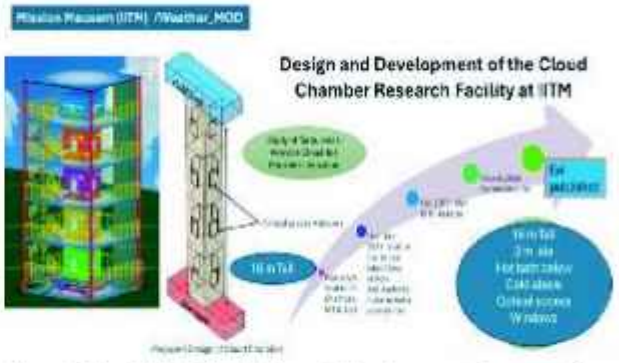


Fig. 4.20: A detailed plan of the largest Convection cloud chamber is formulated by IITM and the project is being executed

4.7.1.5 Rainwater Chemistry Campaign-Monsoon 2025

During the 2025 Monsoon season (June-September), IITM Delhi conducted an extensive Rainwater Chemistry Campaign across ten strategically selected locations encompassing the Indo-Gangetic Plain (IGP) and the Himalayan foothills. This campaign, executed in collaboration with premier research institutions and universities, was designed to capture a wide spectrum of emission regimes and meteorological conditions.

Monitoring sites included:

- Ludhiana, Punjab (Gulzar Group of Institutions) - agricultural biomass-burning region in the northwestern IGP
- New Delhi (IITM Delhi Branch Office) and Noida, Uttar Pradesh (NCMRWF) - urban western IGP environments
- Jaipur, Rajasthan (IIS University) - dust-dominated site
- Lucknow, Uttar Pradesh (Lucknow University) and Varanasi, Uttar Pradesh (Banaras Hindu University) - urban central and central-eastern IGP sites

- Ranchi, Jharkhand (BIT Mesra) - urban eastern IGP site
- High-altitude Himalayan foothill sites: Nainital (~1400 m amsl), Pauri (~1800 m amsl), and Devasthal (~2500 m amsl) in Uttarakhand, representing relatively cleaner, background environments

The campaign's primary objectives included characterizing the spatial distribution of major ionic species in rainwater, assessing its acidic or alkaline nature, and quantifying the atmospheric deposition of acidic and alkaline constituents across the region. The results are expected to provide valuable insights into regional atmospheric processes and contribute to evaluating the carrying capacity of the Indo-Gangetic Plain and adjacent Himalayan regions regarding emissions and air quality. This campaign has been successfully on going since the year 2023 (Fig.4.21).

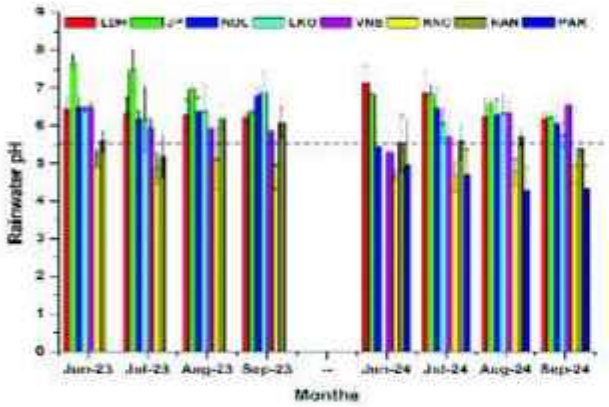


Fig. 4.21: Monthly mean variability of rainwater pH at different locations during Monsoon 2023 and 2024. Samples collected in 2025 are currently under analysis.

4.7.2 Technology Development

4.7.2.1. 3-D Printed AWS following WMO standards

IITM, in collaboration with UCAR, has developed India's first 3D-printed, cost-effective AWS adhering to WMO standards. A dedicated 3D Printing AWS Laboratory at IITM is used to design, calibrate, and test instruments for deployment at urban locations. These stations measure wind speed, wind direction, temperature, wet-bulb globe temperature (for heat stress), pressure, and rainfall, providing valuable insights into urban heat stress.

India's first 3D-printed AWS was installed at IMD Headquarters, New Delhi, and inaugurated by Dr. Jitendra Singh, Hon. Minister of Earth Sciences, during the 151st Foundation Day of IMD (Fig. 4.22). This 3D-PAWS system represents a landmark achievement under Mission Mausam, offering nearly 90% cost reduction compared to comparable commercial systems. Designed as a scalable and affordable solution, it strengthens India's observational infrastructure for weather, climate, and early-warning services.

Fig. 4.22: Inauguration of India's first 3D-printed AWS (3D-PAWS) at IMD Headquarters, New Delhi, by Dr. Jitendra Singh, Hon. Minister of Earth Sciences, during the 151st Foundation Day of IMD.

4.7.2.2 NABL-Accredited Calibration Facility for Weather Sensors

IITM is establishing a NABL-accredited calibration facility for weather and micro-meteorological sensors. NABL (National Accreditation Board for Testing and Calibration Laboratories) ensures that laboratories meet national standards for quality and accuracy.

The facility will provide state-of-the-art calibration services to research organizations, academic institutions, and industries across India. Accurate calibration of sensors is essential for generating reliable data in weather forecasting, climate research, environmental monitoring, and micro-meteorological studies. This initiative enhances the

national meteorological infrastructure and supports standardized, high-quality data for scientific and operational applications.

4.8 Way Forward

Mission Mausam aims to revolutionize India's meteorological monitoring and forecasting capabilities with an earth system perspective to make the country truly weather-ready and climate smart. The focus is on expanding the observational network, upgrading forecasting infrastructure, and using advanced analytical methods, including advanced modelling systems, to produce timely and detailed weather and climate information. By extending forecast lead times, increasing forecast accuracy, and incorporating impact based insights into early warning services, the mission will improve preparedness and resilience across sectors and communities in the country. Continued emphasis on innovation, collaboration, and operational excellence will support more effective decision making and better management of weather and climate risks.

Chapter-5
International Cooperation

During 2025-26, the Ministry of Earth Sciences (MoES) and its constituent institutions significantly strengthened India's international engagement in Earth system sciences. Through sustained collaboration with multilateral organisations such as the World Meteorological Organization (WMO), IOC-UNESCO, European Space Agency (ESA), International Seabed Authority (ISA), and regional groupings including BIMSTEC and BRICS, as well as through bilateral partnerships, India enhanced global scientific cooperation, regional resilience, and leadership in sustainable ocean and climate governance. These efforts also supported India's commitments under emerging international frameworks, notably the Biodiversity Beyond National Jurisdiction (BBNJ) Agreement.

5.1 India Meteorological Department (IMD), New Delhi

A member of the World Meteorological Organization (WMO) since 1949, the IMD continued to play a pivotal role in regional and global meteorological cooperation in 2025-26, providing essential services across South Asia, Southeast Asia, and the Middle East.

5.1.1 Regional Cyclone and Severe Weather Services

IMD operates the WMO-designated Regional Specialised Meteorological Centre (RSMC) for Tropical Cyclones, one of only five such centres worldwide. The Centre provides daily guidance, weekly extended-range outlooks, and three-hourly advisories during cyclonic events for the North Indian Ocean, which are disseminated to all eight member countries of the WMO/ESCAP Panel on Tropical Cyclones, Bangladesh, India, Myanmar, Pakistan, Sri Lanka, Thailand, Maldives, and Oman, through the Global Telecommunication System, email, and dedicated web portals. IMD also continues to serve as the Secretariat of the WMO/ESCAP Panel on Tropical Cyclones for the period 2023-27.

IMD also leads the WMO Severe Weather Forecasting Programme (SWFP) for South Asia, issuing daily guidance on heavy rainfall, strong winds, storm surge, high waves, and cyclonic disturbances, while supporting forecaster capacity across nine participating countries.

5.1.2 Flash Flood, Climate, and Seasonal Prediction Services

IMD also serves as the WMO Regional Centre for Flash Flood Guidance, issuing high-resolution six-hourly threat assessments and 24-hour risk outlooks three times daily at a resolution of 4×4 km, covering India, Nepal, Bhutan, Bangladesh, and Sri Lanka, in collaboration with WMO, USAID, and NOAA.

IMD Pune functions as a Regional Climate Centre (RCC) for South Asia and the Third Pole region, providing climate monitoring, long-range forecasts, data services, and training. India has also been issuing seasonal outlooks under the South Asia Climate Outlook Forum (SASCOF) since the monsoon season of 2010.

The Pune centre of IMD operates as a Global Producing Centre (GPC) for Seasonal Prediction, delivering global seasonal forecasts, disseminated worldwide via the WMO Lead Centre for Seasonal Prediction.

Observational and telecommunication support, including radar imagery sharing through border-area radar networks with neighbouring countries such as Myanmar, Nepal, Bhutan, Bangladesh, Sri Lanka, and Maldives, further strengthened early warning capabilities. Collaboration with ECMWF, NCEP, and the UK Met Office continued to support advances in NWP and modelling.

5.1.3 Early Warning Systems and Capacity Building

In alignment with the UN-WMO "Early Warnings for All" initiative, IMD operationalised impact-based forecasting, multi-hazard early warning systems, and the Common Alerting Protocol (CAP). These capabilities were extended to South Asia, Southeast

Asia, and the Middle East through training and technical cooperation.

IMD also served as a WMO-designated Peer Advisor for implementing Systematic Observational and Forecasting Facilities (SOFF) in five countries.

5.2 Indian Institute of Tropical Meteorology (IITM), Pune

5.2.1 International Research Partnerships and MoUs

An MoU was signed with Yokohama National University, Japan, on 12 March 2025 to enhance Indo-Japanese collaboration in tropical meteorology. On 23 January 2026, IITM entered into a five-year, MoU with the Euro-Mediterranean Centre on Climate Change (CMCC), Italy, focusing on climate modelling, weather prediction, ocean science, and the application of AI/ML.

IITM also continued collaborative research under its ongoing MoU with the Physikalisch-Meteorologisches Observatorium Davos/World Radiation Center (PMOD/WRC), Switzerland, addressing scientific questions related to stratospheric aerosol injection, solar radiation management, and their potential implications for the Indian monsoon.

5.2.2. Strategic Climate Observatories and Bilateral Cooperation

An MoU between the GoI and the Government of Maldives came into force on 25 July 2025 for a period of five years, under which IITM is steering the scientific operation of the Maldives Climate Observatory at Hanimaadhoo. The observatory, supported technically by Stockholm University, Sweden, is strategically located in the Indian Ocean and provides a unique platform to study atmospheric processes associated with the Indian summer monsoon.

5.2.3 International Projects on Climate, Air Quality, and Health

In February 2025, IITM signed an MoU under the Research Council of Norway-funded COPE Project, a multi-institutional collaboration aimed at developing an advanced Early Warning and Decision-Support System for heat stress and air pollution exposure in Delhi and Kolkata. The project involves partners including the Center for International Climate Research (CICERO), Norway; IIT Delhi; NCAR, USA; SwitchON Foundation; the London School of Hygiene and Tropical Medicine, UK; and the University of Queensland, Australia.

In September 2025, IITM was also awarded an European Space Agency (ESA)-Future Earth Project titled "Enhancing Urban Resilience and Air Quality Management in Delhi NCR through Integrated Earth Observation and Decision Support Systems". Implemented in collaboration with institutions from the USA and the UK, the project employs high-resolution Sentinel-2 satellite data and machine-learning techniques to assess particulate matter contributions from open wastelands across 19 districts of the National Capital Region.

5.2.4 Monsoon Research Leadership and International Scientific Events

Under the 5th BRICS STI Framework Programme, IITM leads India's participation in the AIESMx Consortium, involving partner institutions from Brazil and China. The consortium focuses on understanding hydro-climatic extremes driven by natural and anthropogenic influences in BRICS countries using Earth System Models integrated with Artificial Intelligence.

IITM also continued to host the International Monsoons Project Office (IMPO), operational since 30 July 2021 under an agreement with the WMO. IMPO serves as a key international coordination hub for monsoon research under WMO's World Weather Research Programme (WWRP) and World Climate Research Programme (WCRP). In addition, IITM played a leading role in establishing the International Commission on Tropical Meteorology (ICTM) under IUGG/IAMAS, strengthening global collaboration in tropical meteorology research.

During the year, IITM hosted and co-organised several major international scientific events. The 11th WMO Scientific Conference on Weather Modification, held from 3-7 November 2025, was organised by IITM with support from MoES,

WMO/WWRP, IAMAS/ICCP, and ICTM. The conference was inaugurated by Dr. Abdulla Al Mandous, President of WMO, and attracted 229 participants from over 31 countries, featuring 16 oral sessions and approximately 200 poster presentations across ten thematic areas (Fig. 5.1).

Fig. 5.1: WMO President interacting with participants at the 11th WMO Scientific Conference on Weather Modification, IITM.

The Eighth WMO International Workshop on Monsoons (IWM-8), held from 17-21 March 2025, was jointly organised by IITM, MoES, and WMO programmes, and attracted around 320 participants from India and 14 countries, including a dedicated Early Career Researcher programme attended by 140 ECRs.

IITM also jointly organised the India-Italy Workshop on Machine Learning Applications in Climate and Ocean Science (11-12 February 2025) with CMCC, Italy, facilitating focused scientific exchange on emerging AI-based methodologies.

5.3 National Centre for Medium Range Weather Forecasting NCMRWF, Noida

NCMRWF, the apex institute for medium-range weather forecasting under MoES, continued to strengthen India's weather prediction capabilities through partnerships that leverage international satellite data.

5.3.1 Weather and Climate Modelling Partnerships

Under the Weather and Climate Science for Service Partnership (WCSSP) India and the Unified Model (UM) collaboration with the UK Met Office, NCMRWF achieved significant advances in coupled and ensemble numerical weather prediction. These efforts culminated in the development and operationalisation of the Mithuna Forecasting System, India's first fully coupled Ocean-Atmosphere-Land-Sea Ice numerical weather prediction system, marking a major step towards seamless prediction across weather and climate time scales. India's engagement as a core member of the UM Consortium, alongside the UK Met Office, CSIRO (Australia), NIWA (New Zealand), and the Centre for Climate Research (Singapore), continued to support collaborative model development, data assimilation, and ensemble forecasting activities relevant to monsoon prediction and high-impact weather events.

NCMRWF continued bilateral engagement with the National Oceanic and Atmospheric Administration (NOAA), USA, focusing on technical exchanges related to tropical cyclone forecasting systems and data assimilation methodologies. During the year, collaborative activities included work on the Hurricane Analysis and Forecast System (HAFS) and selected aspects of satellite and observational data assimilation.

To strengthen satellite data reception and operational forecasting, NCMRWF signed a MoU with New Space India Limited (NSIL) in September 2025 to establish two Direct Broadcast Network (DBNet) stations at Delhi/NCR and Chennai. These stations will enable real-time reception of data from Low Earth Orbit (LEO) satellites, including Indian and international Earth observation missions such as Oceansat, NOAA, and MetOp.

In addition, NCMRWF hosted the International Satellite Thermophysics Conference (ITSC-25) in Goa in May 2025, providing a platform for engagement with international experts and reinforcing India's role in the global satellite meteorology community. NCMRWF also continued to extend modelling support internationally

through four global models (GFS, GEFS, NCMRWF Mithuna, and NCMRWF NEPS) and two regional models (WRF and the NCMRWF regional model).

5.3.2 BIMSTEC Centre for Weather and Climate (BCWC)

During 2025, BCWC, at NCMRWF, played a key role in strengthening regional cooperation among BIMSTEC member countries in the domain of weather and climate services. The Centre facilitated capacity-building activities, exchange of scientific knowledge and numerical weather prediction products, and collaborative research initiatives among member countries. BCWC supported enhanced understanding and prediction of monsoon variability, extreme weather events, and climate risks over the Bay of Bengal region.

5.4 Centre for Marine Living Resources and Ecology CMLRE, Kochi

5.4.1 Polar Research - Ross Sea Expedition with New Zealand

CMLRE participated in India's maiden scientific voyage to the Ross Sea, Antarctica, aboard New Zealand's deep-water research vessel RV Tangaroa, undertaken in collaboration with Earth Science New Zealand. The joint research focused on mid-trophic level organisms and their roles in ecosystem processes and biodiversity, along with the comparative standardisation of protocols for environmental DNA (eDNA) collection, extraction, and metabarcoding. The outcomes are expected to contribute to the 2027 review of the Ross Sea Marine Protected Area and the Ross Sea Research and Monitoring Plan (Fig.5.2).

Fig. 5.2: Glimpses of the Ross Sea expedition aboard RV Tangaroa with participating international scientists.

5.4.2 CCAMLR and International Ocean Governance

Under the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR), a delegation led by Dr. R. S. Maheskumar, India's Commissioner to CCAMLR, participated in the 44th CCAMLR Meetings held in Hobart, Australia, from 20-31 October 2025. During the year, CMLRE progressed work related to the development of a fishing licensing framework, capacity-building programmes, and MoU with the Russian Federation and South Africa for Scientific Observer exchanges. Preparatory work was also initiated towards a single-window clearance mechanism for evaluating fishing and research proposals under both CCAMLR and BBNJ frameworks.

5.4.3 BBNJ - National Focal Point and Secretariat

Following India's signing of the BBNJ Treaty at the United Nations General Assembly in September 2024, MoES designated CMLRE as the National Focal Point for BBNJ implementation. During the year, preparatory work was initiated for the establishment of the BBNJ Secretariat and Clearing House Mechanism in India. The BBNJ Bill is under formulation with technical inputs from CMLRE, supporting India's engagement with the emerging global framework for conservation and sustainable use of marine biodiversity in areas beyond national jurisdiction.

5.4.4 Ocean Biodiversity Data - OBIS and IndOBIS

CMLRE represented India at the Living Data Conference and the OBIS Steering Group Meeting held in Bogotá, Colombia, from 21-24 October 2025. Dr. Hashim Manjebrayakath presented the status of IndOBIS, highlighting India's contributions to global marine biodiversity data sharing, capacity-building initiatives, and open-access data systems (Fig. 5.3).

Fig. 5.3: CMLRE representation at international ocean biodiversity platforms, including participation in OBIS Steering Group and Living Data Conference.

5.5 National Centre for Coastal Research (NCCR), Chennai

Under the Indo-Pacific Oceans Initiative (IPOI), NCCR organised an international workshop titled "Marine Litter, Climate Change and Biodiversity Loss: A Global Challenge" from 5-9 May 2025, in collaboration with the Australian Institute of Marine Science (AIMS). The workshop brought together researchers and practitioners from across the Indo-Pacific region to examine the interlinkages between marine pollution, climate change, and biodiversity loss, and to exchange best practices and research approaches for sustainable ocean management.

As part of the India-Norway cooperation framework, NCCR hosted a five-day community interactive programme aimed at developing guidelines for seagrass restoration, in collaboration with the Norwegian Institute for Water Research (NIVA), Norway, and the OMCAR Foundation, India. The initiative supported knowledge exchange on ecosystem-based approaches for marine habitat restoration.

Further strengthening bilateral collaboration, NCCR conducted a three-day India-Norway Benthic Habitat Workshop from 2-4 December 2025 in partnership with the Institute of Marine Research (IMR), Norway. The workshop focused on enhancing scientific understanding of benthic ecosystems, their ecological functions, and role in supporting coastal resilience.

5.6 National Centre for Polar and Ocean Research (NCPOR), Goa

5.6.1. International Polar Research Collaboration: Under the India-UAE Memorandum of Understanding on Polar Research, scientists from Khalifa University, UAE, participated in the 45th Indian Scientific Expedition to Antarctica (45-ISEA).

5.6.2 Scientific Diplomacy and Bilateral Engagements: NCPOR hosted high-level international delegations, including a senior delegation from the Russian Federation led by H.E. Mr. Nikolay Patrushev, and a Norwegian delegation led by H.E. Ms. May-Elin Stener, Ambassador of Norway to India, along with Prof. Camilla Brekke, Director of the Norwegian Polar Institute

5.6.3 Global Polar Science Governance and Outreach: India's sustained commitment to Southern Ocean observations was reflected through representation at the SOOS Scientific Steering Committee Annual Meeting 2025 in Copenhagen. NCPOR also maintained a strong presence at the Science and Geopolitics of Arctic-Antarctic (SaGAA VIII) Leadership Conference and demonstrated enhanced operational capability by flagging off India's first direct air cargo shipment to Antarctica.

5.7 Indian National Centre for Ocean Information Services (INCOIS), Hyderabad

5.7.1. Global Ocean Governance and IOC-UNESCO Engagement

An Indian delegation led by the Director, INCOIS, participated in the 33rd Session of the IOC-UNESCO Assembly and the 58th Session of its Executive Council, held from 25 June to 3 July 2025. In his capacity as Co-Chair of the Global Ocean Observing System (GOOS) Steering Committee, the Director

also participated in the 14th GOOS Steering Committee Meeting held at UNESCO Headquarters, Paris, from 19-21 February 2025, co-moderating strategic discussions with NOAA on shaping a fit-for-purpose Global Ocean Observing System.

India's leadership in regional tsunami preparedness was further reflected at the 81st ESCAP Session, where India announced a one-time contribution of USD 500,000 to the ESCAP Trust Fund for Tsunami, Disaster and Climate Preparedness. During the year, the Director, INCOIS, was also elected Vice-Chair of the IOC Sub-Commission for the Central Indian Ocean (IOCINDIO).

5.7.2 Ocean Observing Systems and Indian Ocean Cooperation

INCOIS participated in the 26th Annual Meeting of the Partnership for Observation of the Global Ocean (POGO-26), held from 25-28 February 2025 in Penang, Malaysia. Further, the IOGOOS Secretariat at INCOIS organised integrated meetings of the Indian Ocean Regional Panel (IORP), SIBER, the IndOOS Resource Forum, and the IIOE-2 Steering Group in Port Louis, Mauritius, from 5-9 May 2025, bringing together around 30 international delegates.

5.7.3 Bilateral and Regional Cooperation in Coastal Hazard Monitoring

As part of India-Mauritius ocean cooperation, the WAMAN Wave Rider Buoy was formally handed over to the Government of Mauritius on 8 May 2025, marking the first collaborative activity under the bilateral MoU signed following the Hon'ble Prime Minister's visit to Mauritius. INCOIS also deployed a Wave Monitoring Observatory in Mauritius to enhance regional capability for detecting high-swells originating from the Southern Ocean.

INCOIS further demonstrated regional leadership in oil spill preparedness at the High-Level Regional Meeting on Oil and Chemical Spill Contingency held in Colombo, Sri Lanka, from 30 September to 2 October 2025. INCOIS showcased its operational Oil Spill Advisory System, the only real-time forecasting system currently functional among South Asian Seas member states, with several countries expressing interest in technical support and capacity building.

5.7.4 Hosting of Major International Conferences

INCOIS hosted the first annual meeting of the People-Centred Early Warning for the Indian Coastlines (PCTWIN) project from 8-11 April 2025 in Kochi, Kerala (Fig.5.4). The UKRI-MoES funded initiative brought together international experts, national agencies, the Kerala State Disaster Management Authority, and community representatives from UNESCO-IOC Tsunami Ready villages.

Fig. 5.4: Participants of the first annual meeting of the PCTWIN project.

INCOIS also hosted several internationally significant scientific conferences at its Hyderabad campus during the year (Fig. 5.5). The Fourth Triennial Congress of FIGA, 62nd IGU, and 42nd AHI Annual Conventions (6-8 November 2025) brought together over 300 participants from India and abroad. This was followed by the First Ocean Decade Tsunami Programme (ODTP) Conference (10-11 November 2025), which focused on delivering actionable tsunami warnings within 10 minutes for all at-risk coastlines.

The 32nd International Tsunami Symposium (12-14 November 2025), themed on tsunamis generated by seismic, non-seismic, and complex sources, attracted around 100 leading global experts. The International Indian Ocean Science Conference

2025 (IIOSC-2025), held from 1-5 December 2025, brought together approximately 300 participants, including 67 foreign delegates, marking the culmination of the second International Indian Ocean Expedition (IIOE-2, 2015-2025).

Fig. 5.5: Major international conferences hosted at INCOIS during 2025-26.

5.8 National Institute of Ocean Technology (NIOT), Chennai

5.8.1 Indo-French Deep-Sea Collaboration and Manned Submersible Operations

In August 2025, a five-member NIOT team participated in a joint Indo-French deep-sea expedition aboard IFREMER's research vessel L'Atalante off Lisbon, Portugal. Two Indian aquanauts, Mr. Raju Ramesh and Cdr. Jatinder Pal Singh (Retd.), successfully conducted manned dives to depths of 4,025 metres and 5,002 metres in the Atlantic Ocean using IFREMER's submersible Nautile. This achievement placed India among a select group of nations with demonstrated ultra-deep manned diving capability.

The expedition provided NIOT scientists with hands-on training in submersible piloting, pre-dive systems checks, manipulator-based interventions, acoustic communication, dive trajectory tracking, deployment and recovery operations, and overall dive planning. The collaboration directly supports the development of India's indigenous manned submersible MATSYA-6000 under the Deep Ocean Mission.

5.8.2 Marine Renewable Energy

NIOT organised the two-day International Symposium on Advancements in Marine Renewable Energy (ISAMRE-2025) on 17-18 March 2025. The symposium was inaugurated by Dr. Vijay Kumar Saraswat, Member, NITI Aayog, and brought together researchers, policymakers, industry experts, and students from India and abroad.

5.8.3 Deep-Sea Resource Assessment and Global Partnerships

NIOT continued its international collaboration with the Woods Hole Oceanographic Institution (USA) and IFREMER (France) in deep-sea exploration and technology development. Under the framework of the International Seabed Authority (ISA), India has been allocated nearly 1 lakh square kilometres in the Central Indian Basin for polymetallic nodule exploration and an additional 75,000 square kilometres for polymetallic sulphide exploration. These allocations position India at the forefront of responsible deep-sea mineral resource assessment and environmental stewardship.

5.8.4 Cooperation and Exploration Contracts with the International Seabed Authority (ISA)

The Ministry, as the nodal agency for India, continued seabed mineral exploration activities under contracts with the International Seabed Authority (ISA) during 2025-26. India sustained one Polymetallic Nodules (PMN) exploration contract in the Central Indian Ocean Basin and one Polymetallic Sulphides (PMS) contract in the Indian Ocean Ridges, and additionally signed a new PMS exploration contract at the Carlsberg Ridge, making India the only country globally to hold two PMS contracts with the ISA.

The new PMS contract was signed on 15 September 2025 (Fig. 5.6). Execution of the contracts involves multiple national institutions, with PMN exploration undertaken by NIOT, Chennai; NIO, Goa; and IMMT, Bhubaneswar, and PMS exploration carried out by NCPOR, Goa. As part of contractual obligations, an At-Sea Training Programme was conducted for five candidates from developing countries nominated by the ISA.

Fig. 5.6: Signing of PMS Exploration Contract with ISA.

The Ministry also hosted the 8th Annual Contractors' Meeting of the ISA at Goa in September 2025 and participated in the 30th Sessions of the ISA Council and Assembly, contributing to discussions on the Regional Environmental Management Plan (REMP) for the Indian Ocean.

5.9 National Centre for Earth Science Studies (NCESS), Thiruvananthapuram

Fig. 5.7: Participants of the Hydrological Modelling Training and Workshop at NCESS.

During 2025-26, NCESS strengthened international cooperation through the MoES-UKRI collaboration on Dynamic Risk for Cascading Himalayan Hazards. As part of this engagement, a five-day Hydrological Modelling Training and Workshop (Fig. 5.7) was conducted from 9-13 June 2025 in collaboration with the Danish Hydraulic Institute (DHI). The programme trained 25 researchers in advanced hydrological modelling tools, including FEFLOW groundwater modelling and MIKE+ integrated flood modelling, enhancing national capacity for flood risk assessment and cascading hazard analysis in Himalayan regions. The workshop also facilitated technical exchange with international experts, reinforcing NCESS's role in globally connected hazard research.

Chapter 6

Publications, Patents, Awards and Honours

1. Publications

A total of 925 research papers were published during 2025-26 by MoES institutions with 2800.28 cumulative impact factor.

Table 1: Institute-wise research publications of MoES during 2025-26.

Institution	No. of Publications	CIF
CMLRE	33	60.05
IITM	228	850.20
IMD	159	363.08
INCOIS	92	259.36
NCCR	57	175.76
NCESS	104	291.50
NCMRWF	86	278.04
NCPOR	86	303.60
NCS	20	59.00
NIOT	60	159.69

2. Patents

As part of strengthening indigenous research and innovation, MoES institutions continued to generate intellectual property during 2025-26. The patents granted and filed during the year, covering diverse areas of scientific and technological relevance, are presented in the following Table 2:

Table 2: Patents filed by MoES institutions during 2025-26.

S.No.	Inventors	Title of Patent	Reference No. & Date	Country
1	J. Marry Leema Thilakam, D. Magesh Peter, S. Amsaveni, T.S. Kumar, G. Dharani, N.V. Vinithkumar, R. Kirubagaran, Tata Sudhakar and G. A. Ramadass	Process for green extraction of phycocyanin from marine cyanophycean Algae thereof	202541058065 Dt. 17.06.2025	India
2	Purnima Jalihal, Ashwani Vishwanath, Biren Pattanaik, Abhijeet Sajjan, G Venkatesan, A Karthikeyan	A system for observing of a water body site and a method thereof	202541059284 Dt. 20.06.2025	India

3	Chithra Krishnaswamy, Sankar Mani, Balaji Ramakrishnan	A Method and A System for Pilot Signal Assisted Underwater Acoustic Voice Communication	202541076395 Dt. 11.08.2025	India
4	Dixit Shivsai Ajit, Gupta Abhishek, Choudhary Harish Mangilal, Prabhakaran Thara Applicant: IITM	A system and method for estimating wall friction in smooth-wall-bounded turbulent flows	India: 202421105175 PCT: PCT/IN2025/052169	India & PCT (International)

2.1 Transfer of Technologies to Industries

Ocean observation tools were developed and tested in the field as part of indigenous technology development. These technologies have been transferred to industries for commercialisation as detailed below:

Table 3: Technologies transferred to industries during 2025-26.

Technology Type	Transferred To	Year
Recombinant Ectoine from Deep sea bacteria for skin-care and cosmetic applications (REB)	(REB)M/s. Varre Corporate Solutions, Visakhapatnam (Through NRDC)	2025
C-Phycocyanin from Marine Spirulina	M/s. Varre Corporate Solutions, Visakhapatnam (Through NRDC)	2025

3. Awards and Honours

The awards and honours received by officials from MoES and its organisations during the reporting period are listed below:

IMD, NEW DELHI

- India Meteorological Department (IMD) received the National Award for e-Governance 2025 for its exemplary efforts in leveraging technology for digital transformation and public service delivery through the Multi-Hazard Early Warning Decision Support System.
- Dr. M. Mohapatra, DGM, received the UN Sasakawa Award 2025 for Disaster Risk Reduction & American Meteorological Society (AMS) Scientific and Technological Activities Commission (STAC) Outstanding Service Award 2025.
- Dr. M. Mohapatra, DGM, has been awarded the Sir Gilbert Walker Gold Medal Award by Indian Meteorological Society (IMS).
- Dr. Kuldeep Srivastava, Scientist 'F', received recognition for services to WMO Regional Association II (Asia) during the intersessional period of the 17th Session (RA II-17).
- Dr. M. Mohanty, Scientist 'F', Meteorological Centre (MC) Bhubaneswar, received the award at the Odisha Women's Conclave 2024-2025, Jaydev Bhawan, Bhubaneswar, on 27 January 2025.
- Dr. Mrutyunjay Mohapatra, DGM, received Prananath Samman, 2025 (by Prananath College, Khordha, Odisha on 28 January 2025) & Sir Radhanath Sikdar Memorial Award 2025.
- Hon'ble Chief Minister of Odisha Mr. Mohan Charan Majhi honored Dr. M. Mohapatra, DGM with Ekamra Shree Award-2025 for his outstanding contribution to the field of science and early warning services on 26th February 2025.

- Best Stall Award: RMC Guwahati won the best stall award at Assam Agricultural University, Jorhat.
- Dr. Somnath Mahato, Project SC-III, was conferred the IEEE Young Professional of the Year, award on 11 January 2025, at Pune.
- Mr. Amit Kumar, Scientist-D, was conferred the Young Scientist Award at the 7th Conference on Indian Radar Meteorology (iRAD 2025).
- MC Chandigarh won First Prize from TOLIC Chandigarh for the year 2024-25 on 03/02/2026 for doing commendable work in Rajbhasha.
- MCs received recognition for effective implementation of the Official Language Policy at both urban and regional levels, with MC Ahmedabad securing First Prize and MC Ranchi securing Second Prize.
- Aerodrome Meteorological Office (AMO), Nagpur, became the first among 18 AMOs under IMD to receive the ISO 9001:2015 certification.
- MC Srinagar received an appreciation letter from the Hon'ble Lieutenant Governor, Union Territory of Jammu & Kashmir, regarding the safe and smooth conduct of Shri Amarnath Ji Yatra 2025.
- MC Patna, received an Appreciation Certificate from the Asian Development Research Institute (ADRI), Patna, for providing weather forecasting services to farmers in Bihar.
- MC Thiruvananthapuram received an appreciation letter from the Flag Officer Commanding-in-Chief, Southern Naval Command, for the exceptional meteorological support.
- MC Bengaluru received an appreciation letter from the Karnataka State Natural Disaster Monitoring Centre (KSNDMC) for providing timely forecasts on all significant weather phenomena.
- AMO Bengaluru (Devanahalli) received an appreciation letter from the Airport Authority of India, Devanahalli, Bengaluru, for timely, accurate forecasts.
- MC Agartala received an appreciation letter from the AAI, MBB Airport Agartala for its continued dedication and professional support in delivering high-quality Aviation Meteorological Services.

CMLRE, Kochi

- Dr. Kranthikumar, Principal Scientist-II, received the Best Oral Presentation Award at the IIOE-2 International Indian Ocean Science Conference, organised by INCOIS.
- Dr. Smitha Bal Raj, Scientist-E, was selected as a Member of the CLIVAR/IOC-GOOS Indian Ocean Region Panel for the term 2026-2028.
- Dr. Hashim Manjebrayakath, Scientist-E, was appointed Node Manager of the Indian Ocean Biogeographic Information System (IndOBIS) for OBIS.
- Mr. Davood Nihal, Senior Research Fellow, received the Best Poster Presentation at the ICMBGSD-25, CUSAT, Kochi (9-11 April 2025), and the Best Presentation Award along with the Best Research Scholar Award (Fisheries Science) at the World Congress on Climate Change & its Effects, Kathmandu, Nepal (10 September 2025).

IITM, Pune

- Dr. Suryachandra Rao A., Director, received the Dr. H. N. Siddique Memorial Lecture & Gold Medal from the Indian Geophysical Union.
- Dr. Anoop Mahajan was announced as a National Champion for Argentina in the 3rd Frontiers Planet Prize.
- Dr. Roxy Mathew Koll received the Prof. R. Ramesh Endowment Award from the Ocean Society of India during OSICON-25 (February 2025).
- Dr. Sabin T. P. was appointed Member, CORDEX Science Advisory Team (SAT) under WCRP (from 1 January 2025).
- Dr. Bhupendra Bahadur Singh received the Editor of Distinction Award 2025 from Springer Nature.

- Dr. Aditi Modi was appointed Vice President, Ocean Society of India (OSI), Pune Chapter (2025-2027) and featured as Scientist of the Month (July 2025) by WCRP.
- Dr. Maheswar Pradhan was appointed Member, CLIVAR/GEWEX Monsoons Panel (WG-AAM) for 2025-2027.
- Dr. Ankur Srivastava was appointed Member, WGNE Panel (ESMO Project Office) for 1 August 2025 - 31 July 2028.

INCOIS, Hyderabad

- INCOIS received the Subhas Chandra Bose Aapda Prabandhan Puraskar 2025 for ocean-related hazard early warning services (announced on 23 January 2025).
- Dr. T. V. S. Udaya Bhaskar received the IODE Achievement Award 2025 at the 3rd International Ocean Data Conference, Santa Marta, Colombia (10-14 March 2025).
- INCOIS received the National Geospatial Award 2025 for use of open-source spatial technologies (17 July 2025).
- INCOIS received the Yoga Sangam Patra from the Ministry of Ayush (21 July 2025).
- Dr. Kunal Chakraborty received the AGU Devendra Lal Memorial Medal 2025.

NCESS, Thiruvananthapuram

- Dr. K. Sreelash, Scientist-D, received the AHI Young Hydrologist Award 2023 (awarded on 6 November 2025).
- Dr. Arka Roy, Scientist-D, received the Alexander von Humboldt Research Fellowship (November 2025).

NCMRWF, Noida

- Dr. Rattan Kumar Datta, former Head, received the Sir Gilbert Walker Gold Medal from the India Meteorological Society (IMS), 2025.
- Dr. E. N. Rajagopal, former Head, received the IMS Fellowship, 2025.
- Dr. Ashish Routray, Scientist-F, was inducted as a Life Member, National Academy of Sciences India (NASI), 2025.
- Dr. Indira Rani, Scientist-F, received the IMS Fellowship, 2025.
- Dr. A. Jayakumar, Scientist-F, received the IMS Associate Fellowship.
- Dr. T. J. Anurose, Scientist-E, and team received the IMS Best Paper Award (Modelling).
- Dr. V.S. Prasad was appointed as Chairman WMO- RA II Coordination Panel on Research and Innovation (CP-RI) for the year 2025-27 and Dr. V.S. Prasad was elected as chairman, Ocean Society of India (OSI), Delhi-NCR Chapter (2025-2027).
- Dr. Indira Rani S., Scientist-F, was elected as a member of the WCRP Earth System Modelling and Observation Scientific Steering Group (ESMO-SSG), 2025.
- Dr. Indira Rani S., Scientist-F, was assigned as the ESMO-SSG liaison for the WCRP Working Group for Numerical model Experimentation (WGNE), 2025.
- Dr. Indira Rani S., Scientist-F, was assigned to form a Task Team for Regional Reanalysis intercomparison under WCRP, 2025.
- Dr. Indira Rani S., Scientist-F, was appointed as a member in the Climate Reanalysis Working Group under Momentum Partnership program, 2025.
- Dr. Anumeha Dube, Scientist-E, was appointed as a member of the WMO Joint Working Group on Forecast Verification and Research (JWGFVR), 2025.
- Dr. Anumeha Dube, Scientist-E, became member of the Task Team on Development of Tropical Low/Cyclone Standardized Verification (TT-TCSV), 2025.
- Dr. Sumit Kumar, Scientist-E, elected as Indian lead in TAG Momentum in 2025.
- Dr. Anurose T. J., Scientist-E, was appointed as Chairperson of the Urban Working Group in the Momentum Partnership Programme, 2025.

- NCMRWF received appreciation from DGIS Indian Army for the contribution to the Operation Sindoor through Anumaan Project.

NCPOR, Goa

- Dr. Venkatachalam Siddarthan received the Best Oral Presentation Award at ICMBGSD-2025, CUSAT, Kochi (9-11 April 2025).
- Dr. S. C. Tripathy, Scientist-F, was selected as Vice-Chair and EXCOM Member, Southern Ocean Observing System (SOOS) (14 May 2025).
- Dr. Waliur Rahaman, Scientist-F, received the Rashtriya Vigyan Puraskar - Vigyan Yuva Shanti Swarup Bhatnagar Award 2025 (Earth Sciences).
- Dr. Thamban Meloth, Director, received the CUSAT Distinguished Alumni Award 2025 (4 November 2025).
- NCPOR received the 1st Prize, Rajbhasha Excellence Award 2024-25 from TOLIC, South Goa.
- Dr. Archana Singh received an Excellence Award at SaGAA VIII Conference, New Delhi (24-25 November 2025).

NIOT, Chennai

- Dr. V. Bala Naga Jyothi received the Outstanding Women Researcher Award in Underwater Robotics (1 March 2025).
- Lifetime Achievement Awards were conferred on Dr. M. Ravichandran and Dr. N. Kalaichelvi at the 65th Mupperum Vizha.
- Dr. Dilip Kumar, Scientist-F, received the K. Chidambaram Memorial Award 2024 (12 July 2025).
- NIOT received the Motivational Award from the Town Official Language Implementation ommittee (21 November 2025).

NCCR

- Dr Uma Sankar Panda, Scientist F, has been appointed as the Member of The Technical Working Group of Global Ocean Decade Programme for Blue Carbon (GO-BC) for 2025-26.
- Mr. M. Sambandam, Project Scientist I, received the Best Research Paper Award of the Tamil Nadu State Environment Awards at the Tamil Nadu Climate Change Summit 3.0, Chennai (4 February 2025).

NCS, New Delhi

- Dr. O. P. Mishra, Director, NCS, was conferred the title of Honorary Professor by Vitus Bering Kamchatka State University on 30 September 2025, and received the IGU-Decennial Award 2025 from IGU-FIGA at INCOIS, in recognition of his outstanding contributions to geosciences.

Chapter-7
Governance & Administration

7.1 CITIZEN'S CHARTER

Vision

To excel as a leading knowledge and technology enterprise in the Earth System Science realm, delivering socio-economic benefits to society.

Mission

To provide high-quality services in weather, climate, ocean and coastal state, hydrology, seismology, and natural hazard management; to sustainably explore and utilize marine living and non-living resources; and to advance research in the three poles-Arctic, Antarctic, and the Himalayas.

Our Commitments			
S.No.	**Services/Transaction**	**Success indicators**	**Services**
1	Weather Forecasts and warnings	Timely release of weather forecast and warning to General Public and Meteorological support for Pilgrimage, tourism, mountain expedition, sports etc.	3 to 6 hrs
2	Providing Agro - Meteorological advisories at district level	To provide Agro-meteorological advisories at district level to the farmers	Twice a Week
3	Meteorological support for Civil Aviation purpose	Meteorological support for Civil Aviation purpose	30 minutes
4.	Rainfall Monitoring	Rainfall Monitoring	1 Day
5	Ocean Forecast	Timely release of a. Fishing advisory b. Tuna Fishing	24 Hrs.
		Ocean State Forecast I. General Public	3-6 Hrs.
		ii. Fishing Community	3-6 Hrs.
		iii. Industries	3-6 Hrs.
		iv. Defence/Security/Researchers	3-6 Hrs.
6	Early warning of natural hazards	Timely release of (a) Tsunamis Bulletin	10 Minutes
		Earthquake Bulletin (after)	10 Minutes
		Cyclone Warning Bulletin	3 Hrs.
7	Processing of proposals of holding of Seminars/ Symposia	Approval of Seminars/Symposia proposals.	2 Months
8	Processing of extra-mural proposals in the field of Earth Sciences	Timely processing of proposals from scientists/ scientific institutions	6 Months
9	Payment to vendors	Timely payment to vendors on submission of bills	4 Weeks

10	Processing of requests for filing of scientific positions received from various centres	Timely processing of proposals received from various centres	2 Months
11	Grievance redressal	Timely redressal of grievance a. Acknowledgement	2-3 Days
		b. Final response	21 Days
12	Release of funds to the Responsibility Centres under the control of MoES	Timely processing of proposals received	30 Days
13.	Disposal of applications/ appeals under RTI Act 2005	Timely disposal of applications/appeals	30/30 Days

7.2 Implementation of the 15 Point Programme on Minority Welfare

Due consideration, wherever required, is given to the 15 Point Programme on minority welfare.

7.3 Report of the Comptroller and Auditor General of India

A total of 14 Action Taken Notes (ATNs) pertaining to the Ministry are pending for settlement. The ATNs have not yet been submitted by the Ministry, as these are under various stages of compilation, examination and approval. The pending ATNs relate to paras dealing with issues such as misclassification of expenditure at detailed and object head levels, non-surrender of savings, and significant savings. The details are placed at Annexure - 1.

7.4 Staff Strength

a. Sanctioned Strength of Ministry of Earth Sciences (MoES) including its Subordinate, Attached and Autonomous institutes.

Groups of Posts	MoES+CMLRE+NCCR	NCMRWF	IMD	NIOT	NCPOR	INCOIS	IITM	NCESS	Total
Group A	103+22+19=144	66	525	119	58	49	172	41	1174
Group B	53+8+3 = 64	17	3806	67	18	30	79	29	4110
Group C	55+13+4 = 72	14	2695	46	22	00	68	58	2975
Total	280	97	7026	232	98	79	319	128	8259

NCMRWF - National Centre for Medium Range Weather Forecasting | CMLRE - Centre for Marine Living Resources & Ecology | NCCR - National Centre for Coastal Research | IMD - India Meteorological Department | NIOT - National Institute of Ocean Technology | NCPOR - National Centre for Polar & Ocean Research | INCOIS - Indian National Centre for Ocean Information Services | IITM - Indian Institute of Tropical Meteorology | NCESS - National Centre for Earth Science Studies

b. Detailed breakup of Sanctioned Strength of Ministry (Proper) including NCS + Koyna Project, CMLRE and NCCR.

Ministry/Attached Offices	Scientific/Technical Posts	Non- Technical Posts	Grand Total
Ministry (Proper) including NCS + Koyna Project	*69+15	142+5**+ 24***	255
CMLRE	32	11	43
NCCR	18	8	26
Total	134	190	324

*69 (Scientists) including Koyna Project+15 (Technical staff at Koyna Project)

** 5 Nos. of Sanctioned strength of personal establishment of HMoES w.e.f. June 2024

***24 Nos. of Non-Technical staff in Koyna Project

c. Representation of persons with disabilities in government services.

The Ministry and its subordinate, attached, and autonomous institutes maintain representation of persons with disabilities (PwDs) across Groups A, B, and C posts in line with government norms. While most offices report no vacancies or appointments under reserved categories, a few posts have been filled in certain institutes through direct recruitment or promotion. Efforts continue to ensure PwD representation is strengthened across all scientific and administrative positions.

Representation of Persons with Disabilities in MoES (2025)

Group	Institute	Direct Recruitment (Vacancies reserved/ Appointments)	Promotion (Vacancies / Appointments)
A	NCPOR	- / 2 (VH)	- / -
	NCESS	1 (OH) / 1 (OH)	- / -
	IITM	04/ -	- / -
B	IMD	1 (OH) / 1 (OH)	8 (OH) / 2 (OH)
	NCPOR	1 (VH) / -	- / -
	NCESS	1 (OH) / 1 (OH)	- / -
	IITM	04/ -	- / -
C	IMD	4 (VH), 6 (OH), 6 (HH) / 2 (OH), 2 (HH)	1 (OH) / -
	NCPOR	1 (OH) / 3 (Unidentified posts)	- / -
	IITM	2/ -	- / -

VH = Visually Handicapped; OH = Orthopedically Handicapped; HH = Hearing Handicapped ; "-" = No vacancies / appointments

d. Representation of SC/ST/OBC in government services in respect of Ministry (Proper).

Group	Total No. of employees	SCs	STs	OBCs
A	82	6	0	4
B	40	2	1	12
C (including MTS)	39	7	3	13
Total	**161**	**15**	**4**	**29**

7.5 Progressive Use of Hindi Official Language Act and Rules

During 2025-26, the Ministry continued to ensure effective compliance with the Official Language Policy of the Government of India and the Official Languages Act, 1963. Key initiatives undertaken during the year include:

Policy and Statutory Compliance: Provisions of the Official Languages Act, 1963, and the rules framed thereunder were implemented across the Ministry and its attached and subordinate offices. Checkpoints were established, and ongoing monitoring ensured adherence to statutory requirements.

Dissemination of Official Language Instructions: Orders and guidelines issued by the Department of Official Language were circulated to all wings of the Ministry and its field organizations for timely compliance.

Monitoring and Reporting: Quarterly progress reports on official language implementation were reviewed, and overall progress was evaluated by the Official Language Implementation Committee.

Important activities and achievements:

Hindi Day and All India Official Language Conference: Hindi Day was celebrated on 14 September 2025, and the Fifth All India Official Language Conference was held on 14-15 September 2025 in Gujarat. The events promoted the use of Hindi and facilitated discussions on strengthening its role in governance.

Hindi Fortnight (14-29 September 2025): Eight competitions were organized for employees of all categories to enhance proficiency in Hindi and awareness of Official Language rules. The activities witnessed enthusiastic participation and contributed to increased use of Hindi in official work.

Fig.7.1: Hindi Fortnight: Competitions held to boost Hindi skills and official language use.

Hindi Poetry Recitation Competition (18 September 2025): As part of Hindi Fortnight, Padma Bhushan awardee and environmentalist Dr. Anil Prakash Joshi was invited as the chief guest to deliver a lecture, inspiring Ministry personnel (Fig. 7.2).

Fig. 7.2: Falicitating Dr. Anil Prakash Joshi at Hindi Poetry Recitation, 18 September 2025

Official Language Inspections: Inspections were conducted at five institutions under the Ministry - INCOIS Hyderabad, NCS New Delhi, NCMRWF Noida, NCCR Chennai, and NIOT Chennai - to ensure

compliance with the Official Language Policy. Additionally, the Second Sub-Committee of the Parliamentary Committee on Official Language inspected several Ministry offices, with a delegation led by Joint Secretary Shri D. Senthil Pandiyan.

Hindi Workshops: Workshops were organized on 27 June and 25 September 2025, where guest speakers provided guidance on official language rules and Hindi typing techniques.

All India Official Language Scientific Seminar: NIOT, Chennai, hosted a two-day seminar on 18-19 December 2025 to discuss official language matters in scientific and technical contexts.

Quarterly Progress Report Workshop (12 December 2025): A workshop was conducted for Ministry officials on preparing the Quarterly Progress Report on Progressive Use of Hindi to ensure compliance with Official Language implementation.

7.6 Capacity Building and Human Resources Development: Rashtriya Karmayogi Large Scale Jan Seva Program

Under the Rashtriya Karmayogi Large Scale Jan Seva Program, the Capacity Building Commission (CBC) trained Master Trainers/Karmayogi Coaches (MTs/KCs) from across M/Ds, including officers from the Ministry. These trainers conducted one day Rashtriya Karmayogi (RKY) session for MoES employees in multiple batches during April-July 2025. Subsequently, CBC delivered an intensive Lead Trainer programme, following which trained Lead Trainers conducted three day MTs/KCs sessions at key MoES institutions, training additional coaches. The trained officers have conducted one day RKY trainings across MoES institutions, reaching around 2524 employees to date. This effort has strengthened service orientation across the scientific and administrative workforce of the Ministry.

7.7 PM Gati Shakti National Master Plan (PMGS-NMP):

PM Gati Shakti is a national initiative for coordinated infrastructure planning, supported by a GIS-based digital platform called the PM Gati Shakti National Master Plan (NMP), launched in October 2021. Developed by BISAG-N under DPIIT, the platform brings together data from multiple Ministries to help plan, monitor, and make decisions efficiently. Institutions under MoES, including IMD, INCOIS, and NCS, have provided procedures for sharing key datasets such as rainfall, wind, earthquakes, and ocean-energy parameters. These datasets help in better policy-making, project planning, and coordination between Ministries.

7.8 Implementation of judgements/ orders of the Hon'ble CAT

All the judgements/orders of the Hon'ble CAT or any other courts have been implemented or contested in proper forum within the stipulated time period.

7.9 Vigilance Activities and Achievements

Shri D. Senthil Pandiyan, IAS, has been serving as the Chief Vigilance Officer (CVO) of the Ministry since 1st January 2023. Senior officers have been nominated as Vigilance Officers (VOs) in attached/subordinate offices and autonomous bodies with the CVO's approval. Both preventive and punitive vigilance measures are actively implemented through the CVO and VOs across the Ministry and its institutions.

In line with Central Vigilance Commission (CVC) guidelines, Independent External Monitors (IEMs) were appointed to oversee contracts exceeding Rs. 5 crore.

The Ministry observed Vigilance Awareness Week from 27th October to 2nd November 2025 with the theme "Vigilance: Our Shared Responsibility." Activities included an interactive session for all officers and officials, and a quiz competition aimed at raising vigilance awareness, with prizes awarded to winners.

7.10 Parliament Matters

MoES handled all correspondence with the Parliament Secretariat and responded to 82 Lok Sabha and 88 Rajya Sabha questions during 2025. Implementation reports and status notes were compiled for Parliament assurances. Inputs were also provided for Parliamentary Committee study visits and for issues likely to be raised in Parliament, along with support to other Ministries in framing replies on MoES related matters.

7.11 Budget and Accounts

Budget Estimate of MoES for the year 2024-25 and actuals for 2023-24 and 2024-25 is as below.

(Rs. In crore)										
S. No	Major Head of Accounts	2023-24 Actuals			2024-25 B.E.			2024-25 Actuals		
		Revenue	Capital	Total	Revenue	Capital	Total	Revenue	Capital	Total
REVENUE SECTION										
1	3403- Earth System Science	722.09	0.00	722.09	887.75	0.00	887.75	1255.38	0.00	1255.38
2	3425- Other Scientific Research	63.43	0.00	63.43	69.00	0.00	69.00	12.72	0.00	12.72
3	3451- Secretariat Economic Services	536.89	0.00	536.89	633.94	0.00	633.94	64.89	0.00	64.89
4	3455- Meteorology	936.71	0.00	936.71	923.77	0.00	923.77	1054.41	0.00	1054.41
Total (Revenue)		**2259.12**	**0.00**	**2259.12**	**2514.46**	**0.00**	**2514.46**	**2387.40**	**0.00**	**2387.40**
CAPITAL SECTION										
1	5403-Capital Outlay on Earth System Science	0.00	55.23	55.23	0.00	280.00	280.00	0.00	121.69	121.69
2	5455-Capital Outlay on Meteorology	0.00	93.15	93.15	0.00	276.20	276.20	0.00	875.57	875.57
3	5475- Capital Outlay on other General Economic Services	0.00	1.95	1.95	0.00	2.14	2.14	0.00	2.07	2.07
	Total (Capital)	**0.00**	**150.33**	**150.33**	**0.00**	**558.34**	**558.34**	**0.00**	**999.33**	**999.33**
	Grand Total	**2259.12**	**150.33**	**2409.45**	**2514.46**	**558.34**	**3072.80**	**2387.40**	**999.33**	**3386.73**

Annexure 1

Report of the Comptroller and Auditor General of India						
The number of Action Taken Notes (ATNs) pending as on date for Ministry of Earth Sciences taken from various C&AG reports are given in the following table:						
S.No.	Year	No. of Paras/PAC reports on which ATNs have been submitted to Monitoring Cell after vetting by Audit	Details of the C&AG/PAC reports on which ATNs are pending			
			No. of ATNs not sent by the Ministry even for the first time	No. of ATNs sent but returned with observation and audit is awaiting their resubmission by the Ministry	No. of ATNs which have been finally vetted by Audit but have not been submitted by the Ministry to PAC	No. of ATNs with Audit
1.	2021	Para 3.8.5 (Sl. No. 256,257) Misclassification related to booking of electricity expenditure	01	NIL	NIL	NIL
2.	2021	Para 3.2.2(Sl. No. 13 of Annexure 3.2) Analysis of Savings	01	NIL	NIL	NIL
3.	2022	4.2.2 Sl.No.15 of Annexure 4.2 Analysis of Savings	NIL	NIL	NIL	01
4.	2022	4.2.2 Annexure 4.2 Sl. No. 84 Analysis of Savings	NIL	NIL	NIL	01
5.	2022	4.2.2.2 Annexure 4.3A Sl. No. 38 Other significant savings at minor-head/ sub-head level	NIL	NIL	NIL	01
6.	2022	4.2.2.2 Annexure 4.3B Sl. No. 27 & 28 Other significant savings at minor-head/ sub-head level	NIL	NIL	NIL	01
7.	2025	Para 3.5.3 (Sl. No- 55) Classification errors - Misclassification at detailed head level	01	NIL	NIL	NIL
8.	2025	Para 4.2.2.4(Sl.No.12 of Annexure 4.7) Non surrender of savings	01	NIL	NIL	NIL
9.	2025	Para 4.2.2.3 (Sl. No. 32-35 of Annexure 4.6B) Significant savings at minor-head/sub-head level-100 crore or more	01	NIL	NIL	NIL
10.	2025	Para 4.2.2.2 (Sl. No. 17 of Annexure 4.5) Significant savings at segment level - Revenue Voted	01	NIL	NIL	NIL

11.	2025	Para 4.2.2.2 (Sl. No. 78 of Annexure 4.5) Significant savings at segment level - Capital Voted	01	NIL	NIL	NIL
12.	2025	Para 3.5.4(iv)(Sl. No. 01 of Annexure 3.15) Classification errors - Misclassification at Object head level	01	NIL	NIL	NIL
13.	2025	Full Report of 08 of 2025 (INCOIS)	NIL	01	NIL	NIL
14.	2025	Para 4.2.2.4 (Sl. No.17 of Annexure 4.7) Non-surrender of savings	01	NIL	NIL	NIL
15.	2025	Para 4.2.2.3 (Sl. No.34,35,36 & 37 of Annexure 4.6B) Significant savings at minor-head/ sub-head level	01	NIL	NIL	NIL
16.	2025	Para 4.2.2.2 (Sl. No. 15 of Annexure 4.5) Significant savings at segment level	01	NIL	NIL	NIL
17.	2025	Para 4.2.2.2 (Sl. No. 76 of Annexure 4.5) Significant savings at segment level	01	NIL	NIL	NIL
18.	2025	Para 3.5.2(i)(Sl. No. 01 of Annexure 3.12A) Misclassification of Expenditure	01	NIL	NIL	NIL
19.	2025	Para 3.5.2(i)(Sl. No. 01 of Annexure 3.12B) Misclassification of Expenditure	01	NIL	NIL	NIL
20.	2025	Para 3.5.2(ii)(Sl. No. 01 of Annexure 3.12C) Misclassification of Expenditure	01	NIL	NIL	NIL

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