GENERAL ARTICLE

A Quantum Leap in Earth System Science Research and Services*

M Rajeevan, Gopal Iyengar and Bhavya Khanna

Earth System Science refers to the integrated study of physical, biological, chemical, and social processes that define the conditions on Earth. The earth system approach looks at the planet, linking the atmosphere, oceans and hydrosphere, the terrestrial realm, cryosphere and the biosphere. Earth system science services include weather and climate forecasts, ocean and coastal state forecasts, warnings, seismological monitoring, exploration of polar regions, and living and non-living resources of the oceans.

Dr M Rajeevan is Former Secretary, MoES.

Shri. Gopal Iyengar is Scientist G & Adviser, MoES, New Delhi.

Dr Bhavya Khanna is a Scientist D (Communication in Science), MoES, New Delhi.

HISTORY: How the Ministry of Earth Sciences Came into Being

India had a ground in meteorological sciences in the late 17th century, much before it came under colonial rule. In 1636, Halley, a British scientist, published a treatise on the Indian summer monsoon. He attributed the Indian summer monsoon to a seasonal reversal of winds due to differential heating of the Asian landmass and the Indian Ocean. In the late 17th century, the British East India Company established some of the oldest meteorological observatories in the world in India. The first Indian meteorological observatory was set up in Calcutta in 1785 and in Chennai in 1796. The Asiatic Society of Bengal, founded in 1784, promoted scientific studies in meteorology in India. In 1864, a disastrous tropical cyclone struck Calcutta, followed by failures of the monsoon rains in 1866 and 1871. These events prompted the British Government to establish the India Meteorological Department (IMD), bringing all meteorological work under a central

Keywords
Meteorology, earth science, MoES, weather, climate, ocean, polar sciences, seismology.

*Vol.26, No.10, DOI: https://doi.org/10.1007/s12045-021-1244-7

authority. Mr H F Blanford was appointed as the first Meteorological Reporter to the then Government of India. Since then, IMD has contributed significantly to meteorological sciences. Sir Gilbert Walker and Sir C W B Normand of the IMD did remarkable research on monsoon that provided valuable insights into monsoon and its variability, including global teleconnections.

Post-independence, it was recognized that there is a need to study monsoon dynamics, weather systems and climate-related processes for India's economic development. The Government of India approved the establishment of a dedicated institute for meteorological research in February 1962. As a result, the Institute of Tropical Meteorology (ITM) was founded on 17 November 1962, at Pune. It was organized as a distinct unit of the IMD. ITM, Pune, was transformed into an autonomous organization in April 1971 under the name Indian Institute of Tropical Meteorology (IITM). Over the years, IITM made significant research contributions in tropical meteorology, especially monsoon dynamics and variability, tropical climate variability and climate change, cloud physics, air pollution, etc.

The Government of India approved the establishment of a dedicated institute for meteorological research in February 1962. As a result, the Institute of Tropical Meteorology (ITM) was founded on 17 November 1962, at Pune.

The IMD functioned under the Ministry of Civil Aviation and Tourism post-independence. It was bought under the Department of Science and Technology (DST), along with IITM, Pune, and the National Centre for Medium Range Weather Forecasting (NCMRWF), Noida, in 1985. Parallelly, in 1982, the Government of India established the Department of Ocean Development (DOD), recognizing the importance of ocean-related activities for the country's progress. After its establishment, DOD carried out significant ocean research and developed some societally essential technologies. Under DOD, autonomous institutions including the National Institute of Ocean Technology (NIOT), Chennai, Indian National Centre for Ocean Information Services (INCOIS), Hyderabad, National Centre for Polar and Ocean Research (NCPOR), Goa, erstwhile National Centre for Antarctic and Ocean Research (NCAOR) were bought together. For ocean research, DOD acquired a few research vessels such as Sagar Kanya, Sagar Sampada, and Sagar Nidhi. These vessels helped in collecting

In 1982, the Government of India established the Department of Ocean Development (DOD), recognizing the importance of ocean-related activities for the country's progress.

ocean-related data and exploring and mapping living and non-living ocean resources.

Until the early 2000s, there were no significant efforts to integrate earth system science activities. A closely coordinated program focusing on the use of modern science and technology tools was also missing. In 2005, during the MONEX conference in Delhi, it was discussed that India lagged by at least ten years in atmospheric modelling and had only a hundredth of the computing power available at the major world centres. India's available resolution of the regional weather forecast was limited to about 100 kilometres and the global weather prediction model to about 180 kilometres. The supercomputing facility was restricted to only about 1.0 teraflops. Although earth system science-related institutions (such as IMD, IITM, INCOIS, NIOT, etc.) existed, there was hardly any significant collaboration. Experts felt that this vast lacuna was valid and not an exaggeration.

In 2005, during the MONEX conference in Delhi, it was discussed that India lagged by at least ten years in atmospheric modelling and had only a hundredth of the computing power available at the major world centres.

Recognizing this gap, the Scientific Advisory Council to the Prime Minister (SAC-PM) in 2005 suggested forming a Department of Earth Sciences (DES) and an Earth Commission. The SAC-PM chaired by Prof. C N R Rao executed a task force under the chairmanship of Prof. Roddam Narasimha to chart out a roadmap and plan the integration of earth system science activities in India. Other members of the task force were Dr P Rama Rao, Former Secretary of DST; Dr Harsh Gupta, Former Secretary of Department of Space; and Shri S K Das from the Indian Space Research Organization (ISRO). Prof. D R Sikka, an eminent meteorologist, was an invited member of the team. The choice of selecting Prof. Narasimha as the Chairman proved to be an excellent decision of the SAC-PM. It was widely appreciated considering Prof. Narasimha's comprehensive research experience in earth system sciences. He had spearheaded the development of a parallel computing machine for fluid dynamics calculations and weather prediction as the Director of Council of Scientific and Industrial Research (CSIR)-National Aerospace Laboratory (NAL), Bangalore. He was also instrumental in launching unique scientific campaigns such as the Monsoon Boundary Layer Ex-

The Scientific Advisory Council to the Prime Minister chaired by Prof. C N R Rao executed a task force under the chairmanship of Prof. Roddam Narasimha to chart out a roadmap and plan the integration of earth system science activities in India.

periment and cloud observations and simulation and atmospheric modelling programs.

The Roddam Narasimha-led task force, after several rounds of discussions with stakeholders, recommended the establishment of a Department of Earth Sciences absorbing the Department of Ocean Development and formation of a new scientific ministry, namely the Ministry of Earth Sciences.

The Roddam Narasimha-led task force, after several rounds of discussions with stakeholders, recommended the establishment of a Department of Earth Sciences (DES) absorbing the Department of Ocean Development (DOD) and formation of a new scientific ministry, namely the Ministry of Earth Sciences (MoES), in its report submitted to the Government of India, on 25 September 2005. It was felt necessary to establish a high-power technical body to formulate policy, oversee its implementation, and ensure interdisciplinary integration. In line with Prof. Narasimha's vision and recommendations, the MoES and the Earth Commission (similar to the Space Commission and Atomic Energy Commission) were set up in July 2006 after due approval from the Cabinet. This also bought together meteorological Institutes like IMD, IITM (Pune), NCMRWF (Noida), and DOD's affiliated institutes under one administrative framework. Dr Prem Shankar Goel was appointed as the first Secretary of MoES and Chairman of the Earth Commission.

The Earth Commission, recognized the importance of promoting training and human resource development in earth sciences. It also recommended that funding earth sciences research in specialized centres and universities should be prioritized. The formation of the Earth Commission and reorganization of the DOD into MoES facilitated an integrated view of the earth system science (that is, the ocean, atmosphere, cryosphere and land). This helped in providing the best possible services of oceans, monsoon, cyclones, earthquakes, tsunami, and climate change, etc.

The formation of the Earth Commission and reorganization of the DOD into MoES facilitated an integrated view of the earth system science. This helped in providing the best possible services of oceans, monsoon, cyclones, earthquakes, tsunami, and climate change, etc.

PRESENT SCENARIO: Work and Achievements of the MoES

Since its inception on 27 July 2006, the MoES has rendered numerous earth system science-related services to the country. Some of the work and achievements of MoES are highlighted below.

Weather and Climate Services

The accuracy of weather and climate services, including weather forecasts in India, has improved substantially after MoES came into being in 2006. It has also streamlined collaborations between various MoES institutes and other organizations such as the Indian Institute of Science (IISc), Bangalore, Indian Institutes of Technology (IITs), Indian Space Research Organization (ISRO), Council of Scientific and Industrial Research (CSIR), Indian Council of Agricultural Research (ICAR) and Universities. Under the Monsoon Mission launched in 2012, there was an active collaboration with international universities and academic institutions, which improved modelling capability and helped the training of human resources.

Since 2010, accurate and timely forecasts of cyclones (such as Phailin, HudHud, Titli, Amphan, Tauktae and Yaas) by the MoES have helped save numerous precious human lives. Noteworthy improvements have been made in the track and intensity forecast of tropical cyclones. Between 2006 and 2021, the 24-hours forecast error in track prediction has now reduced from 141 km to 72 km. The landfall error has reduced from 99 km to 18 km. The forecast skill of heavy rainfall has also improved considerably. The false alarm rates in forecasts of heavy rainfall have decreased from 46 to 11 per cent. The probability of detection has increased from 49 to 67 per cent. Most of the improvement in the probability of detection of heavy rainfall at meteorological subdivision levels has occurred in the last six years (from 50 to 77 per cent for 24 hours lead period, from 48 to 70 per cent for 48 hours lead period and from 37 to 66 per cent for 72 hours lead period).

Between 2006 and 2021, the 24-hours forecast error in track prediction has now reduced from 141 km to 72 km. The landfall error has reduced from 99 km to 18 km. The forecast skill of heavy rainfall has also improved considerably. The false alarm rates in forecasts of heavy rainfall have decreased from 46 to 11 per cent.

In the last fifteen years, the number of Doppler Weather Radars (DWRs) has increased from 4 to 27, the upper air observational (radio-sonde) network from 34 to 56, and the automatic weather stations (AWS) from 125 to 727. In addition, 200 Agro-AWS also have been installed. With the increased installed capacity of high-end equipment, there has been a substantial increase in the reception and utilization of satellite data and the country's meteorological network. In 2021, MoES set up a high-resolution rapid refresh (HRRR) system that provides weather forecasts at a resolution of 2 km, updated every two hours with a lead time of up to 12 hours.

As part of the Monsoon Mission, India took initiatives to develop indigenous coupled weather prediction models. As a result, India is now proud to have coupled atmosphere-ocean prediction models for extended range (10 days to one month) and seasonal forecasts (up to one season). MoES currently operates two coupled weather forecasting systems, one developed jointly by the IITM, Pune and IMD and another by NCMRWF, Noida. The horizontal resolution of the global atmospheric deterministic prediction model was improved from 180 km to 12 km between 2006 and 2018. In addition, two ensemble prediction systems for generating probabilistic weather forecasts were introduced with a 12 km model resolution valid for up to 10 days. IMD also adopted a multi-model ensemble forecasting system for generating seasonal forecasts in 2021. In these modelling efforts, IITM, Pune and NCMRWF, Noida played vital roles. Today, the supercomputing facilities have increased at least a thousand times from about 1.0 teraflops to 11 petaflops.

MoES currently operates two coupled weather forecasting systems, one developed jointly by the IITM, Pune and IMD and another by NCMRWF, Noida.

Till 2006, IMD provided city-based forecasts to about 30 cities only, which has increased to more than 700 cities and towns by 2021. IMD also provides agrometeorological advisories to nearly 42 million farmers of the country directly twice a week. The Agromet Field Units (AMFU) have increased from 130 to 330. The resolution of services has enhanced from district to block level. The dissemination of agromet advisories has transformed into digital modes of communication such as SMS and mobile apps. Mobile apps such as *Mausam* and *Meghdoot* disseminate agrometeorological information to the farmers more effectively in a real-time fashion. The World Meteorological Observation (WMO) regional climate centre at IMD, Pune, provides climate services for the entire South Asia. IITM, Pune developed the country's first Earth System Model (ESM) for climate change studies and projections. For the first time, India contributed to

Mobile apps such as *Mausam* and *Meghdoot* disseminate agrometeorological information to the farmers more effectively in a real-time fashion.

the Intergovernmental Panel on Climate Change (IPCC) climate change assessment report of 2021.

MoES institutes (IMD, IITM, NCMRWF and NCCR), developed urban flood warning systems for Mumbai and Chennai. This was an excellent example of how the integration of different components of Earth system science help in the development of a product for public utility and societal benefit.

Polar Sciences

The Arctic, Antarctic, and Himalayas are the three poles of the Earth. Exploring the poles requires capabilities in high-end cutting-edge research. For integrating polar science studies, MoES renamed its institute, the National Centre for Antarctic and Ocean Research (NCAOR), to the National Centre for Polar and Ocean Research (NCPOR). In 2008, NCPOR, Goa, set up a new research station in the Arctic called *Himadri* at Svalbard, Norway. In 2017, a new research station called *Himansh* was established in the Northwest Himalayas to study Himalayan glaciers. NCPOR has been coordinating annual scientific expeditions to Antarctica since 1981. It also hosts expeditions to the Arctic. India is amongst the few leading countries of the world to run permanent research base stations in all three poles of the Earth.

India is amongst the few leading countries of the world to run permanent research base stations in all three poles of the Earth.

India has initiated POLARNET (Polar Aerosol Network) to monitor greenhouse gas and aerosol measurements in all three poles. In addition to NCPOR, other MoES institutes such as NIOT, Chennai and IITM, Pune, have been collaborating to enhance the country's polar research capabilities. Under the polar weather and climate program, MoES has set up a global sea-ice model, regional ocean model, and regional atmospheric model to study polar weather dynamics.

Ocean Services

The Indian National Centre for Ocean Information Services (INCOIS), Hyderabad, is a specialized institute under the MoES, rendering ocean-related services. These include issuing tsunami alerts, oil spill advisories, routine forecasts of waves, tides, and ocean general circulation parameters for various stakeholders, including the navy, industries, and coastal communities. MoES reaches almost 16.5 lakh direct users who utilize the ocean state forecasts, which are issued daily. In addition to ocean state forecasts, INCOIS also issues advisories on Potential Fishing Zones (PFZ) that help almost 7 lakh fisherfolk daily in a big way. These advisories are disseminated through a network of 558 fishing subcentres via various communication channels such as short messaging service (SMS), mobile app, social media, and website.

As part of the tsunami warning system, INCOIS/MoES has completed mapping coastal regions that are highly vulnerable to natural disasters such as tsunami and storm surges using the 3D GIS technique for several locations on the east coast of India.

INCOIS developed a state-of-the-art ocean data modelling system called HOOFS (High-resolution Operational Ocean Forecast and reanalysis System) in 2020, improving ocean state forecasts tremendously.

INCOIS developed a state-of-the-art ocean data modelling system called HOOFS (High-resolution Operational Ocean Forecast and reanalysis System) in 2020, improving ocean state forecasts tremendously. INCOIS also set up a GEMINI mobile system (GAGAN Enabled Mariner's Instrument for Navigation and Information) in 2019. GEMINI disseminates ocean-related information, including warnings of impending dangers collected through GAGAN (GPS Aided Geo Augmented Navigation) directly to fisherfolk and vessels operating in the deeper oceans on cellular devices.

The National Center for Coastal Research (NCCR), Chennai, has analysed shoreline change rate for the Indian coast using Indian satellite images and field measurements.

The National Center for Coastal Research (NCCR), Chennai, has analysed shoreline change rate for the Indian coast using Indian satellite images and field measurements. A comprehensive web-based coastal change information system has been developed to facilitate coastal managers in the development and management of coast-related processes. MoES and its institutes have organized specific campaigns to understand ocean mixing processes in the Bay of Bengal and the Arabian Sea. These processes have provided valuable insights into areas such as monsoon and climate change.

Ocean Observations and Survey

India has the 18th largest exclusive economic zone (EEZ) of approximately 2 million square kilometres, including the Lakshadweep islands and Andaman and Nicobar archipelago. MoES has made significant achievements in oceanic surveys and mapping of EEZ. The EEZ survey comprises nearly 93 per cent of deepwater blocks (of more than 500 meters of water depth) within the Indian EEZ.

MoES has made inroads in survey, exploration, environmental impact assessment, technology development, and extraction of polymetallic nodules over the central Indian Ocean as part of the polymetallic nodules (PMN) program. The PMN program activities are in line with India's contract with the International Seabed Authority. Polymetallic nodules are sources of high-value minerals such as manganese, cobalt, copper, etc. India has submitted its first partial extended continental shelf claim to the United Nations, under active consideration. The country has also conducted a preliminary survey and exploration of hydrothermal sulphides in the Central Indian Ridge (CIR) and Southwest Indian Ridge (SWIR). Hydrothermal sulphides are sources of valuable metals. The International Seabed Authority granted a license and contract to India on 26 September 2016 to identify potential zones of hydrothermal sulphides in CIR and SWIR, which is a 10,000 square kilometres area. Based on the analysis and integrated data interpretation, MoES has identified eleven new locations with potential hydrothermal activity in CIR and SWIR. Deciphering sites of hydrothermal sulphides can give a big boost to the Indian economy.

The International Seabed Authority granted a license and contract to India on 26 September 2016 to identify potential zones of hydrothermal sulphides in CIR and SWIR, which is a 10,000 square kilometres area. Based on the analysis and integrated data interpretation, MoES has identified eleven new locations with potential hydrothermal activity in CIR and SWIR.

MoES institutes (INCOIS and NIOT) have deployed several oceanic observational platforms like ARGO floats and ocean data buoys. These platforms provide real-time ocean meteorological data. Ocean buoys have increased from 19 in 2006 to 51 in 2021. A network of about 220 ARGO floats exists as of date. Moreover, 17 coastal moorings and ten high-frequency radars have been installed to measure coastal currents in Indian coastal waters continuously.

Two gliders and flux mooring have been deployed in the Bay of Bengal for oceanic measurements very recently. The flux mooring was installed in the Indian Ocean for the first time by MoES. Data from ocean buoys have proved valuable in preparing forecasts for tropical cyclones, storm surges, and ocean state.

Ocean Technology

MoES has helped set up various indigenous facets of ocean technology such as desalination plants for converting seawater to potable water in Lakshadweep islands, exploring marine biodiversity and living resources, and developing remotely operated vehicles for ocean exploration.

MoES has helped set up various indigenous facets of ocean technology such as desalination plants for converting seawater to potable water in Lakshadweep islands, exploring marine biodiversity and living resources, and developing remotely operated vehicles for ocean exploration. The National Institute of Ocean Technology (NIOT), Chennai, has developed and implemented technologies to restore beaches in Puducherry and Tamil Nadu. These beaches were lost to erosion in the recent past. NIOT has developed indigenous technology for desalination of water based on low-temperature thermal desalination (LTTD) and has commissioned several plants in Lakshadweep.

Seismological Observations

The National Center for Seismology runs a high-end underground observatory called the BGRL in Karad, Maharashtra. BGRL is equipped with a 3 kilometres deep borehole in Koyna, which would further be dug to a depth of 7 kilometres inside the Earth's crust in the coming five years.

Seismology is the study of earthquakes and related phenomena. The National Center for Seismology (NCS), New Delhi, is a unique and specialized institute of the MoES which coordinates several seismology-related activities in India. Through a widespread network of more than 150 seismological observational stations, NCS provides information and data on an earthquake in India within a few minutes. The NCS also runs a high-end underground observatory called the BGRL (Borehole Geophysics Laboratory) in Karad, Maharashtra. BGRL is equipped with a 3 kilometres deep borehole in Koyna, which would further be dug to a depth of 7 kilometres inside the Earth's crust in the coming five years. BGRL aims to understand the reasons for frequent earthquakes in the Koyna region after the impounding of the Shiv Sagar reservoir in 1962. MoES has executed the seismic microzonation of Bhubaneswar, Chennai, Coimbatore and Mangalore, which are in an advanced completion stage. In eight more cities (Patna, Meerut, Amritsar, Agra, Varanasi, Lucknow, Kanpur and Dhanbad), work has been initiated.

Future Directions

Over the last 15 years, the quality of weather, climate, ocean, and seismological services provided by the MoES has improved significantly due to systematic efforts in augmenting atmospheric, coastal, oceanic, and geophysical data and surveys and polar research; developing accurate modelling strategies, and increasing investments in cutting edge research and human resources development in earth system sciences.

Over the last 15 years, the quality of weather, climate, ocean, and seismological services provided by the MoES has improved significantly due to systematic efforts in augmenting atmospheric, coastal, oceanic, and geophysical data and surveys and polar research; developing accurate modelling strategies, and increasing investments in cutting edge research and human resources development in earth system sciences.

The oceans surrounding India remain largely unexplored. To date, water-derived resources remain amongst the primary means of livelihood for most of the population. Natural disasters including tropical cyclones, flash floods, hurricanes, storm surges, heavy rainfall, and earthquakes can wreak havoc on vulnerable Indian communities. Therefore, it is well accepted that research and efforts must be aligned towards an integrated earth system science approach for deriving solutions. The setting up of MoES in 2006 was a progressive and visionary decision yielding several socio-economic benefits for the nation and fellow citizens. In the last 15 years, the budget estimate of MoES has increased almost 2.5 times, which has improved MoES services manifold.

In the future, MoES envisions adopting higher responsibilities and deliver more earth system science-related services. In 2021, with the Cabinet's approval of its flagship program, the Deep Ocean Mission (DOM) and implementation of the Blue Economy Policy, the MoES has moved a step closer to the vision of Prof. Narasimha. Under the Deep Ocean Mission, India is set to join the ivy league of countries that pioneer ocean exploration technologies, data and services. By 2025, India would execute vast deep-ocean exploration using an indigenously developed manned submersible capable of conducting real-time experiments at a depth of six kilometres below the ocean surface. The country would have more expertise in the mining and extraction of high-value polymetallic nodules and hydrothermal sulphides. The country would be contributing more impactful publications highlighting discoveries of natural living and non-living oceanic resources. With this, improvements in data and services of earth systems science would continue.

Prof. Narasimha's vision of an integrated framework for earth system sciences that took shape with the establishment of MoES has undoubtedly been a game-changer and has proved pivotal to the country's growth and development.

Address for Correspondence
M Rajeevan
Former Secretary
Ministry of Earth Sciences
Prithvi Bhavan, Lodhi Road
New Delhi 110 003.
Email:
rajeevan61@yahoo.co.in

Suggested Reading

[1] **M Rajeevan, G Iyengar, B Khanna B, Ministry of Earth Sciences – Contributing Towards a Weather-ready and Climate-smart India, *Science Reporter*, Vol.58, No.08, pp.51–56, 2021.**

[2] **M Rajeevan, Why should India Invest in Deep Ocean Research? *Current Science*, Vol.115, No.5, pp.807–808, 2018.**