Marine Sciences of the Seas around India between 1874 and 2000 and Prospects for the New Millennium

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THE INDIAN OCEAN: THE OCEANOGRAPHERS' LABORATORY

The Indian Ocean, the only ocean named after a country, is unique because unlike other oceans it is bounded in the north by the Asian continent. The Indian Seas cover 3 million kilometers squared, larger than its land area. India, a peninsular country with major rivers, divides the north Indian Ocean into two basins, the Bay of Bengal on the east and the larger Arabian Sea on the west, bounded approximately between 0° N to 24° N and 60° E to 100° E (fig. 1). Their total shelf area of about 0.84 million kilometers squared, approximates that of the Gulf of Mexico plus the Caribbean Seas, excluding Antilles. The Indian coastline is 7515 km. The Bay of Bengal and the Arabian Sea contribute 59 percent and 41 percent, respectively, to the 2.02-million kilometers squared Indian Exclusive Economic Zone.

From an oceanographer's perspective, the Bay of Bengal and the Arabian Sea constitute an ideal laboratory. The round of meteorological, hydro-

1. As a tribute to my teacher Prof. E. C. LaFond, California, United States, with gratitude I dedicate this paper. My grateful thanks are due to Prof. E. Mann Borgese, International Ocean Institute (IOI), Dalhousie University, Halifax, Canada, for encouraging me to write this review and to Mr. S. Coffen-Smout (*Ocean Yearbook*) for sending several articles of interest and suggestions. I remain grateful to Dr. E. Desa, Director, NIO, Goa, Dr. M. P. Tapaswi, NICMAS, NIO, Goa, Dr. K. Jayappa, Mangalore University, Mangalore, Prof. B. L. K. Somayajulu, Physical Research laboratory, Ahmedabad, and Mr. Aziz-Ud-Din Ahmed Usmani, Counselor, Indian Embassy, Kuwait for kindly providing information on marine sciences in India. For constructive criticism I thank Dr. R. V. Durvasula, Yale University. While saluting several Indian colleagues, past and present for their excellent contributions for the advancement of Indian Marine Sciences, I appeal to the present and future for more focussed mission oriented research in the EEZ. I thank Bala. T and Dr. Joseph, Andhra University, Visakhapatnam, for assistance with the graphics. Dr. C. V. Nageswara Rao's help with proofreading is highly appreciated. The views expressed are my personal reflections and not that of any organization or institution.

0-226-06619-3/02/0016-0008$01.00 *Ocean Yearbook* 16:195–227.

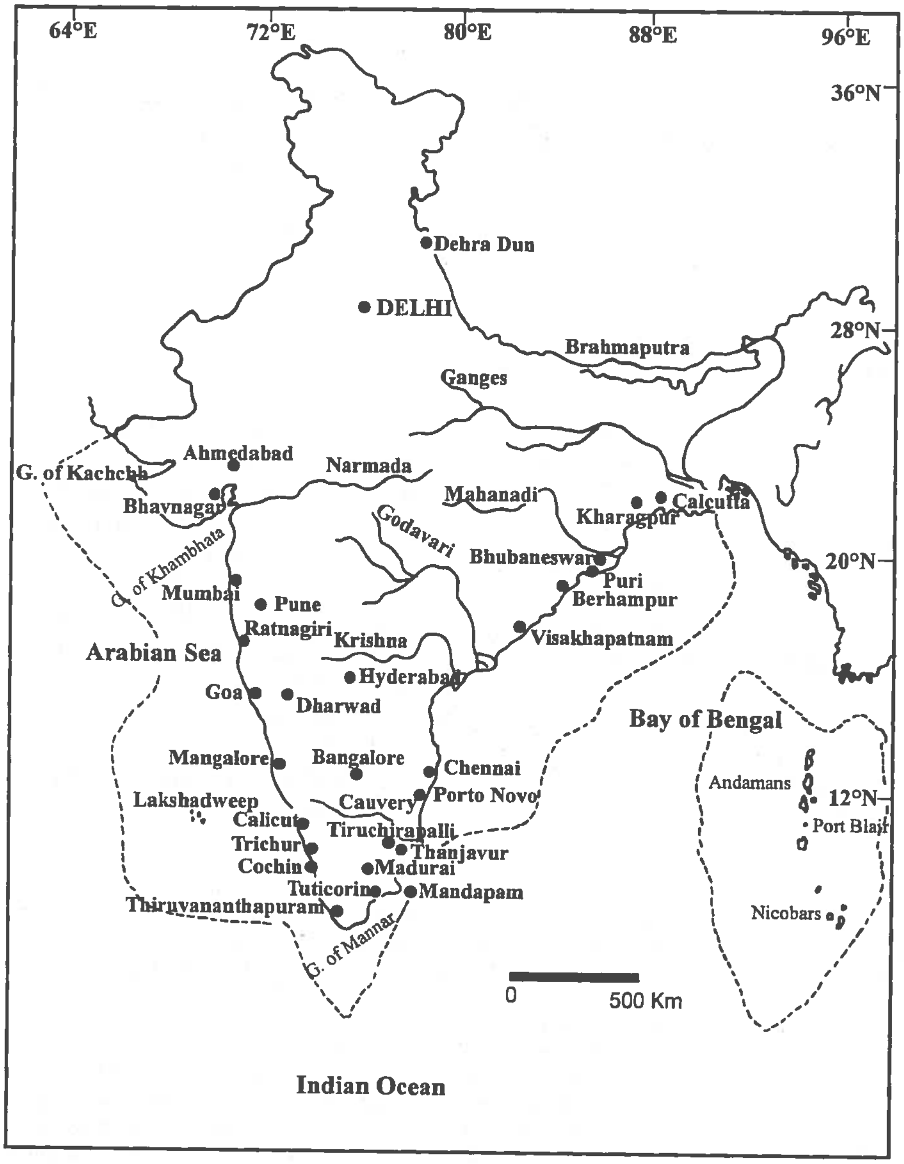
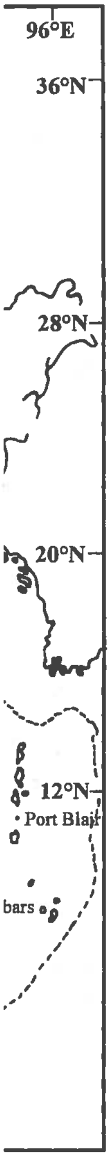


FIG. 1.—India with major rivers, Bay of Bengal, Arabian Sea and the Indian Ocean. The broken line indicates the EEZ.



logical, and biological events is governed by a) influx of large freshwater from several major rivers, b) intense northeast and southwest monsoon winds of which the latter breeds cyclones in the Bay of Bengal, unique to these waters. Additionally, these waters support various tropical biotopes such as estuaries, mangroves, brackish water lakes, coral reefs, islands, and offshore waters with a great diversity of fauna and flora. The steadily growing coastal population (~200 million) heavily utilizes the coastal zone for urban settlements, fishing, mariculture, marine transport, recreation, offshore oil and gas exploration, and dumping of wastes.

The pursuit of marine science during the British colonial rule (pre-1947) was limited to only a few individuals and was purely descriptive. In contrast, independent India has acquired certain capabilities in marine science comparable with other similar nations. This review is not intended to represent a comprehensive coverage of all themes of marine sciences in India but identifies one striking singularity, that is, its rapid growth in the past decade resulting in a large institutional framework capable of mounting challenging research programs at sea. While presenting the progression of marine sciences in India, I discuss some salient features of the seas adjacent to India, and the crucial problems confronting the coastal zone and marine environment in the new millennium and their social relevancy.

BIRTH AND PROGRESS OF MARINE SCIENCES IN INDIA

Five agencies played significant roles and punctuate the progression of marine science activities in India. They are the Indian Marine Survey (1874–1926), coastal universities (1927 to date), International Indian Ocean Expedition (1960–1965), the National Institute of Oceanography (1966) and the Department of Ocean Development (1981).

Indian Marine Survey

The British naturalists initiated marine sciences in India. The Royal Indian Marine Survey (RIMS) initiated a survey of the fauna and flora in 1874, followed by biological collections from a 580-ton vessel, the Investigator I, in 1881, and a 1,708-ton vessel, the Investigator II, in 1908. Francis Day of the Zoological Survey of India published the first two volumes on the fishes of India in 1878. Dr. A.W. Alcock, a naturalist and his associates surveyed marine fauna and flora of the Bay of Bengal, Andamans and Laccadives.[2]

2. A. W. Alcock and A. R. S. Anderson, "An Account of Recent Collection of Deep Sea Crustacea from the Bay of Bengal and Laccadive Sea." *Journal of The Asiatic Society of Bengal* 63 (1894): 141–89.

Similarly, Dr. N. Annandale, another naturalist, published extensively on the Indian Cirripedia.[3]

The British Surgeon-naturalist Col. R.B.S. Sewell laid the foundation for oceanographic studies in the Indian Seas by collecting invaluable data on temperature, salinity, and meteorological information during 1914–1921. Sewell published biological observations, temperature, salinity and some meteorological features in the Bay of Bengal[4] based on observations made from R.I.M.S. *Investigator* II. Oceanographic expeditions Valdivia (1898–1899, Siboga (1899–1900), Dana (1901–1903, 1928–1930), John Expedition (1933) and Galathea (1950–1952)made a few observations in the Indian waters. To celebrate the 50th anniversary of the John Murray Expedition that had investigated seafloor topography and geology of the Arabian Sea, the Intergovernmental Oceanographic Commission (IOC) of UNESCO, with several Egyptian, British, and international organizations, convened a symposium and roundtable discussions and identified gaps in marine scientific knowledge and recommended areas of interdisciplinary research.[5] The John Murray/Mabahiss Expedition had considerable political effect in Egypt, but the scientific results had little effect in the 1930s when the potential importance of seafloor topography and geology studies was not realized.[6] Also, as most of the Expedition results appeared in scientific reports rather than in scientific journals, they failed to reach a wider readership.[7] A special volume of 15 papers was published on the physical, chemical, and biological oceanography of the northwest Indian Ocean and adjacent waters.[8]

Ocean-going Capabilities Usher Modern Oceanographic Research

Colonial India, never a sea power, lacked a maritime tradition. In 1927, the University of Madras initiated marine biological studies for the first time in

3. N. Annandale, "Malaysian Barnacles in the Indian Museum, with a List of the Indian Pedunculata," *Memoirs of the Asiatic Society of Bengal* 1 (1905): 73–87.

4. R.B.S. Sewell, "Geographic and Oceanographic Research in Indian Waters. Part 5. Temperature and Salinity of the Surface Waters of the Bay of Bengal and Andaman Sea with Reference to Laccadive Sea." *Memoirs of the Asiatic Society of Bengal* 9 (1929): 207–356; R.B.S. Sewell, "Geographic and Oceanographic Research in Indian Waters. Part 5. Temperature and Salinity of the Surface Waters of the Bay of Bengal and Andaman Sea," *Memoirs of the Asiatic Society of Bengal,* 9 (1929): 357–424.

5. UNESCO, "Mabahiss-John Murray 50th Anniversary: Marine Science of the North West Indian Ocean and Adjacent Waters," *UNESCO Technical Papers in Marine Science* 31 (1985): 153.

6. G.E.R. Deacon and A.L. Rice, "The Significance of the John Murray/Mabahiss Expedition to the Arabian Seas," *Deep-Sea Research* 31 (1984): 573–581.

7. Ibid.

8. A.A. Alleem and S.A. Morocos, "The John Murray/Mabahiss Expedition Versus the International Indian Ocean Expedition (IIOE)," *Deep-Sea Research* 31 (1984): 583–588.

India. The lack of any ocean-going vessel resulted in a lull in marine sciences for over 4 decades (1913–1952). However, this ended when the Government of India made available a minesweeper *I.N.S. Rohilkhund* to Andhra University for ocean studies. Under the leadership of Prof. E.C. LaFond, Fulbright Visiting Professor during 1952–1956, Andhra University was the first to launch multidisciplinary physical, chemical, geological, and biological oceanographic research study in the Indian Seas. Widely acknowledged as the father of modern oceanography in India, Prof. LaFond conducted nearly 50 oceanographic research cruises and imparted training to more than 24 researchers. Also, Andhra University was the first in Asia to offer postgraduate studies in oceanography, emulating several coastal universities and institutions. Dr. LaFond made seminal contributions on a) the presence of a seasonal anticyclonic coastal current and its replacement by a cyclonic current; b) the occurrence of western boundary coastal upwelling on the east coast of India, contrary to most coastal upwelling areas; c) the presence of seasonal subtropical gyres; and d) the presence of canyons, mostly off the river mouths along the east coast of India.

The International Indian Ocean Expedition (IIOE, 1959–1965) was timely and led to the establishment of the Indian Ocean Biological Centre (IOBC) at Cochin in 1962. IOBC trained several young Indian scientists in archiving IIOE collections and sorting them into various taxonomic groups. Thus, IOBC spawned active research on plankton. Based on the zooplankton analyses, several atlases, handbooks, guidebooks and research papers on various planktonic groups from the Indian Ocean were published. Also, IIOE served as a forum for the Indian scientists to interact and to discuss with specialists all over the world. Unlike the John Murray/Mabahiss Expedition, which pioneered bilateral relations in the field of oceanography, the IIOE was truly international. The Scientific Committee on Ocean Research (SCOR) and the IOC of UNESCO organized and coordinated the IIOE, which involved 23 countries including 11 developing countries bordering the Indian Ocean, 40 research vessels and 180 cruises.[9] From India, *I.N.S Kistna* provided the logistic support and participated in several surveys. Besides *I.N.S. Kistna, I.N.S. Darshak, R.V. Varuna, R.V. Conch* and *M.F.V. Bangada* took part in the IIOE. Again, Dr. LaFond as the chief scientist on board *Anton Bruun* led the U.S. Program of the IIOE into the Bay of Bengal and the Indian Ocean (1963) and contributed to our knowledge of primary production enhanced by upwelling of cold, nutrient rich subsurface waters. The IIOE, the largest multi-ship assault on the vast unknown ocean, tested several hypotheses, made discoveries that contributed to a major revolution of geologic theory. Further, it made a significant social and scientific impact on some of the participating nations[10] and also provided some invaluable

9. D. Behrman, *Assault on the Largest Unknown. The International Indian Ocean Expedition 1959–65.* (Paris: UNESCO, 1981), p. 96; W.S. Wooster, "International Studies of the Indian Ocean. 1959–1965," *Deep Sea Research* 31 (1984): 589–597.

10. Behrman (n. 9 above).

insight regarding similar cooperative ventures.[11] Some of the meteorological, physical, chemical, geological, and biological oceanographic data collected during the IIOE were published as 40 papers in *The Biology of the Indian Ocean*.[12]

The Government of India, committed to ocean research, established the National Institute of Oceanography (NIO) at Goa in 1966 and today it is India's premier oceanographic institute. In 1975, NIO acquired the first Indian oceanographic vessel, the *R.V. Gaveshini*. The Department of Ocean Development (DOD) was established in 1981 as the nodal department for India's ocean development activities and ocean policy statement[13] and addresses the following:

- Seabed mining;
- Extractive metallurgy specific to polymetallic nodules;
- Ocean energy: waves and thermal;
- Coastal and environmental engineering;
- Marine instrumentation;
- Front ranking research in polar sciences;
- Exploration of marine resources and their correlation with oceanographic parameters;
- Integrated coastal and marine management, coastal community development;
- Human resource development;
- Creation of centres of excellence to facilitate optimum utilization of ocean and its resources; and
- Observing, understanding and modeling ocean processes.

The NIO procured an oceanographic research vessel, the *Sagar Kanya* (1983), built in Germany, and a fisheries and oceanographic research vessel, the *Sagar Sampada* (1984), built in Denmark, which conducted several cruises in an extensive area (figs. 2 and 3). By August 2000, the *Sagar Kanya* conducted 154 research cruises. The *Sagar Sampada* had completed 188 cruises by October 2000 on marine living resources in the Exclusive Economic Zone, Arabian Sea and Bay of Bengal. In 1998, NIO chartered the Russian vessels MV *Sidorenko* and R.V *Yuzmorgeologiya* to sample the Central Indian Ridge Region and the Central Indian Ocean Basin. Impressive are the achievements of NIO, and these include several physical, chemical, bio-

11. Wooster (n. 9 above).
12. B. Zeitzschel and S.A. Gerlach, eds., *The Biology of the Indian Ocean* (New York: Springer-Verlag, 1973), p. 549.
13. *India 1999* (New Delhi: Ministry of Information and Broadcasting, Publications Division, Government of India, 1999) a reference annual, p. 733; *India 2000* (New Delhi: Ministry of Information and Broadcasting, Publications Division, Government of India, 2000) a reference annual, p. 930.

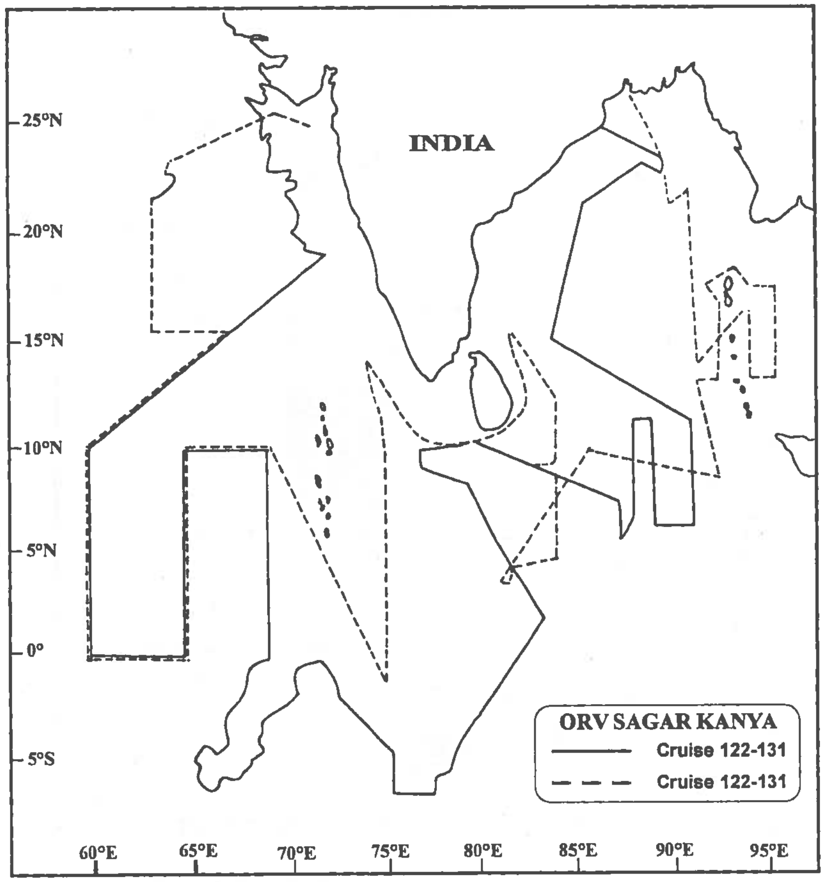


FIG. 2.—Area of *Orv Sagar Kanya* research cruises.

logical, geological, geophysical oceanographic surveys, marine instrumentation, ocean engineering and planning, and data acquisition and processing in and around the Indian Seas. With three regional centers at Mumbai, Cochin on the west coast and Visakhapatnam on the east coast, NIO had 208 scientific, 263 technical and 150 administrative staff in 1998. The NIO also implements a program for monitoring and analysis of sea-level changes at 30 ports along the east and west coasts of India. In cooperation with the Oil and Natural Gas Commission of India (ONGC) and the DOD and the National Institute of Ocean Technology (NIOT), NIO has contributed immensely to the ocean sciences in India and Antarctica. The Indian National Oceanographic Data Centre (INODC) at NIO holds, as of January

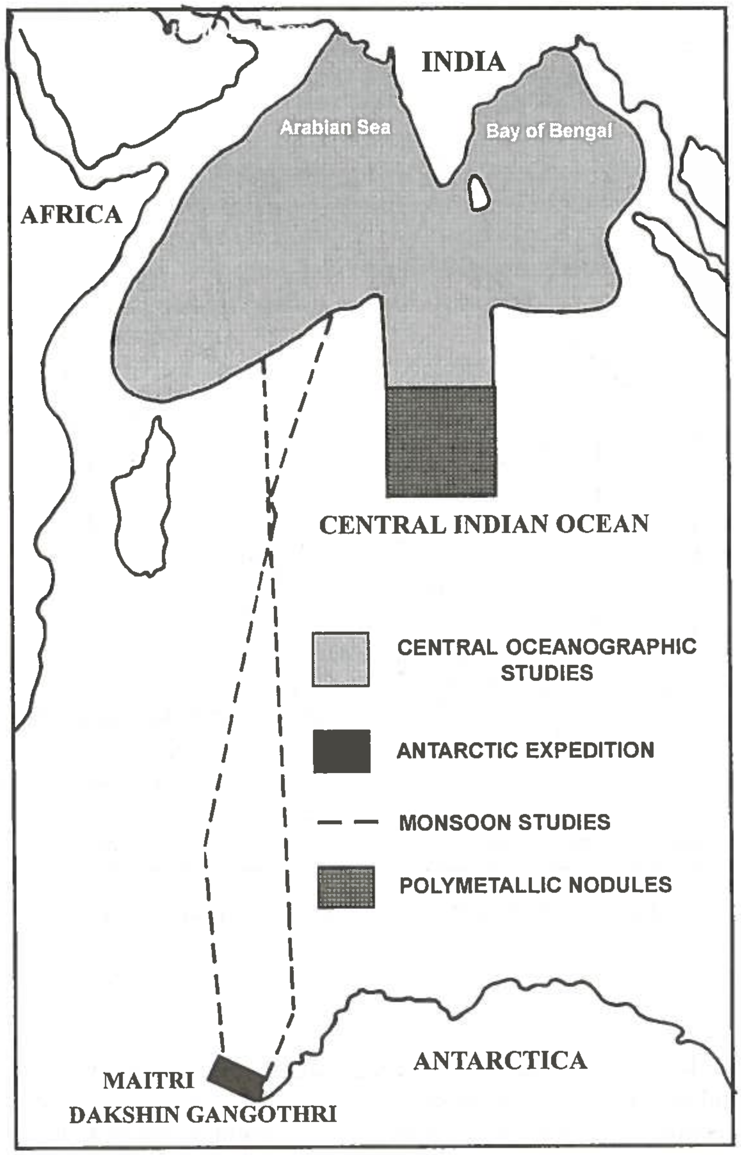


FIG. 3.—Cruise activities in the Bay of Bengal, Arabian Sea, the Central Indian Ocean and the Antarctic. After T.S.S. Rao (n. 19).

1996, data from several oceanographic stations: physics (24661), chemistry (23471), biology (3640), geology (2120), and geophysics (0.1 million line kilometer). As a result of the development of manpower in ocean sciences, India has acquired self-reliance and capabilities to pursue advanced ocean studies for which there is no price tag.

MARINE SCIENCES: SUPPORT

Under the direction of the Prime Minister of India, several ministries or departments support marine sciences. Besides the Ministry of Human Resource Development and Science and Technology, the Petroleum and Natural Gas, Agriculture, Water Resources, Environment and Forests and Defence ministries[14] are involved in fostering marine sciences in India (fig. 4). The various departments and their activities are identified.

The Federal Government of India provides almost 70 percent of the total research and development financing. Indian oceanographic programs are dependent on its 5-year plans. For example, in 1986–1987 the DOD budget was Rupees (Rs.) 121 million, which steadily increased to Rs. 319 million in 1990–1991. For 1991–1992, the DOD budget was Rs. 463 million, including Rs. 160 million for Antarctic research. The DOD ocean science budget for 1997–1998, 1998–1999, corresponded to Rs. 668.6 million and Rs. 737.94 million (table 1) with a substantial increase to 1,067 in 1999 and 1,580 in 2000[15] (and Dr. Tapaswi personal communication.). An additional 10 percent is made available for ocean sciences by the Ministry of Agriculture, the Ministry of Defence and others. Although there has been a steady increase in the marine science budget, the expenditure on ocean sciences is 0.025 percent of total budgetary expenditure of the Government of India.

Contract Services

Contractual services seem to meet about 50 percent of the total budget of the NIO (table 2). There has been a meteoric rise in the National Institute of Oceanography R&D contractual service.[16] The first was for a hydrographical survey (Rs. 0.1 million) for the Bombay Municipal Corporation in 1970 com-

14. Ministry of Information and Broadcasting, Publications Division, Government of India, (n. 13 above).

15. K.S. Jayaraman, "Indian Research Budget Favours Defence," *Nature* 404 (2000): 116.

16. *Annual Report 1995–96* (Goa: National Institute of Oceanography, 1996), p. 67; *Annual Report 1997–98*. (Goa: National Institute of Oceanography Goa, 1998) p. 60. Director, National Institute of Oceanography Goa.

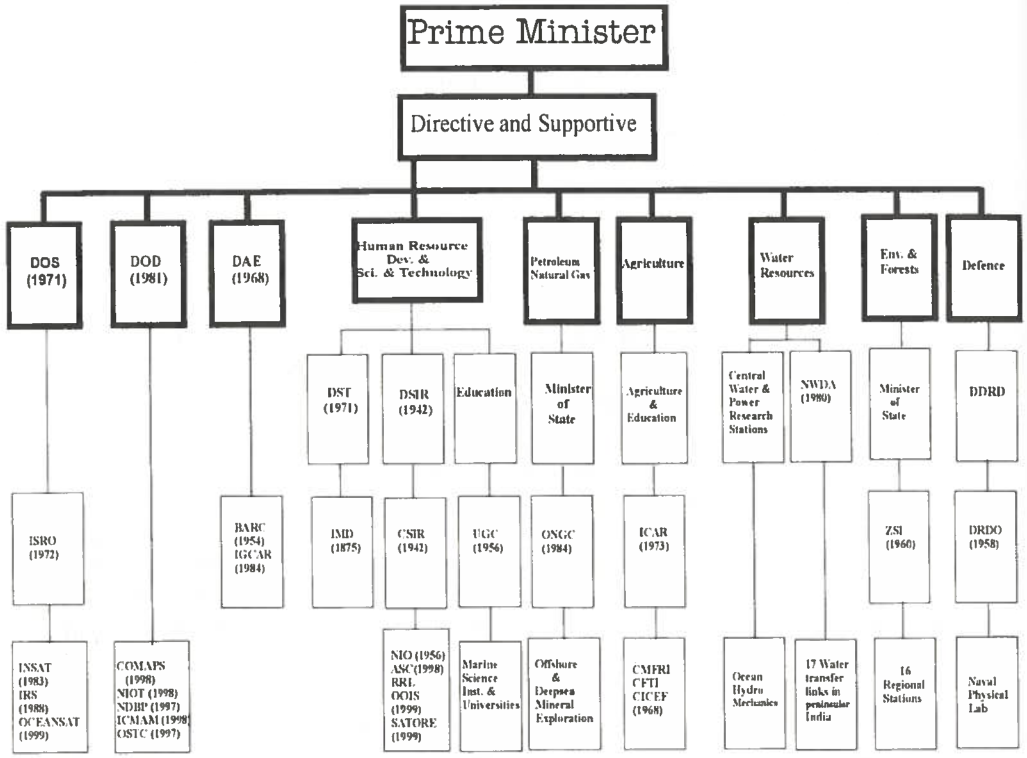


FIG. 4.—Flow chart of ministries responsible for marine sciences in India. Abbreviations used in Flow Chart. (Year in parenthesis indicates foundation year): ASC, Antarctic Study Centre; BARC, Bhaba Atomic Research Centre; CFTI, Central Fisheries Training Institute; CICEF, Central Institute for Coastal Engineering for Fishery; CMFRI, Central Marine Fisheries Research Institute; COMAPS, Coastal Ocean monitoring and Prediction Systems; CSIR, Council of Scientific and Industrial Research; DAE, Department of Atomic Energy; DDRD, Department of Defence Research Development; DOS, Department of Space; DOD, Department of Ocean Development; DRDO, Defence Research and Development Organization; DSIR, Department of Scientific and Industrial Research; DST, Department of Science and Technology; GSI, Geological Survey of India; ICAR, Indian Council for Agricultural Research; ICMAM, Integrated Coastal and Marine Area Management; IGCAR, Indira Gandhi Centre for Atomic Research; IMD, India Meteorological Department; INCOIS, Indian National Centre for Ocean Information Service; INSAT, Indian National Satellite System; IRS, Indian Remote Sensing Satellites; ISRO, Indian Space Research Organization; MECL, Mineral Exploration Corporation Limited; NDBP, National Data Buoy Programme; NIO, National Institute of Oceanography; NIOT, National Institute of Ocean Technology; NWDA, National Water Development Agency; OCEANSAT, Ocean Satellite; ONGC, Oil and Natural Gas Commission; OOIS, Ocean Observation and Information services; OSTC, Ocean Science and Technology Cells; RRL, Regional Research Laboratory; SATORE, Satellite Coastal and Oceanographic Research; UGC, University Grants Commission; ZSI, Zoological Survey of India.

TABLE 1.—OCEAN SCIENCE RELATED EXPENDITURE, 1998–1999
(Rs. Million) (Rs. 1 million = US$23,000)

Department, Agency, Project or Programme	1997–98	1998–99
Antarctic Expedition and Polar Science (DOD)	214.6	196.11
Marine Living Resources	0.02	0.07
Drugs from Sea	25	27.1
Marine Non-living Resources	156	203.14
Ocean Modelling and Dynamics	209.4	133.73
Coastal Ocean Monitoring and Predicting Systems (COMAPS)	19.9	14.98
Coastal Research Vessels (DOD)	33.9	25
Integrated Coastal and Marine Area Management (ICMAM)	NA	58.15
Marine Research and Capacity Building	NA	31.21
Coastal Community Programme	NA	0.66
Island Development Programme	NA	12.4
Intergovernmental Oceanographic Commission for the Central Indian Ocean (IOCINDIO)	9.6	4.97

NA = not available.
SOURCE.—*India 1999* (Publications Division, Ministry of Information and Broadcasting, Government of India, 1999), p. 733; *India 2000* (Publications Division, Ministry of Information and Broadcasting, Government of India, 2000), p. 930.

pared to Rs. 140 million (1997–1998). Of its total annual budget of Rs. 310.2 million, external cash flow through contract services fetch Rs. 167.5 million. The contractual projects undertaken are relevant to national needs and aim at bio-remediation, pollution abatement and environmental needs. A substantial increase in the number of contractual projects during 1997–1998 is evident.

TABLE 2.—NIO'S CONTRACTUAL PROJECTS

Contracts	1995–96	1997–98
Value (Rs. million)	42	140
Number of projects	56	61
Environmental	32	25
Geology and geophysical surveys	7	4
Engineering	7	11
Others	3	7
Grants-in-aid	7	14

SOURCE.—Annual Report 1995–1996. (Goa: National Institute of Oceanography), p. 67; Annual Report 1997–1998. (Goa: National Institute of Oceanography), p. 60.

INTERNATIONAL STATURE

International collaboration with the IOC and UN organizations has been substantial, which contributed to the manpower development and self-reliance. In turn this enabled India to build infrastructure in oceanography in several developing countries such as Mauritius in 1987, to participate in a joint oceanographic programme (*ORV Sagar Kanya*) with 16 Caribbean countries in 1990 and to undertake acoustic tomography studies with Australia in 1994.

India's National Institute of Oceanography made significant contributions[17] to the World Ocean Circulation Experiment (WOCE), Joint Global Ocean Flux Studies (JGOFS), and the Monsoon Trough Boundary Layer Experiment-1990 (MONTBLEX-90). NIO conducted several bilateral research programs with the UnitedStates on biofouling, microfilm formation, association and role of marine fungi with wood borers, biochemical and molecular techniques in ocean trophodynamics, tectonics and petrological implications of fracture zones, and isotopic composition of nitrate and molecular nitrogen in suboxic waters; with the European Commission on organochlorine contaminants together with the Netherlands Institute of Sea Research; with Russia on air-sea interaction and development of circulation models; and with Germany on sedimentation flux in the Bay of Bengal and Arabian Sea and air-sea interaction impacts on rainfall over the Indian subcontinent.

The DOD represents India on the following international programs in ocean sciences:

ATS	Antarctic Treaty System
ASEAN	Association of Southeast Asian Nations
CCAMLR	Commission on Conservation of Antarctic Marine Living Resources
COSTED	Committee on Science and Technology in Developing Countries
COMNAP	Council of Managers of National Antarctic Programme
GOOS	Global Ocean Observing System
IOCINDO	Intergovernmental Oceanographic Commission for the Central Indian Ocean
IOC	Intergovernmental Oceanographic Commission
ISBA	International Sea-Bed Authority
TEMA	Training, Education, and Mutual Assistance in Marine Sciences
SCAR	Scientific Committee on Antarctic Research
UNCLOS	United Nations Convention on the Law of the Sea

17. Ibid.

TABLE 3.—NUMBER OF ABSTRACTS IN AQUATIC SCIENCES AND FISHERIES CITED BY CAMBRIDGE SCIENTIFIC ABSTRACTS

	Bay of Bengal			Arabian Sea			Andaman Sea			Indian Coast		
Year	78–87	88–96	97–99	78–87	88–96	97–99	78–87	88–96	97–99	78–87	88–96	97–99
Total	397	856	257	391	762	320	69	168	42	293	302	36
Physics	16	67	29	36	85	47	7	13	0	17	29	13
Chemistry	31	90	31	62	151	89	1	17	0	6	35	10
Geology	23	93	35	64	123	43	15	48	6	11	70	1
Biology	58	129	28	87	174	76	21	67	12	29	112	16
Fisheries	207	398	114	86	157	41	17	81	0	31	14	0
Oil exploration	5	1	1	14	2	0	3	1	0	3	14	0
Mineral exploration	10	46	13	0	53	15	2	14	1	3	7	0
Pollution	11	65	24	20	44	25	2	2	2	10	19	5
Remote sensing	3	16	8	4	31	8	2	0	0	3	14	2
Defence	0	2	0	0	1	0	0	0	0	5	0	0
Hydrocarbons	5	11	2	14	10	11	2	4	2	1	26	0
Mangroves	6	21	8	4	6	4	3	13	0	6	9	6
Aquaculture	24	109	27	4	6	4	0	11	3	2	5	0
Ocean technology	0	3	0	0	5	0	0	1	0	0	4	0

UNESCO	United Nations Educational, Scientific and Cultural Organization
UNEP	United Nations Environment Programme
WMO	World Meteorological Organization

MARINE SCIENCE PUBLICATIONS

The number of publications on marine sciences in the Indian Seas, a measure of marine science activity, has steadily increased. From 1878 to pre-independence (pre-1947) there were <40 publications, mostly descriptive, which increased to ~100 during 1947–1965 (table 3). The Andhra University,[18] the Marine Biological Association of India, the National Institute of Oceanography and other Indian laboratories have published several excellent thematic monographs or proceedings on the physico-chemical processes and biogeochemistry, mariculture, fauna and flora of the Indian Seas and living resources.[19] The *Indian Journal of Marine Science,* the *Journal of the*

18. "Andhra University Series No. 49," *Memoirs in Oceanography* 1 (1954): 1–162; "Andhra University Series No. 62," *Memoirs in Oceanography* 2 (1958): 237; ed. S.V. Durvasula, *Present and Future of Oceanographic Program in Developing Countries, Andhra University Oceanographic Memoirs* 36, no. 3, (Visakhapatnam: International Association for the Physical Science of the Oceans (IAPSO), 1996): 1–176. Andhra University and International Association for the Physical Science of the Oceans.

19. K. Alagaraswami, ed."Mariculture Potential of Andaman and Nicobar Islands: an Indicative Survey 1983," *Central Marine Fisheries Research Institute Bulletin* 34 (1983): 1–108; P. M. A. Bhattathiri, N. Ramaiah and A. G. Untawale, eds., "Recent Advances in Biological Oceanography 1998," *Indian Journal of Marine Sciences* 27 (1998): 267–530; S. K. Biswas et al., eds., *Proceedings of the Second Seminar on Petroliferous Basins of India, West Coast Basins, Dehra Dun, KDM Institute of Petroleum Exploration, ONGC, 18–20 December 1991, 1993,* Indian Petroleum Publishers; S. A. Chavan, "Status of Mangrove Ecosystem in Gulf of Kachchh" (Symposium on Endangered Marine Animals and Marine Parks, Marine Biological Soc. India, Cochin, Paper No. 42., 1985); B. N. Desai, ed., *Oceanography of the Indian Ocean* (New Delhi: India Oxford and IBH, 1992); *Geological Survey of India, Recent Geoscientific Studies in the Bay of Bengal & Andaman Sea. Special Publication No. 29,* (Calcutta: Geological Survey of India, 1992) p. 278; S. Jones and M. Kumaran, *Fishes of the Laccadive Archipelago. The Nature, Conservation and Aquatic Science* (Trivandrum, 1980), p. 760. Cochin, Marine Biological Association of India; D. Lal, ed., *Biogeochemistry of the Arabian Sea: Present Information and Gaps,* (Bangalore: Indian Academy of Sciences, 1994); T.K.S. Murty, *Mining the Oceans,* (New Delhi: Publication and Information Directorate, CSIR, 1991) p. 98 ; R. Subrahmanyan, *The Dinophyceae of the Indian Seas. Part 2. Family Peridiniaceae Schutt Emend Linedemann,* (Marine Biological Association of India, Memoir II, 1971), p. 333 Cochin, Marine Biological Association of India; R. Nair Vijayalakshmi, ed., "Zooplankton Studies" *Indian Journal of Marine Sciences* 28 (1999): 109–224; T. S. S. Rao et al., eds., *Contributions in Marine Science: A Special Collection of 31 Papers to Felicitate Dr. S. Z. Qasim on his 60th Birthday* (Goa: National Institute of Oceanography, 1987) p. 471; C. S. G. Pillai, "Coral Resources of India with Special Reference to Palk Bay and Gulf of Mannar," *Proc. Symp. Living Resources of Seas Around India.* (Special Publication Central Marine Fisheries Research Institution, Cochin 11, 1973): 70–705; *Glimpses of the Indian Ocean* (Hyderabad: Universities Press [India]

Marine Biological Association of India, and the *Indian Journal of Fisheries,* actively publish results on Indian marine science. This steady increase of publications in marine sciences since 1978 shows greater awareness of these sciences in the Indian Ocean, the Bay of Bengal, and the Andaman and Nicobar Seas.

Fisheries and aquaculture is a major area of focus because of the nation's dependence on harvests from the sea. Similarly, exploration for offshore oil and gas and urbanization of the coastal areas encouraged more research into marine pollution, remote sensing, and geological and geophysical studies. A steady stream of publications embodying data collected from Indian laboratories appears in leading international journals with scientific impact, which bears testimony to the commitment of Indian scientists to pursue good science.

MARINE SCIENCE ACTIVITIES

In recent years, a wide range of topics in marine research has been investigated in India. Marine research has become increasingly concentrated in various federally funded institutions and not in the universities as one would wish. As the universities have neither an oceanographic research vessel of their own nor the necessary budget to charter an oceanographic research vessel, they are dependent on facilities from NIO or similar quasi-government research establishments. This is in contrast to a very dynamic programme in marine sciences at the Andhra University during the 1950s. However, the universities continue to play a major role by encouraging short-term basic research, promoting the diffusion of knowledge, and fostering research personnel to the benefit of research institutions. There is every need for a greater interaction between the universities and the 27 marine research institutions to encourage interdisciplinary collaborative research and joint programmes.

Ltd., 1998) p. 206; S. Z. Qasim and G. S. Roonwal, eds., *Living Resources of India's Exclusive Economic Zone* (New Delhi: Omega Science Publications, 1998) p. 140; S.R. Rao, ed., *Marine Archeology of the Indian Ocean Countries* (Goa: National Institute of Oceanography, 1988) p. 192; T.S.S. Rao and R. Griffiths, *Understanding the Indian Ocean—Perspectives on Oceanography.* (Paris: UNESCO, 1998) p. 187; S. Ramachandran and S. Rajagopal, eds., *The Coastal Zone—a Perspective* (Chennai: Anna University, 1990); Sarma S. Nittala, ed., "Coastal and Estuarine Processes Around India," *Indian Journal of Marine Sciences* 28 (1999): 345–482; B.L.K. Somayajulu, ed., *Ocean Science: Trends and Future Directions* (New Delhi: Indian National Academy & Academia Books International, 1999) p. 290; G. N. Swamy, V. K. Das and M. K. Antony, eds., *Physical Processes in the Indian Seas* (Goa: Indian Soc. Physical Science of Ocean, Dona Paula, 1992); J. N. Goswami and S. Krishnaswami, eds., "Isotopes in the Solar System," *Proceedings of the Indian Academy of Sciences. Earth and Planetary Sciences* 107 (1998): 235–437.

In 1927, the Madras University, Chennai was the first to initiate faunal surveys and plankton studies. The Andhra University launched multidisciplinary oceanography studies in 1952 and conducted 52 cruises into the Bay of Bengal and investigated the impact of monsoons and currents on the hydrography, plankton distribution and primary production. The texture and mineralogy of coastal and offshore sediments, clay mineralogy, history and evolution of deltas, and bathymetry of the Bay of Bengal were also investigated. This university also pioneered studies on the hydrobiology of major estuaries of the River Godavari, Chilka Lake, and pollution in coastal waters. The Centre of Advanced Studies in Marine Biology, Annamalai University, carried out investigations on the physicochemical conditions of the Vellar estuary and microbiology in the adjacent mangroves. The Cochin University of Science and Technology, Kochi initiated studies on surficial marine geology, formation of mud banks, their impact on the intertidal fauna and on the hydrobiology of the extensive backwater system that acts as nursery grounds for commercially important prawns and fishes. Marine geological studies such as sediment transport into estuaries, mineralogy of clastic sediments, onshore-offshore sediment transport, sediment grain size, and sediment movement are actively pursued by Mangalore University in Manglaore, Karnatak University in Dharwad, and Goa University in Goa.

While studies on the coastal engineering, ocean corrosion, storm surge simulation, and design of remotely operated vehicles were carried out by the Indian Institute of Technology (IIT) Chennai, IIT Delhi studied numerical 3-D circulation models and simulation models for upwelling and downwelling off the east coast of India. Paleoclimatology and paleoceanography were studied at IIT Kharagpur. Modelling studies aimed at understanding the physical mechanisms between monsoons and El Niño and the Southern Oscillation are being carried out by the Indian Institute of Science, Bangalore.

Other educational institutes or universities such as the Tamilnadu Veterinary and Animal Sciences University, Tuticorin, the Bharathidasan University, Tiruchirapalli, the Kerala Agricultural University, University of Agricultural Sciences, the Konkan Krishi Vidyapeeth, Ratnagiri, and the Berhampur University pursue studies of regional interest.

There are 27 major government or quasi government sponsored institutions (e.g., Council of Scientific and Industrial Research [CSIR], Indian Council of Agricultural Research [ICAR]) engaged in marine sciences. The Zoological Survey of India (ZSI), Calcutta, one of the oldest in India, and its several branches have been engaged in extensive field surveys of the marine fauna and flora, fisheries, and their biodiversity and protection. Most of the fisheries education and its application to coastal resources is carried out by the Central Fisheries Technology Institute (CFTI), Cochin. The Central Marine Fisheries Research Institute (CMFRI), with centres at Mandapam, Cochin, Mumbai, Tuticorin, Mangalore and Minicoy (Lakshadweep), has been investigating planktological conditions, growth of coral reefs in relation to environmental factors, food and feeding behaviour, reproductive biology, and population dynamics of major fisheries. The Central Institute of Brackishwater Aquaculture, Chennai, investigates pathogens and immunoassay of shrimps and fishes. Issues concerned with fisheries export development, particularly the prawn fishery, are addressed by the Marine Products Export Development Authority of India (MPEDAI), Cochin. Biodiversity and growth of coral reef populations are actively studied by the Andaman and Nicobar Centre for Ocean Development, Port Blair, Andamans, while the Central Agricultural Research Institute, Port Blair, has made significant contributions to the isolation and identification of chemicals and drugs from the sea. The Naval Materials Research Laboratory (NMRL), Mumbai, conducts investigations on boring and macrofouling organisms, bacterial flora in mangroves, and on bacteria causing metal corrosion. Central Salt and Marine Chemicals Research Institute (CSMCRI), Bhavnagar, Gujarat, investigates the growth, cultivation, and exploitation of seaweeds and their biochemistry.

Rapid advances have been made in remote sensing applications in coastal management and pollution studies by the Centre for Earth Science Studies, Thiruvananthapuram, the Indian Space Research Organization (ISRO), Bangalore, and the Indian Institute of Remote Sensing (NRSA), Dehradun. Marine engineering, oil exploration technology, wave energy studies, and deep-sea mining are being carried out by the National Institute of Ocean Technology (NIOT), Chennai, and the Centre for Earth Science Studies, Thiruvananthapuram. NIOT operates the Department of Ocean Development research vessels *Sargar Purvi* and *Sagar Paschimi* in their coastal studies. The Geological Survey of India (GSI), with marine wings at Calcutta, Visakhapatnam, Cochin, Thiruvananthapuram, Mangalore and Mumbai, pursues geotechnical studies and marine sediment transport studies. The GSI operates the research vessel *Samudra Shaudhikama.*

The Physical Research Laboratory (PRL), Ahmedabad, has made significant contributions to the study of atmospheric chemistry, satellite-based monsoon studies, ocean-atmospheric interaction, sea-level changes, geochemistry and dating of marine sediments, and boundary layer heat fluxes. The Indian Institute of Tropical Meteorology, Pune, has been carrying intensive studies on the upper-layer circulation, modelling, and hydrodynamic structure of the oceans. Utilizing the research vessel *Sagardhwani,* the Naval Physical and Oceanographic Laboratory (NPOL), Cochin, conducts research on underwater acoustics. The Baba Atomic Research Centre (BARC), Mumbai, investigates bedload transport of dredged spoil, concentrations of tritium in surface waters, and atomic minerals in beach deposits, while its sister institute the Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam, near Chennai, is engaged in water quality and pollution studies of coastal waters.

RECENT ADVANCES OF INDIAN MARINE SCIENCES

Monsoons and Circulation

The role of monsoons in the circulation and formation of water masses in the Indian Seas was studied in considerable detail. In the Bay of Bengal, sensible heat flux of 40 W/m^2 resulted in severe cyclonic storms, 20 W/m^2 in good monsoon years, and 10 W/m^2 in poor monsoon years.[20] A cyclonic gyre resulting in an eastward flow known as the East India Coastal Current (EICC) flows poleward during February–April when saline oceanic waters enter the Bay. The EICC is equatorward during the northeast monsoon that is, November–December, when the bay is brackish due to a run-off of $123 \times 10^{10} m^3$.[21] Three water masses, namely low salinity surface water, high salinity intermediate water advecting from the Arabian Sea, and deep water of circumpolar origin, are formed in the Bay of Bengal. Marked gradients in several hydrological conditions, annual particle flux patterns, and geochemistry of sediments are reported. Off western India, where the impact of the rivers is less severe compared to the east coast, during the southwest monsoon (May to August) local wind sets in a coastal circulation.[22] The West India Coastal Current (WICC) flows poleward during November–March.[23] During the northeast monsoon (November–January), against a weak equatorward wind stress, thermohaline-forcing or Kelvin waves cause intrusion of low saline Bay of Bengal water, resulting in a poleward current.[24]

Upwelling

An analysis of the heat content of the Indian Ocean in terms of amplitude and phase of the annual and semiannual frequencies showed a dramatic drop during the summer monsoon in the Arabian Sea and the Bay of Bengal,

20. K. V. Devi, K. G. Reddy and G. R. L. Rao, "A Study of the Energy Flux in Relation to Meteorological Systems over the Bay of Bengal during the Southwest Monsoon," in *Ocean Technology: Perspectives,* eds. V. Agadi Sushilkumar, V. K. Das and B. N. Desai. (New Delhi: Publications Information Directory, 1994) pp. 347–56.

21. S. R. Shetye et al., "Hydrography and Circulation in the Western Bay of Bengal during Northeast Monsoon," *Journal of Geophysical Research C-Oceans* 101 (1996): 14011–14025; S. S. C. Shenoi, P. K. Saji and A. M. Almeida, "Near-surface Circulation and Kinetic Energy in the Tropical Indian Ocean Derived from Langrarian Drifters," *Journal of Marine Resources* 57 (1999): 885–907.

22. S. R. Shetye, A. D. Gouveia and S. S. C. Shenoi, "Circulation and Water Masses of the Arabian Sea," in *Biogeochemistry of the Arabian Sea: Present Information and Gaps,* ed. D. Lal (Bangalore: Indian Academy of Sciences 1994): 107–23.

23. Shenoi et al. (n. 21 above).

24. Ibid.; Shetye et al. (n. 22 above).

mostly pronounced in the 50–300 m layer.[25] This results in upwelling in the coastal regions.[26] Throughout the Arabian Sea during July–September the thermocline gradient showed large variations, that is, between 0.04°/m and 0.14°/m,[27] and depended on the interaction of warm water masses. In the Bay of Bengal during the Southwest Monsoon, subsurface waters upwell due to Ekman transport.[28] However, local coastal upwelling is weakened in regions with warm freshwater discharges from the Brahmaputra, the Ganges, Mahanadi, and the Godavari rivers.[29]

Oxygen Minimum Zone

In the Bay of Bengal, because of the low salinity, the discontinuity layer is shallow and restricts the thickness of the oxygen minimum zone (OMZ),[30] and in contrast, in the Arabian Sea the OMZ is thicker, most intense, and deeper. In the Arabian Sea it appears to be related to an increase in particulate organic carbon originating from *in-situ* production of organic matter and probably represents an intense denitrifying layer in offshore areas of relatively low primary production.[31] Isotopic studies suggest a possible coupling between nitrification and denitrification as an important mechanism of nitrogen oxide production.[32]

Remote Sensing

India made rapid progress in the application of satellite platforms for ocean research. Several Indian remote sensing satellites (IRS-1A/1B) were used

25. R. R. Rao and R. Sivakumar, "Observed Seasonal Variability of Heat Content in the Upper Layers of the Tropical Indian Ocean from a New Global Ocean Temperature Climatology," *Deep-Sea Research* 45 (1998): 67–89.

26. E. C. LaFond, "Oceanographic Studies in the Bay of Bengal," *Proceedings of the Indian Academy of Sciences* B46 (1957): 1–46.

27. K. G. Radhakrishnan et al., "Thermocline Climatology of the Arabian Sea-A Review," *Marine Freshwater Research* 48 (1997): 465–72.

28. LaFond (n. 26 above).

29. S. R. Shetye et al., "Wind-driven Coastal Upwelling Along the Western Boundary of the Bay of Bengal During the South West Monsoon," *Continental Shelf Research* 11 (1991): 1379–408.

30. C. K. Rao et al., "Hydrochemistry of the Bay of Bengal: Possible Reasons for a Different Water-column Cycling of Carbon and Nitrogen from the Arabian Sea," *Marine Chemistry* 47 (1994): 279–90.

31. S. W. A. Naqvi and M. S. Shailaja, "Activity of the Respiratory Electron Transport System and Respiration Rates Within the Oxygen Minimum Layer in the Arabian Sea," *Deep-Sea Research Part II Topical Studies in Oceanography* 40 (1993): 687–95.

32. S. W. A. Naqvi et al., "Nitrogen Isotopic Studies in the Suboxic Arabian Sea," *Proceedings of the Indian Academy of Sciences. Earth and Planetary Sciences,* 107 (1998): 367–78.

in the earlier stages followed by second generation satellites IRS-1C and 1D that had improved spatial resolution, extended spectral bands, stereo-viewing, and faster re-visit capability. Most of the achievements are in coastal zone studies for wetland-landform surveys, shoreline changes, mapping coral reefs, tidal wetlands, mangrove forests, sediment transport during pre- and post monsoon, and provide decision support for coastal zone planners.[33] India has the capability to develop and launch state-of-the-art satellites for ocean applications. Using the indigenous polar satellite launch vehicle (PSLV), India successfully launched IRS-P4 (Oceansat-1) from Sriharikota on 26 May 1999.[34] The Oceansat-1 carries an ocean colour monitor (OCM) and a multifrequency scanning microwave radiometer (MSMR) that would be most useful in ocean dynamic studies and in evaluation of marine resources. Cartosat-1, with 2.5 m spatial resolution and 30 km swath, and Resourcesat-1, with a spatial resolution of 6 m and a swath of 25 km, will be operational by 2002. The Resourcesat-1 will focus on coastal zone applications, particularly in the fragile mangrove ecosystems.[35]

Biological Production and Fisheries

The phytoplankton cycle usually follows a bimodal peak distribution, with the major peak coinciding with the enrichment of surface waters by upwelling of nutrient rich, cold subsurface waters. Massive blooms of red-tide proportions occur, but not necessarily associated with fish kills or anoxic conditions. Daily production ranges between 0.08 g $C/m^2/d$ and 5.4 g $C/m^2/d$,[36] with an overall average[37] of 0.076 g C/m^2 for the Arabian Sea and 0.3 g C/m^2 for the Bay of Bengal. Annual primary production in coastal waters is about 250 g C/m^2, while that of coral reefs was $>$1200 and $<$2500 g C/m^2. Both algal biomass and primary production increased in a north to south direction in the Arabian Sea and from east to west in the Bay of Bengal.[38] In the Bay of Bengal, primary production is elevated due to the enormous river discharge that contributes to the humus and phosphate, but only in the top 25 m, unlike in the Arabian Sea. The calculated total annual column

33. P. S. Desai, A. H. Gowda and K. Kasturirangan, "Ocean Research in India: Perspectives From Space," in Perspectives on Ocean Research in India, *Current Science* 78 (2000): 268–78.
34. Ibid.
35. Ibid.
36. D. V. Subba Rao, "The Bay of Bengal" in *Seas at The Millennium,* Ch. 71, ed. C. Sheppard (London: Elsevier Science Ltd., 2000): 1–14.
37. A. Pant, "Primary Productivity in Coastal and Offshore Waters of India during Two Southwest Monsoons, 1987 and 1989," in *Oceanography of the Indian Ocean,* ed. B.N. Desai, (New Delhi: India Oxford and IBH, 1992): 81–90.
38. Ibid.

production for the Bay of Bengal is 37 percent of the 1064 Mt for the Arabian Sea.[39]

In the western Arabian Sea, a high mesozooplankton biomass exists throughout the year and in the northern Indian Ocean, the mass occurrence of a bathypelagic chaetognath is associated with high productivity and the occurrence of an oxygen minimum layer.[40] Areas subjected to industrial pollution had low zooplankton species diversity. The coral reef area of the Gulf of Mannar had a high level of meroplankton production that coincided with the fishery potential in the area. No precise estimates of vertical transfer coefficients, between phytoplankton-zooplankton and commercial fisheries are available. At the secondary level, a marked difference was suggested in the vertical transfer coefficients, with 22.7 during southwest monsoon and 8.0 during the northeast monsoon.[41] The estimated fishery potential for the EEZ is 3.92 Mt compared to the current 2.69 Mt.[42] As deep-sea fin fishes, cephalopods, shrimps, lobsters and tuna would constitute this, the additional harvest of deep-sea fish is recommended.[43]

The national Project on Drugs from the Sea subjected 450 species of biota for chemical and bioevaluation for antiviral, antidiabetic, anticholesterol, anti-anxiolytic, wound healing, and larvicidal activities.[44]

Antarctic Surveys

India has conducted 18 annual expeditions to the Antarctic between 1981 and 1999. The establishment of *Dakshin Gangothri* and *Maitri,* India's permanent station in the Schirmacher Oasis, Antarctica, has provided a platform for more than 1250 researchers from about 50 research institutions and universities. The 18th and 19th Indian Antarctica Expedition teams are exploring their way from *Maitri* to the South Pole. Some of the anticipated benefits from Antarctic research are 1) to build a climatological data base for application in the prediction and forecasting of Indian monsoons; 2) study of the ozone hole; 3) geological mapping of hitherto unmapped areas; and 4) identification of Antarctic microbes for use in human and organic waste

39. S. Z. Qasim, "Biological Productivity of the Indian Ocean" *Indian Journal of Marine Sciences* 6 (1977): 122–37.
40. Nair R. Vijayalakshmi, ed., "Zooplankton Studies," *Indian Journal of Marine Sciences* 28 (1999): 109–224.
41. D. H. Cushing, "Upwelling and Production of Fish," *Advances in Marine Biology* 9 (1971): 255–334.
42. V. S. Somvanshi, "Fishery Resources in the Indian EEZ. Recommendations for Deep-sea Fisheries Development," *Indian Journal of Marine Sciences* 27 (1998): 457–62.
43. Ibid.
44. *India 1999* and *India 2000* (n. 13 above).

degradation. The Antarctic Study Centre (ASC) has formed as an autonomous institute since 1998. Due to continued involvement of research in the Antarctic, in 1983 India became a consultative member in the Antarctic Treaty System. With the assistance of the Russian Ministry of Natural Resources, India's capabilities to mine polymetallic nodules in the Central Indian Ocean Basin earned India the status of a registered Pioneer Investor since 1987. An area of 150,000 km^2 was allotted to India for mining of polymetallic nodules, of which the Department of Ocean Development relinquished 30 percent.[45] During the 8th plan (1992–1996), 35 percent and 20 percent of the total budget was invested on the Antarctic research and the polymetallic nodule programme, respectively.[46] To qualify as a pioneer investor under the United Nations Convention on the Law of the Sea, India spent US$30 million before 1983 and incurs continued expenditure to preserve this status.[47]

SIGNIFICANCE

Oceanography, a constituent of the marine sciences, is multidisciplinary and addresses issues both in the coastal and offshore environments. It has several broad goals: (i) management and rational utilization of living and nonliving resources; (ii) development of national expertise in marine sciences; (iii) generation of a vast storehouse of physical, chemical, geological and biological information to predict the patterns of distribution of organisms in space and time; (iv) identification of the influence of abiotic processes on the biota; (v) assessment of the effects of marine meteorology, monsoons, ocean circulation, tidal waves, hurricanes, climatic changes and sea-level fluctuations on nearshore processes and coastal populations; (vi) protection and preservation of marine habitat; (vii) control of marine wastes and urban wastes to safeguard the health of the coastal marine environment and estuaries; and (viii) investigation of issues related to marine mining, jurisdiction and transboundary disputes, and socioeconomic considerations in the management of regional seas. These are consistent with the Ocean Policy Statement (OPS) of the Government of India (1981), that is, development of sustainable and rational utilization of its living and nonliving resources and protection and preservation of the marine environment. The various marine science activities presented earlier show that India is solemnly committed

45. *India 2000* (n. 13 above).

46. J. Yates and G. S. Roonwal, "Marine Science and Technology in India: Current Status," *Marine Policy* 18 (1994): 59–68; P. N. Desai, "Integrated Coastal Management, Ocean Policy and Hidden Risks," in *Subtle Issues in Coastal Management,* eds. R. Sudarshana et al. (Dehra Dun: Indian Institute of Remote Sensing, 2000): 25–32.

47. Yates and Roonwal (n. 46 above).

to ocean research. Over the past 3 decades it acquired the necessary national expertise and met some of the goals. A vast body of data has been acquired on the qualitative and quantitative abundance and seasonal distribution of the fauna and flora at the species, population, community, or ecosystem levels in relation to environmental variables. India's many achievements in basic marine sciences have provided scientific directions for promotion of offshore fishing and oil and gas exploration. The NIO and the ONGC have significantly contributed to the Bombay High offshore development.

Although the levels of various pollutants are documented, their sources and pathways along the food-chain and impacts on societal health are to be addressed. The data collected during IIOE and the various cruises in the seas need to be critically analyzed to relate inter-annual variability in the intensity of the monsoon to phytoplankton cycles, which in turn influences the recruitment, fecundity, and larval survival of commercially important fisheries. Similarly, massive time series data for nearly 70 years on the sardine and mackerel landings exist and a critical analysis of how physical forcing affects their abundance along the lines of Longhurst and Wooster would be useful.[48]

The Government of India issued a notification on the protection of the Coastal Regulation Zone (CRZ) in 1991 and a similar one is being prepared for the Ocean Regulation Zone (ORZ). Suggestions to remedy and to restore these ecosystems to a healthy state will be possible only if their structure and functioning are understood. To augment its domestic food and fuel requirements of its teaming millions, India should look to a healthy marine ecosystem and develop the ability to predict the processes governing the abundance of living and nonliving resources. A discussion on some high priority research areas follows.

RELEVANCE AND PRIORITIES OF MARINE RESEARCH

Coastal Zone Management

It will be absolutely necessary for India to develop an integrated coastal zone management policy with wise practices for sustainable human development. Due to multi-user activities such as fisheries, mariculture, urbanization, recreation, coastal mining, shipping, and their resultant pollution, the coastal environment is severely stressed. The Central Pollution Control Board has identified several critically polluted "hot spots" in Gujarat, Kerala, Tamil Nadu, Andhra Pradesh, Orissa, and West Bengal. The recent announcement

48. A. R. Longhurst and W. S. Wooster, "Abundance of Oil Sardine (*Sardinella Longiceps*) and Upwelling on the Southwest Coast of India," *Canadian Journal of Fisheries and Aquatic Science* 47 (1990): 2407–19.

of division of the entire Indian coastline into 11 segments with 77 institutions in charge under the ocean development department is welcome.

Estimates by NIO show that the Indian coastal zone receives annually about 4 billion m^3 of domestic sewage, 40 million m^3 industrial sewage, 50 million m^3 of river-borne effluents, 33 Mt of land wastes, and 5 Mt of fertilizer residues, besides several thousand tons of pesticides and detergent residues. The cities of Bombay and Calcutta alone discharge 365 and 400 Mt of raw sewage into the coastal waters. Some of the other polluters include thermal power plants, nuclear power plants, reverse osmosis desalination plants, tanneries, sand dune mining industries, pharmaceutical industries, pulp and paper mills, oil refineries, manufacturers of plastics, chlorine, fungicides, antifouling chemicals, petrochemicals, and paints. Antipollution laws are not effective. Although the effects of anthropogenic activities are not monitored at various points along the coast, eutrophication is evident in the nearshore waters off Bombay where a 40 percent increase in phosphorus over 1959–1974 was registered.[49] In addition to the desalination plants at Tuni (Andhra) and Jamnagar (Gujarat), more plants are planned to meet the potable water demands. During mid-2000 at Ramanathapuram, near Chennai, one more plant was commissioned and eight more are planned. The impact of these desalination plants on the marine biota needs to be assessed. The gravity of the situation is evident in the example of the 100-year-old tanning industry in Tamil Nadu, which generates 25 tons of solid waste, and over 30 million litres of effluents daily. While the World Health Organization permissible limits of total dissolved salts are 2,100 mg/l, these tanneries are trying to reduce it to 4,000 and considered disposing the effluents into the sea by closed channel till the Supreme court halted this.

Of greater concern is the barium, radium, and uranium pollution contributed by the Ganges and Brahmaputra rivers. In the Hoogly estuary, the uranium levels are between 3.5 and 3.9 μg/l, the highest for any estuary.[50] The weighted mean uranium input from Mahanadi estuary is 36 t/y.[51] Arsenic poisoning in the Ganges delta is also documented.[52] Although the linkages between river discharge and arsenic are not yet established, poisoning due to arsenic pollution in downstream areas of Bengal and Bihar is a potential threat to human health. Many edible bonyfishes, oysters, prawns, and

49. R. Sen Gupta, S. Naik and V. V. R. Varadachari, "Environmental Pollution in Coastal Areas of India," in *Ecotoxicology and Climate*, eds. P. Bourdeau et al. (Chichester: UK SCOPE, John Wiley & Sons Ltd., 1989): 235–46.

50. B. L. K. Somayajulu, "Uranium Isotopes in the Hoogly Estuary, India," *Marine Chemistry* 47 (1994): 291–96.

51. S. B. Ray, M. Mohanti and B. L. K. Somayajulu, "Uranium Isotopes in the Mahanadi River-estuarine System, India," *Estuarine and Coastal Shelf Science* 40 (1995): 635–45.

52. S. K. Acharya et al., "Arsenic Poisoning in the Ganges Delta," *Nature* 401 (1999): 545.

shrimp are known to accumulate arsenic. Because of their impacts on human health, sources, sinks and processes regulating their distribution need to be investigated.

Ballast Water Introductions of Exotic Biota

In post-independent India, shipping activities are on the increase, with annual traffic during 1996–1997 of about 225 Mt. It is projected to be 390 Mt by 2000–2001 and 650 Mt by 2005–2006.[53] To meet the demands new ports (Paradeep, Kakinada) have been constructed. Several thousand transoceanic ships call at Kandla, Mumbai, Jawaharlal Nehru Port, Marmagao, New Mangalore, Kochi (Cochin), Tuticorin, Chennai, Kakinada, Visakhapatnam, Paradeep, Calcutta-Haldia, and Port Blair. Thousands of tons of ballast water are discharged into the coastal seas around India. Also, the sediments and scrapings of fouling organisms resulting from maintenance and dry-docking operations introduce several exotic organisms that could have far-reaching ecological impacts. Although the fauna and flora in the Indian Seas have been well studied since 1878, several species of polychaetes, commercially important wood-boring isopods *Limnoria insulae, L. unicornis, L. platycauda,* and the pelecypod *Xylophaga mexicana,* new to this region, have been reported to occur since 1961 (Subba Rao, in preparation). Some of the new introductions have now become pests and may out-compete the native fauna for resources. Quarantine measures based on a long-range study of such exotic introductions will be necessary.

Habitat Loss and Marine Protected Areas

Although information on the Indian coastal zone is incomplete and at times inaccurate, an inventory of the nation-wide status of coastal habitats[54] reveals the following: a) loss of 25 percent of mangroves; b) degradation of coral reefs in the Gulf of Kachchh due to large deposition of mud; and c) increase in the reclamation of backwaters, lagoons, mud flats and mangroves. Case studies from the West Coast on Kuchchh,[55] Gulf of Cambay,[56] and Gujarat

53. A. P. J. A. Kalam, with Y. S. Rajan, *India 2020, A Vision for the New Millennium,* (Delhi: Viking Press, 1998), p. 312.

54. Ibid.

55. S. Nayak, "Critical Issues in Coastal Zone," in Sudarshana *Subtle Issues in Coastal Management* (n. 46 above), pp. 77–98.

56. D. Mitra, R. Sudarshana and A. Mishra, "Rapidly Changing Coastal Environment: Hidden Risks of Coast of Gulf of Cambay, Gujarat," in Sudarshana *Subtle Issues in Coastal Management* (n. 46 above), pp. 149–58.

reveal the Gulf of Cambay is destined for irreversible changes suggested by the following:

- Multi-date landsat imagery indicated significant shoreline changes in the Mahi and Narmada estuaries between 1972–1980, resulting from changed course, shoaling and erosion.
- Loss of 562 hectares of mangroves between 1996–1999.
- Conversion of a large tidal flat area into a chemical industrial complex.

On the microtidal Orissa coast in the east, increased human activity has led to a 50 percent reduction in the Chilka Lake area since its origin around 3,500 years BP, and a further reduction of 255 km^2 between 1929 and 1988.[57] The Zoological Survey of India conducted several expeditions in the Chilka lagoon and recorded 800 species.[58] However, the Irrawady river dolphin, *Orcaella brevirostris,* once found in large numbers, has become rare.[59] For construction of ports and harbours, 2,500 ha of mangroves were cleared. About 200 ha of mangrove land was brought under prawn culture in 1987. Between Gopalpur and Rushikulya, mining operations of sand dunes (500 t/h) may result in shoreline changes. Due to large-scale alteration of the coastline, sea level is expected to rise submerging the low-lying tracts of Sunderbans and Chilka Lake. When deprived of mangroves, such coastlines would be more prone to storm surges, erosion, and spread of saline waters in low-lying coastal lands. The potential for mercury pollution exists near Rushikulya estuary. These activities could endanger the mass nesting of the sea turtle *Lepidochelys olivacea* that is protected.

Between 1966 and 1993 in Tamil Nadu, the total mangrove area of 14,897 ha was reduced to 3000 ha. Further, there has been active destruction of corals due to indiscriminate use as raw material, pollution, and through tourism. Large-scale urbanization of Mumbai, Chennai, Calcutta, and many other coastal cities is expected to rise from the present 15 percent to almost 40 percent in the next decade[60] and this will exert greater stress on the coastal marine environment.

Only five Marine Protected Areas (MPAs) exist, and to facilitate strict

57. K. Mahapatra, "The Coastal Zone of Orissa, Bay of Bengal; Status and Framework for Sustainable Management," in Sudarshana *Subtle Issues in Coastal Management* (n. 46 above), pp. 99–116.

58. Fauna of Chilka Lake, Wetland Ecosystem Series 1 (1995): 1–672, Zoological Survey of India, Calcutta, India.

59. P. Dhandapani, "Status of Irrawady River Dolphin *Orcaella Brevirostris* in Chilka Lake," *Journal of the Marine Biological Association of India* 34 (1992): 90–93.

60. Nayak (n. 55 above).

TABLE 4.—MARINE PROTECTED AREAS AROUND INDIA

Existing	Conservation and Activities	Proposed	Conservation and Activities
Bhitar Kanika Wildlife Sanctuary, Orissa	Turtles	Gulf of Khambhat Wildlife Sanctuary	Turtles and mangroves
Gulf of Kutch, Kutch	Mangroves Commercial fishing, tourism	Kundapar Wildlife Sanctuary, Karnataka	Mangroves and shore birds
Gulf of Mannar National Park	Coral reefs, dugongs	Chilka Lake Wildlife Sanctuary, Orissa	Turtles
Andaman Nicobar	Coral reefs, turtles, dugongs, Saltwater crocodiles, wildlife sanctuary	Point Calimere, National Park, Khijadia	Turtles
Wandur Marine National Park, Andaman, Nicobar	Coral reefs, turtles	Kazhiveli Wildlife Sanctuary	Mangroves and water fowl
		Sundarbans Lakshdweep Archipelago	Estuarine park turtles

SOURCE.—Based on G. Kelleher, C. Bleakley and S. Wells, *A Global Representative System of Marine Protected Areas.* Vol. III. (Washington, D.C.: The Great Barrier Reef Marine Park Authority, The World Bank, The World Conservation Union (IUCN), 1995), p. 147.

conservation measures there is a great need for more MPAs[61] (table 4). Besides the seven proposed MPAs, other important coastal sites and the biota that need conservation (given in parentheses) include: Gahirmatha Wildlife Sanctuary and Mahanadi Delta, Orissa (crocodiles, mangroves, and turtles); Chilka Lake, Ramsar site (migratory waterfowl); Pulicat Lake Sanctuary, Andhra (migratory shore birds); Coringa Sanctuary and Krishna Reserve Forest in Andhra Pichavaram Forest Reserve, Tamilnadu (mangroves, crocodiles); and Phansad Wildlife Sanctuary (mangroves).

Fisheries and Mariculture

To meet the growing demand for food, marine fishery production needs to be increased from the present 2.4 Mt, particularly in some of the underutilized offshore waters. It is obvious that protein deficiency exists in India where the majority of its one billion population receives a daily average <8 g animal protein compared to 77 g in North America. The projected total

61. G. Kelleher, C. Bleakley and S. Wells, *A Global Representative System of Marine Protected Areas, Vol. III* (Washington, D.C.: The Great Barrier Reef Marine Park Authority, The World Bank, The World Conservation Union (IUCN), 1995), p. 147.

annual protein requirement in India is about 25 Mt. A potential for 3.92 Mt exists.[62] Most of the fishing activity is limited to shelf waters. For example, on the east coast of India, 70 percent of the catch is from depths >50 m and the highest densities are in the 60–80 m depth range. In the Indian coastal waters the fishing fleet is estimated to be 60 percent higher than the optimum,[63] and intensive mechanized trawling and bottom gill nets have resulted in a reduced catfish catch by 39 percent and *Arius tenispis,* which constituted 61 percent of the catch, has disappeared.[64] However, recent studies in the southern-west offshore waters (41–80 m deep) revealed a potential for 0.26 Mt, much higher than the previous estimates of 0.15 Mt. These productive waters are underutilized[65] for threadfin breams, bull's eyes, lizardfishes, and flatheads. Similarly, the bathymetric zones between 51–100 m and above 200 m in the northeastern region in the Indian EEZ (between lat. 16° 00′ and 20° 30′ N; long. 81° 30′ E and 87° 15′ E) were found highly productive in driftfish, for example, carangids and catfish, and yielded 830 kg/h and 1615 kg/h, respectively.[66]

The Bay of Bengal is the shallowest tuna fishing area in the world and the catch is particularly good between 65–120 m, which is the boundary between the surface uniform layer and the sharp gradient layer of temperature and dissolved oxygen.[67] Research into the linkages between the mixed layer, changes in the depth of the thermocline and catchability of tuna need to be explored and should be coordinated at a regional level to provide capacity building for the rational utilization of this fishery.[68] Off Sri Lanka in international waters (50–100 m), about 1200 boats larger than 40 ft conduct

62. K. Hanumantha Rao, S. B. Choudhury and M. V. Rao, "Harvest-problem and Prospects: Indian Scenario," in Sudarshana *Subtle Issues in Coastal Management* (n. 46 above), at 133–42.

63. Ibid.

64. D. V. Subba Rao, "Carrying Capacity: the Limits to Mariculture," in Sudarshana *Subtle Issues in Coastal Management* (n. 46 above), pp. 53–65.

65. P. Bensam et al., "Demersal Finfish Resources in Certain Areas of the EEZ of Southwest and Southeast Coast of India," *Proceedings of the Second Workshop on Scientific Results of FORV Sagar Sampada,* eds. V. K. Pillai et al. (New Delhi: India Department of Ocean Development, 15–17 February 1994, 1996): 375–85.

66. N. G. Menon et al., "Finfish Resources in the Northeastern Region in the Indian EEZ," in Pillai *Proceedings of the Second Workshop on Scientific Results of FORV Sagar Sampada,* pp. 295–304.

67. Y. Kurita et al., "Relation Between Tuna-catches and Oceanic Condition in Bengal Bay," *Bulletin of the Japanese Society of Fisheries and Oceanography* 55 (1991): 18–24.

68. F. Marsac, "Oceanographic Research in Relation with Tuna Fisheries Assessment: the Regional Tuna Project of the Commission de L'ocean Indien," in *Present and Future of Oceanographic Programs in Developing Countries, Vienna and Honolulu,* ed. S.V. Durvasula, (IAPSO Publication Scientifique No. 36 and Andhra University Oceanographic Memoirs No. 3. Visakhapatnam, Andhra University, 1996) pp. 158–75.

multiday (>10 days) fishing trips with gillnets and longlines for skipjack tuna (*Katsuwonus pelamis*), followed by yellowfin tuna (*Thunnus albacares*). A few have diversified their fishing effort and started longlining for the deep-swimming large yellow and bigeye (*T. obesus*) tunas.[69]

It is crucial that the commercially important fisheries in the coastal habitats are sustained at an optimal level. A great potential exists for brackish water fish farming in the various estuaries and lagoons, particularly Chilka Lake and Lake Pulicat. There are several areas suitable for brackish water shrimp culture in addition to the 26 percent currently used. Along the Andhra coast on the east, 76,589 ha, mostly fertile land traditionally used for cultivation of rice, were rushed into shrimp culture, popularly known as the "dollar crop." This fishery, which fetched US$100 million in 1993 and is projected to the tune of US$300 million in 2000, was totally decimated, leaving behind useless salted ponds. This collapse was due to disease and the lack of a holistic scientific approach, that is, site-specific evaluation of the carrying capacity without risking the environment equilibrium.[70] Molecular biological techniques for microbial control of disease and genetic improvement of shrimp should be pursued to sustain shrimp farming.

Offshore Oil and Natural Gas

The oil crisis of 1972 necessitated offshore exploration off Bombay. Discovered in 1974 and known as the Bombay High, this region is located between the Saurashtra arch in the north and the Vengurla arch in the south and bound on the west by the Carlsberg Ridge. It proved to be rich, having a number of oil and gas fields with a potential of 9 billion tons of hydrocarbons and an annual yield of 26 Mt of oil. Other basins studied for hydrocarbon exploration include Kutchchh, Sauraahtra, Cambay, and Kerala-Konkan in the Arabian Sea. Seismic surveys and magnetic anomaly investigations were carried out to determine the sedimentary structures and stratigraphy of the Andaman Basin between lat. 6° N and 14° N and long. 91° E and 94° E. On the east coast of India, several wells were drilled on the Gondwana and Cretaceous sediments of Krishna-Godavari Basin, Cauvery and Mahanadi delta area. In Godavari Basin, the Kakinada Indian Oil Liquid Natural Gas (LNG) consortium has a massive $4,312 million project including a $811 million 1000 MW power project. It has 13 LNG ships that export 130 Mt LNG presently and will be acquiring another 5 or 6 to export LNG to Japan and Korea.

69. P. Dayaratne and R. Maldeniya, "Recent Trends in the Tuna Fisheries of Sri Lanka," *Proceedings of the Sixth Expert Consultation on Indian Ocean Tunas, Colombo, Sri Lanka, 25–29 September 1995,* eds., A. A. Anganuzzi, K. A. Stobberup and N. J. Webb, (Colombo: IPTP, vol. 9, 1996): 40–46.

70. Subba Rao (n. 64 above).

The National Institute of Oceanography collaborates actively with the Oil and Natural Gas Corporation, the Gas Authority of India Ltd., and the National Geophysical Research Institute in exploring and assessing the gas hydrates reserves in the continental margins. Only 30 percent of the nation's oil demands are met domestically. The gap between the indigenous production and the demand is increasing at an alarming rate. There is a need to drastically improve the falling oil production and exploration activities are to be revamped by drilling deep-water wells.

Ocean Thermal Energy Conversion (OTEC)

It will be necessary to enlist ocean thermal technology as an ally in the plurality of approaches necessary to meet the energy requirements of India. NIOT is building a 1 MW floating demonstration OTEC plant 40 km off the shores of Tamil Nadu, which should be operational soon. As the OTEC plants utilize temperature differences between the cold deep water (>1000 m) and the surface, the Swatch of No Ground at the head of the Bay, several canyons (Andhra, Krishna and Mahadevan) off the east coast of India may be conducive to OTEC. The proximity of these canyons to the coastline is an advantage. OTEC plants can meet power requirements for islands such as the Andamans. The estimated OTEC potential of this region is 50,000 MW, representing 150 percent of India's total installed generating capacity.[71] Also, utilizing the Oscillating Water Column (OWC) principle, NIOT is constructing a pilot plant for conversion of wave energy. At Vizhinjam, Kerala, an OWC plant is being developed with an average 150 kW power capacity. The Gulf of Cambay, Gulf of Kachehh and the Sunderban Delta Region could generate 7300 MW, 1000 MW and 15 MW, respectively.[72] Energy from the oceans, besides being clean, is an emerging area of importance and industries should be encouraged to play a greater role in this energy development.

Weather Forecasting

As life in India revolves around the seasonal wind pattern and cyclones, forecasting coastal marine climate should be given high priority. During May to November, the Bay of Bengal experiences, on average, a total of 40 severe cyclones compared to 17 in the Arabian Sea. Orissa and the West-Bengal on the east coast, and Kerala, Gujarat-Saurashtra on the West Coast, are the worst affected and experience enormous loss of human lives, property, crops and cattle. The recent super cyclone with over 260–300 km/h off the Orissa

71. Yates and Roonwal (n. 46 above).
72. Ibid.

coast (Oct. 1999) was the worst in history, causing a loss of 5000 people, 25,000 houses and property damage of Rs.10 trillion in 1500 villages. The institution of a disaster plan would have averted the suffering. The India Meteorological Department has a network of cyclone detection systems with a range of 400 km at Calcutta, Paradeep, Visakhapatnam, Machilipatnam, Chennai, Karaikal on the east, Port Blair and Bhuj, Mumbai, Goa and Cochin on the west coast, which are not adequate. Intra-seasonal variations in the monsoons and detailed examination of the breeding cycles of the cyclones in real-time mode need to be studied. OCEANSAT has recently launched a study of the relationship between monsoon variability on subseasonal and interannual scales to variations of the convective systems on the planetary scales to predict the coupling of the monsoons to the oceans.[73] It is envisaged to give priority by 2005 for remote sensing and Ocean Technology Satellite imagery for tracking, monitoring and for operational forecasts of cyclones, and assessment of damage.[74]

CONCLUSIONS AND LOOKING INTO THE NEW MILLENNIUM

India is strongly committed to marine science research in the Indian Seas and the Antarctic. Since 1952, several coastal universities, the NIO (1966) and the DOD (1981) continue to address processes associated with monsoon circulation patterns, production processes and fisheries. The DOD, the nodal agency for ocean sciences, invested heavily in modern oceanographic research and capacity building to pursue research, evident from the multidisciplinary research cruises in the Exclusive Economic Zone (EEZ) and far-flung annual oceanographic expeditions to the Central Indian Ocean, Antarctica and to the Caribbean Seas.

The coastal seas of India are one of its most valuable economic resources. The destruction and ruin of the Andhra coast due to decimation of the shrimp industry, the near-emergency state of arsenic poisoning in the Ganges Delta and the unbridled dumping of enormous quantities of raw sewage and industrial effluents are examples of environmental disasters. India should focus on its own shores first and balance the needs of a billion people with the needs of the environment. Compelling reasons to focus research on applied aspects in the EEZ include the following: a) the EEZ contributes more to the production than the offshore; b) most of the nation's fishing is limited only to the EEZ; and c) the existence of several critically polluted "hot spots" in the EEZ off Gujarat, Kerala, Tamil Nadu, Andhra Pradesh, Orissa and West Bengal. India's 200 million coastal population im-

73. S. Gadgil, "Monsoon-Ocean Coupling," in *Perspectives on Ocean Research in India, Current Science* 78 (2000): 309–22.

74. Ibid.

poses increasingly serious environmental stresses, resulting in rapid deterioration of the EEZ. Before the impacts become irreversible and serious, it is essential that an independent Integrated Coastal Development Agency (ICDA) be established to sustain continuity in coastal marine science studies, with a mandate for a) protection of coastal habitats and their biodiversity; b) sustainable management of living and nonliving resources; c) regulation of marine pollution; d) development of Ocean Thermal Energy Conversion; and e) development of a reliable marine weather forecast network. Further, under the stewardship of ICDA, a coastal research vessel dedicated to coordinated seagoing activities by various coastal universities should be available. Success of ICDA is contingent upon fostering cohesiveness between the various scientific agencies to ensure that national priorities are addressed.

In rapidly developing countries like India, at a time of scarce resources, scientists, entrepreneurs and policy makers should work towards an expeditious advancement of science and technology to meet the nation's demands. Compared to the total ocean sciences budget, the proportion of expenditure on Antarctic research continues to be high at 32 percent (1997–1998) and 27 percent (1998–1999), while that on the marine environment and coastal zone was 3 percent and 2.1 percent.[75] Investments on Coastal Ocean Monitoring and Prediction Systems (COMAPS), Integrated Coastal and Marine Area Management (ICMAM), coastal research vessels and coastal community programme account for ~14 percent of the total marine science budget when pooled (table 1) and need to be substantially increased. Economically unrewarding pursuits need be restructured, adjusted to the budgetary constraints and issues of social relevance of oceanography are to be preferred.

Oceanography being a "luxury science," two important aspects of program evaluation and cost effectiveness are to be considered. We should ask and answer the difficult but necessary question, that is, would India's national needs be better served if attention was focused towards integrated coastal management for sustainable development of resources, environmental protection, and both prediction of natural disasters and their prevention? Arguments advanced and meriting serious consideration are for an ultimate trade-off between factual recommendation and value demands and for the role of micro-debates on specific actions and exact social goals to determine the social value of oceanographic research.[76] India has to invest more in science (about 2 percent of GDP rather than the current 0.9 percent).[77] The suggestion to shift from the 80 percent so-called basic research in India to relevant research applied to the immediate needs of the society should be

75. *India 1999* and *India 2000* (n. 13 above).

76. C. S. Davos, "On Determining the Social Relevance of Oceanography" *Progress in Oceanography* 44 (1999): 457–68.

77. C. N. R. Rao, "Science in the Future of India," *Science* 286 (1999): 1295.

noted.[78] Education of the public at all levels about the precious coastal environment and the need for its preservation is necessary. Such environmental learning facilitates formation of an environmental nongovernmental organizations (NGO) community at the grass roots level and its consciousness-building efforts. The various industries that use the coastal waters should be made to abide by the polluter-pays principle, if necessary through legislation. For India to catch up and become a front runner in marine science and technology in the new millennium, the user industries should be levied a pollution tax to sponsor long-term relevant research on coastal seas. The Government of India has taken the right step with the recent first-time appointment to cabinet of a reputed working scientist (Dr. A. P. J. Kalam) as its science adviser on bringing cohesiveness to the various scientific agencies and ensuring that the golden triangle of the R&D laboratory, academia and industry emerges and India's national priorities are addressed.

78. S. Maiti, "Science and Technology Education and Research in India," *Journal of the Indian Chemical Society* 75 (1998): 185–89.