INDIAN NATIONAL SCIENCE ACADEMY

INDIAN NATIONAL REPORT FOR IUGG 2011

XXV IUGG GENERAL ASSEMBLY
28 JUNE - 7 JULY 2011
MELBOURNE, AUSTRALIA

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NATIONAL COMMITTEE FOR INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS (IUGG) AND INTERNATIONAL GEOGRAPHICAL UNION (IGU)

(www.iugg.org and www.igu-net.org)

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PREFACE

This report has been prepared on the behalf of the Indian National Science Academy (INSA), New Delhi. I have a great pleasure in presenting this report to the International Union of Geodesy and Geophysics (IUGG) at its General Assembly in Melbourne, Australia during 28th June, to 7th July, 2011. The report summarizes Indian activities in the geophysics and geodesy for the period of January 2007 to December 2010 and is structured to reflect eight associations of IUGG.

The quadrennium 2007-2010 has been very exciting for the earth system sciences internationally and India is no exception to it. Four International Science Years namely, International Year of Planet Earth (IYPE, 2007-2009), International Polar Year (IPY, 2007-2008), Electronic Geophysical Year (EGY, 2007-2008) and International Heliophysical Year (IHY, 2007) were successively complemented during this period. These years have brought a lot of visibility and importance to the earth science research. India was a lead associate of these initiatives.

Indian researchers have been actively involved in the Antarctic and Arctic studies and assessments of Himalayan glaciers, which have been summarized by Rasik Ravindra in the chapter on Cryospheric Sciences. B. Nagarajan and V.M. Tiwari report on the activities related to Gravimetry and Geodesy and underlined the Indian efforts of redefining geodetic datum, electronic tide gauges installation and applications of space geodetic techniques. Archana Bhattacharyya compiled a report on the contributions in the Geomagnetism and Aeronomy. S.N. Rai and S.K. Jain reviewed studies on the Hydrological Sciences. Work related to climatic changes particularly monsoon and extreme rainfall is discussed by N.N Singh and A. Ranade. S.S.C. Shenoi has addressed Indian efforts in understanding ocean around India. The extensive contributions of India in seismological and Earth's interior are presented by J.R. Kayal and R.K. Chadha. K.S. Krishna, T. Pal, and J.S. Ray have documented the volcanological studies during the report period.

I am thankful to all colleagues who contributed and who helped to compile this report. I would also like to thank the IUGG National Committee members and officers of the Indian National Science Academy, especially Drs. A. K. Moitra and Brotati Chattopadhyay, for their help in bringing out this Report.

Harsh K. Gupta, FNA
Chairman, National Committee for IUGG-IGU,
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CONTENTS

INDIAN ACTIVITIES ON INTERNATIONAL SCIENCE YEARS (2007-2009)

Harsh K. Gupta

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The triennium year 2007, 2008 and 2009 had been celebrated as International Year of Planet Earth (IYPE), International Polar Year (IPY), Electronic Geophysical Year (eGY) and International Heliophysical Year (IHY). The aim of these International Science Years was to highlight the significance and relevance of Earth System Sciences to the public through the outreach programme and enhancing scientific research through Science Programme. The basic existence of mankind is because of unique property of the Planet Earth and Space around it. However we do not realise its importance and know very little about it. Global climate change, sea level rise, deglaciation, geological hazards and demand of earth resources for higher standard of living and increasing population has resulted in degradation of the health of Planet Earth. Realising the importance, the year 2008 was proclaimed as Year of the Planet Earth by United Nation. India was amongst the first few countries to take initiative to emphasise the importance of sustainable Earth System (Figure 1).

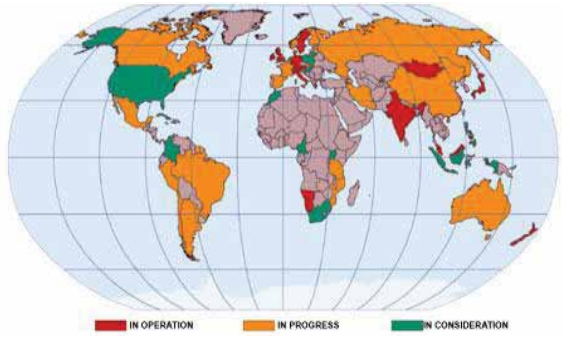

Figure1: Map displaying progress in developing national committees for IYPE. India was amongst few countries that has national imitative in the early phase (EPISODE, 2006)

A national committee was constituted by the Indian National Science Academy (INSA) on the International Years in 2006. This committee was entrusted to identify and document the planned scientific initiatives and strengthen the activities of bringing Earth System Sciences to society. The committee formulated the following plans in the very beginning

- *Counseling to strengthen the outreach programme of the various government departments and non-government organizations*
- *Organization of a workshop on the activities of International Years at INSA*
- *Organization of all Indian Student contest as a part of the International student contest for the official launch of IYPE during Feb 12 & 13, 2008 at Paris.*
- *Encouraging India's participation in the International Events*
- *Committee also recommended Coordinators of individual Years.*

Indian scientific community had responded very well to the International Science Years. Numerous activities and events have marked the International Science Years in India. They are documented and posted on the website particularly developed for it (http://iypeinsa.org).

The website was updated periodically to communicate the latest information about International Years and Indian activities during these years. The central secretariat located at the National Geophysical Research Institute, Hyderabad served as a nodal agency for interlinking the information and activities of different organisations in and outside India.

International Year of Planet Earth- IYPE

The International Year of Planet Earth (IYPE) started with a well planned mega event under the auspices of Indian Science Congress which is held every year in the first week of January and is the largest scientific meeting in India, covering all disciplines of natural sciences. More than 5000 participants, from India and abroad, took part in the annual mega event, Indian Science Congress-2007 . "Planet Earth" was chosen as the focal theme for the 2007 Science Congress. Hon'ble Prime Minister of India, Dr. Manmohan Singh, inaugurated the Science Congress on 3rd January 2007 at Annamalai University and stressed on the importance of earth sciences and the need of the hour as to how to stop degradation of planet earth. Hon'ble Minister for Science and Technology and Ministry of Earth Sciences, in his address underlined the Government of India's commitment of integrating all earth science related activities, and the Governments creation of a separate Ministry of Earth Sciences. India is currently the only country in the world, which has a dedicated ministry for Earth Sciences. It was emphasised that Earth Sciences touched the basic aspects of life on earth and it was of prime importance to realize its worth. Hon'ble President of India, Dr. A. P. J. Abdul Kalam, addressed the scientists and had a separate session with the students from all over the India. He formally launched Planet Earth related activities in India by releasing symbolic balloons.

Figure 2: Then Hon. President of India, Dr. A.P.J. Abdul Kalam released the balloons to commemorate the INTERNATIONAL YEAR of PLANET EARTH

A dedicated session on International Science Years was organised during the Indian Science Congress, which was very well attended. Details of the workshop are posted on the webpage (http://iypeinsa.org).

International Polar Year Activities

The Indian chapter of the International Polar Year (IPY) 2007-2008 was launched at National Centre for Antarctic & Ocean Research (NCAOR), MoES on 1st March 2007 by Prof. U. R. Rao, former Chairman, Indian Space Research Organization with subsequent lectures by Dr. Rasik Ravindra, Director, NCAOR & Dr. S. R. Shetye, Director, National Institute of Oceanography, Goa. A "calendar of events" was released by Prof. U.R. Rao that listed outreach activities to be undertaken. NCAOR had sponsored the visit of two students to Antarctica during the 25th Indian Antarctic Expedition (IAE) under the "Students Participation Programme". A series of lectures were delivered by one of them at more than twenty schools & colleges in the rural & suburban areas of Maharashtra, India. Students from several schools and colleges and scientists/visitors from various Indian institutes/foreign countries have visited NCAOR & its laboratories, especially ice core laboratory, to get a firsthand experience of polar research. NCAOR, in collaboration with WWF-India, has carried out competitions such as poster & model making, stamp designing, petition writing etc. for school children during 2007-2009. The first competition, poster making & slogan writing, was held at New Delhi on April 10, 2007 and prizes were distributed by the H'ble Minister of Science & Technology and Earth Sciences on the Earth Day, 2007. The winners of these competitions were invited for launching of the XXVII Indian Antarctic Expedition at Goa and were felicitated by the Secretary, Ministry of Earth Sciences on 5th December 2007. The award winning posters were published in the form of a calendar for the year 2008-09 that was freely distributed. Moreover, under the "Popular Book Series" initiative of the Ministry of Earth Sciences, a book entitled "Story of Antarctica" was published by NCAOR for free distribution among school children. Similar books on "Story of the Oceans" and "Glaciers - The Rivers of Ice" have already been published & distributed to students in different states of India. NCAOR also celebrated the International Polar day on 4th December 2008 that involved lectures, short movies, competitions & activities focusing on research above the Polar Regions for school

children and the launch of a "virtual weather balloon" by them.

International Heliophysical Year (IHY)

- *A one-day meeting held at Indian Institute of Astrophysics (IIA), Bangalore, on January 13, 2007, to discuss various public outreach (PO) activities, was attended by many scientists from various national centres. Scientists at IIA came up with a concept design of simple experiments to study the Sun in the visible and radio wavelengths. Prototypes of these instruments were on display during the IIA Open House Days on August 9-10, 2007. IIA has also taken the initiative of arranging an adequate number of these instruments to be produced for distribution in schools and colleges throughout the country.*
- *Posters on Sun, Space Weather, and Solar-terrestrial relations were on display as the main theme at an exhibition celebrating IHY 2007. The exhibition also included a demonstration by Navnirmiti of Mumbai, on details of using low-cost tools to understand the Sun.*
- *At the Inter University Centre for Astronomy and Astrophysics (IUCAA), Pune, PO activities include producing small telescopes, such as refractor telescopes with 40mm lens, and demonstrating to children how to observe the Sun by projecting the solar image.*

An important part of PO activities was public lectures on IHY themes, particularly for school and college students by scientists from Indian Institute of Geomagnetism (IIG) and other institutes. IHY related public debates and training programmes have also been conducted by the Radio Astronomy Centre (TIFR, Ooty) from mid-2006 to mid-2008 in several schools and colleges, at which students were provided with training on how to use the radio telescope and how to carry out data analysis.

Electronic Geophysical Year (eGY)

Electronic Geophysical Year (eGY) activities in India were limited. Nevertheless, several government organisations, particularly institutes of Indian Space Organisation had developed a large data base, their inventories and availability for common man. Details of the same can be found in the presentations posted on http://iypeinsa.org.

Acknowledgements: *This article is based on the reports submitted by Indian National Committee on International Science Years. Many colleagues have contributed in preparing this report. I have had generous support from INSA and all the members of national committee. I thank them for their thoughtful efforts during these years.*

INDIAN CONTRIBUTION TO RESEARCH IN CRYOSPHERE SCIENCES

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The Cryosphere is the second largest component of the climate system, after the ocean, that stores about 75% of the world's freshwater. In terms of the ice mass and its heat capacity, therefore, it plays a significant role in the global climate. The main components of the Cryosphere are snow, river/lake ice, sea ice, glaciers and ice caps, ice shelves, ice sheets and frozen ground. All parts of the Cryosphere contribute to short-term climate changes, with permafrost, ice shelves and ice sheets also contributing to longer-term changes including the ice age cycles. Considering its implications on climate and sea level changes, monitoring and evaluation of Cryosphere regions and the climate change effects on Cryosphere are crucial (IPCC, 2007).

Indian researchers have been carrying out scientific research in all major components of the global Cryosphere regimes like the Himalayas, Antarctic and Arctic regions. Various ministries and departments of Government of India like the Ministry of Earth Sciences, Ministry of Mines, Ministry of Defence, Department of Science and technology; Department of Space etc have been encouraging the cryospheric research through various R&D organizations and institutes. Some of the leading organizations involved in the field of cryospheric research include: Geological Survey of India (GSI), National Centre for Antarctic and Ocean Research (NCAOR), Snow and Avalanche Study Establishment (SASE), Space Application Centre (SAC), Wadia Institute of Himalayan Geology (WIHG), National Institute of Hydrology (NIH), Indian Institute of Geomagnetism (IIG), Physical Research Laboratory (PRL), as well as various Universities and IITs. Major objectives of the glaciological studies being conducted in India include:

- *To monitor, assess and model the glaciers and ice caps vis-à-vis the ongoing global warming;*
- *To study the dynamics and the rate of change in glaciers and ice cover to understand its impact on hydrology, ecology and climate;*
- *To assess the climate change using ice as an archive of information on past climate and its future implications.*

1. Himalaya

The Himalayan mountain system is home to the world's highest peaks, which includes about 50 peaks which are more than 7500 meters above mean sea level. The Himalaya forms the most important concentration of snow covered region outside the polar region and the Himalayan glaciers are highly sensitive to the on-going warming. Recently, GSI (2009) has updated the detailed glacier inventory of Indian Himalayas and summarized details about glaciers in the districts of Uttrakhand, Himachal Pradesh and Jammu and Kashmir States and compiled the available water resources in form of glaciers (see Sangewar and Shulka in GSI (2009).

There are 9575 glaciers spread across the Indian part of the Himalaya (GSI, 2009), some of which form the perennial source of major rivers. Changes in glaciers are one of the

clearest indicators of alterations in regional climate, since they are governed by changes in accumulation (from snowfall) and ablation (by melting of ice). The difference between accumulation and ablation or the mass balance is crucial to the health of a glacier. GSI (op cit) has given details about Gangotri, Bandarpunch, Jaundar Bamak, Jhajju Bamak ,Tilku, Chipa ,Sara Umga Gangstang, Tingal Goh Panchi nala I , Dokriani, Chaurabari and other glaciers of Himalaya. Raina and Srivastava (2008) in their 'Glacial Atlas of India' have documented various aspects of the Himalayan glaciers covering their origin, classification, landforms, snow cover assessments and basin wise inventory of the glaciers.

Glacier assessment and mass Balance studies

Indian scientists have now been utilizing modern remote sensing techniques, in addition to the conventional ground surveys and the geographical information system to study the glaciers, store the results and present the information to both scientific and popular audiences.

Several Indian workers from GSI, WIHG and SAC have studied the Himalayan glaciers for their physiography and mass balance. Gangotri, Dokraini and Chhota Sigri glaciers are some such examples. Shukla et al., (2009) have used satellite remote sensing data to map debris cover and assess its temporal changes over a glacier in the Chenab basin in Himalaya. Further, studies have indicated that similar spectral responses between supraglacial debris (i.e. debris on the glacier) and the periglacial debris (i.e debris alongside glacial boundary) in the solar reflection region, hamper the accurate determination of boundaries of debris covered glaciers. Shukla et al (2010) has tested the thermal infrared bands (ASTER data), which has the potential in resolving ambiguities that exist in earlier methods between supraglacial debris and periglacial debris. The results of this approach are promising and show that the combined optical and thermal information has great potential for effective mapping of debris-covered glaciers. Motivated by this concept a novel synergistic approach for extraction of debris-covered glacier has been adopted in a recent publication by Shukla et al., (2010) which involves the use of integrated optical and thermal dataset for delineation of debris covered glacier boundaries as considerable temperature differences are found to exist among them.

Kulkarni et al (2011) have attempted to understand the changes in the Himalayan Cryosphere using remote sensing techniques. From their studies on the changes in glacial extent, glacial mass balance and seasonal snow cover; they have estimated the glacial retreat for 1868 glaciers in 11 basins since 1962 at 16% (overall deglaciation). The monitoring of the seasonal snow cover in 28 river sub-basins in central and western Himalayas, as per them, indicated snow retreat even during winters. Gurung et al (2011) have examined changes in snow cover in the Hindu kush-Himalayan region using MODIS data from 2000 to 2010. The snow cover depletion curve for 2000-001 reveals peaks in the month of February.

The study by Shukla et al., (2009) has revealed that the glacier area has reduced from a total of 110.5 km^2 to 96.8 km^2, indicating an overall deglaciation of 13.7 km^2, receding about 756 m. Negi et al., (2009) and Shukla et al. (2009) have successfully demonstrated the applicability of remote-sensing data in monitoring glacier terrain, particularly mapping debris-cover area.

Changes in mass balance control a glacier's long term behaviour and are the most sensitive climate indicator on a glacier. Wagnon et al (2007) and Berthier et al., (2007) have used SPOT5 images and SRTM data to study the mass balances for the glaciers in Himachal Pradesh. Their study reveals that the overall depletion in the snow cover and rapid ice losses in from the glaciers in the Spiti/Lahaul region. However, Shukla and Mishra (2007) from their studies on the recession pattern of glaciers in Bhaga Basin of this region state that glaciers of Lahaul Himalayas are retreating at slower rates than those located south of Pir Panjal range. Keshri et al., 2009

has presented two new indices namely NDGI (Normalized Difference Glacier Index) and NDSII (Normalized Difference Snow Ice Index). The combination of the previous NDSI with NDGI and NDSII allows discrimination of snow, ice and ice mixed debris in a systematic manner. In order to assess glacier mass balance, which is a ratio between accumulation area and total glacier area, a technique based on AAR is used extensively in the Himalayas for the mass balance estimation. During the study period 2005-2009, annual mass balance, snout retreat, glacier discharge measurement and meteorological observation have been carried out by the WIHG. Mass balance is a more dynamic and important parameter to understand a large retreat. The main objective of this work by WIHG was to evaluate change in glacier mass and dynamic processes viz-a-viz climate change and annual difference in mass balance and snout retreat processes. Raina (2008) has compared the balance of two glaciers in Himachal Pradesh, one in North facing (Gara glacier) and the other Souith-facing (Gorgarang glacier). He also concluded that a relative excessive winter snow precipitation leads to a positive balance or a reduced negative balance. However a retreating glacier may to continue to retreat even under high winter accumulation.

Glacial monitoring

The Himalayas possess one of the largest resources of snow and ice, which act as a huge freshwater reservoir. Monitoring the glaciers is important to assess the overall reservoir health. Kulkarni et al., (2007) has carried out an investigation on 466 glaciers in the highly glaciered Himalayan basins, namely Baspa, Parbati and Chenab. This study has included small mountain glaciers and ice fields as well as the developed and easily accessible valley glaciers. Glaciers occur on the monsoonally influenced slopes of the Himalaya where precipitation exceeds 2500 mm/yr, mean annual temperatures at the snowline are about -2°C to -4°C, the ice is warm based with basal ice temperatures approaching 0°C (Ganjoo R.K, 2009c). It has been observed that the glacial area has been reduced as much as 21% from the middle of the last century whereas the number of glaciers has increased due to fragmentation. Numerous investigations by international and national scientists in the past have suggested that glaciers are retreating as a response to global warming. Systematic and meticulous glacial inventory of 1962 and 2001 have now clearly demonstrated that extent of fragmentation is much higher than realized earlier. Loss in glaciated area for large glaciers was 12% compared to 38% for small glaciers which is explained by three fundamental glacial parameters, namely depth, mass balance and rate of melting at the terminus. Since glacier response time is directly proportional to its depth, small glaciers are considered as more sensitive to global warming. The observations made in the investigation by Kulkarni et al., (2007) suggest that small glaciers and ice fields are significantly affected due to global warming from the middle of the last century. In addition, larger glaciers are being fragmented into smaller glaciers. However, Sangewar (2007) while giving an overview of the data on the mass balance of three glaciers viz Gara, Gor-Garang and Shaune-Garang glaciers in Sutlej catchment, has stated that out of the seventeen years between 1974 and 1991, five years recorded positive balance for all the monitored glaciers.

While Uphadyay (2009) has given an alarming version of the recession of Siachen glacier, Ganjoo and Koul (2009) have argued that there is no rapid melting of Siachen glacier as claimed by Uphadyay (2009). As per them, the eastern part of the Siachen glacier shows faster withdrawal of the snout, essentially due to ice calving which is true for almost all major glaciers in the Himalayas. The western part of the glacier has reduced due to action of melt water released from the retreated tributary glacier. The Siachen glacier shows hardly any retreat in its middle part and thus defies the hype according to Ganjoo and Koul (2009). Their field studies from other glaciers in India also corroborate the fact that inter- and intra-annual variations in weather parameters have more impact on the change in glaciers of NW

Himalayas, rather than any impact due to global warming. Raina and Sangewar (2007) based on the long term studies on the Siachen glacier have also come to the conclusion that the Siachen glacier of J & K has not shown any appreciable retreat between 1958 and 1985.

Scientists from WIHG have covered several aspects of the glaciers of Uttaranchal such as the glacial morphology, glacial landforms, snout fluctuations, recession/retreat and mass balance of Chaurabari and Dokriani glaciers. (Dobhal and Mehta Manish, 2010, Dobhal et al., 2010, Chaujar and Dobhal, 2009, Dobhal and Mehta, 2008 dobhal et al 2007)). Their studies have shown that the net annual frontal retreat for the period between 2004-05 and 2008-09 for Dokriani glacier has varied from 14 m/yr to 21 m/yr (15.7m/y for 2000-07) while that for Chorabari glacier has varied from 10.2 m/yr to 5 m/yr.

Study of secular movement of Bhagirath Kharak and Satopanth glaciers was undertaken by Nainwal et al (2008), who have given the retreat of Satopanth and Bhagirathi glaciers of Uttrakhand as 22.88 m/y and 7.42 m/y for 1962-2005 and 6.5m/y & 1.5m/y for 2005-2006 respectively. Koul and Ganjoo (2009) from their study of Naradu Glacier (Himachal Pradesh) show a variable rate of retreat ranging from 4.3 m and 2.9 m per year for the period between 2000 and 2003. Similarly Bali et al (2008) have reported 6.39m/y retreat for the Pindari glacier for the period between 1966 and 2007. Anthwal et al (2006) have linked retreat of the Himalayan glaciers to the climate change.

Cryosphere and hydrology

Studies on the sediment load of the glacial melt streams and run off have been conducted by National Institute of Hydrology.

Others, including Akthar et al., (2008) have estimated the water resources in three river basins in the Hindukush-Karakoram-Himalaya region associated with climate change using two models, HBV-Met and HBV-PRECIS.

An impact of climate change on snowmelt runoff in eastern Himalayan Rivers has been studied by Bhadra et al (2009). Kumar et al (2008, 2009) have conducted studies on the solute dynamics of melt water of Gangotri glacier signifying the importance of the projects related to water resource development. Bhutiyani et al (2007 and 2008) have worked on the air temperatures and changing stream flow patterns in western Himalaya while Singh et al (2008) have given an account of the hydrological characteristics of Gangotri glacier. Several workers (Sharma et al, 2010, Joshi V. 2009, Joshi and Sharma 2007 have studied the probable hazards and the issues of the disaster management related to the ice covered Himalayan regions.

Cryosphere and climate associated studies

Due to the characteristic geographical setting of the Himalaya from west to east, the differences in temperature and precipitation regime are not only well marked but also distinctly reflected in many of the environmental responses which are very useful in climatological investigations. Motivated by opportunities, Borgaonkar et al., (2009) have prepared a 458-year-long regional tree-ring-width index chronology of Himalayan cedar from three high-elevation sites of Western Himalaya. Such dendroclimatological studies indicate a significant positive relationship of tree-ring index series with winter temperature and summer precipitation and inverse relationship with summer temperature. He has also noticed the higher growth in the recent few decades coinciding with the rapid fluctuations of the Himalayan glaciers.

Milap (2009) has analysed the historical, palaeoclimatic dating and ground survey data for last several centuries to conclude that the Miyar glacier of Chenab sub basin has been more or less stable for last 134 years . Juyal et al (2009) have reconstructed the last glacial to early Holocene history from lake sediments of Higher Himalayas which indicates that sedimentation continued between 25K to 13 K years BP.

Several researchers have studied the subject of aerosol radiative forcing and possible recession of glaciers (Ramanathan, et.al 2007, Hedge et al 2007, Pandithurai et al 2008, Das et al 2008 etc). Examination of relationship between temporal changes in AOD (Aerosol Optical Depth) and the recessional trend of Dokriani glacier in Bhagirathi valley has revealed a reasonable correlation(R^2= 0.86) between the two by (Das et al 2010). They (op cit) conclude that Increased AOD over the Himalayan region had led to the enhanced aerosol heating and thus the recessional trend.

2. Antarctica

The Antarctic continent itself makes up about 10% of the land surface of the Earth with the combined area of the ice sheets and ice shelves being about 14 x 10^6 km^2. Ninety eight percent of Antarctica is covered by thick ice sheets that contains about 90% of the world's 'permanent' ice and 70% of its fresh water. The cryosphere, hydrosphere and atmosphere in and around Antarctica are the closely interactive components of a complex climate system, with global, regional, as well as local influences. Ravindra (2008), Ravindra et al (2008), Ravindra and Tiwari (2011) and Ravindra (2011) have given exhaustive review of the Earth science studies including research in glaciology and the significance of such studies in Polar region.

Glacier dynamics studies

Global Positioning System (GPS) campaigns were conducted in the Schirmacher Oasis in the central Dronning Maud Land of Eastern Antarctica to understand the velocity and strain-rate relationship (Sunil et al., 2007, 2009; Reddy et al., 2010). The study has revealed that the magnitude of the horizontal velocity is in the range 1.89–10.88ma^{-1} with an average of 6.21ma^{-1}, in the north-northeast direction. The study also suggested that the distribution of velocity can be spatially correlated with topography, subsurface undulations, fractures/crevasses (coinciding with high velocities) and the influence of 'the blockage' due to Schirmacher Oasis. The surface strain analysis indicates that the region of extensional strain coincides with the surface gradient and crevasses, while the region of compressional strain is due to the blockage caused by Schirmacher Oasis and nunataks. The general trend to low (compared to other glaciers) velocities (~11ma^{-1}) is primarily attributed to the fact that this part of the ice cap is located in a region of exposed nunataks which extend along the ice-shelf grounding line. The Nivlisen ice shelf motion constrained using the DG GPS site with the base station Maitri and nearby International GNNS service (IGS) stations suggest the influence of ocean tidal effect, wind stress, and ocean currents (Sunil and Reddy, 2010). Further studies in association with Synthetic Aperture Radar (SAR) suggested the need to have long-term continuous monitoring of GPS records to understand the secular variations and the influence of atmospheric conditions on the velocity field (Reddy et al., 2010). The GSI has also been conducting studies on the accumulation/ablation on the ice shelf since 1985. The significance of the wind deposited snow results in average accumulation in range from 0.45 to 0.55 m/year (Dharwadkar et al., 2010)

Sea ice studies

The sea ice surrounding the Antartic continent has a maximum winter extent of some 20 million km^2, the seasonal waxing and waning of which is one of the largest seasonal signal on planet Earth, leading to large scale effect on the climate, oceanography and biological productivity. The Indian studies in the field of sea ice reconstruction have used remote sensing data as well as modelling methods. Sea ice edge variability analysis during 1982-2004 using satellite passive microwave observation revealed that maximum Antarctic sea ice concentration trend of 0.01 degrees/ year was found during the summer season of 1982-1998 (Bhandari and Khare, 2009). On a regional scale, the Ross and Weddle sea show positive trend whereas Bellinghausen/ Amundsen sea show negative trend. Simulation of sea ice using Semtner's 3 layer sea ice model and Winton's reformulated three

layer sea ice model were conducted in comparison with the observations (Mitra and Das, 2007). The study has shown that both the models are able to capture seasonal variability of Antarctic sea ice using only thermodynamics. Artificial neural network (ANN) was also used for simulation of Antarctic sea ice are anomalies (Thripathi and Das, 2008). ANN is able to simulate the broad tend of the sea ice area anomalies when the dominant annual and half yearly cycles are present. However, the prediction skill of model for intraseasonal variability degrades when the trends are removed. The relationship between Antarctic sea ice variability and Indian Ocean SST suggest a most persistent positive correlation with the SE Indian Ocean region (Rai et al., 2008).

Mass balance studies

The mass balance study of the Antarctic ice sheet is of great importance due to role on the global sea level and climate change. Mass balance studies were conducted by the Indian scientists using a combination of automated weather stations with ultrasonic sensors, Ground Penetrating Radar (GPR) as well as stake measurements. Geological Survey of India has been carrying out stake measurements for snow accumulation in the ice shelves of the Schirmacher and Nivlisen ice shelf region. Data from other sources like snow/ ice cores have provided valuable information on the spatial and temporal variability of snow accumulation in this region. Near the erstwhile Indian station 'Dakshin Gangotri' site (70º 5.62'S, 12 º E), a net accumulation of 62.7cm was recorded as per the long term (1999-2001) measurement program using stake measurements. A recent quantitative study of surface energy and mass balance near the Schirmacher region close to the non-glaciated region revealed that there is high rate of ablation during summer with a seasonal mean of 0.0172 metre water equivalent (m.w.e) per day (Gusain et al., 2009). Over a period of 10 November 2007 to 7 February 2008, the mass balance was -1.53 m.w.e., with a good correlation between the estimated and observed hourly ablation of the glacier. Sublimation and melt processes contributed 16.5% and 83.5%, respectively, to the net summer ablation (Gusain et al., 2009).

Long-term monitoring of the DG glacier retreat

Monitoring of glacier snout and the continental ice margin was initiated as long-term project by the Geological Survey of India in 1983. For the last two decades annual fluctuations in continental ice margin are being monitored along Dakshin Gangotri Glacier Snout, a prominent glacial tongue, in the central part of Schirmacher Oasis (Latitude: 70º45' S; Longitude: 11º33' E). The snout was monitored from fixed survey points on a yearly basis and average annual recession rates were computed for this glacier. Dakshin Gangotri glacier snout monitoring, continuing from 1983, shows a significant recession of 6.5 to 7m per decade (Dharwadkar., 2010; Gaur and Prasad, 2007). This is possibly indicative of the warming effects on this coastal region in Antarctica. The domain of observation has been lately extended by eight kilometres covering the continental ice margin on either side of the snout. Studying the continuous data on recession available from 1996 to 2005 and the average annual temperature of Schirmacher Oasis, it has been suggested that the rate of recession of DG glacier is affected by the average annual temperature recorded for the year previous to the year of glacier observation (Chaturvedi et al., 2009).

Climatic reconstruction using ice cores

Study of ice core proxy records provide one of the most direct and accurate method to study the Antarctic climate change beyond the instrumental limits. With this backdrop, India had initiated shallow ice core studies in the coastal regions of East Antarctica in the 1990s. With the setting up of dedicated and sophisticated facilities for the storage, archival, processing and analysis of ice cores at NCAOR, the program received the much needed fillip. Since then several shallow depth (<100 m) ice cores were collected from the coastal Dronning Maud Land, leading to important research findings on the Antarctic

climate variability during the past few centuries and their global implications. The Indian initiatives are also part of the multi-national collaborative programme of International Trans Antarctic Scientific Expedition (ITASE), and IPICS (International participation in Ice Core science), the frontline scientific activity of Scientific Committee on Antarctic Research (SCAR).

The high-resolution (seasonal to annual) ice core studies conducted at NCAOR revealed the utility of ice records to reconstruct the natural environmental processes like the global volcanic eruptions, microbial life in frozen environments, as well as the polar and extra-tropical climatic tele-connections during the past hundreds of years. The sulphate profile of ~470 years record of IND 22/B4 ice core revealed sulphate anomalies related to global volcanic eruptions with major volcanic events influenced the short-term climatic conditions. Study of tephra from this core revealed presence of a plethora of microbial cells adhered to the surfaces of tephra (Laluraj et al. 2008). These tiny living entities together with the particles on which they are adhered, appears to provide a significant micro-niche in accreted ice, hitherto known. The nitrate record of the above ice core revealed synchronous changes with records of solar activity, showing relatively enhanced nitrate concentration during periods of reduced solar activity like the Dalton Minimum (~1790-1830 AD) and Maunder Minimum (~1640-1710 AD). Our study suggest that the nitrate concentrations in Antarctic ice cores appears to be influenced by production rates, processes in the atmosphere, as well as the temperature at the site of precipitation (Thamban, 2010; Laluraj et al., 2010). The oxygen isotope ($\delta^{18}O$) records the core revealed a significant warming trend of 2.7°C for the past 470 years, with an enhanced warming during the last several decades (Thamban, 2010).

In order to assess the temporal isotopic variability of ice cores as high-resolution quantitative proxy record of air temperatures, an ultra-high-resolution (>12 samples per year) ice core record was analyzed in relation to instrumental records (Naik et al., 2010 a & b). The study revealed utility of shallow ice cores in reconstructing the past changes in major climatic modes like the El Niño Southern Oscillation (ENSO) and Southern Annular mode (SAM) (Naik et al., 2010 a). A detailed study was conducted on the regional atmospheric circulation changes associated with a reversal in the sign of the relationship between the SAM and near-surface temperatures in coastal parts of East Antarctica based on instrumental data from Halley station as well as an ice core from coastal Dronning Maud Land (Marshall et al., 2009). The study revealed that the key factor affecting the regional SAM-temperature relationship is the relative magnitude of two climatological low pressure centres to the west and east of the area, which determines the source region of air masses advected into the locality.

Further detailed analysis of the $\delta^{18}O$ record of an ice core from the central Dronning Maud Land region covering a period of past one century (1905-2005) revealed significant relation to SAM, which varied in time. A significant warming of 1°C during 1905-2005 is revealed in the surface air temperature estimated using the $\delta^{18}O$ record, confirming that the coastal Dronning Maud Land region East Antarctica is probably the only region in east Antarctica showing significant warming trend of 0.1°C per decade (Naik et al., 2010 b).

Biogeochemical study of coastal Antarctic snow

In the Polar Regions, the sources of reactive halogens have been proposed to be sea-salt in surface snow, aerosols, frost flowers and photodegradable halogenated carbons of biological or anthropogenic origin. Recent studies have shown that chemically Antarctica is not very pristine as there are supply of various chemical species like the reduced sulfur species such as dimethylsulfide (DMS), oxidizing chemicals such as NOx, nitrate ions, formaldehyde, ozone and hydrogen peroxide as well as halogen-containing compounds. Therefore, snow–ice interfaces in both laboratory and the field have become a very

challenging medium for exploring new and unexpected chemistry relevant to our atmosphere. With this backdrop, NCAOR has initiated collection and analysis of spatially distributed snow samples that could provide fundamental and new information on the biogeochemical cycling in Antarctic snow as well as the influence of bacteria and other microbes in their cycling.

Glacio-chemical analysis of 55 surface snow deposits from the Ingrid Christensen Coast revealed that the sea spray contribution dominated the supply of Na^+, Cl^-, K^+ and Mg^{2+}, whereas the estimated enrichment factors suggest that crustal input was the primary source for Ca^{2+} (Thamban et al., 2010). The distribution pattern of sea spry constituents was influenced by the distance from the sea as well as the altitude. Significant shifts in $Cl^-/ssNa^+$ ratios among the inland sites suggest the existence of fractionation of Cl^- and the estimated non-sea-salt sulphate ($nssSO_4^{2-}$) in the snow samples revealed large variations with significant fractionation similar to that observed in frost flowers. Secondary sulphur species ($nssSO_4^{2-}$ and MSA) within the snow samples suggest that both vary independent of each other, possibly influenced by the local biological activities. The $nssSO_4^{2-}$ data revealed that several summer snow deposits in the study region are significantly fractionated, apparently related to the sea ice existence during the summer (Thamban et al., 2010).

Biogeochemical analysis of the above samples revealed that elevated nutrient concentrations in ice cap snow may be responsible for the observed enhanced growth of microalgae in snow with subsequent production of bromo-carbons which explains the high bromide concentration in snow. The activated bromine atoms in the Antarctic atmosphere could react with ozone leading to BrO enhancement with subsequent DMS oxidation and production of sulphur aerosols. Since BrO based DMS oxidation is much faster than OH/NO_3 pathway, elevated bromide in Antarctica could contribute more towards formation of cloud condensation nuclei (CCN) at the expense of ozone (Antony et al., 2010). This crucial finding suggests that biogenic sources of halocarbons are important because of the significant effect of halogens on ozone depletion

Microbiological studies in fresh snow deposits in coastal Antarctica revealed the crucial role of bacteria in the biogeochemical cycling in snow within the coastal Antarctica. A first report of Cellulosimicrobium cellulans bacteria were made from Antarctic snow (Antony et al., 2009). Remarkably, the C. cellulans strain from Antarctic snow demonstrated physiological traits that were markedly different from that of the mesophilic C. cellulans type strains, confirming the importance of modified physiological properties in helping it to survive in extreme cold environments (Antony et al., 2009).

Other Cryosphere related studies

In addition to the above, Indian researchers contribute to related areas of research like influence of snow is atmospheric scavenging, as well as contribution of snow melts to the hydrology of lakes and water bodies in Antarctica.

Measurements of the small-, intermediate-, and large-ion concentrations and the air–earth current density along with simultaneous measurements of the concentration and size distribution of aerosol particles in the size ranges 4.4–163 nm and 0.5–20 μm diameter are reported for a drifting snow period after the occurrence of a blizzard at a coastal station, Maitri, Antarctica (Kamra et al., 2005). Ion concentrations of all categories and the air–earth current simultaneously decrease by approximately an order of magnitude as the wind speed increases from 5 to 10 ms^{-1}. Scavenging of atmospheric ions and aerosols by the drifting snow particles contribute a great lot the size distribution in the region. The rate of decrease is the highest for large ions, lowest for small ions and in-between the two for intermediate ions. Total aerosol number concentration decreases in the 4.4–163 nm size range but increases in the 0.5–20 μm size range with wind speed. The size distribution of the nanometre particles shows a dominant maximum at ~ 30 nm diameter throughout the period of observations and the height of the

maximum decreases with wind speed. However, larger particles show a maximum at ~ 0.7 µm diameter but the height of the maximum increases with increasing wind speed.

Understanding the genesis of melt water lakes in Antarctica are intimately related to the accumulation and melt water processes. Ravindra et al., (2002) have described the genetic aspects of more than 100 such lakes that exist in the Schirmacher Oasis. These lakes have been classified as proglacial, landlocked and epiglacial lakes based on their morphological and genetic aspects. These lakes have apparently originated during the late Pleistocene related to the retreat of glaciers.

3. ARCTIC

India initiated cryospheric studies in Arctic region in 2007, by launching its first expedition to the Ny-Alesund region in Arctic. The Ny-Alesund region located within the Svalbard archipelago has several glaciers of which four major ones are - Kongsvegen, Midre Lovenbreen, Austre Broggerbreen and Vestre Broggerbreen. Considering the extensive work already carried out by the Norwegian researchers on the former three glaciers, Indian studies were concentrated on the Vestre Broggerbreen glacier, in order to understand its mass balance, nature and composition of the snow, geomorphic framework of the glacier and to assess the logistic requirements for future studies. The main organizations concentrating on the glaciological studies in the Arctic region are GSI, NCAOR and the Lucknow University. The latter have conducted preliminary geomorphological and glaciological studies in the area around Ny Alesund. (Singh et al, 2010, Singh and Rasik Ravindra, 2009 a& b, Singh and Rasik Ravindra 2010 a,b, Singh 2009.). The project entitled, "Parameterisation of Glaciers of Northern Hemisphere to variation of climate-Inter annual and Intra annual" envisages mapping the bed rock topography of the glacier and study the mass balance of this glacier to compare the data with other glaciers in the region. NCAOR will undertake a new project entitled, "Study of snow biogeochemistry in the Svalbard region" with the major objective being to study the distribution of soluble ions, trace metals and volatile halogenated organic carbons in the snow pack along with the microbial diversity to understand the snow-air exchange and biogeochemical processes influencing atmospheric composition and climate in the Svalbard region. The studies in the field of Cryobiology have recently gained impetus in India with workers such as Srinivas et al, (2009), Reddy et al (2009), Shivaji et al,(2009) publishing their work on bacterial diversity of the cold active enzymes in the glacial regions of Ny Alesund. Microbiological studies in Arctic region by Singh et al (2011) have also indicated significant antioxidant potential of Arctic lichens.

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GEODETIC AND GRAVITY STUDIES IN INDIA (2007-2010)

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1. Introduction

This article summarizes most of the activities of Indian researchers related to the themes of International Association of Geodesy (IAG) during the quadrennium 2007-2010. A number of scientific organizations and research institutions in India are involved in gravity and geodetic measurements and their analyses. Numerous efforts by these institutions contributed greatly to improve our knowledge of crustal deformation phenomena, lithospheric structure, resource exploration, tidal model and so on. In the following pages, brief description of the work is presented, which is primarily based on institution's report.

2. Geodetic networks: Reference Frame and Datum

Survey of India has taken new initiatives in the field of Geodesy and Geodynamics by Setting up of Ground Control Points(GCP) library for Realization of Horizontal Reference system, Redefinition of Indian Vertical Datum, Augmentation and expansion of Indian Tide Gauge Network and Real Time GPS Network. Expansion of GPS permanent Station network and setting up new CORS GPS Permanent station at IISM campus are some of the few initiatives which has been taken by the department .

Under the Modernization of Indian Tide Gauge/ GPS Network, Survey of India has already installed a network of Tide Gauge stations collocated with GPS receivers and real time data transmission facilities through VSAT which has been a major input for Indian Tsunami Warning System.

The GCP Project for redefinition of Horizontal Datum consists of Primary control points at spacing of approximately 250 to 300 km. In all, 292 such precise control points have been established, observed and computations completed during the period under report. These first order control points have been monumented and protected with fencing.

In the Redefinition of Indian Vertical Datum project, High Precision Levelling forming a framework covering 45,775 linear km in fore and Back direction has already been completed along with Gravity observations on the established bench marks along levelling lines by SOI. In all eleven Levelling circuits comprising of twenty nine Levelling lines with nineteen junction points have been adjusted using the least square techniques.
A Permanent GPS station with Real Time Data Transmission facilities has been established in Indian Institute of Surveying and Mapping, Survey of India Uppal Hyderabad. Continuous GPS observations at National Geophysical Research Institute (NGRI), Hyderabad, Indian Institute of Sciences (IISc) Bangalore and Maitri, Indian Antarctic Station serve important data sets to IGS and IERS for realising ITRF reference frame. The GPS PS at IISM being on high quality Sheet Rock can also provide major inputs towards the realization of reference frame.

3. Modernisation of Indian Tide Gauge Network

A great deal of effort has been made for the extension and modernisation of Tide Gauge Network. Aftermath great earthquake of Sumatra and subsequent tsunami on 26th December, 2004, SOI has initiated the project

entitled "Modernization and expansion of Tide Gauge Network along Indian coast and its Islands". Presently 26 state-of-the-art digital tide gauges co-located with the dual frequency GPS receivers at strategic locations all along the Indian Coastline and its Islands are established. Tidal and GPS data recorded at remote locations is being transmitted in real time to the centrally located hub station at National Tidal Data Centre / National GPS Data Centre, Geodetic & Research Branch, SOI, Dehradun through a dedicated VSAT network.
In SOI Real Time GPS Network at present, fourteen stations have been configured and a ***GPS Geodetic Network*** *has been successfully established to monitor base line variations for crustal deformation and other associated studies. The present network consists of three stations in Andaman & Nicobar Islands, two station in Lakshadweep Islands and other ten well distributed stations along the east and west coast of India. Apart from this, data from a network of 42 permanent GPS stations across the country is also being received and archived. The Real Time GPS Data Centre at Faculty of Geodesy, IISM, Hyderabad is well equipped with Real Time Data Processing Software such Trimble Integrity Manager and GPS Net and Post processing software such as Bernese 5.0 & GAMIT.*

Survey of India has taken up the first step towards disaster management and mitigation by planning to link 21 Geospatial Data Centers (GDC's) through dedicated VSAT intranet network. Under this network, it has been envisaged to exchange high volume of digital topographical data between GDC's to the central station located at the National Geospatial Data Centre (NGDC) located at Dehradun.

4. Precision Project Surveys for some select sites

SOI has carried out the precision geodetic surveys for ascertaining dam deformation, verticality of the minarets of historical monuments, tunnel alignment surveys and in the various parts of country as mentioned below.

- *Dam Deformation Studies were carried for Rihand Dam, for Jamrani Dam and SriSailam Dam Projects.*
- *Precision survey for ascertaining the Verticality of the minarets of Qutub Minar and Taj Mahal.*
- *Tunnel alignment surveys and checking of alignment was carried out for developmental projects, namely, Kol Dam, Loharinag Pala HE Project and Tapovan Vishnugad HE Project.*

5. Geodetic Observations for Earthquake Studies

Several national research institutes (e.g. IIG, NGRI, SOI, WIHG, IIG) have established GPS stations for monitoring crustal deformation in plate boundary regions like Himalaya and Andaman. These measurements enrich our knowledge of earthquakes processes. For example, post Sumatra earthquake monitoring shows deformation of 10-40 cm that allowed to provide recurrence time of M>9 earthquake in the Sumatra –Andaman region. GPS measurements in Andaman also indicated that the transient stresses generated by viscoelastic relaxation process in the lower crust through upper mantle are capable of rupturing major faults. Based on far and near field GPS offsets, this work reveals that substantial segmentation of slip occurred along the Andaman Islands with the southern quarter slipping ~ 15 m in unison with the adjacent Nicobar and Northern Sumatra segments of length ~ 700 km. Following the 2005 Kashmir earthquake, the GPS velocity at GUMR (southeast of the rupture zone) is 8.6 cm/year, which is significantly higher than the Indian plate velocity indicating near-field shallow postseismic crustal deformation
In peninsular India, GPS and gravity measurements are being made in Koyna region, known of triggered seismicity in campaign mode. Significant seasonal gravity changes are observed, that are also corroborated with GPS data. These seasonal

changes observed in gravity and GPS data have important implication on effect of loading of reservoir and in turn earthquake processes in the region. The relatively rapid decay of GPS-measured deformation rates in the 2001 Mw 7.6 Bhuj intraplate earthquake region of NW India indicates increasing effective viscosities from 3 x 10^{18} Pa s in the first 6 months to 2 x 10^{19} Pa s of the mantle during the 6-year observation period, consistent with a time and stress-dependent rheology, such as power-law flow by dislocation creep.

6. SG and AG Gravity Observations

Two Superconducting Gravimeters (SG) are set up as a part of multi parametric geophysical observatories. One is being operated at Guttu, in Himalayan region by Wadia Institute of Himalyan Geology (WIHG), Dehradun and other is set up in Kutchch by Institute of Seismological Research Gandhinagar. These SGs are recording Earth's gravity field with 0.1 µGal accuracy continuously. A series of absolute gravity measurements using FG5 Absolute Gravity meter (AG) have been made at NGRI, Hyderabad to monitor long-term gravity changes and a network of absolute gravity stations cutting across India is established and monitored periodically.

7. Gravity Survey for Resource exploration

National intuitions, Geological Survey of India (GSI), ONGC, OIL, NGRI and other exploration companies are mainly engaged in gravity surveys for exploration of natural resources. Some of the target areas are Ganga basin, Brahmaputra valley, NW India and central India. A few of them are mentioned below.
Gravity survey is carried out in the Sandur schist belt, south India for iron ore exploration. Gravity studies are undertaken in the Narayanpet kimberlite field. More than 5000 of gravity measurements are made in the eastern part of the Deccan syneclise covered with a grid spacing of ~4 Sq. kms. Modelling of gravity anomalies provided a 3D basement configuration of the eastern part of Ganga Basin, Three dimensional modeling of the gravity anomalies was carried out to delineate the basement undulations Sadiya Block, Upper Assam. Delineation of old underground coal mines and study of migration front before and after sand stowing was suggested from gravity studies.

8. Gravity Studies for Geodynamics

The wavelet analysis of bathymetry of western offshore covering western Basin, Laxmi ridge, Laxmi Basin, Panikkar Ridge, continental slope and continental shelf, indicates the nature of crust of Laxmi Basin as continental. Gravity data across NW Himalaya have been modelled and interpreted to delineate the major tectonic boundaries using wavelet transform and other spectral methods. Gravity and geoid measurements across the arc in the NW – Himalaya show a long wavelength flexure in the crustal level. This also shows a mid-crustal lateral in-homogeneity along the arc as confirmed by the GPS measurements. Computation of gravity-gradiometry tensors have been completed from a regional density model across the Western Continental Margin of India along with parts of the Alps and the Andes. To delineate lithospheric structure, about 4500 gravity measurements were carried at an interval of 3 to 5 km in a corridor on either side of the geotransect from Palani to Kayanakumari. Analysis of gravity anomalies supports the idea that the Achankovil Shear Zone is an intra-cratonic litho-tectonic feature and the two provinces across it are related by a continual progression in single metamorphic terrain rather than an ancient geo-suture. The gravity gradient image is derived from the bouguer anomaly map prepared from newly collected observations combined with earlier gravity data. The horizontal gravity gradient map of the area south of 14^0N reveals a continental mosaic of gravity trends akin to structural domains such as the Eastern Dharwar Craton, the Eastern Ghats Mobile Belt, the extended Eastern Ghats Mobile Belt, the Southern Granulite Terrain, and the Western Dharwar Craton

9. Tools and Application Development

A method for optimal designing of 2-D gravity survey network is proposed and used in the gravity studies over Jabera-Damoh region of

the Vindhyan Basin, which is considered as a potential hydrocarbon bearing area. A scheme using L_p norm modified Voronoi tessellation is developed that circumvent the need of several polygons to construct the causative bodies in modeling of gravity anomalies. Inversion techniques and computer programs are developed for the calculation of listric fault structure with variable density. A computer program is developed to compute regional and residual anomalies from gravity data by implementing the finite elements method. MATLAB codes are written to compute Gravity Gradient Tensors (GGT) due to arbitrary shaped bodies and also to derive GGT from gravity data.

10. Local Gravimetric Geoid

Precise information of geoid undulation is vital for determining orthometric height using GPS and understanding the subsurface mass distribution of the earth. There are global gravity models that allow determining geoidal undulations; however, the global models are constrained by spatial resolutions. Thus determination of geoid heights over local area is obtained through the GPS- leveling observations or calculated from terrestrial gravity values. Gravimetric geoid using spherical FFT is computed in two regions of India; one over South India region, where a large geoidal depression exists and other in northern Indian region. Computed gravimetric geoid is compare with global model and with geoid determined from GPS-leveling data.

11. **Satellite Gravimetry and Its Application**

Satellite altimeter-derived geoid/gravity maps of adjoining ocean of India are prepared. Satellite altimetry derived gravity data are extensively used for exploration studies and lithospheric models over aseismic ridges in the Indian Ocean. These studies include: geoidal decay vs. crustal age analysis over the $85^{o}E$ and Ninetyeast ridge, isostatic mechanism over Chagos Laccdive Ridge, studies of rifted margins and so on. A composite high resolution satellite gravity image has been generated covering part of Antarctica to the western Indian offshore to analyze its tectonic implications. Study of the morphological characteristics patterns and their correlation to different spreading rates over the Carlsberg ridge has been carried out. A 3D lithospheric density model of the southern part of the Andaman-Sumatra subduction zone is build from joint modeling of satellite derived gravity and geoid data. The extent of subduction and depth increases from the north to the south with reference to the trench. Southward from $10^{0}N$ the presence of Ninety East Ridge is reflected in the flattening of the anomaly curve on the subducting plate.

The Gravity Recovery and Climate Experiment (GRACE) satellite data are analyzed for hydrological changes. Using eight years of GRACE data total water storage variability over India is computed. Temporal changes in the earth's gravity field as recorded by GRACE Satellite Mission reveals large scale mass loss that is attributed to excessive extraction of groundwater. Besides, hydrological applications, GRACE data are also used to understand co-seimic deformation due to large mega-thrust earthquakes in the subduction zones.

12. Mapping of Sea Bottom Topography

Detailed bathymetry modelling has been carried out over a part of the western offshore including Bombay High with high resolution gravity data. Comparison of satellite-derived predicted and available in-situ bathymetry for three profiles over Bombay High region shows satisfactory results.

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Indian contributions in the research areas of International Association of Geomagnetism and Aeronomy (IAGA-IUGG) January 2007 – December 2010

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Research carried out by Indian scientists in the field of Geomagnetism and Aeronomy during the period 2007-2010 dealt with a wide range of topics related to the areas covered by the five divisions of the International Association of Geomagnetism and Aeronomy (IAGA) extending from internal magnetic fields to solar wind and interplanetary magnetic field. This report is largely based on information provided by a subset of the nearly 30 centres in India, which are engaged in research in these areas.

1. Internal Magnetic Fields

1.1 Theory of planetary magnetic fields

The heat required for driving thermal convection in the liquid part of planetary cores, which is considered as the main source for the generation of magnetic field through a dynamo process, comes mainly from secular cooling, latent heat release upon solidification of iron alloy, and possibly from radiogenic heat sources. For terrestrial planets that have a growing solid inner core, such as the Earth, release of lighter elements at the inner core boundary also contributes to convection through compositional buoyancy force. Difference in thermal and compositional diffusivities may lead to double-diffusive effects, which have been studied for the planet Mercury using a double diffusive dynamo model. Significant changes in the resulting magnetic field have been found in double-diffusive models. Influence of thermal and compositional driving sources on double diffusive convection for a large Ekman number of 10^{-3} and moderate Rayleigh numbers has also been studied.

1.2 Electromagnetic induction and electrical conductivity

Electrical and electromagnetic methods have been found to be useful in delineating sedimentary horizons with potential for hydrocarbon that are located below flood basalt provinces, because of the good electrical conductivity contrast between basalts and underlying sediments. A joint inversion scheme incorporating seismic reflection and refraction, magnetotelluric (MT), and deep electrical resistivity datasets has been developed. Efficacy of the scheme was tested for a model comprising a thin sedimentary layer sandwiched between a thick basalt cover and a granitic basement and joint inversion incorporating all the datasets was found to yield good estimates of the structure.

High Voltage Direct Current (HVDC) power transmission systems require setting up of specially designed ground electrodes at terminal ends of the transmission line to close the circuit with an earth return path. The design parameters of these electrodes need the information about the electrical conductivity structure within a radius and depth of several km of the site in order to ensure that the injected current penetrates deep enough into the earth. MT and electrical resistivity tomography (ERT) tools have been employed to investigate the detailed deep and shallow electrical conductivity structure, respectively, of several potential sites in India. This information has been useful for the electrode design and the selection of ground electrode sites.

MT and Geomagnetic Depth Sounding (GDS) techniques were used to study the sub-surface electrical conductivity structures in different

parts of India. Electrical imaging from the northern part of Lakshadweep Islands using GDS and Long period MT data has delineated a mid-crustal conductivity anomaly, which suggests rheological stratification. MT surveys carried out over the Shillong plateau and lower Brahmaputra valley in North east India have delineated the Dauki fault as a NE–SW striking low angle thrust. The results suggest that a large fraction of the seismicity over the Shillong plateau is associated with the Dauki thrust, contrary to the earlier belief that this fault zone is relatively aseismic. Another significant observation in the eastern syntaxial region is the delineation of the Mishmi thrust as a high angle thrust. These results when viewed together with the observations of the global positioning system (GPS) studies suggest strong shearing of the Indian lithosphere in the NE Indian region. MT studies also delineated a deep seated EW striking thrust south of Jhansi over the Bundelkhand craton, which was earlier known to be a featureless granitic land mass.

An integrated study using vertical resistivity sounding (VES) and ground magnetic data has been carried out in Dhule region of Maharashtra to understand the aquifer system and the movement of ground water flow in the Panjhara watershed. The study indicates the presence of carrier and barrier stretches along the dykes. VES in the coastal area of Konkan in Kudal-Malvan region, western Maharashtra indicated extensive influence of saline water intrusion.

A new technique based on the Bayesian neural network (BNN) theory using the concept of Hybrid Monte Carlo (HMC)/ Markov Chain Monte Carlo (MCMC) simulation scheme is developed to interpret 1D and 2D Direct Current (DC) inversion of VES data collected over the Koyna region. The HMC-based BNN approach is fast and turns out to be a promising inversion tool to solve non-linear resistivity problem and the results are useful for interpreting the fracture and lineament in seismically active regions.

Geophysical field studies have been conducted for hydrocarbon exploration in Eastern part of the Deccan Syneclise, Central India, covering an area of 40,000 sq. kms with 350 magnetotelluric (MT) sites, 50 deep resisitivity soundings, 7600 gravity sites and 600 line kms of seismics. The results clearly show the possible thick (2 km) sub-trappean sediments, EW oriented, sub-basin in the central and western part of the area, bounded by Tapti lineament in the south and Khandwa lineament in the north which might be responsible for the formation of Mesozoic basin. The results have provided information on the complex variation of Deccan traps, the volcanic plugs etc. Details of configuration of trap/sediment interface, sediment/basement interface provide clues to understand the region from the view point of hydrocarbon potential.

Detection of buried sedimentary basins below the trap cover in northwestern part of the Saurashtra region and large thickness of buried sediments in southern part of the Kutch region, led to plans to initiate marine investigations in the Gulf of Kutch region located between the Saurashtra region towards south and the Kutch region towards north. For this purpose, marine MT was applied on an 'experimental basis' in collaboration with SIO, San Diego. The National Institute of Oceanography (NIO), Goa, has undertaken marine seismic studies in the region. The data were acquired along selected profiles oriented in near E-W direction and also along NW-SE direction. The Tertiary sediment thickness was found from integration of marine seismics and marine MT data,

Successful identification of deeper anomalous conductive feature related to geothermal sources in Tatapani in Chattisgarh and Puga in Jammu and Kashmir, using the MT technique, has paved the way to search for more geothermal regions in India. In this direction, Wide band MT study has been taken up covering both AMT and MT frequency range in four different regions. The results have brought out anomalous conductive features, both near the hot springs as well as away from them. Based on the geological and tectonic set up, the magnitude of conductivity, its spatial variation etc., the nature of the geothermal source is inferred.

Resourcesat-1 (IRS-P6) LISS-III satellite images covering an area of approximately 302,500 sq. km in Central India was digitally processed and interpreted to present a schematic map of the

geology and to elucidate the structural fabric of the region, in order to supplement the information obtained from seismic, MT, deep resistivity and gravity surveys. In the present study, the remote sensing data of four different bands were analysed. New features indicated from Remote Sensing (RS) image analysis were verified by ground checks. The lineaments, dykes indicated from the RS analysis are correlated with major trends of the subsurface features.

Multi-parametric geophysical measurements have been initiated near Koyna epicentral zone, Maharashtra, to search for earthquake precursors. As a part of this experiment, continuous monitoring of MT signals: two electric and three magnetic components in a frequency band of 900 Hz – 0.00033 Hz – have been initiated at two locations on either side of the Koyna fault. From preliminary spectral analysis, and estimation of impedance, apparent resistivity, and phase parameters no perceptible variation has been observed which can be claimed as a distinct precursory phenomena related to earthquakes with a magnitude M>4 and <5. However, distinct variation is observed at the time of origin of the earthquakes, which can be considered as co-seismic activity

1.3 Palaeomagnetic and Rock Magnetic studies

A state-of-the-art paleomagnetic and rock magnetic laboratory has been established at the regional center of the Indian Institute of Geomagnetism (IIG) at Allahabad with the installation of SQUID magnetometer, Vibrating Sample Magnetometer, MFK-1 Kappa bridge, thermal demagnetizer, magnetic separator, triangular polarizing microscope, and petro-thin re-sectioning and grinding machine to determine paleomagnetic and rock magnetic characteristics of rocks. Magnetic fabric and palaeomagnetic studies on the Pune region Deccan flows reveal that the source for the flows belonging to the Bushe Formation could lie west of Pune, while that for the Poladpur Formation could lie in the NNW direction. Pole positions estimated from the oriented samples of the Kachchh rift basin fall close to that of the Deccan Super Pole and are concordant with the poles reported from the Deccan Province suggesting that the flows and intrusives of the Kachchh region are related to Deccan volcanism. Ages of the basic intrusives of Chopan region in southern Uttar Pradesh, which traverse the Archean granitoid and early Proterozoic meta-sedimentary rocks of Sonbhadra district, were assigned to the Palaeo-Proterozoic. Recent Ar/Ar dates (plagioclase mineral) for two sites of the studied region are found to be 2073±2 Ma constraining the present study VGP as well as the Newer dolerite dykes VGP.

Palaeomagnetism Laboratory of the National Geophysical Research Institute (NGRI) has carried out investigations on the Dyke Swarms of Dharwar Craton to find out the India position and the Apparent/True Polar Wander Path for India during PaleoProterozoic period. Studies have been conducted on kimberlites from eastern Dharwar Craton to find out the position of Indian subcontinent during Rodinia. Investigations are going on in the areas of Cauvery and Kachchh Basins on Magnetostratigraphy to give the age assignments and also to fill the gap in the Palaeomagnetism data set between Rajmahal and Deccan Traps and to place the Indian subcontinent in this gap to find out the position during this period and also to correlate the Magnetostratigraphy of Kachchh sediments with the well established European Mesozoic Geomagnetic Polarity Time Scale.

The anisotropy of magnetic susceptibility (AMS) technique has been used on samples from the Lonar crater to evaluate the direction and obliquity of meteorite impact on this crater. Mineral magnetic properties like concentration and magnetic grain sizes were used to study seasonal sediment movement along the beaches. Measurements of mineral magnetic properties have been used to identify pollution hotspots in Mumbai and Navi Mumbai. Environmental magnetic studies are being carried out in Himalayas for long term climate reconstruction and monsoon studies. Archaeomagnetic studies are also being carried out where palaeointensity field values using archaeological artifacts from different parts of India are determined.

2. Aeronomic Phrnomena

2.1 Middle atmospheric processes

Lidar measurements of middle atmosphere provided an evidence for the presence of interaction between planetary wave and stratospheric circulation during the sudden stratospheric warming events. Anomalous relationship between the observed sodium airglow intensities and sodium concentrations, observed in the low latitude mesosphere during coordinated campaigns conducted with an airglow photometer and sodium Lidar, is explained by the effects due to collisional quenching of the excited states that give rise to sodium airglow. Further, investigation with a similar set of observations brings out the importance of altitude dependence of the collisional quenching in the determination of sodium airglow emission.

Balloon-borne measurements of ultraviolet dayglow emissions carried out on 8 March 2010 revealed mesospheric gravity wave related fluctuations whose amplitudes were larger towards equator as compared to the other regions. Rocket-borne measurements of electron density were conducted from Sriharikota to study the fine structure of low-latitude mesospheric neutral turbulence. Spectra of electron density fluctuations were obtained using the continuous wavelet transform and the turbulence parameters were estimated. The study shows that turbulence is not present continuously in the mesosphere but exists in layers of different thicknesses varying from 100 m to 3 km, interspersed by regions of stability.

A physics based model, which determines the air mass, solar zenith and sunlight intensity as a function of latitude, longitude, and local time of the balloon position has been devised to minimize the impact of solar radiation effects on an indigenously developed balloon- borne GPS-aided Radiosonde, for estimating temperature, pressure, humidity, and wind vectors in the height range of 1 km to 45 km.

2.2 Atmospheric tides and waves

Studies using the MF radars at the equatorial station Tirunelveli and off-equatorial station Kolhapur were carried out to understand latitudinal structure of atmospheric tides. Radar wind observations from widely spaced stations in Japan, Australia, UK and Brazil revealed (i) significant longitudinal variation of intraseasonal oscillations (ii) significant longitudinal differences in interannual and seasonal variations in tidal characteristics. The monthly tidal amplitudes from radar observations at Tirunelveli revealed a pronounced signature of quasi-biennial oscillation and a long-term trend in the annual cycle of the meridional component of winds in the mesosphere-lower thermosphere (MLT) region.

2.3 Equatorial electrojet (EEJ)

Day-to-day variability of the average daytime mesopause temperature and wind has been studied in conjunction with the duration of the EEJ (DEEJ) and the time of EEJ maximum (TEEJ) in the noon hours. Planetary waves are found to maximize in amplitude during January-March months and to modulate the mesopause temperature, zonal wind, duration and peak of EEJ nearly simultaneously. Correlations between the Integrated EEJ strength and the equatorial ionization anomaly (EIA) parameters like the total electron content (TEC) at the crest, location of crest, and EIA Strength for the Indian sector have been investigated using measurements from six GPS TEC receiver stations along the 77º E meridian, and EEJ strength from the magnetometer data from Tirunelveli and Alibag. The time delay corresponding to maximum correlation has been identified as the response time of the equatorial ionosphere. The analysis has been done for March (vernal equinox) and July (summer) of solar minimum year 2006. The response time has been found to vary with season typically from 100 to 160 minutes.

Scope of the Coherent Radio Beacon Experiment (CRABEX), initiated with the aim of

studying large-scale upper atmospheric processes over equatorial and low-latitude regions, is being enlarged through radio beacon payload RaBIT for 'YOUTHSAT' whose signals would be recorded by the CRABEX meridional chain of receivers. RaBIT payload antenna has been integrated with the satellite.

2.4 Sudden Stratospheric Warming effects on the equatorial ionosphere

The low latitude manifestations of the Sudden Stratospheric Warming (SSW), a high latitude wintertime phenomenon, have been delineated in a series of studies. Tidal and planetary wave signatures delineated in ground magnetic field variations, showed that the vertical coupling between the MLT region and ionosphere through upward propagating planetary waves was operative only during some of the wave episodes. Linkages between the semi-diurnal tide, SSW and the counter electrojet were established. Studies of MF radar echo characteristics under various electrodynamical conditions depicted some observations peculiar to the equatorial region.

In an investigation of the variations of daytime equatorial mesopause temperature (EMT) during polar SSW events over high latitudes, amplified wave signatures of quasi-16 day period were seen both in the EMT and zonal mean polar stratospheric temperature (at 10 hPa). It was found that the counter Electrojet (CEJ) occurrence showed a periodicity of ~16 days during the SSW period. A study based on the NCEP-NCAR reanalysis of stratospheric wind and temperatures showed that (i) a dynamical feature similar to the zero-wind line appeared over the tropics ~ 60 days prior to the major warming and progressed poleward and (ii) enhanced planetary wave activity was seen almost simultaneously. It was found that the stratospheric temperature at ~30 km over Trivandrum showed a sudden cooling prior to the SSW and the first event of CEJs occurred around this time. The equatorial ionosphere-thermosphere system underwent a change in response to SSW, manifested through (1) strengthening of the EEJ intensity in the pre-noon hours, followed by the occurrence of strong afternoon CEJ (2) decrease in the morning foF2 values and its subsequent enhancement during the evening time (3) large excursion of the h'F between 1800-1900 LT followed by a decrease between 2100-2230 LT, (4) unusual decrease in the overall 630 nm dayglow emission intensity with pronounced noon-time bite outs and (5) abnormal decrease in TEC between 1600-1900 LT sector. The above mentioned changes are not seen during non SSW period. These results are interpreted in terms of non linear interaction of semi-diurnal tides with planetary waves which are globally strengthened during the SSW periods.

2.5 Airglow studies

Investigations on the daytime OI 630.0 nm airglow emission brightness from a low latitude station indicate that waves with periodicities of 12–20 min, and 2 h exist over a wide spatial range of around 8°–12° magnetic latitudes. It is shown that wave periodicities due to neutral dynamics are influenced by those that affect the EEJ strength variation as well up to ~ 8^{o} magnetic latitude. Furthermore, the investigation also indicates a strong solar influence on the magnitudes of dayglow emissions.

Low-latitude optical signatures of a magnetic storm have been investigated using the all-sky imaging observations made at Panhala near Kolhapur. Transient, narrow, streaks seen in 557.7 nm OI green line emission have been attributed to particle precipitation driven by ring current injection during the magnetic storm. Propagation characteristics of atmospheric gravity waves derived from the OH airglow image data from Allahabad during January to May 2008 show that north-eastward motions were distinctly dominant in April and May. A model was used to compute the velocity of the neutral wind, which blocks the propagation of gravitational waves. An all-sky airglow imager deployed at Tirunelveli in January 2007 to monitor small-scale gravity wave motions at heights of ~90 km revealed a rich variety of small-scale wave motions like bands, walls, bores and ripples. These observations were interpreted in terms of the passage of quasi-monochromatic gravity waves, presence of thermal ducts providing channels for the passage of bore-like disturbance, and

convective instabilities feeding energy to small-scale ripples.

A photometric system based on a grating spectrometer developed at the Space Physics Laboratory (SPL), has been used for systematic measurement of the temporal variations of daytime Na airglow emission intensity at 589.6 nm. A multi-wavelength photometer has been developed in-house for monitoring airglow emissions of different wavelengths originating from various layers of upper atmosphere during nighttime to supplement the ongoing daytime measurements. The flight model of the 'Limb Viewing Hyper Spectral Imager (LiVHySI)' , which can make simultaneous measurements of the intensity of many airglow emissions at different wavelengths, emanating within 90-600 km altitude in the limb of the earth, has been tested and calibrated for being flown on ISRO's satellite mission 'YOUTHSAT' in 2011.

2.6 GPS studies of the *t*otal electron content

The day-to-day variabilities in the columnar total electron content (TEC) derived from GPS observations, and the equatorial electrojet (EEJ) strength during January to March 2006, suggest that 16-day oscillations are present in both data. Further these waves are dominant in the TEC obtained in the equatorial ionization anomaly region. The observed 16-day period in the TEC is attributed to changes in the equatorial electric field strength due to variations in the atmospheric tides from below.

Using the measurements of total electron content (TEC) of the ionosphere at 18 stations across the length and breadth of India, covering the crest and trough of the Equatorial Ionization Anomaly under GAGAN (GPS Aided Geo Augmented Navigation), a model has been devised which would successfully predict the TEC between 8-30^{o} latitude and 60-100^{0} longitude zone. In this model, observations at 77^{0} longitude are considered as reference and the solar zenith/ neutral wind control are applied to estimate changes in TEC at different longitude sectors from that at 77^{0} longitude utilizing a first principle based Parametric Ionospheric Model (PIM). The model has now been modified to include the variabilities in Kp and F10.7 cm flux to represent the impact of geomagnetic storms at low latitudes. A case study for the severe geomagnetic storm of August 24, 2005 (Dst -158 nT; Kp ~ 9), revealed that ISRO-TEC model successfully predicted temporal variations in TEC even at longitudes far away from the reference longitude at 77^{0}. The model is now being used to generate super-truth data for GAGAN certification process.

2.7 Equatorial ionospheric irregularities

Simultaneous measurements of TEC, double derivate TEC index (DROTI), L- band scintillations, ionosonde measurements and radar maps are used to study dynamics of the equatorial ionospheric plasma bubbles. When the irregularities reach higher altitudes as seen in the radar map during pre-midnight periods, strong scintillations on an L-band signal are observed at higher latitudes. During magnetically quiet periods, plume type radar echoes are recorded during post-midnight period that is devoid of L-band scintillations. Effect of magnetic activity on equatorial F region plasma drifts in the Indian longitude region is studied using spaced receiver scintillations on 251 MHz signal recorded at Tirunelveli for the period of 1996-2006.

Coordinated observations using a narrow spectral band (0.3 nm) airglow photometer with a narrow field-of-view (3^{o}) along with a VHF radar opened up new vistas to characterize different plasma structures associated with Equatorial Spread F (ESF). Plasma enhancement structures in buoyancy-dominated altitude region, as predicted by earlier numerical simulation investigation, were identified based on simultaneous VHF radar and airglow observations. A few other varieties of plasma structures that include confined structure in a limited altitude region and fossil plasma bubbles that became active at a later time had been observed.

Observational evidence from the Indian longitudes, for the presence of gravity wave like perturbations with periods of 20-30 minutes, acting as probable seeds for Equatorial Spread F (ESF) irregularities has been obtained based

on the daytime optical measurements of the mesopause temperature and the intensity of the thermospheric O (^{1}D) 630.0 nm dayglow emissions using the unique Multi Wavelength Dayglow PhotoMeter from Trivandrum. It has been shown that under 'identical' background ionospheric conditions within a solar epoch, the power of the gravity waves have a deterministic role in the generation of ESF. The mesopause temperature simultaneously observed, indicated that possible source regions for these perturbations lie in the lower atmosphere. Another important aspect of the ESF namely, its persistence characteristics has been studied during different seasons and geomagnetic activity levels under maximum (2001) and minimum (2006) solar activity conditions over the magnetic equatorial location of Trivandrum. Analysis of ionograms recorded at this location during both the years showed that one could make a first order estimate of the duration of ESF by knowing the magnitude of the F region vertical drift velocity (Vz), associated with the evening time pre-reversal enhancement of the F region zonal electric field, and the magnetic activity index Ap for that particular day.

The equinoctial asymmetry in the occurrence of ESF has been examined using ionosonde data at Trivandrum and SHAR for the year 2004. There is a higher percentage occurrence of ESF during vernal equinox compared to autumnal equinox. The mean post sunset vertical drift at TRV is nearly comparable for the two seasons. The vertical drift at SHAR is seen to be much lower than that at TRV during autumnal equinox. It is seen that significantly larger poleward wind is present during autumnal equinox compared to vernal equinox in the post sunset period prior to the triggering of ESF. This study indicates the important role of the neutral dynamics even during equinoctial periods in effecting the seasonal pattern of ESF.

Dependence of L band scintillations in the EIA region on a parameter that represents the strength and asymmetry of EIA, derived from latitude profile of CRABEX-TEC data at Trivandrum, has been examined using the GPS scintillation data from four stations along the 77º E longitude belt in the EIA region and CRABEX data from Trivandrum. This study has indicated that there is a threshold level of this parameter above which L band scintillations occur. Range-spread due to ESF at the magnetic equator, as inferred from ionograms, have been examined in relation to the duration and strength of L band scintillations in the EIA region for equinoctial months during 2004-2006. Ionosonde data from Trivandrum and GPS data from four stations covering the EIA region have been used for the study. The results show that the maximum scintillation index in the EIA region is linearly dependent on the spread of ESF traces for both the equinoxes. The corresponding duration of L band scintillations is also found to be linearly dependent on the duration of ESF at the magnetic equator.

Quasi-periodic (QP) echoes, identified in range-time-intensity (RTI) plots as tilted striped striations, are coherent radar echoes believed to be associated with the sporadic E-layers (Es). These echoes are associated either with Kelvin-Helmholtz Instabilities (KHI) or with gravity waves. These processes, however, have always been treated in isolation and been assumed to be unconnected to each other. Evidence is presented towards the interplay between KHI and gravity waves in generating QP echoes using VHF radar data from Gadanki, with gravity waves acting as seed to generate KHI resulting in QP echoes as seen by the coherent backscatter radars.

2.8 Space weather impacts on low latitude ionosphere-thermosphere system

An investigation involving nonlinear numerical simulation revealed that the storm-induced eastward electric field during nighttime over equatorial region is a necessary but not a sufficient condition for the development of the pre-midnight plume structure in the lower F-region altitude. The importance of the pre-seeded structure developed during post-sunset hours is realized for the evolution of pre-midnight plume event. This, in turn, can throw light on the night-to-night variability of storm-time ESF. Distinctive effects of interplanetary electric field (IEF) and substorm on equatorial zonal electric field have been identified. It is shown that while the fast fluctuations (~ 40-45 minutes) in the vertical drift are governed by IEF

during a storm that encompassed multiple substorms, the slowly varying component of ionospheric height variations corroborate with the slowly varying component of the variation in the auroral electrojet index, AE. A striking event that shows a prompt effect of an X class solar flare (X6.2/3B) in the neutral optical dayglow emissions is investigated in detail. As a response to this flare, the daytime redline (OI 630 nm) column integrated emission intensity measured from low latitudes showed a prompt increase of around 50%. This prompt enhancement in the thermospheric dayglow seems to be caused mainly due to an increase in photoelectrons due to a sudden increase in the solar EUV flux associated with this flare. Imprint of eastward electric field disturbance corresponding to the onset of the expansion phase of a magnetospheric substorm on OI 630.0 nm dayglow emission intensity recorded from low latitudes is brought out based on a number of space-borne and ground-based measurements. Enhancements in 630.0 nm dayglow intensity over low latitudes are attributed to the possible supply of O_2^+ ions by the eastward electric field induced by the onset of substorm, highlighting the complexities in the magnetosphere-ionosphere-thermosphere system.

The National Atmospheric Research Laboratory (NARL) hosts a number of state-of-the-art instruments to study the atmosphere and the near-earth space environment. At present a 53 MHz high power radar, lidar, ionosonde, GPS receivers, and airglow instruments are used to study space weather. Upgradation of the 53 MHz radar with capability of studying the ionosphere-thermosphere system using the incoherent scatter technique and the development of a 30 MHz coherent scatter radar are in progress. NARL is also actively engaged in studying Space Weather using a network of GPS receivers under the GAGAN system. In the recent past, a major initiative has been taken at NARL to study Space Weather under the aegis of 'Studies on Atmospheric Forcing and Responses (SAFAR)'. As part of the CAWSES program to study space weather, NARL has carried out major campaigns in collaboration with the international working groups to study the ionospheric variabilities owing to the varying solar activity including disturbed periods and the lower atmospheric forcing through neutral dynamical/electrodynamical coupling. Also gravity wave forcing of the E region and the consequent coupling effects on the equatorial F region pre-reversal zonal electric field and equatorial plasma bubble evolution have been studied. A close relation between the wave forcing and the post-sunset F region electric field/ plasma bubble development has been noted. NARL has carried out a campaign to study in detail the variability in the electric field in the Indian and Indonesian sectors in an effort to study the non-migrating tidal effects. A couple of space weather events also have been studied in detail to understand the magnetosphere-ionosphere and high latitude-low latitude coupling.

Ionosonde observations on 05 October 2000 revealed the presence of an additional F layer (F3) close to dawn. The layer rapidly drifted upward and reached beyond the range of the ionosonde (800 km) by 07:15 IST. The F3 layer reoccurred in the evening around 1600 IST at an altitude of ~550 km. This event was investigated in detail using SUPIM model incorporating the observed electrodynamic drifts from ionosonde and HWM for winds. The analysis revealed that the unusual F3 layers observed at Trivandrum at dawn and dusk during geomagnetic storms are associated with southward turning of IMF Bz, suggesting that the layers could be caused mainly by strong prompt penetration eastward electric field (PPEF).

The responses of the E and F regions of the ionosphere are investigated during different solar flares using GPS TEC data, ionosonde data and magnetometer data. The study shows that the signatures of flares in the magnetic field over the magnetic equator generally reveal an enhancement during strong X class flares. However during some flare events it produces a reverse signature in the magnetic field especially during times of weak electrojet/counterelectrojet. The latter was observed for the great solar flare of October 28, 2003 during the time ~ 1115 UT when the electrojet was relatively weak. These magnetic field changes as measured over Trivandrum are found to corroborate well with the UV flux

variations during flares as obtained from GOES satellites. The study points towards a local time dependent response of the equatorial E-(dynamo) region to the flares. Further, owing to the dependence of the ionization density on the incoming solar EUV/UV flux, the F region response is also found to correspond well with the variations of satellite measured UV flux variations. It has been found that, for solar flare events in the northern summer season, the maximum enhancement is seen at the low latitude regions, not over the magnetic equator. However, the latitudinal pattern of TEC enhancements in winter reveals maximum increase at the magnetic equator. Of all the flare events examined, the most dramatic F region enhancement over Indian longitude sector has been observed to be of ~ 10 TECU on 28 October 2003, while for the rest the increase is found to be below 2 TECU.

2.9 Solar eclipse studies

The VHF radar at Gadanki was used to study the solar eclipse event of 11 August 1999 wherein progressive splitting in radar backscattered echo layers in association with the increase in the degree of sun's obscurity was observed during the period of eclipse. At the time of maximum obscuration (which was 85 %), as many as three echo regions were noticed between 90 km and 115 km, when normally during this period of a day in summer, a single echo layer, centered around the height of 95 km, would be observed over Gadanki. The period of observations fell during one of the strong meteor showers. It was surmised that 'finger like' ion layers comprised of long lived metallic ions, provided necessary density gradient for the growth of irregularities that produced the radar echoes. This result suggests that multiple metallic ion layers possibly exist quite often, but become visible only when the background electron density decreases considerably. SPL conducted a multi-instrumented, multi-institutional rocket campaign from Trivandrum and SHAR to investigate the effects of the annular eclipse of January 15, 2010 on the neutral energetics and dynamics. A neutral wind probe developed at SPL was flown along with quadrupole mass spectrometers and Langmuir probes. High altitude (~500km) RH-560 flights were conducted from SHAR during the eclipse and a normal day, while RH-300 (~ 100km) & RH 200 (~70km) flights were conducted from Trivandrum near the dip equator. Investigations of the equatorial ionosphere during annular solar eclipse on 15 January 2010 using rocket-borne probes indicate changes in the electric fields in addition to the conductivities during solar eclipse.

2.10 Global electric circuit

A.C. and D.C. components of global electric circuit are being monitored at Tirunelveli and Maitri, Antarctica, by studying atmospheric electric field, air-earth currents and Schumann resonance (SR) in magnetic field. From the diurnal UT-pattern of the SR intensity three major thunderstorm regions (South-East Asia, Africa and South America) were identified. Sunrise and sunset effects on the observed SR intensity were also seen. Data from campaign mode and permanent station observations during two solar eclipses on July 22, 2009 and January 15, 2010, show significant drop in the SR amplitude during the eclipse period. SR amplitude is found to be significantly higher in the local Antarctic summer, thereby confirming the dependence of these global oscillations on local ionospheric conditions.

3. Magnetospheric Phenomena

3.1 Boundary layer waves

Broadband electrostatic noise (BEN) is commonly observed in different regions of the Earth's magnetosphere and the frequency of these BENs lies in the range from lower hybrid to the local electron plasma frequency and sometimes even higher. A linear theory of low-frequency waves is developed in a four-component magnetized plasma consisting of three types of electrons, namely cold background electron, warm electrons, warm electron beam, and ions. For the auroral region parameters, the model predicts excitation of electron acoustic waves in the frequency range of 17 Hz to 2.6 kHz.

3.2 Nonlinear waves and solitary structures

Electrostatic solitary waves have been observed in several regions of Earth's magnetosphere. A general formalism has been developed to study the nonlinear propagation of large amplitude electron and ion acoustic solitary waves. The results from this model have been used to explain electrostatic solitary waves observed by the Cluster satellites in Earth's magnetosheath region. One dimensional particle simulation code to study electric field structures in the auroral region of the magnetosphere and the electron beam instabilities as generation mechanism of electrostatic solitary waves in the magnetosphere, which were observed by FAST, Polar and other satellites, was developed. Results have been compared with observed electrostatic solitary waves in the auroral acceleration region.

3.3 Magnetic storm-substorm processes

Observations from several spacecraft missions have shown the storm time ring current to be dominated by the ionospheric oxygen ions (O^+) during intense magnetic storms. These ions play an important role in the excitation of electrostatic and electromagnetic waves in ring current region. Using kinetic approach the quasi-electrostatic low-frequency modes driven by the energetic oxygen ions and energetic protons are studied in the storm time ring current.

3.4 ELF/VLF Studies

In a collaborative project with BHU, Varanasi and ARIES, Nainital, three VLF stations were set up at Allahabad, Nainital and Varanasi to understand the temporal / spatial occurrence, generation and propagation mechanism of VLF events and their implication in low latitude ionosphere / magnetosphere system. Observation, and numerical modeling studies are being carried out for phenomena like lightning discharges, radio atmospherics / tweeks, whistlers, VLF emissions etc. and possible D-region ionospheric perturbations by phenomena such as transient luminous events (TLE's), lightning induced electron precipitation (LEP's), cosmic gamma-ray flares, solar eclipses, geomagnetic storms, and earthquake precursor activities. A new experiment for the observation of TLE's generated by lightning discharges above active thunder clouds was setup to probe TLE's like Sprites, Jets, Gigantic jets, Blue starters, etc and to understand lightning electrical discharges and its effect on near Earth space environment. A special campaign to monitor dynamics of D-region ionosphere during July 22, 2009 total solar eclipse showed that lower boundary of D-region was pushed up by 6-8 km during different phases of eclipse while electron density reached nighttime level.

3.5 Antarctic geomagnetism

IIG has established a permanent station in sub-auroral latitudes at Maitri where digital fluxgate, search coil, and proton precession magnetometers monitor geomagnetic variations on a continuous basis. A fluxgate magnetometer is operated during the austral summer at Bharati, Larsemann Hills (L ~ 14) just south of the conventional auroral oval. A 4 x 4 antenna array imaging Riometer monitoring cosmic noise absorption at 38.2 MHz was installed at Maitri to study particle precipitation. Various sensors are installed at Maitri to study the different components of atmospheric electricity. Regions surrounding the Indian base have experienced rapid decline in geomagnetic field during the last century. Continuous geomagnetic field measurements at Maitri have revealed that the rate of decline in magnetic field has reduced considerably during this decade. Simultaneous magnetic data from Bharati and its near conjugate station, Hornsund, were used to identify substorms. Since the substorms were triggered pole-ward of auroral region, the standard AE indices failed to monitor such substorm activities, nevertheless typical low latitude features of substorm, for example, positive bay and Pi2 burst on the night side were distinctly evident.

4. Solar Wind and Interplanetary Field

4.1 Interplanetary scintillation studies of CMEs

The interplanetary scintillation (IPS) observations obtained from the Ooty Radio Telescope and the multi-antenna system

operational at the Solar-Terrestrial Environment Laboratory (Japan) have been used to reconstruct the three-dimensional perspective views of solar co-rotating plasma and outward-flowing solar wind by iteratively fitting a kinematic solar wind model to IPS data. This technique permits reconstruction of the density and velocity structures of coronal mass ejections (CMEs) and other interplanetary transients. The three-dimensional reconstructions have been obtained over 3-AU diameter heliosphere. The reconstructions agree well with in-situ signatures observed by Wind and ACE spacecraft.

A study on the link between the travel time of the CME to 1 AU (combined with its final speed at the Earth) and the effective acceleration within the Sun-Earth distance indicates that (1) for almost all the events, the speed of the CME at 1 AU is always less than or equal to its initial speed measured in the near-Sun region, (2) the distributions of initial speeds, CME-driven shock and CME speeds at 1 AU clearly show the effects of aero-dynamical drag between the CME and the solar wind and in consequence, the speed of the CME tends to equalize to that of the background solar wind, (3) for a large fraction of CMEs (for ~50% of the events), the inferred effective acceleration along the Sun-Earth line dominates the above drag force. The net acceleration suggests an average dissipation of energy ~10^{31-32} ergs, which is likely provided by the Lorentz force associated with the internal magnetic energy carried by the CME. The particle acceleration by the CME-generated shock is also consistent with the support of propagation with the additional energy possessed by the CME.

A study on the three-dimensional evolution of solar wind density and speed distributions associated with coronal mass ejections (CMEs) reveals that (1) three-dimensional IPS images possibly show evidence for the flux-rope structure associated with the CME and its radial size evolution; the overall size and features within the CME are largely determined by the magnetic energy carried by the CME. Such a magnetically energetic CME can cause an intense geomagnetic storm, even if the trailing part of the CME passes through the Earth; (2) IPS measurements along the radial direction of a CME at ~120 $R_\odot$ show density turbulence enhancements linked to the shock ahead of the CME and the core of the CME. The density of the core decreases with distance, suggesting the expansion of the CME. However, the density associated with the shock increases with distance from the Sun, indicating the development of a strong compression at the leading edge of the CME. The increase of stand-off distance between ~120 $R_\odot$ and 1 AU is consistent with the decceleration of the CME and the continued outward expansion of the shock. The key point in this study is that the magnetic energy possessed by the transient determines its radial evolution.

Several fast CMEs have been studied in detail to explore the relationship among the propagation characteristics and the type II burst-associated shock waves in the corona and solar wind. Different coronal/interplanetary density models have been used to compute speeds of shocks in the metric and decametric radio wave portions of the spectra, which have been compared with the velocity of the CMEs as observed in the plane-of-the-sky white-light observations and calculated with a cone model. The propagation of the ejecta has been followed using IPS data from Ooty. A multi-wavelength study of two homologous flare events and their CMEs provides evidence that opposite rotation of opposite polarity sunspot regions plays a crucial role in building the magnetic energy required for the flare process. Sunspot rotation is also the primary driver of helicity production and injection into the corona. The newly emerging magnetic flux leads to the destabilization of large-scale filaments. The interaction between filaments results in magnetic reconnection and formation of cusp-shaped structure. The cusp also suggests the formation of a magnetic null point in the high corona. The correlation between the separation of flare ribbons and the expansion of the cusp structure indicates that large-scale reconnection and particle acceleration occurred during the cusp eruption. The IPS technique shows that the flux rope is oriented about 50 degree with respect to the ecliptic plane and therefore, in spite of a strong shock, the Earth-directed CME could cause only a moderate storm (Dst -85 nT) at the Earth.

A study has been made to understand the turbulence spectrum of solar wind, in the near-Sun region (R < 50 $R_\odot$), using the IPS measurements made with the Ooty Radio Telescope at 327 MHz. The results clearly show that the scintillation is dominated by density irregularities of size ~100 - 500 km. The small-scale end of the spectrum, although significantly lower in magnitude, is flatter than the dominant large scale part. Further, the spectral power covered in the flatter portion rapidly increases as the Sun is approached. Results on the turbulence spectrum at distances < 50 $R_\odot$ provide quantitative evidence on the radial evolution of Alfven waves generated fluctuations.

A large amount of IPS data obtained from the Ooty Radio Telescope has been employed to study the three-dimensional evolution of density turbulence in the heliosphere over the period 1995–2010. The large-scale features of solar wind speed and density turbulence of the current minimum are remarkably different from that of the previous cycle. The results are consistent with the magnetic-field strength at the poles and the warping of heliospheric current sheet. The results on solar wind density turbulence show that (1) the current solar minimum is experiencing a low level of coronal density turbulence, (2) the scattering diameter of the corona has decreased steadily starting from year 2003, i.e., during the declining phase of the activity, and (3) the turbulence at a given distance in the heliosphere, irrespective of latitude, has remained nearly at the same level between years 1989 and 2003, but decreased steadily after 2003 to a current value of ~50% at the equatorial region. The current solar cycle minimum seems to have peculiar properties that are likely related to weak magnetic fields. These results suggest that the source of solar wind changes globally, with the important implication that the supply of mass and energy from the Sun to the interplanetary space has significantly reduced in the present low level of activity

4.2 Solar Corona

With aims of understanding physical processes involved in coronal heating and acceleration of solar wind, researchers at the Indian Institute of Astrophysics (IIA) have been carrying out observational studies of the solar corona using data from space based instruments, e.g. Coronal Diagnostic Spectrometer (CDS) and SUMER onboard
SOHO, as well as using its own ground based radio astronomical facilities. The spectrsocopic studies using open source space data have focused on the dynamics of plasma in polar coronal holes and in polar off-limb regions and have yielded an assessment of background physical conditions as well as an understanding of transient dynamical phenomena in these regions. These results have implications for the coronal heating and the acceleration of the solar wind.

A large fraction of work on the solar corona in the recent past has focused on spectroscopic studies of the corona, especially in the bright emission lines in the visible and near-infrared regions of the spectrum. A study of Coronal Mass Ejections (CME's) and associated phenomena using data from SOHO/LASCO has focused on estimating the driving power of internal magnetic energy of flux-rope CMEs and associated statistical characteristics of the energetics of such CMEs. Using similar data, there have also been studies of post-flare turbulence and associated acceleration of electrons. Study of the long wavelength (metre and decameter) radio emission from the solar corona, through imaging at these wavelengths using the Gauribidanur radio-heliograph, has been a unique and significant area of research in the study of solar eruptive events (e.g. flares, prominence eruptions and CME's), because this instrument provides excellent complementary information to those obtained using space instruments. Several aspects on the time and frequency structures of various kinds of radio bursts in the meter-decameter wave band and the imaging of CMEs have been studied. Estimation of physical quantities such as density, temperature and magnetic field of the emitting plasma in the eruptive coronal structures during their various evolutionary stages is the main aim of these studies. Several results concerning the temporal and frequency characteristics of Type I and Type II radio bursts have been obtained and association of these

bursts with M and X class flares and CME's have been studied.

The scientists and engineers of the solar radio astronomy group at IIA are involved in the development of hardware and software for radio astronomical instrumentation. Construction and implementation of a low-frequency (30-110 MHz) antenna system for observations of polarized radio emission from the solar corona, and the Gauribidanur radio array solar spectrograph (GRASS) have formed significant developmental activities. They are also involved in the Brazilian Decimetre Array, being built by the Instituto Nacional Pesquisas Espacias (INPE), Brazil, for observations of Sun and various Galactic, extragalactic radio sources. IIA scientists have contributed to the array configuration design, software for data calibration and image synthesis. They have also designed and constructed a digital backend receiver for the telescope. In its present configuration, the array has 5 parabolic dish antennae of 4 m diameter each, set up as a one-dimensional array in the east-west direction. The frequency of operation is 1.6 GHz. The length of the longest baseline in the array is 216 m. The temporal and angular resolution are 100 ms and 1.5' respectively. The array is located at Cachoeira Paulista (Lat: 22.69° S; Long: 45.01° W).

5. Geomagnetic Observatories, Surveys, and Analysis

5.1 Geomagnetic observatory network

India has a network of 13 permanent magnetic observatories located in different parts of India. Of these ten are equipped with modern magnetometers to monitor geomagnetic field variations at 1 Hz. The INTERMAGNET system at Alibag observatory complements this set up. Search coil magnetometers are installed at six observatories to monitor variations at 64 Hz. Near real time transmission of digital data at one minute interval from four observatories (Alibag, Pondicherry, Nagpur and Jaipur) to the headquarters of IIG commenced in 2009. Annual magnetic data bulletins for all the magnetic observatories in India are published by IIG. Quarterly prompt reports of magnetic data depicting the Equatorial Electrojet strength (EEJ) are also prepared. Processed one minute data of H-component for Alibag station are regularly sent to Kyoto GIN for the preparation of Dst index on monthly basis. Magnetic observatory at Alibag serves as a calibration center for magnetic instruments and compasses used by other organizations in India.

IIG maintains a World Data Center (WDC) for Geomagnetism in Mumbai. As part of the electronic Geophysical Year (eGY) activities, the center has initiated preservation of old data volumes/records and Metadata for digital archival of geomagnetic data recorded during 1846 – 1903 at Colaba, and since 1904 up to the present time at Alibag. During the period 2007-2010, geomagnetic hourly values and digital images of magnetograms for the years 2004 to 2008 have been sent to the five other WDCs for Geomagnetism.

5.2 Geomagnetic data analysis

Close correlation between field aligned current (FAC) density and variations in the declination component 'D' at the low latitude station Alibag is found during intense storm events suggesting strong association of FACs with low latitude ionospheric currents for such events. Relation between solar wind dynamic pressure enhancement and observed amplitudes of geomagnetic field variations at equatorial and low latitude Indian stations is studied using ground geomagnetic and satellite data for magnetic storm events which occurred during solar cycle 23. Multi-point observations of long-period ultra low frequency (ULF) waves directly driven by solar wind demonstrate that periodic fluctuations in solar wind density and dynamic pressure drive coherent ULF waves on the ground. Enhancement in the amplitude of ULF waves at dip-equator on the dayside suggests the penetration of polar electric field to the equatorial latitudes. Fuzzy mathematical model is applied to geomagnetic data at equatorial and non-equatorial observatories for pattern recognition during geomagnetic storms. Penetrating electric fields and currents from high latitudes to the equatorial latitudes and associated changes in day time DP2 currents are investigated using simultaneous observations from ground and satellite data

during intense magnetic storm periods. During the main phase of magnetic storms, close correspondence is found between penetration of strong convection electric field to the equator and large drop in polar cap potential.

5.3 Geopotential studies

Depth to the bottom of the magnetic sources (Curie isotherm depth) was estimated from a) aeromagnetic data and b) the lithospheric model of the CHAMP satellite data. It was found that the calculated Curie isotherm is shallow over the mobile belts and deeper in the cratons. The Curie depth was found to be generally shallower than the Moho depth (from DSS) implying that it possibly represents a thermal boundary rather than a compositional change. Further, it was found that high magnitude earthquakes are associated with high gradients in Curie depth. Crustal model derived from combined analysis of high resolution satellite derived free air gravity and magnetic data over 85° E ridge suggests that the ridge has a different nature at latitudes north and south of 15°N latitude. Above 15°N the ridge appears to be a geo-morphological feature within the sediments above the basement. Below 15°N, the ridge appears to be oceanic and would have formed due to horizontal compressional forces of the lithosphere preceding development of the subduction zone at Andaman trench.

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Hydrological Sciences: A report to IAHS 2011

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Introduction

Hydrogeologically, the Indian territories can be divided into three major groups: unconsolidated, semi-unconsolidated and consolidated (or hard rock) formations. Indo-Gangetic plains, dune soil of Thar Desert in the north-west and coastal alluvium of Quaternary to recent ages characterized with the primary porosity form the first group of unconsolidated formations. The Indo-Gangetic plain is traversed by major Himalayan rivers like Indus, Ganges, Brahmaputra, Yamuna and their tributaries. This plain is one of the largest repositories of surface and groundwater in the world. Proterozoic, Paleozoic and Mesozoic sediments distributed all over the country constitute the second group of semi unconsolidated formations. Deccan traps, Archaean granites and gneissic complexes, consolidated sediments and Pre-Cambrian meta-sediments form the third group of consolidated formations. About 2 Million sq. km (or 60%) of the total surface area of Indian territories is covered by consolidated formations. The weathered zones, intervening intertrappeans, fractures and joints serve as a potential groundwater reservoir in consolidated geological formations. The average annual rainfall over the country is estimated 1170 mm which is more than the global average rainfall of 700 mm. Even then about 80% of the Indian territories fall under semi-arid to arid conditions and faces acute shortage of quality water supply. This is because of vagaries of monsoon, topographic variations, prevailing semi-arid to arid climatic conditions and varied nature of hydrogeology. To assure secured and safe drinking water supply to all citizens and to meet the irrigation and industrial requirements, the federal government of India has initiated an ambitious technology mission entitled "WAR (Winning, Augmentation and Renovation) for Water" in response to an order of the Supreme Court of India dated 28th April 2009. Objectives of the missions are to find methods and their implementation for : (1) rain water harvesting , (2) managing flood waters, (3) treatment of waste water, (3) converting saline water into fresh water, and (4) any other methods or suggestions for protection and preservations of wet lands and related issues. More emphasis has been given to the sustainable development and management of ground water resources because it is the only source of drinking water for almost entire rural population. During reporting period adequate works have been carried out by various government and non-government organization in different field of hydrological sciences which have been listed in the reference section of this report. However, this report describes some selective works under the titles: (1) Ground water exploration, (2) Management of groundwater/surface water resources; (3) Rainfall, runoff, flood and climate variability effects, (4) Water quality, (5) Aquifer's parameter identification, and (6) Basic research in the following sections.

1. Ground water exploration:

For Ground water exploration, aquifer's mapping using integrated geophysical and geological surveys, remote sensing and GIS techniques, and their development through creating infrastructures such as dug-wells, bore-wells, hand pumps etc.

have been carried out in different part of the country such as in Vindhyan terrain of Gurudev Nagar, Mirzapur district, U.P (Yadav et al. 2007) and Robertsganj in Sonbhadra district , U.P. (Yadav and Singh, 2008), in granitic terrain of Maheshwaram watershed (Kumar, et al, 2007) and Waipally watershed (Dhakate, et al. 2007, Orowe, et al 2008, Dhakate and Singh, 2008, Prasad, et al., 2008, Mondal, et al. 2008) of Nalgonda district and Seethanagaram Mandal of Vizianagaram district (Monadal, 2008), in A.P state, in volcanic Deccan basaltic region of Katol and Kalmeshwar taluks of Nagpur district covering 170 Km^2 area of 23 villages (Rai et al. 2010, 2011), Chiplun taluk of Ratnagiri district (Rai, et al., 2010,) and around Aurangabad city (Kumar, et al. 2010) in Maharastra State. An attempt has been made for mapping of aquifer geometry and surface and sub-surface faults in Gangetic Plain by integrating remote sensing and well log data. (Samdder, et al.2007). Characteristic responses to pumping in hard rock fracture aquifers of Trissur district, Kerala have been analyzed for their hydrogeological significance (Kukillaya, 2007). Evaluation of ground water development prospect in the Kadalundi basin in Malapuram district of Kerala has been done by analyzing the pattern of water level fluctuation in different physiographic regions, the depth to water level and saturated thickness in different seasons, the hydrogeological properties of the rocks within the basin, the ground water assessment, the ground water quality etc. (Prasad et al, 2007). Lineament density modeling has been done to identify high potential aquifers in hard rock areas of Nawapara and Kalahandi districts in Orissa state (Sikdar, et al., 2007). Jha et al (2008) have carried out geo-electrical sounding to decipher aquifers at a site under the Salboni Block of West Medinapore district of West Bengal. Detailed geophysical, hydrogeological and hydrochemical investigations have been carried out to identify potential fresh ground water resources and to quantify vulnerable part of Androtт island of Lakshadweep (Singh et al., 2009). Ground water exploration works have been also carried out in Mayurakshi watershed which covers an area of about 1860 Km^2 falling in Dunka and Deogarh district of Jharkhand state (Chowdary et al, 2009) and Bakhar watershed in Mirzapur district of U.P. (Girish Kumar, et al. 2009). Hodlur et al (2010) have presented a method for the resolution of fresh and saline water aquifers by analysis of electrical rsistivity data.

2. Management of ground water/surface water resources:

The consequence of unsustainable exploration of ground water in the form of water table decline, depletion of ground water resources, ground water pollution, land subsidence etc are becoming evident in many parts of the country. Artificial recharging of ground water is the most effective measure to reverse the declining trend of ground water level and to protect its quality from polluted surrounding environment, if exists. Jha (et. al 2009) have suggested three low cost and easy to implement recharge techniques for alluvial aquifer systems through augmentation of river flow, recharge through irrigation/drainage canals and paddy fields. A comprehensive review on the applications of remote sensing and GIS technologies for ground water management and development has been presented by Jha et al. (2007). A tank cum open dug well system has been developed for artificial recharging and irrigation (Srivastava, et al., 2009). The system comprises of a series of tanks with open dugwell in the recharge zone of the tank that reharvest back the seepage water. This system was evaluated in a field experiment in Keonjhar district of Orissa. Percolation tanks are widely used for increasing recharge of ground water. A software "SODPET" is developed for design of percolation tank. The output results include capacity of the tank for most economic recharge per unit investment, total recharge during the year, recharge during monsoon and post monsoon months and expected storage level at the end of the monsoon (Srivastava et al. 2007). Area and locale specific watershed plans are generated for Mayurkashi watershed using remote sensing and GIS techniques (Chowdary et al. 2009). Shekhar and Prasad (2009) have presented options to manage ground water in the Yamuna flood plain of Delhi to overcome the scarcity of water supply to the national capital city. Rao et al.(2007) have presented results of an operational model in order

to suggest the optimal pumping from skimming wells operated from optimal locations in the Yamuna river flood plain of Delhi such that they are staggered in space and time to obtain the least saline water. In the light of increasing deterioration of ground water supply in Rajasthan state, rainwater harvesting practices in the Wakal river basin in southern Rajasthan were studied to determine the effects of artificially recharged ground water on the supply and quality of ground water (Stiefel, et al, 2009). Limaye(2010) has presented a review on groundwater development and management in the Deccan traps occupying more than half a million Indian territories. Rai (2009) has presented a review on merit and demerit of several ground water development activities carried out in different part of the country.

3. Rainfall, runoff, flood and climate variability effects

A new lumped conceptual model based on the soil conservation service curve number (SCS-CN) concept has been developed for continuous simulation of rainfall-runoff processes in watershed (Geetha et al., 2008). A normal annual rainfall map is prepared for Himalayan region, lying in Uttarakhand state (Basistha, et al., 2008). Historical daily runoff has been simulated for the Chenab river basin up to Salal gauging site using a snowmelt model(SNOMOD) to study the impact of plausible hypothetical scenarios of temperature and rainfall on the melt characteristic and daily runoff of the Chenab river basin (Arora, 2008). Regional flood frequency analysis of north–bank of the river Brahmaputra has been carried out for estimation of floods of various return periods for both gauged and ungauged catchments of the study area (Bhuyan et al, 2010). Runoff regimes in Himalayan basins are controlled mainly by melting of snow and ice cover. Melting is dependent on air temperature. Global atmospheric general circulation model (GCMs) has been developed and used to study the effect of changes in temperature on the stream flow which has contribution from snowmelt, rainfall and base flow in the Satluj river basin (Jain et al., 2010). Forty major perennial springs under different lithological controls in parts of Kashmir Himalaya were studied to understand the response of springs discharges to regional climatic variability (Jeelani, 2008). The study revealed that the regional /global warming and below normal precipitation in the period of snow accumulation (PSA) has triggered the receding of glaciers and attenuation of spring discharges. Solute dynamics of melt water of Gangotri glacier system in terms of association of different chemical compounds with the geology of the area is being investigated by (Kumar, et al., 2009).

4. Water quality

Groundwater pollution mostly due to presence of high concentration of Arsenic, fluoride sea water intrusion, and unplanned disposal of industrial hazards and other anthropogenic/geogenic sources has been reported from different parts of the country and is a mater of serious concern. The following section describes a few cases of ground water pollution .

Arsenic

Influence of fluvial geomorphology and quaternary morphostratigraphy on arsenic contamination of ground water from parts of Damodar fan-delta and west of Bhagirathi river in west Bengal has been investigated by Acharya and Shah (2007). Bhattacharya and Mukherjee (2008) have investigated contamination of shallow aquifers by arsenic in upper reaches of Tista river at Siliguri-Jalpaiguri area of West Bengal (2009). Ground water in four districts of Manipur state situated in Manipur valley is arsenic contaminated. Water samples from these districts were analysed to quantify the amount of arsenic contamination and source of contamination (Chakraborti et al, 2008).

Fluoride

Hydrogeological investigation carried out in the rural parts of Yavatmal district of Maharastra state has revealed high fluoride concentration in deeper aquifers compared to shallow aquifers. Physicochemical conditions like decomposition,

dissociation and subsequent dissolution along with long residence time might be responsible for leaching of fluoride in to ground water (Madhnure et al., 2007). Isotope and hydrochemical investigations have been carried out in the Ilkal area under Bagalkot districts of Karnataka to determine source and mechanism of fluoride released into ground water and to understand ground water hydrochemisrty (Tirumalesh, et al. 2007). The study points to contribution from surface waters contaminated by anthropogenic activities. Reddy et al.(2011) have used a multifaceted approach to understand the mechanism responsible for the spatial distribution and dynamics of fluoride in highly contaminated granitic aquifer (up to 7.5mg/l) of Wailapally watershed in Nalgonda district of A.P. Mondal et al. (2010) have highlighted the utility of resistivity and induced polarization (IP) surveys, using hydrochemical constituents as constraint, for successful delineation of Fluoride contamination of ground water (0.71-19 mg/L) of Kurmapalli watershed of Nalgonda district, A.P.

Sea water intrusion

In many coastal regions of Orissa, Andhra Pradesh, Tamil Nadu, and Gujarat, the intrusion of sea water towards inland fertile soils has been reported mostly due to pumping of ground water from coastal aquifers in excess to their replenishment. Ground water quality assessment of shallow aquifer using GIS in part of Chennai City, Tamil Nadu has been carried out. From the higher TDS and Cl/HCO3 ratio. It is inferred that the sea water has intruded into a considerable area adjoining the coast due to over exploitation of ground water (Singh and Lawrence, 2007). Sea water ingression study along the Guhagar coast of Maharastra with reference to the harmonious water resources development has been carried out. The pros and cons of constructing engineering structures for preventing sea water ingress and strategy to enhance groundwater recharge for increasing fresh water column in the lower reaches of Creeks, tidal inlets and their tributaries, without causing harm to the delicate ecosystem of mangrove have been analysed (Umrikar and Thigale, 2007). A systematic hydrochemical study has been carried out in coastal aquifer under administrative jurisdiction of Tuticorin, Tamil Nadu (Mondal et al., 2010). Trace element concentration in ground water of Peasarlanka island in Krishna delta has been analysed by Mondal et al (2010).

Industrial pollution

Investigation has been made to identify ground water vulnerability to pollution by using geoelectrical and hydrochemical investigations in an important industrial town Mettur in Tamin Nadu state. (Srinivasamoorthy, et al, 2011). Results of a study on contamination of Uppanar River and Coastal waters off Cuddalore in Tamilnadu state signify that industrial growth has affected the aquatic environment (Jonathan, et al., 2008).

Pollution by other sources

Water pollution due to other anthropogenic and geogenic sources has been also investigated. A framework to evaluate and map environmental hazard with reference to special distribution of major and trace metal contamination and its relationship with lithology in Chandrapur district of Maharashtra using geospatial, statistical and GIS tool is addressed by Satapathy et al.(2009). A detailed water quality analysis is carried out in the quaternary aquifer system of the alluvial Ganga Plain in Bah Tehsil of Agra district to identify the factors causing the variation and escalation of chemical constituents and salinity in the aquifers (Misra and Misra, 2007). Hydrogeochemical investigations are carried out in different blocks of Burdwan districts, West Bengal in order to assess its suitability for drinking as well as irrigation purposes (Gupta et al., 2008). In order to know the quality of ground water for domestic and irrigation uses in Upper Gunjanaeru river basin of Cuddapah basin, A.P., water sample were analysed for various parameters (Raju, et al, 2007). GIS based quality assessment of spatiotemporal characteristics of ground water qulity of upland sub-watersheds of Meenachil river, a part of Western Ghats in Kottayam district of Kerala was carried out to find out suitability of ground water for drinking and agricultural

purposes (Vijith and satheesh, 2007). GIS has been applied for identification of ground water quality suitable zones in a part of Chittoor, A.P. for domestic and irrigation purposes (Yammani, 2007). Ground water quality has been investigated in many parts of the country such as East Godavari district of A.P. (Rao, 2007), Bhiwani region of Haryan state (Garg et al., 2009), Bhalswa landfill area of Delhi (Srivastava and Ramnathan , 2008), Ankleshwar industrial state in Gujarat(Kumar, 2008), Muzaffarnagar district of U.P. (Tyagi et al. 2009), Central Ganga Plain in U.P. (Umar et al. 2009), Upper catchment of Damodar river basin (Singh et al., 2008), in and around Kolkata wetland (Sahu and Sikdar, 2008), Delhi (Kumar, et al, 2009), Patiala and Muktsar districts of Punjab (Kumar, et al. 2007, 2009), Potharlanka island in Krishna delta (Mondal, et al. 2008) and Andrott islands of Lakshadweep (Sarwade, et al. 2007).

5. Aquifer's parameter identification

Estimation of aquifer parameters is of utmost importance to construct predictive models which in turns are used for judicious management of ground water/ surface water resources from both quantitave and qualitative point of views. A simple method and an optimization method for explicit estimation of specific dispersivity and injected mass due to instantaneous injection of a solute are proposed by Singh (2007). Using this method, the data for different flow rates and injected masses can be analysed simultaneously. A methodology has been developed to estimate the hydraulic conductivity and transmissivity of hard rock aquifers from geoelectrical parameters (Chandra et al, 2008). An electrical resistivity method has been used to determine aquifer parameters in the Ganga-Yamuna interfluve in northern India (Sinha et al, 2009). By using this method, an existing relationship between the geoelectrical and hydraulic parameters has been modified. A remote sensing based hydrogeomorphological approach is proposed to upscale aquifer transmissivity from point or well scale to aquifer scale and is applied to the piedmont alluvial system of Doon valley of Uttarakhand state(Srivastav et al., 2007). For predicting fate of non conservative pollutants downstream from source using advection-dispersion-decay equation, estimation of longitudinal dispersion coefficients is required a priori. An innovative approach has been proposed towards the estimation of longitudinal dispersion coefficients using regime channel concept (Muthukrishnavellaiswamy, et al, 2009). Natural recharge and aquifer's parameters in a watershed located in east coastal belt around Tuticorin town, Tamilnadu are estimated using radio tracer and pumping test analysis (Rangrajan et al., 2009). A simple method for quick estimation of leaky aquifer parameters has been suggested by Singh (2009).

6. Basic research

An understanding of the quantitative and qualitative changes in ground water dynamics because of existing and proposed management schemes is prerequisite for their proper development and management. Mathematical models are used for assessiing the future behaviour of ground water, in both quantitative and qualitative terms, in response to various operating or proposed development schemes related to recharging, pumping, waste disposal etc and in making judicious selection of a sustainable development scheme out of many proposed scheme without resorting to expensive field experiments. An analytical model for 2-D water table variation in an aquifer basin with inclined impermeable base incorporating the effect of depth-dependent evapotranspiration is developed by Singh et. Al. 2008. An analytical model has been developed by solving Boussinesq equation to predict water table fluctuations due to time varying recharge, and withdrawals from multiple basins, wells and leakage sites (Rai and Manglik, 2010a).Rai and Manglik (2010b) have developed an analytical model to predict the dynamic behaviour of the water table in the presence of seepage owing to intermittently applied canal irrigation and ground water pumping from any number of well located any where within the investigated area.. A new numerical tool is presented which models the two dimensional contaminant transport through saturated porous

media using a meshfree method called the radial point interpolation method (RPIM) with polynomial reproduction (Praveen Kumar and Dodagoudar, 2008). A novel Hybrid Monte Carlo-based Bayesian neural network inversion scheme is developed for the interpretation of DC Resistivity data (Maiti e al., 2001). This method, on contrary to the other traditional inversion scheme, does not require a prior initial model for successful optimization. This method was applied to large number of DC Resistivity sounding points from the seismically active zone of Koyana region for mapping the subsurface Resistivity structure in order to decipher aquifers. Feed forward ANN model with quick propagation (QP) as training algorithm has been used to forecast the salinity under varied pumping rates (Banerjee et al, 2011). The accuracy, generalization ability and reliability of the model are verified by real field data from Kavarati, an island of Lakshdweep. An Artifical Neural Network (ANN) based methodology is developed to identify unknown pollution sources in ground water with partially missing concentration observation data (Singh and Datta, B., 2007). Singh et al (2008) have presented Transformation technique for water table estimation in a 2-D aquifer with inclined base subjected to variable ET. A Semi analytical model for drawdown due to pumping a partially penetrating large diameter well is developed by Singh (2007). Singh (2009) has presented a generalized analytical solution for groundwater head in a horizontal aquifer in the presence of subsurface drains.

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The Large-Scale and Spatio-Temporal Extreme Rain Events (EREs) over India

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Summary

During principal period of the monsoonal rainy season (18 June through 16 September), daily only 26.32% area of India (PAI) experiences wet condition, over which rainfall occurs at the rate of 26.3mm/day. Keeping in view current research interest to understand effect of climate change on the extreme rainfalls, characteristics of six types of large-scale and one 1-DLLG (1-degree latitude longitude grid) spatio-temporal extreme rain events (EREs) over the country have been studied using 57 years (1951-2007) of daily rainfall available on 1-DLLG resolution. Highest 1-day rainfall of the ERE concerning rainfall intensity (ERE-RI) occurred on 25 July 2005 in which 45.9PAI received rainfall at the rate of 73.3mm/day, and that of the spatio-temporal ERE concerning areal extent (ST-ERE-AE) on 25 July 1983 in which rainfall occurred at the rate of 23.3mm/day over 64.0PAI. In 2005, the country received the highest rainwater of 1-day (98.2bcm; billion cubic meter) through 25-day (971.9bcm). The rainfall amount of the 1-DLLG ST-ERE of 1- to 5-day durations showed significant increasing trend.

Qualitatively, a positive correlation is seen between monsoon circulation intensity and rainwater over India.

Introduction

Extreme rain events (EREs), severe floods, hydrometeorological disasters and climate change are of serious concern due to rising trend in the global atmospheric temperature. It is believed that 'hydrological cycle is supposed to be intensified under global climate change background'. Experiences suggest that the EREs are embedded in the large-scale, long period intense rainfall activities during the summer monsoon period. Every year some parts of the country experience floods even during large-scale droughts. On 26-27 July 2005, an unprecedented heavy rainfall occurred at Santacruz, Mumbai that caused enormous loss to life and property. This motivated several research programs on point and area-averaged extreme rainfalls. These studies are of limited help to understand association between atmospheric circulation and extreme rainfall. In this status report, we intend to document characteristics (climatology and trends) of large-scale actual and extreme wet spells over the country during 1951-2007 (57 years) from a recent study by Ranade and Singh (2010).

In order to identify large-scale (for the country as a whole) EREs, first a large-scale wet (dry) spell has been defined as 'a continuous period with individual day more (less) than 10.4% area of the country under wet condition (actual daily rainfall over 1-DLLG {Degree Lat-Lon Grid} more than DMMR {daily mean monsoon rainfall} over the particular grid)'. On each day of the monsoon period, 10.4% area of the country experiences wet condition. A particular 1-DLLG is declared under wet condition and the day as wet day (WD) if actual rainfall exceeds its DMMR. The DMMR is the daily mean rainfall during normal monsoon period over the grid. The DMMR varies from less than 2mm/day in extreme northwest India to more than 24mm/day along central West Coast. The southern tip of peninsula experiences 80 wet days (WDs) during the year due to tropical and oceanic influences, the extreme northeast India 75 WDs due to oceanic and orographic influences and the extreme northern India 70 WDs due to tropical-extratropical interactions and orographic effects. Over remaining parts of the country, the WDs vary from 55 over southeast coastal areas to 15 over northwest dry province as the tropical and oceanic influences decrease and extra-tropical and continental influences increase. For the country, 5 January is the driest day with only 2% area under wet condition and 21 July through 10 August the wettest days during which 32% area experience wet condition.

Large-scale Wet Spell (LSWS) and Main Monsoon Wet Spell (MMWS)

Having obtained the total area of the country under wet condition for each day of individual year, there are five computational steps further to identify large-scale wet-dry spells.

1) *For each day, calculate percentage area of the country under wet condition (total wet area divided by total geographical area, $3.3x10^6$ km^2);*
2) *Normalize the actual daily percentage area by dividing by the normal percentage area (10.4%);*
3) *Smooth out the normalized percentage area by applying the 5-point low-pass binomial filter; and*
4) *Identify the large-scale wet spell (LSWS) if normalized, smoothed percentage area equal to or greater than 1.0, and large-scale dry spell (LSDS) otherwise.*

Normally, six LSWSs and five intervening LSDSs occur over the country each year. Two short LSWSs (each of duration ~6 days and rainfall intensity {RI} 23.7mm/day) and two long LSDSs (each of duration ~32 days and RI 0.3 mm/day) occur during 3 April through 17 June, a long LSWS (duration 91 days and RI 26.3 mm/day) during 18 June through 16 September and three short LSWSs (each of duration ~8 days and RI 24.6mm/day) and three medium size LSDSs (each of duration ~12 days and RI 0.3 mm/day) during 17 September through 15 November. The third and the longest LSWS will be referred to as the MMWS. Normally, 26.32% PAI (Percentage Area of India) experience wet condition the MMWS. Hence, space-time distribution of seasonal rainfall is as '70% of the all-India monsoon rainwater occurs over 26.32PAI during 91 days of the MMWS, and the other 30% spread over 73.68PAI during 122 days of the monsoon period June through September'. The parameters of the MMWS do not possess any significant long-term trend.

Large-Scale Extreme Rainfall Events (LS-EREs)

Following seven types of EREs over the country during the MMWS period have been identified, analyzed and their characteristics documented.

i. *the ERE concerning rainfall intensity (ERE-RI) of 1- to 25-day durations;*
ii. *the ERE concerning rainfall areal extent (ERE-AE) of 1- to 25-day durations;*
iii. *the ERE concerning rainwater (ERE-RW) of 1- to 25-day durations;*
iv. *the spatio-temporal ERE-RI (ST-ERE-RI) of 1- to 25-day durations;*
v. *the spatio-temporal ERE-AE (ST-ERE-AE) of 1- to 25-day durations;*
vi. *the spatio-temporal ERE-RW (ST-ERE-RW) of 1- to 25-day durations; and*
vii. *the spatio-temporal 1-DLLG ERE of 1- to 150-day durations.*

For the first three EREs analyses (i to iii), only grids under wet condition on day one and then wet on consecutive days are considered. An assumption has been made in the identification of 2-day and longer duration wet spells. If a grid received rainfall continuously over long period, but there were dry days embedded in a stream of wet days. In such situation, if daily mean rainfall of 'm-day' period exceeded 'm' times the DMMR of the particular grid, the entire m-day was treated as LSWS. For example, if the rainfall of two consecutive days exceeded twice its DMMR, the grid has been considered under wet condition for both days. Similarly, if three consecutive days total rainfall exceeded thrice its DMMR, the grid was considered under wet condition for all the three days. Largest area under wet condition occurs for day one, and the area gradually decreases with the duration of the wet spell. This is expected to provide some useful information for hydrology, agriculture, water resources, climate change and disaster.

In the following three analyses (iv to vi), wet condition of any particular grid on any particular day was decided irrespective of the conditions on preceding day(s).The area under wet condition on each day was considered as an independent event. For example, a set of grids may be under wet condition for 1-day, but a different set of grids under wet condition for 2-day. The information is useful for weather services and agricultural purposes.

Every year some parts of the country experience intense rains and heavy floods even during large-scale droughts. Location and time of occurrence of extreme rainstorm and associated flood vary drastically from one year to another. Unprecedented rain event of

26-27 July raised apprehension whether spatio-temporal features of EREs over the country were changing. Results of detailed investigation on spatio-temporal variability of 1-DLLG EREs of 1-day to 150-day over the period are also reported in this paper.

In the era of changing global climatic conditions, analyses of different types of extreme rainfall events are expected to provide critical information to the researchers and users alike about characteristics of extreme rain events.

The ERE-RI

Development of annual maximum rain event series is essential in the ERE studies. From the available 1-DLLG daily rainfall of the country, the 1-day annual maximum rain event in respect of rainfall intensity (ERE-RI) has been obtained in four steps: i) for the year 1951 getting the area of the country under wet condition for each day of the MMWS; ii) calculation of mean rainfall intensity (RI; mm/day) over the wet area on that day; iii) screening out the day with highest RI; and iv) repeating the process for the next year, and so on, till 2007. Corresponding to the day with highest RI, document the areal extent of the wet condition and its date of occurrence. Repeat the whole exercise for the annual maximum rain event in respect of RI (ERE-RI) of 2-, 3-....and 25-day durations. The choice of longest duration up to 25-day for the ERE-RI is made keeping in view the shortest duration of the MMWS i.e. 28 days.

On 1-day ERE-RI, normally the rainfall intensity is 43.2mm/day over 25.8% wet area of the country, and it occurs around 2 August. As the duration of the ERE-RI increases, rainfall intensity and wet area decrease in an exponential manner, and starting date of the event gradually shift prior to 2 August. For 25-day ERE-RI, normally the RI is 22.7mm/day and area under wet condition 10.8PAI, and the event starts around 3 July. The most severe 1-day ERE-RI occurred on 25 July 2005 with RI 73.3mm/day and 45.9PAI experienced wet condition.

The ERE-AE

Incorporation of extremeness of the areal precipitation along with precipitation amount is essential for the identification of heavy large-scale rain events. The time series of 1-day to 25-day annual maximum rain event in respect of areal extent (ERE-AE) has been developed following the process similar to the ERE-RI. In this case annual rain event with maximum areal extent (AE) has been picked up. On 1-day ERE-AE, normally 49.8PAI experiences wet condition with the RI of 29.1mm/day, and the event occurs around 23 July. For 25-day ERE-AE, the area under wet condition exponentially decreases 35.1PAI and the RI to 14.9 mm/day and the starting date gradually shift to 18 July. The most severe 1-day ERE-AE occurred on 25 July 1983 in which 64.0PAI experienced wet condition with RI 23.3 mm/day.

The ERE-RW

The rainwater accounts for both rainfall intensity and areal extent, therefore, analysis of annual maximum rain event in respect of rainwater (ERE-RW) is expected to provide more useful for hydrological and water resource purposes. Normally on 1-day ERE-RW, 46.2 bcm (billion cubic meter or km^3) of rainwater is received over the country. The mean maximum rainwater increases in an exponential manner with the increase of duration of the event. For the 25-day ERE-RW, the mean rainwater is 394.1 bcm. The most severe 1-day ERE-RW occurred on 24-25 July 2005, when 98.2 bcm rainwater occurred sufficient to fill 10 largest dams of the country. This rainstorm continued for 17 days (up to 10 August), the country received 503.1 bcm of rainwater- one-third of the surplus rainwater normally available for surface storage, deep ground water recharge, and river/stream flows. The annual maximum rainwater series (1951-2007) is highly correlated (CC = 0.71) with the corresponding wet area and moderately correlated with the rainfall intensity (CC = 0.47). Hence, normally the ERE-RW is relatively well spread and more intense.

The ST-ERE-RI, the ST-ERE-AE and the ST-ERE-RW

In the preceding three analyses, only grids continuously under wet condition for specified duration are considered. The set of wet grids for 2-day is a subset of the wet grids for 1-day, the set of wet grids for 3-day is a subset of the wet grids for 2-day which is a subset of wet grids for 1-day and so on. In the following three analyses, this constraint is dropped. That is for 1-day, consecutive 2 days, consecutive 3 days etc set of grids under wet condition could be different. In other words, for specified

duration the grids under wet condition were freely selected from the entire domain of the country. For 1-day, the mean and the most severe event of both the ERE-RI and ST-ERE-RI are the same.

ST-ERE-RI – For 1- to 25-day duration, normally the RI decreases in an exponential manner from 43.2mm/day to 28.9mm/day and the wet area from 25.8PAI to28.6PAI, and it occurs around 15 July to 2 August. The most severe 25-day ST-ERE-RI occurred in 2007 when it rained over 41.0PAI at the rate of 33.8mm/day starting from 16 June.

ST-ERE-AE – For 1- to 25-day, normally the RI decreases in an exponential manner from 29.1mm/day to 27.1mm/day and the wet area from 49.8PAI to 33.9PAI, it occurs around 16 July to 24 July. The most severe 25-day ST-ERE-RI occurred in 2005 starting from 12 July when it rained over 43.9PAI at the rate of 31.5mm/day.

ST-ERE-RW – For 1- to 25-day, normally the RW increases in an exponential manner from 46.2 bcm to 679.5 bcm, and it occurs around 14 July to 22 July. The most severe ST-ERE-RW of 2005 produced rainwater of 971.9 bcm over the country in 25 days starting from 12 July. So, unprecedented rain event over Mumbai region on 26-27 July 2005 was embedded in this long period large-scale intense rain spell over the country.

There is no spatially coherent robust long-term trend in any parameters of the ERE and ST-ERE over the period 1951-2007.

The 1-DLLG ST-ERE

On 26-27 July 2005 (0300 UTC 26 July 2005 to 0300 UTC 27 July 2005), the India Meteorological Department (IMD) observatory at Santacruz International Airport (19.11°N, 72.85°E) on the north side of the metropolis Mumbai (18°56'N, 72°51'E) located on the west coast of India between the Arabian Sea and the Western Ghats mountains recorded the highest 1-day rainfall of 944 mm. However, the non-IMD rainguage at Lake Virar (15 km northeast of Santacruz) recorded the same day rainfall of 1049.0 mm. Detailed spatial analysis of rainfall of 26-27 July 2005 shows that northern Mumbai received torrential rains but southern part was relatively dry. Therefore, the rainfall of 27 July 2005 for 1-DLLG around Santacruz is drastically low (473.3mm). Nevertheless, for 1-DLLG this is still the highest 1-day rainfall amount during the period of study (1951-2007). Using satellite and radar inputs combined with synoptic and thermodynamic analysis, it is concluded that formation of mesoscale convective systems over Mumbai region comprising super thunderstorm cells and their interaction with the synoptic scale low pressure area from the Bay of Bengal led to the concentrated very high intensity rainfall. It may be noted that active monsoon conditions over north Konkan are usually associated with a trough off the West Coast of India, formation of lows/depressions over north Bay of Bengal, presence of mid-tropospheric cyclonic circulation (MTC) off north Maharashtra-south Gujarat coast between 700 and 500 hPa and strong pressure gradient along the coast. The extreme event caused enormous loss of life and property. Attempts have been made with some success to simulate this extreme rainfall event using numerical weather prediction (NWP) models. Perhaps similar meteorological condition can be attributed as possible cause of heavy rainstorms across the country.

This analysis is intended to understand whether unprecedented extreme rain event over Mumbai (India) on 26-27 July 2005 was an isolated episodic ERE or a realization of long-term trend in the spatio-temporal EREs over the country. The annual maximum 1-DLLG rainfall series (1951-2007) for 1-day has been developed by screening yearwise highest rainfall amount from among the 365/366 daily rainfall of the 287 1-DLLGs. Similarly, the annual maximum 1-DLLG rainfall series for 2-, 3-…150-day duration has been developed for an elaborate analysis of the spatio-temporal features of the extreme rain events over the country. For each of 1-day, 2-day, 3-day.....150-day durations, map of India showing location of annual maximum 1-DLLG rain event has been prepared. A large wandering over almost the entire country is seen in the occurrence of 1-DLLG spatio-temporal EREs (ST-EREs) of 1-day to 5-day durations. For 6- to 30-day durations the 1-DLLG ST-EREs showed a tendency to occur relatively frequently along the West Coast. For more than 30-day durations, the extreme rainfall occurred every year along the West Coast. Thus, the orographic effect of the Western Ghats produces long duration extreme rainfall events during the monsoon period. The synoptic meteorological aspects of the interactions between Arabian Sea monsoon and the Western Ghats (the off-shore trough) also play a crucial role. The mean of 1-day 1-DLLG ST-ERE is 340.7mm, and it increases in an exponential manner to 4612.3mm for 150-day duration. The highest

1-day 1-DLLG rainfall of 473.4mm occurred over Mumbai region on 27 July 2005. With the increase of duration, the highest rainfall amount increases in an exponential manner. For 150-day, the highest rainfall is 7797.5mm which occurred along the West Coast in 2006 starting from 11 May.

From application of different statistical tests, a robust significant long-term rising trend is inferred in rainfall amount of the 1-DLLG ST-EREs of 1- to 5-day durations (Figure 1). Compared to the period 1951-1977, the 1- to 5-day extreme rainfall has increased by 9 to 15 percent during 1978-2007 and the longer duration extremes (6- to 150-day) by 1 to 6 percent (statistically not significant). In recent decades, the 1-DLLG ST-ERE has shown a tendency to occur at an earlier date by 12.5 days- the mean date during 1951-1977 was 9 August and during 1978-2007 27 July. However, this temporal shift is statistically not significant due to large standard deviation (44.5 days) in the interannual occurrences of the 1-DLLG ST-ERE. From the results it appears that, the unprecedented rainfall over Mumbai on 26-27 July 2005 is a realization of significant rising trend in the 1- to 5-day 1-DLLG ST-EREs across the country. However, this could be an impact of global warming on the Indian summer monsoon circulation and the associated rainfall activities. It appears that during global warming the 'heat-low' over northwest India and upper tropospheric anticyclone over Tibet-Himalaya highlands shift westward. Consequently, the area of convergence and associated rainfall activities show a tendency to shift westward from central to northwest India. However, this proposition requires investigation. The researchers have reported westward shift in the summer monsoon rainfall over northern India due to rising trend in the northern surface air temperature.

The Major Convergences in the Oriental Monsoon Circulation

Local (point) unprecedented rain events are embedded in long-period large-scale extreme rainfalls. We provide a background of meteorological conditions that caused unprecedented rainfall over Mumbai region on 26-27 July 2005. The seasonally (boreal summer) occurring, large-scale lower tropospheric converging air with embedded various secondary circulations (line, circular, meander-eddy, wave, thunderstorm and orographic ascent) produce frequent rains/rainspells over the Asia-Pacific region is popularly known an Asian summer monsoon circulation. The Coriolis force, orography and diabetic heating affect large-scale monsoon flow. During active phases of the Oriental monsoon circulation, seventeen convection-convergence zones develop which produce rainfall (Figure 2). Following factors are responsible for the occurrence of different convergences (accumulation of mass or moisture).

i. *two large-scale flows in opposite direction;*
ii. *two large-scale flows in one direction but with different velocity,*
iii.
iv. *resulting in development of shear zone;*
v. *between the two subtropical anticyclones;*
vi. *formation of trough due to orography;*
vii. *presence of low pressure area in the vicinity; and*
viii. *effect of Coriolis force.*

1. Western North Pacific Convergence (WNPC) - *Outflows from the Australian High and the South Pacific High after crossing the equator become southwesterly which converge with an outflow from the North Pacific High to form northwest-southeast oriented line converge over the western North Pacific Ocean.*

2. East Asian Convergence (EAC) *– It is a southwest-northeast oriented eddy convergence over the Korea-Japan-North Pacific Ocean. The warm tropical airflows from the North Pacific Ocean High and the monsoon flow over the Arabian Sea, the Bay of Bengal and the South China Sea, and cold extratropical westerlies combine to form this convergence over eastern Asia.*

3. East Indonesia Convergence (EIC) *– It is a circular convergence between cross equatorial flow and the North Pacific easterlies over eastern Indonesia.*

4. West Indonesia Convergence (WIC) *– It is like the EIC but over western Indonesia.*

5. Andaman Islands Convergence (ANC) *– A circular convergence develops due to wind*

shear in the monsoon flow over the Andaman Nicobar Islands.

***6. Indo-China Peninsula Convergence (ICPC)** – The main monsoon flow takes a meander over the Indo-China peninsula causing development of a convergence.*

***7. Bay of Bengal Convergence (BBC)** – The monsoon flow takes a U-turn over head Bay of Bengal resulting frequently into circular convergences (low, depression, cyclonic storm and severe cyclonic storm). The disturbances travel westward/northwestward under the steering influence of the monsoon flow, and produce ample rainfall along their path.*

***8. Northeast India- Myanmar Convergence (NEIMC)** – A U-turn in the monsoon flow and orographic effect causes this convergence over northeast India and Myanmar region.*

***9. Yangtze River Convergence (YRC)** – A line convergence develops over the China's Yangtze River basin due to a direct collision between northwesterly and the monsoon flow.*

***10. Sri Lankan Convergence (SLC)** – A convergence develops over Sri Lankan area due to formation of trough in the monsoon flow between the Arabian Sea and the Bay of Bengal.*

***11. East Coast of India Convergence (WCIC)** – This convergence occurs along the East Coast as a north-south trough develops in the monsoon flow after crossing the Western Ghats due to meandering of the flow before converging into the 'heat low'.*

***12. Indo-Gangetic Plains Convergence (IGPC)** – It is a line-cum-eddy convergence over the Indo-Gangetic Plains. The monsoon flow from the Arabian Sea and northwesterly from the Iranian High forms a line convergence over central India, and the combined flow forms eddies over the Indo-Gangetic Plains before converging into the 'heat low'. This is also popularly known as monsoon trough.*

***13. West Coast of India Convergence (WCIC)** – Frequently a trough forms and convergences occur in the monsoon flow along the West Coast due to orographic effect of the Western Ghats. The most intense rainspells occur over this part of the country.*

***14. Gujarat-Kutch Convergence (GKC)** – A circular convergence develop at mid-tropospheric level (600-400 hPa) over Gujarat-Kutch region, which gives rise to intense and ample rainfall.*

***15. Pakistan-Afghanistan Convergence (PAC)** – Similar to the YRC a line convergence develops over Pakistan and Afghanistan border.*

***16. Central Arabian Sea Convergence (CASC)** – It is a line convergence between northwesterly outflow from the Iranian High and cross equatorial flow from the Mascarene High over the central Arabian Sea.*

***17. Saudi Arabia Convergence (SAC)** - It is similar to the YRC over Saudi Arabia.*

Following changes in the monsoon circulation can be seen much before the occurrence of intense ST-ERE over any location across of the country.

i. intensification of the monsoon circulation (low-level convergence into heat low over Middle East and Siberia-Mongolia, upper level divergence from the anticyclone over the Tibet-Turkey sector, outflows from the anticyclone in all directions, subsidence over the eight deep highs and return flows from the deep highs converging into the heat low;

ii. accumulation of huge moisture in the atmosphere and thickening of the moist layer;

iii. integration of the WCIC, the IGPC and GKC and development of a huge low-pressure spread over Indian subcontinent, Middle East and China-Mongolia sector; and

iv. occurrence of depression/cyclone over northwest India.

During 2005, intensification of the monsoon circulation started around 12 July, attained a peak round 26-27 July, which continued up to 10 August with small variation. Daily percentage area of the country under wet condition and rainwater over the wet area during 20 July through 6 August 2005 is shown in Figure 3.

CONCLUSIONS

- *Warming of global troposphere causes intensification vertical moisture flux convergence, which causes frequent*

occurrence of small-scale, short-period intense extreme rain events, while their horizontal integration causes large-scale, long-period heavy rainspells.

- *Monitoring global tropospheric on the real time basis using adequate network of surface and upper air observations with quality instruments is essential to forecast short range (few hours to few days) behavior of the convergence zones.*

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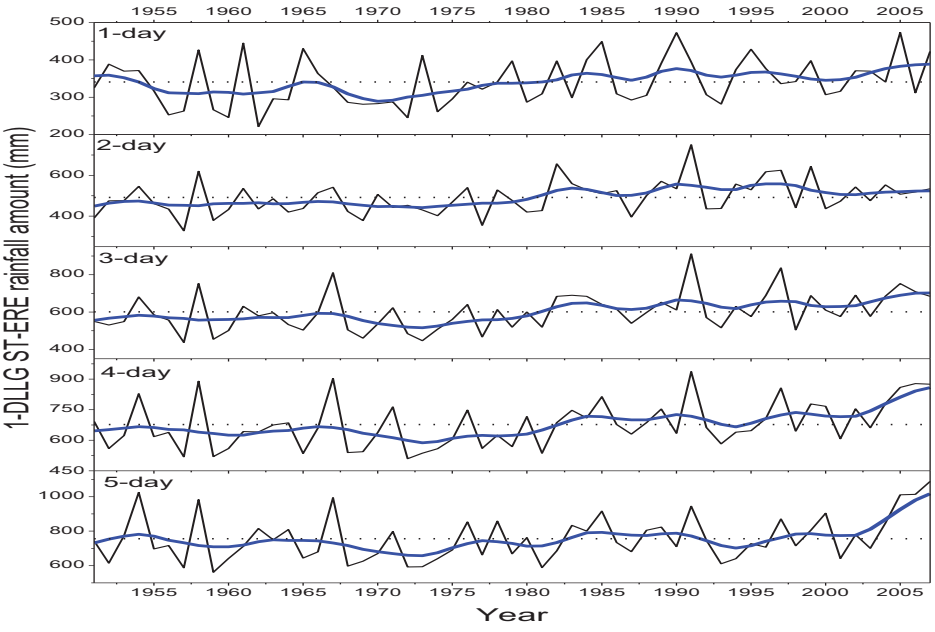

Figure 1. Interannual variation in 1-day 1-DLLG ST-ERE rainfall (mm) and its date of occurrence. Thin curve is the actual values and the thick curve 9-point Gaussian low-pass filtered values.

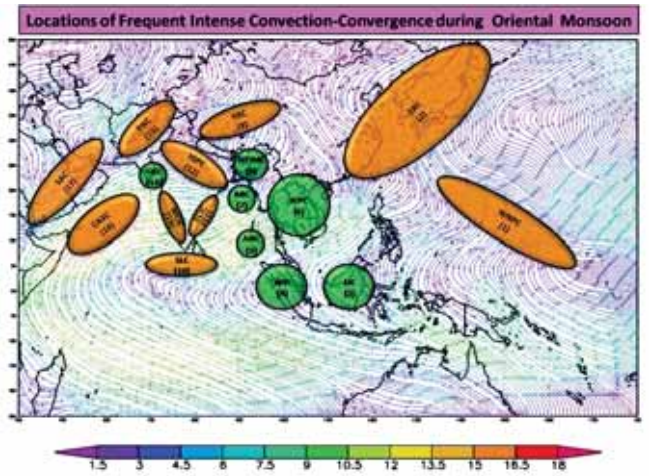

Figure 2. Low Level (1000-850 hPa) wind pattern and location of the 17 major convergences in the Oriental monsoon circulation.

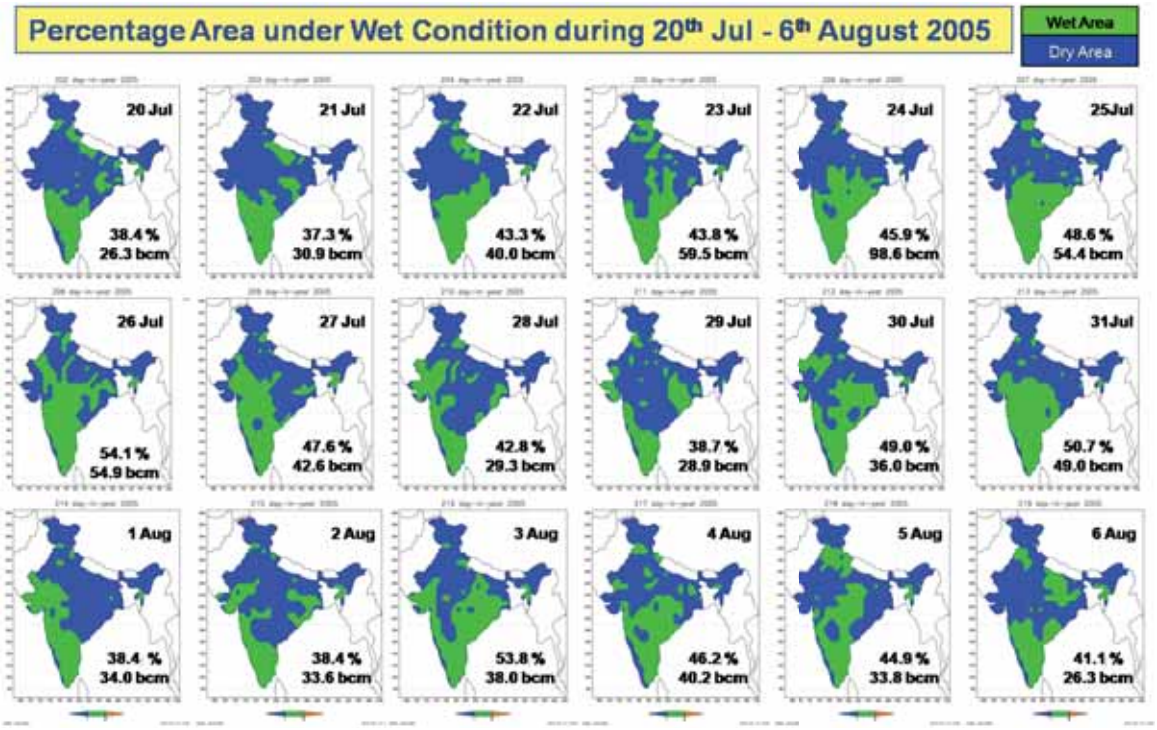

Figure 3. Percentage area of India (PAI) under wet condition and the rainwater (in bcm) over the wet area during 20th July – 6th August 2005.

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Physical Sciences of the Ocean: A report to IAPSO 2011

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Indian contributions in the research areas of International Association for the Physical Sciences of the Ocean (IAPSO-IUGG) during 2007-2010 are categorised under the topics on:

- *(i) ocean circulation,*
- *(ii) physical processes in the seas around India,*
- *(iii) ocean-atmosphere interaction,*
- *(iv) waves and internal waves,*
- *(v) remote sensing of oceans,*
- *(vi) tides, sea level and storm surges,*
- *(vii) sediment transport and coastal erosion,*
- *(viii) physio-chemical processes in the estuaries,*
- *(ix) water quality and pollution levels in the near-shore waters,*
- *(x) bio-geochemistry,*
- *(xi) climate change,*
- *(xii) tsunami and*
- *(xiii) ocean acoustics, optics and instrumentation.*

All together 461 research papers were published during 2007-2010 involving 825 researchers from 148 research institutes/universities. Forty one papers were co-authored with 31 researchers from other countries (24 countries). This indicates the interest of Indian researchers in collaborating with foreign researchers. The spurt that occurred in the research related to the effects of tsunami on the Indian coast continued during 2007-2010 also. Another note worthy feature of the publications during 2007-2010 is that the number of papers that used numerical/mathematical models increased compared to previous years. Thirty nine papers published during this period used numerical/ mathematical models as a tool to understand and document the physical processes in the Indian Ocean including the coastal seas. Similarly, several papers utilised sophisticated quantitative methods to analyse as well as to understand the data.

The papers categorised under the category of ocean circulation (21 publications) dealt with open ocean currents including their macro and micro features like eddies, boundary currents, etc using observations or models or both. A few of them also, dealt the ocean circulation using paleo indicators like isotopes or foraminifera.

The papers on the physical processes (64 publications) in offshore as well as coastal waters of seas around India, equatorial and southern Indian Ocean and Gulf of Aden utilised observations (in situ and satellite) and models. Those publications reported on the analysis of basic mechanisms involved in the physical processes and also the linked the physical processes to the distribution of nutrients in the ocean. A sizable number of them analysed the variability (intra-seasonal, seasonal, annual and intra-annual) of oceanic parameters associated with various physical processes. Those publications concentrated on the coastal waters of India and adjoining seas also documented the ecological variability associated with the physical processes, effects of estuarine flow on ocean circulation, waves and currents in the Gulfs, Bays, coastal waters, etc. Few publications reported on the use of techniques like soft computing, multiple regression, etc for the prediction of tidal currents and for the estimation of chlorophyll

concentration in the coastal waters. One publication described the water masses in the Gulf of Aden and another one described the hydrodynamics observed along a section from Africa to Antarctica.

The publications categorised under, ocean-atmosphere interaction (45 publications), covered the response of ocean to tropical cyclones and monsoons, effects of ocean-atmosphere interaction on monsoons, air-sea fluxes, Indian Ocean Di-pole (IOD), El Nino etc. Some of them also dealt with the variability of atmospheric parameters over the ocean and also contrasted them with the variability over land. In general, a majority of them probed the relationship between monsoonal activity over India in the light of ocean-atmosphere interaction.

Seven publications only appeared during the period, 2007-2010, dealing with waves and internal waves in the localised regions. The publications on internal waves dealt with their impacts on the propagation of sound in the water and the impact of stratification them. The publications on surface gravity waves explored the possibility forecasting the waves using neural networks and numerical models.

Ten publications in the field of remote sensing analysed the satellite data and suggested appropriate algorithms to be employed to retrieve chlorophyll content in the surface waters of coastal and open ocean waters around India and the sea surface winds. A few of them compared the satellite derived parameters with other measurements and models.

Twenty five publications had tides or sea level or storm surges as their core theme. They analysed the tidal propagations or tidal amplitudes along the coast of India using numerical models or through the analysis of time-series data. Few of them also looked at the effects of tides on pollutant dispersion and sediment transport. The publications on sea level described the sea level variability at specific locations on the Indian coast in short as well as long time spans. The publications on storm surges reported the results from models and also made the assessment of the vulnerability of coastlines.

Sediment transport and coastal erosion issues along the stretches of Indian coastline remained the core theme of 37 publications. Some of them discussed about the mitigation methods to contain the coastal erosion and some discussed the impacts of anthropogenic activities on the coast. Remote sensing and GIS technologies were used extensively for the monitoring and assessment.

A sizable number of publications (73 publications) focused on the tidal and physio-chemical processes in the Indian estuaries. A few of them linked these processes to mangrove vegetation and sediment distribution in the estuaries. Some of the publications dealt with the distribution and variability of heavy metals in the estuaries. Some publications also dealt with the bio-chemical process in the Indian estuaries.

Forty seven publications were on water quality and environment. Most of them examined the water quality of coastal and shelf waters and their variability during the tidal cycle. A few of them also dealt with sewage pollution, pesticides, trace metals and heavy metals like mercury.

A sizable number of publications, 29 publications, during this period were on biogeochemistry of deep ocean and coastal waters. Some of them examined the distribution of phytoplankton in relation to ocean dynamics.

Sixteen publications examined the physical aspects of climate change through the analysis of data and models; especially the coupled models of ocean atmosphere. Some of them examined the changes in climate using paleo indicators. Indian researchers

continued to show their interest in documenting the impacts of 2004 Indian Ocean tsunami. Forty six publications dealt with the effects of tsunami, vulnerability of the coastal stretches including creaks and estuaries, and inundation mapping. A few of them focused on the mitigation measures like the construction of shore protection walls.

Thirty one publications were on the subjects like ocean acoustics, optics and measurement techniques.

In summary this report gives an account of the publications emerged from Indian researchers during January 2007 to December 2010 in the field of physical sciences of ocean; mainly pertaining to the Indian Ocean. While, preparing this report we concentrated on the peer reviewed publications ignoring the presentations in symposia and conferences. The number of research papers presented in symposia and conferences will be much higher or equivalent.

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Seismological Research in India: 2007-2010

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1. Introduction

Seismological investigation started with the great 1819 Kutch earthquake (Intensity XI, MM Scale, Oldham, 1928; M ~ 8.4, Richter, 1958; modified to Mw 7.8 by Johnston and Kanter, 1990) in western India. The 1897 great Shillong earthquake (Intensity XII, MM Scale; Ms ~ 8.7, Richter 1958; modified to Ms 8.0 by Ambraseys and Douglas, 2004) is the first Indian earthquake that was instrumentally recorded outside India was investigated in great detail by Oldham (1899). This great earthquake made the then authorities to establish the first Seismological Observatory in Alipore (Calcutta), India in 1898 under the auspices of the India Meteorological Department (IMD). The number of observatories rose to eight in 1950, and then to 15 by 1960 (Kayal, 2008). Till early 1990s the national network consisted of about 60 seismological observatories, out of which four were equipped with the WWSSN (World Wide Seismograph Station Network).

The 1993 devastating intra-plate earthquake (Mw 6.1, depth ~ 6.0 km) that caused about 10,000 casualties in the Killari village, Latur district of Maharasthra state in central India changed the seismological network scenario in the country. The IMD national network was upgraded to three-component digital broadband (BB) seismic observatories, and several Institutes and Universities were also funded by the Department of Science and Technology (now Ministry of Earth Sciences, (MoES), Government of India, for establishment of BB observatories. At present the whole country is equipped with about 200 BB observatories including several telemetric and semi-permanent networks like that in Koyna-Warna, northeast India, Delhi, western Himalaya and in several dam projects. It may be mentioned that the 1997 Jabalpur earthquake (Mw 5.8, depth 35 km) in the Narmada rift basin in central India is the first strong/damaging earthquake which has been well studied using the digital BB network seismograms (Bhattacharaya et al., 1997). Thus digital seismological data acquisition and research started since late 1990s. A brief account of these seismological research activities during the period 2007-10 by several Institutes is given here.

After the great Sumatra earthquake (Mw 9.3) on December 26, 2004 which triggered unprecedented tsunamis, the MoES, Govt of India established the Indian Tsunami Early Warning Centre (ITEWC) at the Indian National Centre for Ocean Information Services (INCOIS), Hyderabad. A 17-station Real Time Seismic Monitoring Network (RTSMN) is in operation since 2007 for this centre.

The present report is based on the available research publications/reports (2007-10) from several Institutes. This report is divided into three sections: i) Himalaya Region, ii) Peninsular India, and iii) Northeast India-Andaman-Sumatra Region.

2 Himalaya Region

The ~2500 km long Himalaya plate boundary generated three great earthquakes (M≥ 8.0), from west to east these are the 1950 Assam, 1934 Bihar and 1905 Kangra earthquakes,

and produced several large earthquakes (M≥ 7.0) during the past century (Fig. 1). Several seismological investigations have been carried out during the reported period 2007-10 to understand seismicity and tectonics of this long Himalayan seismic belt; status of these studies is highlighted here:

2.1 Paleoseismicity

Recent paleoseismological observations suggest a few past great earthquakes in the central Himalaya during AD 1119-1292 (Rajendran and Rajendran, 2010). This observation shed new light on the proposed central seismic gap between the 1934 Bihar-Nepal and the 1905 Kangra great earthquakes.

2.2 Broadband Network and Precursor Observatory

A 40-station BB seismic network is established in the western Himalaya by the Wadia Institute of Himalayan Geology (WIHG) since 2007. Out of these, 10 stations are connected with the VSAT, and the data are recorded by telemetric system at the WIHG, Dehradun for real time monitoring of the Himalayan earthquakes. Along with this telemetric network, the WIHG has established a multi-parameter geophysical observatory at Guttu (Garhwal Himalaya) since 2007 to monitor precursor anomalies. Further, a permanent GPS network and a few campaign mode GPS surveys are carried in the western Himalaya by the WIHG during the reported period for crustal deformation studies in relation to the present seismic activity.

The National Geophysical Research Institute (NGRI) established a 32-station BB network and the Geological Survey of India a 10-station BB network in the eastern Himalaya during the reported period. The WIHG also established a 17-station BB network in the eastern syntaxis zone. These data are used for detailed seismicity, tomography, attenuation and receiver function studies as briefly stated below.

2.3 Recent Seismicity

Recent digital seismic data of the local networks in the Himalaya show that the Himalayan earthquakes are not only confined at shallow depth ≤ 20 km, above the plane of detachment as was envisaged in the conceptual tectonic model, but the earthquakes also occur in the lower crust at depth down to ~ 50 km in the dipping Indian lithosphere. Average Fractal correlation dimension Dc ~0.9 is indicative of near linear faults in the region, while a b-value of ~ 1.02 implies a highly active region. Crustal deformation (GPS) studies shed new light on the plate motion and strain rate in the Himalaya. Earthquake precursor measurements like gravity, seismic, radon gas etc provided some encouraging precursor results for the devastating 2008 Muzaffrabad (Kashmir) earthquake (Mw 7.6).

2.4 Seismic Tomography

The high precision BB seismic phase data are used to estimate 3-D variation of P and S wave velocity structure and Vp/Vs ratio using Local Earthquake Tomography (LET) method. The results revealed major tectonic structures/faults, but the plane of detachment is not well imaged. Ambient noise data recorded by about 70 broadband seismic stations from the INDEPTH-IV network are used for tomographic inversion. The study provides estimates of crustal thickness across the Indo-Gangetic plains and the Himalaya.

2.5 Attenuation (Q) structure

Attenuation or Q structures of some parts of the western Himalaya are estimated. The Q values are mostly less than 200. The intrinsic as well as scattering attenuation parameters (Q values) are estimated. It is observed that the intrinsic attenuation is dominant at shallower depth (<10 km), and with increasing depth intrinsic and scattering attenuation effects have almost equal effects on coda attenuation.

2.6 Anisotropy

Azimuthal anisotropy within the Himalayan collision zone and southern Tibet, obtained by applying the SKS-splitting technique to waveforms from BB seismic stations, reveal significant variations in the strength and orientation of the fast axes. Stations in the Sikkim Himalaya show strong anisotropy south of Main Central Thrust (MCT) with delay times

~1 s. The fast polarization directions are nearly parallel to the strike of the Himalaya mountain chain.

2.7 Receiver Function

In the western Himalaya, joint inversion of the P and S receiver functions suggest high uppermost mantle velocities; the arrival of the Ps converted phase from the 410 km discontinuity is 2.2 s earlier than in IASP91 global model. The fast direction in the lower layer is parallel to the trend of the Himalaya.

The mantle transition zone (MTZ) structures beneath eastern Himalaya and southern Tibet are investigated. The early arrival times (~1.7s compared to IASP91) of the P-to-s conversions from the 410 km discontinuity are attributed to the higher shear wave velocities. In contrast, the conversions from the 660 km discontinuity are either normal or delayed (up to 1s) providing evidences for a thickened MTZ beneath the eastern Himalaya/Tibet region.

2.8 Seismic Microzonation

Under the MoES programme, microzonation of the urban cities in several cities in the Himalaya and foothills region are jointly taken up by different organizations. Detailed microzonation seismic hazard maps for the Dehradun city and Sikkim Himalaya are published.

3 Peninsular India

Peninsular India constitutes one of the prominent and largest Precambrian shield areas of the world. The Indo Gangetic Alluvial Plains (IGAP) separates the Himalayas to the north and the peninsular India Stable Continental Region (SCR) to the south. The SCR earthquakes are still enigmatic having strong association with rift basins and extended crust. During the last decade there have been three devastating earthquakes in the SCR, two in the rift basins, the 2001 Bhuj earthquake (Mw 7.7) in the Kutch rift and the 1997 Jabalpur earthquake (Mw 6.0) in Narmada rift, and one in the shallow extended crust, the 1993 Killari earthquake (Mw 6.3) in the Laur district in central India. As stated above, since 1997 the national network is up graded to BB network, and these data contributed significantly in seismological research, the results obtained during the last three years are highlighted here.

3.1 Paleoseismicity

Paleo-liquefaction features, combined with archeological data, provide evidence for occurrences of two previous earthquakes at the 2001 Bhuj earthquake source zone about 4000 and 9000 years ago.

3.2 Receiver Function

Shear-wave receiver function analysis indicates that among the fragment of Gondwanaland, the thinnest lithosphere is under Indian continent. The lithospheric roots in South Africa, Australia and Antarctica are between 180 and 300 km deep, whereas the Indian lithosphere extends only about 100 km deep. It is inferred that the plume that partitioned the Gondwanaland may have melted the lower half of the Indian lithosphere, thus permitting faster motion.

3.3 Anisotropy

Azimuthal anisotropy obtained by analyzing the SKS and SKKS waveforms from 85 earthquakes recorded at 35 BB seismic stations in the SCR India show that the delay times (δt) between the fast and slow axes of anisotropy are close to 1s, which is the global average for continental shield regions. Most of the fast axes azimuths are explained by the absolute plate motion related strain. Further, the attenuation characteristics are studied and it is found that the effect of scattering is maximum at frequency corresponding to scale length of heterogeneities, and the seismically active regions exhibit low intensity of scattering compared to stable ones.

3.4 Reservoir Triggered Seismicity

The world's largest reservoir triggered earthquake (Mw 6.3) occurred in Koyna in 1967, and since then it's a filed laboratory for the seismologists to understand reservoir triggered seismicity (RTS). Seismic activity in the Koyna-Warna region is being constantly monitored since 2005 through a 10-station telemetric BB network. During January 2008 to February 2009 the Warna region showed an

enhanced seismic activity. Moment tensor inversion of the larger events show normal fault mechanisms. Forecasts of earthquakes (M.>4.0) are successfully attempted based on nucleation hypothesis (Gupta et al., JGSI, 2007). The co-seismic water level changes in wells are also studied to simulate volumetric strain that show good agreement with magnitude and reported volumetric strain.

3.5 Bhuj Aftershock Network

After the devastating 2001 Bhuj earthquake the Gujarat state Government has established a 50-station BB network in Bhuj, Kutch basin area. An Institute of Seismological Research (ISR) is established by the state Government in Gandhinagar, Gujatrat to study the Bhuj earthquakes. The NGRI also continued its semi-permanent network to monitor the aftershocks since 2001. All these data have contributed significantly to study tectonics, tomography and the deeper structures in the Kutch basin. In addition, the ISR has instrumented the area with permanent and campaign mode GPS networks, 50-station permanent Strong Motion network and with three multi-parameter geophysical observatories.

3.6 Microzonation and Seismic Hazard Mapping

A detailed study on microzonation and seismic hazard is made for the Bhuj area and also for the Ahmedabad city in the Gujarat state during the reported period. Further, under the programme of earthquake risk and disaster mitigation, the National Disaster Mitigation Authority (NDMA) has taken up a joint project with different organizations to revise the seismic hazard map of the country.

4 Northeast India-Andaman-Sumatra

4.1 Northeast India Region

The northeast India region, the zone V in seismic zoning map of India, produced two great earthquakes (M> 8.0), one in 1897 in the Shillong Plateau and the other in 1950 in the Assam-Tibet border at the Assam syntaxis zone. About 20 large earthquakes, 7.0 $\leq$ M < 8.0, occurred in the region since the 1897 great Shillong earthquake. The region is well instrumented with about 45 BB seismic stations by the IMD, NGRI, NEIST (Northeast India Science & Technology), GSI (Geological Survey of India) and Universities. A 17-station telemetric network is in operation by the VSAT link for online data transfer to the Geoscience Division, NEIST, Jorhat. In addition, the Earthquake Engineering Department, IIT-Roorkee runs a 40-station strong motion network in the region. Further, the WIHG established a 13-station BB array for more than a year in the syntaxis zone during the reported period. These data are analysed at the respective institutes and also by several other organizations on collaboration. A few results are highlighted here.

4.1.1 Seismicity and Tectonics

The Arunachal Himalaya earthquakes at the Himalayan collision zone are mostly confined to 70 km, where as the Indo-Burma zone earthquakes show a dipping seismic (Benioff) zone and go down to 200 km. In the Shillong Plateau the earthquakes are mostly confined within a depth of 35 km, and are explained by pop-up tectonics of the plateau. To the east of the Shillong Plateau lies the Mikir massif, which is separated from the Shillong massif by the long northwest-southeast Kopili fault. Intense seismic activity recorded along this fault down to 45 km depth is explained by transverse tectonics. The recent two felt earthquake, the Mw 5.4, August 19, 2009 in the Assam valley and the Mw 6.3, September 21, 2009 earthquake in the Bhutan Himalaya are explained by transverse tectonics of the gigantic ~ 400 km long and ~ 50 km wide Kopili fault zone. Recent paleoseismic study by the NGRI scientists revealed that a few past earthquakes occurred at the Kopili fault zone.

Crustal discontinuities are studied using the BB digital waveforms of the local earthquakes; the seismic phases that are reflected at the discontinuities are inverted to estimate the depths. The results show that the Conrad discontinuity is at 18±0.5-20±0.5 km beneath the Shillong plateau-Mikir Hills, and the Moho discontinuity is at 30±1.0 km beneath the Shillong plateau and at 35±1.0 km beneath the Mikir Hills.

Stress inversion study shows that the maximum compressive stress rotates from NE–SW across the inner and northern arc to E–W near the Bengal basin. This rotation is consistent with the deformation partitioning reflected in the rotation of relative displacement vectors, from a SSW-directed Sunda–Burma motion to a WSW-directed Burma–India motion.

4.1.2 Seismic Tomography, b-value and Fractal Mapping

Seismic tomography, b-value and fractal mapping clearly imaged the seismic source zones beneath the Shillong plateau and the Kipili fault with high Vp, high b-value and fractal dimensions. The thick (~20 km) sediments of the Bengal basin to the south of the Shillong plateau have been well identified as a low velocity zone.

4.1.3 Attenuation structure

The coda wave attenuation, quality factor Qc increases with the increase of frequency with an average attenuation relation $Qc = 52.32 \pm 1.07 f^{(1.32 \pm 0.04)}$*. The spatial distribution of Qc indicates that the Mikir Hills, Arunachal Himalaya and western part of the Shillong plateau are characterized by lower attenuation.*

4.1.4 Receiver Function

The receiver functions show an azimuthally varying crustal structure in the Assam syntaxis region. The overall thickness of the crust across the syntaxis is ~55 km, much less compared to that observed in the northwest and central Himalaya (~70 km); this is attributed to slower rate of convergence in this part of the collision zone.

4.1.5 Microzonation Seismic Hazard Mapping

A detailed hazard and risk analysis is made to achieve design PGA (peak ground acceleration) and response spectra related to earthquake source, site and attenuation using available strong ground-motion data of recent earthquakes recorded in the region. The microzonation seismic hazard/risk maps are published. Synthesis of strong ground motion and response spectrum are also studied for the region.

4.2 Andaman-Sumatra Region

The Burmese-Andaman-Sumatra-Sunda arc defines a ~5500 km long boundary between the Indo-Australian and Eurasian plates, from Myanmar to Sumatra and Java to Australia. The plate boundary separates the northeast moving Indian plate from the southeast Asian plate that includes Burma, Andaman and Sunda microplates. It has been suggested that the Indian plate converges obliquely toward the Asian plate; the oblique convergence caused formation of a sliver plate between the subduction zone and the right-lateral Sumatra and Java fault systems in the southern part and the Sagaing fault system in the northern part, and opened the Andaman Sea Ridge (ASR) in the Andaman Sea. The nature of convergence varies from continental type in the Burmese arc to oceanic type in the Andaman-Sunda arc. The Andaman-Sumatra arc is seismically very active, and falls in the category of highest seismic hazard zone (V) at par with the northeast India region.

4.2.1 Seismicity & Tectonics

The Andaman-Sumatra section of the subduction zone had produced several large and great earthquakes in the past; some of which generated destructive tsunamis. Largest among them are the historical earthquakes that occurred in 1833 (M~8.7), 1861 (M~8.5), 1881 (Mw 7.9) and 1941 (Mw 7.7). While these large earthquakes ruptured only a few hundreds of kilometers (~200-300 km) of the plate boundary, the 2004 tsunamigenic mega thrust earthquake (Mw 9.3) and its large series of aftershocks ruptured more than 1300 km length of the arc between Sumatra and Andaman islands, stripping the regions that were ruptured in the past as well as the intervening unbroken patches. Post-2004, the seismicity along the Andaman segment is dominated by extensional events, the largest of which occurred at Coco Island on August 10, 2009 (Mw 7.5).

After the 2004 Andaman-Sumatra earthquake, the Andaman-Nicobar islands were well equipped with BB seismic stations by the IMD, GSI and NGRI, and with the GPS instruments

by the GSI and NGRI. These data are well studied and published in the international journals as listed below.

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Indian research on geological and geophysical studies of present and past volcanic activities of the Indian shield and adjoining deep-sea regions: 2007-2010

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1. Introduction

During the last four years (2007-2010) Indian earth scientists from different institutions (Geological Survey of India, National Institute of Oceanography, National Geophysical Research Institute, University of Kolkata, etc.) have devoted significant time for investigations of past and present volcanic activities of Indian shield and adjoining ocean regions using geophysical data and geological samples. The investigations are more focused on volcanism of the Andaman-Nicobar Islands and mantle plume generated aseismic ridges of the Indian Ocean, such as Ninetyeast, Chagos-Laccadive, Comorin and 85°E ridges. The studies have been successfully carried out by compilation of existing underway geophysical data available at NIO database, NGDC database and industry and by acquiring new geophysical data and geological sampling from the Ninetyeast Ridge and from the Andaman Islands region. The datasets are methodically analyzed, modeled and interpreted for understanding the geological processes related to structure and tectonics of the volcanic features. These studies have led to better understand the origin of the volcanic ridges and their isostatic compensation mechanisms, plume-spreading ridge interactions during the emplacement of the volcanic edifices and recent volcanic activities in Andaman Islands region.

2. Investigations of major volcanic features of the Indian Ocean

The Indian Ocean includes numerous elevated features such as linear volcanic ridges, seamount chains, oceanic plateaus, submerged micro-continents, etc., which eventually led the Indian Ocean to comprise several of the oceanic basins. The Ninetyeast and Chagos-Laccadive ridges are the most prominent linear volcanic features in the seas surrounding the Indian continental margins, besides there are other smaller volcanic features, such as Comorin Ridge, 85°E Ridge, etc. The observations and interpretations of each geological feature is comprehensively mentioned below.

2.1 Structure and isostatic model of the Comorin Ridge

Bathymetry, gravity and magnetic profile data across the Comorin Ridge and in its vicinity, north central Indian Ocean were investigated using transfer function and forward model techniques to determine the elastic plate thickness (Te) and crustal thickness (t), thereby to understand the mode of isostatic compensation and origin of the ridge. The ridge stretches for about 500 km in NNW-SSE direction with variable reliefs along the strike and gradients across the flanks. Geophysical profile data show that the ridge is associated with low-amplitude gravity anomalies compared to ridge relief, suggesting that the anomalies are compensated at deeper depths. From Admittance analysis an Airy model or local compensation with an elastic plate thickness of about 3 km and crustal thickness of 15-20 km is suggested for southern part of the Comorin Ridge (south of 5°N), whereas for the northern part a flexural plate model with an elastic thickness of about 15 km is obtained. The

admittance results together with results from forward modeling of gravity anomalies reveal that the south part was emplaced relatively on weak oceanic crust, implying that the lithosphere beneath this part of the ridge was deformed due to both surface and sub-surface loads, while the north part was emplaced on the continental crust. The results coupled with published plate kinematic models of this region suggest that the Comorin Ridge was evolved at about 90 Ma during the rift stage of Madagascar from the southwest of India. Further we have demarcated the continent-ocean boundary on west of Sri Lanka and southern tip of India, which runs across the strike of the ridge, placing northern part of the ridge on continent and southern part on oceanic crust. Eastern flank on southern part of the ridge is steep-faulted up to 0.6 km and is controlled by the 79°E FZ and then by continent-ocean boundary.

2.2 Structure and evolution of the 85°E Ridge

The 85°E Ridge extends from the Mahanadi Basin, off northeastern margin of India to the Afanasy Nikitin seamount in the Central Indian Basin. The ridge associates with two contrasting gravity anomalies: negative anomaly over the north part (up to 5°N latitude), where the ridge structure is buried under thick Bengal Fan sediments and positive anomaly over the south part, where the structure is intermittently exposed above the seafloor. In contrast to this, the ridge consists of alternate streaks of positive and negative magnetic signatures distributed for asymmetrical extents. Ship-borne gravity and seismic reflection data are modeled using process oriented method, and the analysis suggest that the 85°E Ridge was emplaced on approximately 10-15 km thick elastic plate (Te) and in an off-ridge tectonic setting.

The gravity anomalies of the 85ºE Ridge are reconstructed with possible crustal structures of different geological ages since the ridge formation. At the time of ridge emplacement, that is during the late Cretaceous the ridge was associated with a significant positive anomaly with a compensation generated by a regional flexure of the Moho boundary. By early Miocene the ridge was approximately covered by the post-collision sediments and led to alteration of the initial gravity anomaly to a small positive anomaly. At present, the ridge is buried by approximately 3 km thick Bengal Fan sediments on its crestal region and about 8 km thick pre- and post-collision sediments on the flanks. This geological setting had changed physical properties of the sediments and led to alter the minor positive gravity anomaly of early Miocene to the distinct negative gravity anomaly. The study shows that the negative gravity anomaly signature the 85ºE Ridge has changed through time from its inception (positive anomaly) to present (negative anomaly).

Further both positive and negative magnetic anomalies of the 85°E Ridge are modeled using its seismic structure and geomagnetic polarity reversals. This shows that the ridge was formed during the period of rapid changes in Earth's magnetic field, earlier to that, the underlying oceanic crust was created in Cretaceous super-long normal polarity phase. The results further reveal that the positive and negative magnetic signatures of the ridge have been created, in general, by a relief of the ridge and polarity contrast between the ridge material and adjacent oceanic crust, respectively. On correlation of ridge's magnetization pattern to the geomagnetic polarity timescale, it is believed that the 85°E Ridge volcanism started at anomaly 33r time (~80 Ma) in Mahanadi Basin by a short-lived hotspot, thereafter the process continued towards south and finally ended at ~55 Ma in the vicinity of the Afanasy Nikitin seamount.

2.3 Structure and tectonics of the Ninetyeast Ridge

A major scientific expedition in the Indian Ocean was accomplished onboard R/V Roger Revelle (KNOX06RR) to investigate the evolution of the Ninetyeast Ridge and to understand the spreading activity particularly in close proximity to the Kerguelen hotspot. Magnetic anomaly studies of both the Central Indian and Wharton basins have provided precise locations of lineations from 19 through 34 and fossil ridge segments, which ceased spreading at 65 and 42 Ma. The lineation offsets are further constrained by narrow gravity features of the satellite gravity data and interpreted them as oceanic fracture zones. From the trends of NER bathymetry and fracture zones it is found that the NER trends in N10°E and obliquely crosses N5°E oriented fracture zones. Thus the 89°E FZ in the south borders the Ninetyeast Ridge on east side, while in the north the same FZ borders the ridge on

west side. In both locations it exerts significant control of the morphology of the ridge.

Interpretation of magnetic data revealed that the age of oceanic crust to the west of the 86°E FZ increases towards north from early Cenozoic to late Cretaceous, while the crust to the east of the 90°E FZ increases its age in both north and south directions about middle Eocene fossil ridge segments. Contrasting to these trends, the crust between the FZs near NER shows a complex age succession together with fossil ridge segments of different ages (65 and 42 Ma). Newly determined radiometric ages of the NER reveal that the ridge was emplaced from 77 to 43 Ma at a rate of 118±5 km/Myr (Pringle et al., 2008). The age of the ridge is decreases towards the south with remarkable linearity. The radiometric ages indicate that the ridge was formed at a rate of twice that of the formation of adjacent oceanic crust (48 – 58 km/Myr).

The Wharton spreading ridge segments, particularly in a strip between 86°E FZ and 90°E FZ and the Kerguelen hotspot were often in close proximity due to ridge jumps. Excess heat from the hotspot activity may have weakened the lithosphere and possibly led to southward ridge jumps at discrete ages. A large offset transform fault (86°E TF) once connected the India-Antarctica and Wharton ridges, appears to have become mechanically unstable whenever both the Kerguelen hotspot and ridge-segments are in close proximity. These conditions possibly have facilitated the ridge-segments to jump southward repetitively during the period 65 – 42 Ma. The difference in lengths of the NER (~3980 km) and adjacent oceanic crust (~2000 km) of the same age span is remarkable and requires a geodynamics explanation. Apparently southward ridge jumps lengthened the portion of Indian plate beneath the NER as the spreading ridge segments migrated southward to stay with a southward drifting of Kerguelen hotspot. Taking into account of spin axis deviation by no more than ~5° over the last 130 Myr, we provide an approximate estimate of 42 mm/yr hotspot drift towards south-southwest direction for the formation of extra track of the NER.

Elastic plate thickness along Ninetyeast Ridge from 28°S to 8°N has been determined using flexural modeling and admittance analysis of 72 gravity and bathymetry profiles. The results suggest that, southern (south of 22°S) and northern (north of 2°N) part of the ridge are flexurally compensated with elastic plate thickness values of >12 and >18km respectively. Admittance analysis suggests that the central part (20°S to 2°N) of the ridge has Airy type compensation with crustal thickness 15-20 km. However, Te values derived using flexural modeling along profiles revealed that that central part of the ridge could be further divided into 1) south-central part (18°S to 8°S) were the Te values constantly decreases from 20km to 5km and 2) north-central part (8°S to 2°N) were Te values randomly varies between 2-25 km.

Crustal structure of the Ninetyeast Ridge are interpreted using 2D gravity forward modeling of five east-west gravity profiles taking constraints from seismic results in view of its isostatic compensation. The results suggest that the crustal structure beneath Ninetyeast Ridge shows considerable variations. In the southern part at ~26°S, the ridge topography is compensated by down flexing of crustal layers 2B, 2A and 3A with amplitude of about 2.5-3 km. In the south-central part (~13.5°S) suggests very thick (20 km) oceanic crust beneath the along with underplated body of ~10 km thick. In north-central part gravity models at 3°N suggest thickening of crust beneath the ridge topography, in contrast at 4°N the shows a different crustal structure, where the volcanic load is supported by down-flexing of crustal layers. These crust mantle configuration derived from the 2D forward modeling is in good agreement with the Te values obtained along the respective profiles.

Based on the present results and available plate reconstruction models a plausible evolutionary model for the Ninetyeast Ridge is proposed. The southern part of the ridge was emplaced on a lithosphere of intermediate strength possibly along the edge of Indian plate whereas northern part was emplaced in an intraplate setting. The highly variable isostatic compensation mechanism in the central part of the ridge could be as a manifestation of the complex interaction of the Kerguelen hotspot and spreading ridge segments. The north-central part must have emplaced on a crust of highly variable age produced by multiple southward ridge jumps whereas the south-central part on a crust of uniformly increasing age produced as a result of a major southward ridge jump.

2.4 Nature of the Laccadive Ridge and Seaward Dipping Reflectors (SDR)

The Laccadive Ridge is the northern segment of the Chagos-Laccadive Ridge system and lying roughly parallel to the southwest coast of India between 8°N and 16°N. It is a most significant aseismic ridge on the Western Continental Margin of India (WCMI) with an average width of ~270 km, comprised of about twenty islands and banks and popularly known as Lakshadweep. The eastern and western limits of the ridge are bounded by fault scarps, which apparently separate the ridge from Laccadive and Arabian basins respectively.

The ridge is associated with subdued positive free-air gravity anomaly and was considered to indicate a compensation of its mass at deeper depths. Several hypotheses were proposed for the origin of the Laccadive Ridge. But the results from recent geological and geophysical studies suggest that the Laccadive Ridge originally consists of thinned continental crust, which subsequently was heavily intruded–extruded by magmatic rocks during the passage of the Indian plate over the Reunion hotspot. Earlier seismic reflection data also led to identification of several rotated fault blocks, thereby to infer continental ribbon structures of the Laccadive Ridge.

Admittance analysis of gravity and bathymetry data of the Laccadive Ridge suggests that the ridge is compensated with an Airy model, whose average crustal thickness, density and effective elastic plate thickness are 17±2 km, 2.7×10^3 kg m^3 and 2–3 km, respectively. These findings when integrated with the published results suggest an Airy model of isostasy for the ridge and stretched continental nature of lithosphere loaded with magmatic material by the Reunion hotspot volcanism.

In a recent study, several seismically imaged Seaward Dipping Reflectors (SDRs) sequences are reported, for the first time, below sedimentary column along western flank of the Laccadive Ridge. Seaward dipping reflectors are characteristic features of volcanic rifted margins and are interpreted as voluminous basaltic flows emplaced during the continental rifting. Therefore, the occurrence of SDRs along the southwest continental margin of India strongly suggest extrusive volcanic episodes under sub-aerial condition during rifting between the eastern Madagascar and Laccadive Ridge which was a part of Indian mainland. Seaward of the SDRs, the Laccadive Ridge gradually thins and juxtaposed with the early Tertiary normal oceanic crust of the Arabian Basin. The seaward feather edge of the SDR sequences indicates continent-ocean boundary along the western margin of the Laccadive Ridge.

3. Recent volcanism in Andaman-Nicobar Islands region and volcanic provinces of the Indian shield

About sixty potentially active volcanoes including Barren Volcano lie along the SE Asian volcanic rim in the northeastern Indian Ocean. During the last 4 years, from 2007 to 2010 significant work has been carried out on two Neogene volcanoes, Barren and Narcondam, in Andaman Sea. The features are generated by an oblique subduction process that is presently undergoing between India and SE Asian plate. Besides, systematic geological studies have also been carried out in different volcanic provinces of the Indian shield.

3.1 Barren Volcano

The Barren Volcano, located at 12° 17′ N, 93° 51′ E, has records of prehistoric and historic eruptions and is in an active state since May 2005. A sub-aerial and mild Strombolian eruption of Barren Volcano was re-initiated on 28th May, 2005, after a lull of nearly ten years. An overall composition of the lava and pyroclasts ranges from basalt to andesitic basalt. The basaltic volcanics are porphyritic in nature, where the phenocrysts represented by plagioclase (18-25% vol), olivine (1-4% vol), clinopyroxene (0.5-2.5% vol) and few iron oxides are set in glassy groundmass. The eruption started from two vents with one vent located at the southern base and the other vent located at the slope of main volcanic cone. The eruption was weak to moderately violent with ejecting out dark grey to grey ash laden juvenile steam raising up to 300 m high column and intermittent jets of coarser particles. The eruption became violent during the period, January-February, 2006 and this was evident from three vents and huge amount of pyroclasts were ejecting out and were pushing along the slope of the cone and subsequently the hot pyroclast debris after crossing the valley, were reaching the sea. The

violent nature of eruption ejecting out huge mass of pyroclasts, suggests that the initial Strombolian nature changed to sub-Plinian type eruption. The main approach valley to the centre of the island had been totally covered by a thick pile of assorted pyroclasts. The intensity of the explosions were relatively mild compared to explosive eruptions took place in June 2005. Two cinder cones with approximately 500 m high, developed to the southwest of the main crater by accretion of coarser tephra comprising lapilli, cinder, spatter and blocks along with the spread of ash.

The geochemical studies suggest island arc tholeiitic characters for the Barren volcanic samples. The calculated fractional crystallization trend shows an accumulated nature for the lava erupted in 2005 and evolved path for lava erupted since 2006. The evolution of relatively anhydrous basaltic magma of the Barren volcano has been explained through diapiric model. Isotopic ratios $^{87}Sr/^{86}Sr$ ~0.7039-0.7041, $^{143}Nd/^{144}Nd$ ~0.51270 and $^{206}Pb/^{204}Pb$ ~18.565-18.617, of the volcanics indicate the source nature, $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ and trace elements and ratios of incompatible trace elements in the basaltic rocks point to the occurrence of additional evolutionary processes and/or to a role of a heterogeneous magma source. The most primitive magma (Mg# 71, Ni 218 ppm, Cr 557 ppm), displaying the lowest Th content (0.39 ppm), found in the Barren Island is also the most primitive in the Burma-Andaman-Java Arc. Enrichment of LIL compared to HFSE suggests enrichment of mantle peridotite source by a subduction zone component. High Zr content is suggestive of low degree of melting of the mantle for all the eruptions.

Multibeam bathymetry and magnetic studies of the Barren Island reveal that the Barren volcanic cone is generally associated with a broad-high amplitude magnetic anomaly with exceptions in places where dykes/ faults intersect the conical surface. Magnetic anomaly map around the Barren Island region shows high and low magnetic anomaly with dominant low anomaly zones in the south and north of it. The positive high in the south of present crater is possibly the basaltic body formed in the early stage of Barren Volcano. A dyke on the northwestern face of the Barren Island, runs in NE-SW direction and probably acting as feeder dyke and responsible for the present activity. Lowering of Curie Isotherm depth by 1.3 km (changed from 3.21km to 4.51km) from January 2009 to December 2009 suggest that the activity of Barren Island will not be vigorous in near future.

3.2 Narcondam Volcano

The Narcondam Island in the Andaman Sea is a part of the volcanic chain of the Burma-Java subduction complex and represents a dacite-andesite domal volcano. The Narcondam Island records only dacite-andesite magmatism, whereas the Barren Volcano situated in the same volcanic chain, erupts only basaltic magma.

Petrography and geochemistry of sample studies show that Narcondam Volcano is represented by dacite-andesite lava displaying magma mixing effects. The textures as well as compositions of the phenocrysts of the volcanics exhibit disequilibrium caused by magma mixing. The sodic plagioclases, occurring as unreacted grains in dacite and as cores of the reacted grains in andesite, as well as the presence of rhyolitic glass as inclusions, record rhyolite as one magma source. On the other hand preponderances of phenocrysts of basaltic origin (high Fo olivine and Mg rich pyroxene) as well as basaltic glass as matrix and inclusions in the phenocrysts in andesite suggest basalt as another source magma. Additional geochemical parameters (e.g. Sr/Y, Zr/Y, Th/La, U/La, Ba/La) of Narcondam lavas positively correlate with increasing SiO_2 but are anchored at the mafic end within compositions observed at Barren Island volcano. The shift in isotopic values from typical Barren Island values to those of Narcondam samples is likely caused by crustal contamination resulting from magma residence in the upper plate involving assimilation of extended continental crust and/ or sediments from the fan associated with the Irrawaddy Delta at the Myanmar continental margin which extends to the Narcondam volcano region.

Similarities in the geochemistry of both lava suites include strong and comparable depletion in Nb and Ta (K_2O/Nb ~0.7; Ba/Nb 130-250), low, MORB-like Nb/Zr (0.01-0.03) and nearly constant U/Th (0.15-0.22). These characteristics suggest a genetic link between both magma suites, but there are geochemical differences such as elevated trace elemental abundances and ratios in Narcondam lavas compared to Barren Island lavas. These include elevated Ba, Rb, and U concentrations and high Ba/Zr and

Nb/Zr. Additionally, isotopic ratios of Barren Island rocks are $^{87}Sr/^{86}Sr$ ~0.7039-0.7041, $^{143}Nd/^{144}Nd$~0.51285-0.51296 and $^{206}Pb/^{204}Pb$ ~18.063-18.309, whereas for Narcondam volcanics isotope ratios are $^{87}Sr/^{86}Sr$ >0.705, $^{143}Nd/^{144}Nd$ ~0.51270, and 206Pb/204Pb ~18.565-18.617.

Besides the presence of dacite-andseite lava, recent record of the pyroclastic flow deposits along the peripheral part of the island has been reported. The nature of eruption and the transport mechanism of different units of the pyroclastic deposits have been documented. The andesitic pyroclastic flow deposit is restricted to the periphery of the dome whereas the central part of the dome is occupied by dacitic lava. The pyroclasts are represented by the poorly vesiculated blocks, lapilli and ash. During the explosive eruptions of a new pulse of andesitic magma, the earlier dome disintegrated to form a hot avalanche. The centre of the dome was occupied by a subsequent dacitic eruption.

The high magnetic anomaly in the north may be an indication of basaltic magma from Narcondam Volcano. The fluctuations of the magnetic anomalies over the Alcock seamount suggest that it is traversed by several faults and intrusive bodies

3.3 Volcanic activity in Central Andaman Trough

Study of seabed sediment samples collected from the Central Andaman Trough shows the records of Andaman Trough volcanic activity. Bathymetric study reveals the presence of ENE-WSW trending spreading valley of the Central Andaman Trough with a sediment cover and two very prominent volcanic seamounts in the western part of the area. The coarse fractions of sediments indicate the presence of abundant glass shards with basaltic to basaltic andesite composition. Interestingly, unlike Barren and Narcondam volcanics, these glass shards show phenocrysts dominantly represented by well-formed crystals of olivine (Fo87-89), chrome spinel along with minor clinopyroxene (diopsidic augite), rare plagioclase (bytownite) and apatite. Features that indicate overall grain rounding resulting from the transport process as well as features that indicate post-emplacement alteration viz. (palagonitization, hydration, skin cracks and solution and precipitation) are not abundant in the shards, thereby implying their in-situ and recent origin.

3.4 Study of volcanic provinces of the Indian shield

Systematic geological studies have been carried out in different volcanic provinces of the Indian shield including their differentiation centres. The studies of Eastern Deccan volcanic province, Sylhet Trap volcanic provinces, Khasi mafic volcanic rocks of the north eastern India, Dibang Valley Ophiolites in Arunachal Pradesh and Hypabyssal rocks of Singhbhum region of Eastern India have brought out interesting results for understanding the evolution of volcanic provinces.

In Southern Indian Shield, specifically in Hutti greenstone terrene region it is found enriched and depleted arc basalts with high Mg-andesites and adakited. The occurrences of an ophiolite suite in Dibang Valley, Arunachal Pradesh has been reported for the first time. The entire succession is overlain by metabasalt carapace interlayered with metapelitic pelagic sedimentary rocks.

The sylhet trap volcanism (~117 Ma) of the North Eastern India has some differentiation centres. The Mawpyut complex (25°29'N, 92°10'E) of Jaintia Hills District, Meghalaya distinctly occurs as a pluton intrusive into adjacent low grade metasedimentary Shillong Group of rocks. This Mawpyut pluton reveals development of two broad lithotypes namely ultramafic (olivine clinopyroxenite, clinopyroxenite and plagioclase bearing ultramafic) and mafic (mostly gabbro, orthopyroxene gabbro, olivine gabbro-norite, mela gabbro,and mela gabbro-norite) with minor presence of later syenitic veins. Though, in general, the pluton shows mineralogical variations, the field- boundaries among these petrographic types are not discernible. Careful consideration of major and trace element chemistry of the constituent lithomembers clearly suggest progressive insitu fractionation of common parent magma. The other important differentiated complex related to Sylhet Trap is Samchampi- Samteran alkaline Complex (SSC) (26°13'N, 93°18'E) of Mikir Hills and occurs as a plug like pluton within the Precambrian granite gneisses country rocks. The pluton is also traversed by younger intrusives of nepeheline syenite and carbonatite. Development of

sporadic, lumpy magnetite ore bodies is also recorded within the pluton. The ore bodies, on microscopic studies, indicate that magnetite is often associated with hematite and ilmenite depicting different textural patterns. Geochemistry of the ore bodies strongly suggests formation of these ore bodies as late stage segregation from a differentiating alkaline magma in a fluid enriched milieu.

The tectono-magmatic history of the Eastern Indian shield has a varied nature embracing plutonism/ volcanism right from ~Archean (represented by Older Metamorphic Group) to ~Neo Proterozoic (marked by Newer Dolerites). The investigation of Newer Dolerites in eastern Indian shield indicate presence of at least four distinct petrographic types viz, dolerite, porphyritic dolerite, micropegmatitic dolerite and gabbro. Studies of constituent mineralogical attributes indicate that these petrographic types are linked up with one another to common parent magma. Detailed petrographic and mineralogical studies of the Newer Dolerites helped to classify the constituent minerals as per modern nomenclatorial rules. Use of relevant thermo-barometric methods yields a temperature of 1300°C to 630°C at a pressure ranging from 0.01 to 5.33 kb. On the basis of available field, petrographic and mineral-chemical data, it has been suggested that cooling of the parent intruding magma initiated at shallow to moderate depth. The cooling/re-equilibration temperature became substantially lower on the influence of waning stage of magmatic crystallization (possibly in presence of H_2O) or metamorphic reconstitution accompanying crystallization.

The Aravalli- Delhi orogen of northwestern India manifests mafic volcanism of Proterozoic age. On the basis of isotopic studies, an enriched mantle- source for these lavas has been envisaged. Plate-plume accretion tectonics is also believed to have played an important role to explain the occurrence of these Proterozoic mafic volcanic rocks. In Delhi Super group, evidence from sandstone-detritus suggests syn-sedimentary volcanism. Recently, on the basis of paleomagnetic and geochronologic studies on Malani Igneous suite, much important findings have been obtained regarding the configuration of Rodinia and the assembly of Gondwana.

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