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NATIONAL COMMITTEE FOR INTERNATIONAL UNION OF GEODESY & GEOPHYSICS (IUGG) 2000-2003

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PREFACE

On behalf of the IUGG National Committee of the Indian National Science Academy, it is a great pleasure for me to present the Indian National Report for the period January 1999 through December 2002, to the 23rd General Assembly of IUGG, at Sapporo, Japan.

This has been a very fascinating period for Geodesy and Geophysics in our country. While the Survey of India celebrated 200 years of their establishment, highlighted the great trigonometric survey done some 200 years ago between Cape Camorin and Banot in high Himalayas; Bhuj had the distinction of having the most damaging earthquake on 26th January 2001. This was the largest and deadliest earthquake in the subcontinent since the 15th August 1950 Assam earthquake.

Prithvish Nag and B. Nagarajan have compiled a report on Geodesy and Gravimetry involving the work done by several major organizations in the country. They have underlined the transition from GTS to GPS. Lakhina has reported on Geomagnetism and Aeronomy. He points out that India offers a unique geophysical location for investigating complex processes related to the earth's interior as well as electro-dynamical processes occurring in the ionosphere and the magnetosphere. He underlines that very useful work has been done by Indian scientists in investigating problems related to dynamics of earth's interior, solar-terrestrial relationships and space weather using experimental, analytical, and modeling techniques. S N Rai reports on Hydrological Sciences and draws attention to the increase in demand of water supply with the passage of time. India has 1/6th of world's population with only 4% of world's water supply. His compilation provides in brief the work done in hydrology, including ground water assessment and development, water quality, ground water recharge, rain fall-runoff, flood, sedimentation and glacier's hydrology. Thapliyal reports on Meteorology and Atmospheric Sciences. He mentions that more than 30 organizations, including universities and institutes, carry out work related to monsoons, atmospheric modeling and dynamics, climate studies, air-sea interaction, atmospheric boundary layer, satellite meteorology, atmospheric physics and related experimental studies. Results of important programmes like INDOEX (Indian Ocean Experiment), BOBMEX (Bay of Bengal Monsoon Experiment) and ARMEX (Arabian Sea Monsoon Experiment) are reported. Chadha and Srinagesh have prepared the section on Seismology and Physics of Earth's Interior. The report period saw a major overhauling and addition of new broadband digital data acquisition capabilities in the country and new trends in research. Bhuj earthquake drew the attention of all scientists in the country. Abhijit Bhattacharya reports on Volcanology and Earth's Interior, and highlights important findings in the Himalayan region, Deccan Province, Central India, and other important geological units of the country.

In a nutshell, it may be said that the period of 1999 through 2002 witnessed a very active research phase in IUGG-related work in India.

I am thankful to all the contributors of the articles in the Report, to R.K. Chadha and D. Srinagesh in helping me in compiling this Report, Mrs. Prerna Singh and P. Radhakrishnan for secretarial assistance. I would also like to thank the IUGG National Committee members and officers of the Indian National Science Academy, especially Dr. A.K. Moitra, for their help in bringing out this Report.

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GEODESY AND GRAVIMETRY

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Introduction:

Geodetic and gravity surveys provide critical inputs in understanding the geodynamics of the earth system. Various organizations and institutions in India are involved in geodetic measurements of crustal deformation with which one can test geophysical models to infer earth's dynamics. In addition to these measurements, more recently Global Positioning System (GPS) techniques are being used to study local and region problems of crustal deformation. Nonetheless, because of the time scales involved, older geodetic data (including leveling, triangulation and repeat gravimetric) continue to be important for many geophysical studies. In the following pages, a brief account of the work carried out in the field of geodesy (geodetic and geophysical) in the country during the period Jan 1999 to Dec. 2002 is given. The report deals with the work carried out by:

- Geodetic & Research Branch, Survey of India, Dehra Dun, Uttaranchal.
- Indian School of Mines, Dhanbad, Jharkhand.
- Space Applications Centre, Ahmedabad, Gujarat.
- Indian Institute of Geomagnetism, Mumbai, Maharashtra.
- Geological Survey of India, Kolkata, West Bengal.
- Andhra University College of Science & Technology, Visakhapatnam, Andhra Pradesh.
- Center for Earth Science Studies, Thiruvananthapuram, Kerala.
- National Geophysical Research Institute, Hyderabad, Andhra Pradesh.
- Oil and Natural Gas Corporation Limited, Dehra Dun, Uttaranchal.

Geodetic & Research Branch is one of the oldest and a specialized directorate of Survey of India with the primary responsibility of providing precise first order horizontal and vertical control in India and its islands for topographical mapping in the country, geodynamic studies and Project surveys etc. National gravity and geomagnetic coverage, monitoring and maintenance of tidal stations all along Indian coast (both on mainland and islands) etc., are also few of the additional responsibilities vested with this directorate.

Over the years with the improvement of technology particularly after the dawn of satellite era, the requirement of speed and accuracy has increased considerably. To keep itself at par with the rest of the world, of late this directorate has adopted modern technologies.

The specialized tasks being carried out by the directorate during the period under report are as enumerated below:

1. Horizontal and Vertical Control and GPS Surveys
2. Gravimetric Control
3. Geomagnetic Control
4. Tidal observations
5. Project Surveys

Horizontal and Vertical Control and GPS Surveys

Horizontal Control

Horizontal control of the first order is provided primarily as the framework for the topographical mapping. This information is also being used for other project surveys, geodynamic and dam deformation studies and checking of the verticality of archaeological structures. For densification of horizontal control and other studies which have been undertaken during the period under report, GPS observations at 462 stations, 470 line km. EDM traverse and 18.0 line km. Invar

Base were observed in the various parts of the country.

A project to redefine the Indian Geodetic Datum in context to Deep Continental studies has been taken up with an aim to i) to adjust Indian Geodetic Network using the method of simultaneous least square adjustment of linear equations by including all Laplace Azimuths (272) and Base lines (12) observed / measured before and after 1880 adjustment, as well as inclusion of all new and revised Geodetic Series Observed after 1880 adjustment, ii) to determine the seven transformation parameters between World geodetic system 84 (WGS-84) and our local geodetic system, so as to make use of all Doppler / GPS observations presently available and to make available in future and iii) to critically examine the suitability of Everest Spheroid as our local reference datum.

The Indian Geodetic Datum adopted in 1880 is the Everest Ellipsoid, which is based upon the adjustment of available geodetic data and has been designed using the computational means, mathematical models and adjustment techniques available at that time. This datum is not suitable for High-Precision Geodetic and allied activities of modern age as it was developed using inadequate volume of data, measurements of base lines in Indian foothills gave distortions to the tune of 3 ppm and other unavoidable factors which existed at that time. Thus the challenging task for an integrated re-adjustment of all the geodetic data available today and redefinition of the datum using such adjustment has been undertaken.

Vertical Control

Densification of Vertical Control:

For densification of vertical control 580 line km. High Precision Leveling in Fore and Back direction was carried out in the country during the period under report. Earlier, the First Level Net for India included data collected from 1858 to 1909, was adjusted in 1909 thus establishing the First Vertical Datum for India. The methodology and instruments used for data acquisition during that period did not meet the accuracy requirements laid down later, in 1912, by the International Geodetic Conference. But the quality of data improved later with the introduction of Invar Staves in 1929-30 and also with the adoption of Vignal's formulae for leveling errors and tolerances as adopted by IAG in 1948. The Adjustment of 1909 also suffered from an arbitrary system of weighting and was constrained to fit the Local Mean Sea-Level values at 9 ports.

A large number of High Precision Leveling lines have been run in the last 6 decades across the length and breadth of the country using the latest Instruments and Invar Staves. A need was therefore felt to have a Second Adjustment of the India Level Net including all lines completed till date.

The first Phase of Second Level Net Adjustment was done in 1983. It covers the Peninsular Shield considered to be geologically stable. 50 Leveling lines were included in 17 circuits for this adjustment. Local MSL of Bombay based on 38 years observations with mean epoch 1955 was taken as the datum instead of the mean of 9 ports taken at the time of First Level Net Adjustment. Now it has been decided to use geo-potential number and compute Helmert Orthometric Heights at places for redefining the vertical datum for India.

GPS Surveys

Geodetic & Research Branch of the Survey of India has been associated with crustal movement studies using geodetic techniques in various regions of India. Studies to monitor seismotectonics of central region of southern peninsular shield covering an area of around 500 x 500 sq. km. which include prominent features viz., Narmada-Son lineaments, Godavari & Kakenada-Midnapur fault zones was taken-up during the period under report.

- Five permanent stations with inter-station spacing of 40-60 km and GPS stations located across and along the fault zones at a distance of order 2-10 km, were established.

- GPS and High Precision Leveling Survey were conducted during the period from 1999 to 2002 to detect horizontal and vertical surface deformations if any, respectively.

- GPS observations for densification, geodynamic studies have been carried out in the Southern Peninsular Shield and the various parts of the country. During the period under report, GPS observations were carried out at the 96 GPS stations. 27 deformation pillars were also constructed and observations conducted on them for earthquake monitoring.

- A network of GPS stations consisting of quadrilaterals and triangles has been established for monitoring seismotectonic activities.

- GPS observations were also carried out on 11 stations to provide control to various government agencies such as Indian Space Research Organization, Defense Research Development Organization and India Air Force.

GPS observations for Geodynamic Studies

To study the post earthquake geodynamic processes GPS observations were carried out in the states of Gujarat and Uttaranchal. Observations on 33 stations each in Gujarat and Uttaranchal were carried out during the period under report.

A three years project "GPS campaign for monitoring crustal movements in around Palghat Gap Region southern Peninsular India" sponsored by the Department of Science and Technology, Government of India has been taken up since 2001. The project is aimed to study the seismogenic potential of Palghat gap, the major topographic expression in the Western Ghat region in Kerala with Particular reference to the epicentre of 1994 Vadakkancherry tremor. Three GPS semi permanent stations (less than 100 km) were established on the terraces of the PWD Rest Houses at Kodungalore (Trichur district) Tirur (Malappuram district) and Shornur (Palghat district) in Kerala. Monuments comprising of RCC pillars measuring 60 cm tall and 30 cm x 30 cm square face were constructed having 15 cm. Stainless steel bolt embedded within it to mount the GPS receivers. The GPS data logging went on for four days simultaneously at these stations using Trimbble's 4000 SSi Dual frequency - multichannel geodetic receivers and choke-ring antenna. Subsequently during 2002, three more semi-permanent (less than 100 km) were also established on the basements rocks at Attappadi (Palghat district), Nelliampathy (Palghat district) and Peechi (Trichur district). Besides four local stations (less than 20 km) near Shornur were also established on the basements rocks at Kundanur, Vellur, Amaiyur and Ezhimanged around the epicentral region of the 1994 Wadakkancherry tremor.

GPS Observations to Compute Transformation Parameters

The reference frame for the GPS is World Geodetic System – 1984 (WGS – 84). GPS measurements at terrestrial sites, therefore gives co-ordinates on WGS-84 datum. This datum is different from the Indian Geodetic Datum i.e., Everest Spheroid. All Survey of India topographical maps are based on this datum. In order to make optimum use of GPS based co-ordinates system, it has become very essential to determine Transformation Parameters for conversion of co-ordinates from WGS-84 Spheroid to Everest Spheroid and vise versa. This project is at the final stage completion. Reconnaissance and observations on 248 stations were carried out during the different field seasons and the adjustment of GPS observation network was done in the Everest Spheroid.

GPS Data Centre and Permanent GPS Stations

National GPS Data Center has been set up in Survey of India for archival and distribution of GPS data from several permanent stations setup for seismotectonic studies in India under the aegis of the Department of Science & Technology, Government of India. The data archived at National GPS Data Center will be distributed to various sister scientific organizations on demand basis for seismotectonic studies in India. Survey of India has the responsibilities of 5 permanent stations. Data from 8 Permanent stations has been received at the Data Center so far, for archival, analysis and distribution.

Gravimetric Control

The gravimetric work carried out by Survey of India include, execution of a program of 15 km gravity mesh, observations along selected profiles and leveling lines, computation and study of various gravity anomalies, repeat gravity observations in earthquake prone areas etc. At present, there are 56 standard gravity stations in the country, which are being used for densification work. The 15 km. gravity mesh coverage of the entire country is being carried out which will be subsequently used for preparation of Gravity Anomaly Maps (Free air, Bouguer & Isostatic) at various scales both in analogue and digital form for distribution to geoscientists on demand. In continuation of gravity studies being carried out in the country under National Gravity Program, Survey of India has established 1013 Gravimetric Stations during 1999-2002 which brings the total number of stations observed so far to about 13713 stations which covers approximately 59% area of the country. Efforts to develop high-resolution geoid combining EGM96 global geopotential model and terrestrial gravity anomalies for India are under progress.

Gravity Observations on Bench-Marks along H.P. Leveling Lines

Gravity observations are integral part for measurements of height above vertical datum (i.e. geo-potential number). The gravity observations on 555 bench-marks along various H.P. Levelling lines above 20° Latitude in India have been carried out during the period under report and 2393 bench-marks were connected by gravity observations in connection with adjustment of Level Net in India. Thus, the number of stations observed so far along selected profiles and for other control provided at an interval of 1 to 8 km. including the number of benchmarks is about 14,843. The total number of stations at which gravity values have been observed up to December 2002 has gone up to 34,691. This includes 56 standard gravity stations and 8807 benchmark stations.

Gravity Observations for Geodynamic Studies

Several gravity measurements have been done to study geodynamics of local and regional scale in certain earthquake prone areas of the country. For example,

- Repeat gravimetric observations on 245 gravity stations during 1999-2000 and 213 gravity stations during 2000 and 555 stations were carried out in 2001-2002 in and around earthquake affected area of Gujarat, Rajasthan, Uttaranchal, H.P. and Haryana.

- Repeat gravimetric observations on 129 gravity stations during 1999-2000, were carried out in Kangra-Dharamshala area of Himachal Pradesh.

- Repeat gravimetric observations have also been carried out on 200 gravity stations during 2000-2001 in Gujarat and Rajasthan.

- Repeat gravimetric observations on 220 gravity stations simultaneously with H.P. Levelling on bench-mark stations have been carried out during 2001-2002 along the existing H.P. Levelling lines in Gujarat and Rajasthan.

Geomagnetic Control

Geomagnetic observations all over the country are necessary for development of Geomagnetic Modelling of Earth and for preparation of Geomagnetic Anomaly Maps. Observations of Declination, Horizontal Force and Vertical Force at 138 repeat stations, 104 Profile stations and 15 field stations were carried out in various parts of the country for preparation of Isomagnetic charts for Declination, Horizontal Force and Vertical Force for epoch 2000.0.

Tidal Observations

The responsibility of carrying out systematic tidal observations and monitoring of tidal stations were entrusted to Survey of India in 1877 and since then data collection work is continued at a network of tidal observatories located along East and West Coasts and also Andaman & Nicobar and Lakshadweep Islands. Sea-Level data from about 24 Tidal observatories, collected during the last 10 decades, is utilized mainly to determine Mean Sea-Level to serve as the Vertical Control Datum for heights for the country and for tidal predictions for navigational purposes. Tide tables are printed a year in advance and made available to National/ International users to facilitate their navigational activities. Monthly/ Annual Mean Sea-Level of the functional ports are also sent to Permanent Service of Mean Sea-Level (PSMSL) UK as an International commitment.

Continuous and updated actual tidal data received from various observations along Indian coast have been used:

- to determine Mean Sea-Level and Mean Tide-Level.
- to compare with prediction to determine percentage accuracy.
- for Analysis and Investigation to improve tidal predictions.
- to study Sea-Level variation and other Scientific Investigations.

National Tidal Data Centre

A National Tidal Data Centre was established under the project National Ocean Information System (NOIS) and Sea Level Monitoring and Modelling Project (SELMAM) which were funded by the Department of Ocean Development, Government of India. Indian Tide Tables comprising of tidal predictions of 76 ports (44 standard ports between Suez and Singapore and 32 received from foreign coasts viz. European, African, Chinese, Japanese and South East Asia Coasts) are published annually. Hugli River Tide Tables comprising of tidal predictions of 6 Hugli River ports viz., Mayapore, Gangra, Haldia, Sagar, Garden Reach and Diamond Harbour are also published annually.

Precision Leveling Surveys for some select dam sites

In order to provide accurate planimetric and height control in connection with investigation and planning for various irrigation and Hydro-Electric Projects in various parts of the country the precise traverse and base measurements and High Precision / Precision Leveling were carried out during the period under report. Some of these projects are, Tala Hydro Electric Project, Tehri Hydro Development Corporation, Koteshwar Dam Project, Bhakra Dam Project, Ban Sagar Feeder Canal Project, National Atlas and Thematic Mapping Organization (NATMO) Kolkata, Purlia Pumped Storage Project, Jhuj Canal Project (GERI) and Rihand Dam Project.

Geodetic Leveling for Earthquake Studies

(i) 214 line km. of Precision Leveling was carried out in both directions on line Parli to Latur in the state of Maharashtra for Earthquake Movement Studies, during season 1999-2000.

(ii) 138 line km. of Precision Leveling was carried out in both directions on line Tuljapur to Borgaonbuzurg in the state of Maharashtra for Earthquake Movement Studies, during season 1999-2000.

(iii) 212 line. km. of Precision Leveling was carried out in both directions on line Latur to Matala in the states of Maharashtra and Karnataka for Earthquake Movement, during season 1999.

(iv) 586 line km. of H.P. Leveling was carried out on line Jabalpur to Bilaspur and Maharajpur to Sagar for Peninsular Shield & Earthquake Studies, during season 1999.

(v) 488 line km. of H.P. Leveling was carried out in both directions on line Devaprayag to Badrinath in the state of Uttaranchal for Earthquake Movement Studies, during season 1999-2000.

(vi) 250 line km. of H.P. Leveling was carried out on line Gendawad to Gangotri portion Gendawad to Dunda in the state of Uttar Pradesh and Uttaranchal for Earthquake Movement Studies, during season 1999-2000.

(vii) 544 line km. of H.P. Leveling was carried out on line Saharanpur to Gangotri in U.P. and Uttaranchal for Earthquake Studies, during season 1999-2000.

(viii) 338 line km. of H.P. Leveling was carried out on line Jabalpur to Bilaspur in Madhya Pradesh for Earthquake Studies, during seasons 1999-2000.

(ix) 252 line km. of Precision Leveling was carried out on line Latur to Borgaon buzurg in both directions in Maharashtra for Earthquake Movement Studies, during season 2000-2001.

(x) 296 line km. of H.P. Leveling was carried out on line Santalpur to Bhuj in Gujarat for Earthquake Studies, during season 2000-2001.

(xi) 140 line km. of H.P. Leveling was carried out on line Dhulia to Bijapur in Maharashtra for Earthquake Studies, during season 2000-2001.

(xii) 184 line km. of Precision Leveling was carried out in both direction on line Parli to Parli in Maharashtra for Earthquake Movement Studies, season 2000-2001.

(xiii) 85 line km. of H.P. Leveling was carried out on line Saharanpur to Gangotri portion Bhaironghati to Gangotri in Uttaranchal for Earthquake Studies, during season 2001-2002.

(xiv) 1175 line km. of H.P. Leveling was carried out on line Santalpur to Lakhpat via Bhuj, Bhachau for Earthquake Studies in Gujarat, during season 2001-2002.

Specific Research Programs

Exploration for Oil

Advent of satellite altimetry has been a boon for oil exploration. The underlying concept of the technique, 'Satellite Gravity Method', is that the sea surface height, measured by satellite altimeter, when corrected for dynamic variability e.g. tides, waves, eddies etc. corresponds to mass distribution of the underlying earth. Satellite Gravity Method is highly cost-effective requiring limited ship-borne surveys. SAC (ISRO) and KDMIPE (ONGC) have jointly developed the methodology / related software for generating offshore geoid and gravity maps and an Atlas of the satellite-derived geoid/ gravity maps over the surrounding Indian offshore in 1:7 million, 1:3.5 million and 1:2 million scales has been generated. Gravity anomaly maps generated are useful to ONGC particularly beyond 200 m. isobath. Few potential sites identified are west of Bombay High, North of Laccadive ridge (Arabian Sea) and Palar basin, and part of Bengal Fan Delta (Bay of Bengal). The gravity maps have been used by the Directorate General of Hydrocarbons for giving Tenders to outside agencies. Efforts are on to obtain copyright for the technique "Satellite Gravity Method for Offshore Exploration".

Coal

The gravity surveys in Nuagaon-Teleshi block of Talchir Gondwana basin, Angul district Orissa indicated a high Bouguer anomaly of the order of 40 mgal having a corroborative magnetic anomaly of the order of 400 nT. This anomaly has been interpreted to be due to the presence of high-density rock within the basement as well as due to basement uplift. The surveys have established the presence of Coal bearing Barakar formation at shallow level in the uplifted block.

Diamond

Gravity magnetic surveys carried out around Mundapalli and Telepukapani villages, Bargarh district, Orissa for kimberlite/ lamporite brought out a high gravity anomaly zone of the order of 0.6 mgal over a strike length of 1.8 km in Mundapalli area. This amomaly zone is associated with high amplitude magnetic anomalies and low resistivity values. Gravity surveys for exploration of kimberlite/ lamporite pipe rocks in Anantapur and Mahboobnagar district, Andhra Pradesh, indicated a gravity high in SE part of the area. In the Tokepal area, Chattisgarh, the gravity surveys indicated a bull's eye anomaly that is encouraging and is being examined further for diamond prospect.

Gold

Gravity surveys in Dona, East block of Jonnagiri schist belt, Kurnool district, Andhra Pradesh indicated two major faults. One of these indicated a possible zone for gold mineralization. Gravity surveys carried out in Tsundupalle schist belt, southern extension of veligallu schist belt, Andhra Pradesh, have brought out the disposition of Tsundupalle schist belt as gravity high and high nosings. The geologically mapped two linear bands in the northern part of the schist belt appears as a single band in the gravity map with width varying from 2 to 3 km and depth about 2.5 to 3 km. Three E-W gravity trends showing higher gradients are indicative of prominent crustal breaks. The intersection of these linears/ trends with the N-S trending schist belts are considered favourable zones for gold and basemetal mineralisation and emplacement of kimberlite pipes.

Chromite

Gravity-magnetic surveys in Cuander-Bhushal area, Dhenkenal district, Orissa, indicated a number of magnetic anomalies. Two of these anomalies are associated with gravity high of the order of 0.5 to 0.6 mgal, but are of limited strike length.

Groundwater

Gravity surveys in Sivaganga district, Tamil Nadu have brought out a column of thick sediments that may have a bearing in groundwater exploration.

Tectonic Studies

Bouguer gravity values along a section Tanakpur-Pithoragarh-Tawaghat road Uttaranchal, show decreasing trend towards northeast. A broad gravity high of about 40 mgals has been obtained around Pithoragarh and a sharp gravity gradient is recorded between Dharchula and Tawaghat indicating probable thinning of crust around Pithoragarh.

Repeat Micro gravity surveys during the last two years along Siliguri-Gangtok transect revealed a change in gravity values with a maximum variation of the order of 96 microgal. Repeat measurements will be continued for at least five years.

Gravity-magnetic surveys of semi-regional nature along Mairang-Shillong and Barapani-Nongpoh have revealed major structural elements falling in and around Tyrsad-Barapani shear zone.

A gravity magnetic profile along Bhuj-Nakhania-Sumarasar, Gujarat, over a length of 24 km from south to north, has indicated a variation in gravity values from - 5 mgal in south to + 5 mgal in the north. A disturbed zone has been indicated about 12 km north of Bhuj with high gravity and magnetic values indicating probable uplift of high density and high susceptibility material.

Geophysical Mapping

A total of about 1500 (1999-2000) and 800 (2001-2002) stations at an interval varying from 500 m to 1 km were occupied by gravity measurements in logistically different terrains of upper Assam and Arunachal Pradesh for identification (delineation) of basement structures. Another 6000 stations were occupied by gravity measurements at a station interval of 2 km in the area adjoining Narmada-Tapti rivers to delineate the Mesozoic sediments beneath the Deccan trap cover. The Bouguer gravity anomaly maps have indicated deepening of granitic basements towards north of Lucknow - Kanpur area. A major lineament trending NE - SW has been delineated by gravity magnetic surveys.

Gravity and magnetic surveys in the east of Kolar schist belt, Karnataka have brought out a linear contact zone between granitoid gniess and charnockitic group of rocks with a high gradient from Tirupathur to Ambur. Bouguer gravity contour map in the northern part of Chitradurga schist belt, Karnataka has shown a trend in the NW-SE direction and is influenced by two E-W structural features, one between Pondarahalli and Nandipura and the other between C.K. Halli and C.R. Halli. Gravity anomalies of Manganese deposits of Vizianagaram districts, Andhra Pradesh were interpreted by modelling. The locates of supergene enrichment were identified and the structures of Manganese horizons delineated. The exercise of modelling led to the Geological setting compatible with geological processes.

Gravity surveys are being carried out imparts of Eastern Ghat region covered by 17º 30' N to 18º 45'N and 82º, 30' E to 84º 15' E with the objective of identifying faults and correlating the frequent earth quake occurrences in the region with these faults. Some space and frequency domain methods of interpreting Gravity anomalies of sedimentary basin, when the density of the constituent sediments increases with depth, were developed. These methods were applied to interpret gravity anomalies of Pranhita-Godavari valley.

The Bouguer gravity profile along Kotban-Hodal-Palwal-Ballabhgarh-Badarpur traverse in Haryana has indicated a gravity low between Bamnikhera and Palwal, which is flanked by two highs on either side. Presence of horst and graben type structures are inferred. Bouguer gravity contour map in Haryana indicated nosing towards southwest, between Pakasma and Samchana, and nearly a parallel trend between Kultana and Matan where contours are bulging towards northeast. This indicates a subsurface displacement of blocks.

The Ghaziabad–Hapur- Garhmuketeshwar gravity-magnetic profile in U.P., shows a flat trend from Ghaziabad to east of Hapur before Koli river indicating a variation of Bouguer gravity value from -55 to -58mgal. After crossing the Koli river, the gravity values have shown an abrupt change of -20 mgal in a stretch of 35 km. The sudden fall in gravity values may be interpreted as a fault/ downwarp in basement. Regional gravity-magnetic surveys between Kanpur to Sheopura and Pilwa to Ras, Ajmer, Pali and Naguar districts, Rajasthan have delineated a gravity high zone trending NE-SW over a length of 38 km indicating the extension of Aravalli range under soil cover. A fault zone running parallel to the gravity high zone has also been inferred in the western part of the area.

Gravity magnetic surveys in Dauki-Amlarem-Muktapur area in Meghalaya revealed significant structural elements/fault in the area. A gravity high closure around Shillong city corresponding to a magnetic bipolar amomaly to the west of Shillong was also observed.

Gravity surveys in the area between Sursura and Beawar, Ajmer district Rajasthan, recorded higher gravity gradient zone in the west and gentler in the east indicating asymmetrical structure of the basement configuration.

Bouguer gravity contour map in south Purulia/ Tamar-Porapahar rift zone in Purulia district, West Bengal, indicated a significant feature along E-W direction that could be correlated to Tamar Porapahar south purulia shear zone. The gravity contour map in Purulia clearly depicts a shear zone striking E-W. The gravity values vary from -14 mgal from north to +4 mgal towards the south of the area.

Gravity surveys in Kerala were done to delineate deep continental structures and associated tectonics in and around Palghat gap region bounded by 10-12 N and 75.7 - 78 E, During the first phase of the work (1983 to 1984), 41 auxiliary gravity bases have been established with respect to Coimbatore Airport gravity base station. Subsequently, 128 auxiliary gravity bases have also been established in similar manner. In addition, direct air ties have been made with the help of daily domestic flights in 1987 to update observed gravity values at Coimbatore and Trivandrum airport gravity bases with respect to the IGSN-71 gravity base at Bangalore airport. Datum corrections for Coimbatore and Trivandrum airport gravity bases have been estimated to be -16.83 mGals and -16.60 mGals respectively. These bases have been used to occupy intermediate stations at closely spaced interval for detailed studies. At present, there are 172 gravity base stations including two IGSN-71 gravity bases at Trivandrum and Coimbatore Airport, and 3200 detailed gravity observations mostly concentrated in and around Palghat gap region. All the usual gravity corrections have been applied to the observed gravity data, except tidal and terrain corrections, and anomalies have been estimated. The contour maps of elevation, Free air, Bouguer and crustal thickness have been prepared. The anomalies are being interpreted to understand deep continental structure and associated tectonics.

An Absolute Gravimeter was procured and installed at NGRI. First absolute gravity measurements to accuracy of microgal were recorded at NGRI, Hyderabad. It is proposed to make absolute gravity base network in India.

Mapping of Sea Bottom Topography

Geoid's variation over the area of interest has been used for prediction of bathymetric anomaly along the satellite tracks using a model. ERS-1 35 days repeat cycle altimeter data were used to derive sea-bottom topography over a part of the western offshore (14-19º N, 67-72º E.)

Joint Gravity Map

A joint Gravity map over the Indian subcontinent using EGM96 (Earth Gravity Model), NGRI gravity and ERS-1 altimeter data has been generated over the Indian Peninsula and its surrounding oceans which is being further studied for regional tectonic patterns.

Coastal Geomorphology

Mapping of coastal landforms and monitoring shoreline changes along entire India coast in 1:250,000 and 1:50,000 scales has been completed.

Geoid Modeling

Geoid investigations in India have remained sketchy. The continental margins of India continue to remain poorly understood with regard to their structure, tectonics and evolution. In the absence of well - distributed seismic data, geoid data can provide important insights in this direction. Similarly, the oblique subduction of the northeastern Indian Ocean lithosphere at the Andaman island arc trench system deserves special attention. The oblique subduction is further rendered complex by the presence of the Ninety East Ridge overriding the subducted lithosphere. Geoidal surface over the eastern Indian offshore has been generated using ERS-1 altimeter data. Also, three- dimensional residual geoid variation over the Andaman trench valley has been generated and the related subsurface modeling studies have been initiated.

GPS studies to estimate strain field

Many GPS campaigns have been undertaken in various earthquake prone zones of India viz. Western Maharashtra, Bhuj region of Gujarat, Chamoli region in Uttaranchal, North Eastern Indian region. Some of the important results are:

- Magnitude of the average horizontal velocity of Deccan trap region in ITRF 96 is 51 mm/yr N 47º E. The estimated dilatational strain is about 0.4 micro strain/yr in average.
- An extensional strain regime is observed along the west coast transcending into a region of compressive strain towards the interior of the shield area. The extensional strain regime coincides with the West Coast Geothermal Province.
- The Murbad region in Thane district of Maharashtra is under E-W compression and N-S expansion regime. Intra-plate movements are detected around Amberji.
- The East, West, North, South and vertical components of the baseline Lodai - Ratanpar (passing through the epicentral area) show no co-seismic displacements associated with 26th Jan., 2001 Bhuj Earthquake.
- N-S compressional strain of about 0.1 micro strain/yr found in between Ratanpar and Dhamdkapir.

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GEOMAGNETISM AND AERONOMY

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Introduction

During the period 1999-2002, there was a spurt in the research activities related to the area of Geomagnetism and Aeronomy. India offers a unique geophysical location for the investigations of the complex processes related to the Earth's interior as well as the electrodynamical processes occurring in the ionosphere and magnetosphere. Indian scientists have made use of this situation to investigate some important problems related to the dynamics of the Earth's interior, solar-terrestrial relationships and space weather using experimental, analytical, and modeling techniques

Much international collaboration also took place during this period to conduct experiments and analyze the data from equatorial and low latitudes to understand the electroject and other geomagnetic phenomena. There are about thirty centers engaged in research related to Geomagnetism and Aeronomy in India. The present report is based on the material received from those organizations that responded to our request to submit their input for the National Report for IUGG-2003. Their cooperation is thankfully acknowledged.

Indian Institute of Geomagnetism, Mumbai

The Indian Institute of Geomagnetism (IIG), a premier research organization under the Department of Science and Technology, is devoted to the study of Geomagnetism from all possible point of views. The research activities of IIG are organized into three main areas:

- Observatory and Data Analysis (ODA)
- Upper Atmospheric Sciences
- Solid Earth Geomagnetism

The main research activities of these three divisions and the Instrumentation Division for the period 1999-2002 are given below.

Observatory and Data Analysis (ODA)

IIG operates a chain of ten permanent observatories recording continuous magnetic variations. Modern absolute instruments, Declination Inclination Magnetometers (DIMs) are being used to record and maintain the stability in the baseline, which is a crucial parameter in computing the final absolute values from variation data.

The INTERMAGNET system is being operated at Alibag and the DIGITAL data is transferred in near real time from Alibag to Colaba. The processed binary data are sent to the Geomagnetic Information Nodes (GIN's) at Boulder, USA and Kyoto, Japan within 48 hours of receipt of data at H.Q. The data can now be viewed in near real time on the web at the WDC, Kyoto website.

Magnetic observatory at Trivandrum, established in 1957 in the campus of Kerala University, was closed down on 30th October 1999. However continuity in the data is maintained by the Geomagnetic Observatory operating at IIG's Equatorial Geophysical Research Laboratory (EGRL), Tirunelveli. The magnetic observatory at Jaipur was recommissioned in the year 2002. In addition to the Digital Fluxgate Magnetometer, an IZMIRAN-IV variometer is also set up for analogue recordings at Jaipur.

Under the newly initiated Geomagnetic Activity Forecasting Program, state of the art Digital Fluxgate Magnetometers have been installed at Tirunelveli, Pondicherry, Visakhapatnam (east coast station of India) and Jaipur magnetic observatories. The data from these observatories are received at H.Q. in near real time and will be used for geomagnetic data based research and predicting geomagnetic activity, especially from low latitudes as the contribution of the low latitude geomagnetic data in assessing the magnetic disturbance parameters is important.

Antarctic Geomagnetism

The Institute has been pursuing a vigorous programme on Antarctic Geomagnetism. The Institute continues to participate in the summer and winter expeditions to Antarctica every year. Two of our staff were selected for the team leadership in two winter expeditions. Analog as well as digital instruments record valuable geomagnetic data. Also a fluxgate magnetometer and a Riometer recording the 30 MHz cosmic radio noise were simultaneously operated at Maitri to study the characteristics of ionospheric absorption caused by magnetosphere-ionosphere particle precipitation. A new experiment on atmospheric electric current as a part of the Global Electric Circuit (GEC) study was started at Maitri.

Geomagnetic data based investigations

Geomagnetic data based investigations are done by the scientists of IIG to understand the complexities of equatorial electroject (EEJ) and counter-electrojet (CEJ) and solar quiet (Sq) variations. Magnetic effects of intense solar flare were studied using the data from the ten geomagnetic observatories in the Indian longitude sector. The solar flare effect (sfe) as registered on the magnetogram is manifested by an enhancement of the ionospheric current system existing at the start of the flare. An equatorial enhancement of H component of the geomagnetic field due to sfe was found to be similar to the latitudinal variation of Sq(H) at low latitudes.

It is found that over the last 75 years, at the location of DAKSHIN GANGOTRI/ MAITRI, the total field (F) has dropped at the rate of about 120 nT per year. Data of 3-fluxgate magnetometers operating simultaneously at Maitri, Dakshin Gangotri and Orvin Mountains in Antarctica were analysed for the magnetic pulsation with periods between 30 sec. and 3000 sec. and interpreted in terms of the mobile auroral current systems that drift over the stations. The geomagnetic data are also used to study the processes of ionosphere-magnetosphere coupling and substorm dynamics.

The short-term variability in the geomagnetic field during the total solar eclipse of 11^{th} August 1999 was studied using the magnetic observatory chain operated by IIG and the special observations taken at Akola and Baroda in the path of totality. The gradient of the field was found to be different in pre-totality and post-totality times. Such types of gradients were not observed at the same time on controlled days.

A few sudden commencement great geomagnetic storms recorded during the solar cycle 22 were studied by analyzing magnetic records from selected low latitude Indian stations. Strong daytime equatorial enhancement in intensity of the geomagnetic Pc5-6 pulsation during several magnetic storms was observed from an array of 5 Indian stations. Magnetic storm of 31^{st} Dec. 1967 and 1^{st} Jan. 1968 was studied using data of ground based magnetometers and ionosonde station in India, Africa and American sectors.

Magnetic data from the Indo-Russian network that was in operation during the International Equatorial Electrojet Year (IEEY) have been analysed to study the spatial and frequency characteristics of the equatorial enhancement. The analysis shows that equatorial electrojet acts as simple amplifier that enhances any input electromagnetic field by a factor of 3-5.

Triggering of sub storm by isolated interplanetary (IP) shocks was studied using the data from satellites like, ACE, GOES-8 & GOES-10 and ground magnetometer data for four selected events of 2001. Response of the sudden increase in the solar wind dynamic pressure was reflected in the ground magnetic records as the sudden commencement. The phenomenon of geomagnetic bays, which gives important information on the onset time of substorms, was studied by analyzing the INTERMAGNET one-minute digital magnetic field data.

Three major solar flare events of the solar cycle 23 were identified to study the characteristics of the geomagnetic field components at latitudes ranging from the equator to the latitude of Sq focus in the Indian longitude sector.

Upper Atmospheric Sciences (UAS)

Ionospheric and upper atmospheric studies

Amplitude scintillation on 250 MHz radio signals recorded at a network of stations in the Indian sector during the last five years have been analyzed to study the characteristic features of ionospheric irregularities. Scintillations recorded on the 250 MHz radio beacon at Mumbai and Pondicherry were analyzed to look for the possibility of field line resonances at equatorial latitudes. Dual frequency data for fluctuations in the total electron content (TEC) along the path of GPS signals to the equatorial station Ancon (1.5^{O} dip), sampled at a rate of 1 Hz, has been used to separate this contribution from the slower TEC variations. A theoretical model, using the transmission line analogy, has been developed to investigate the coupling between the *E* and *F* regions through field-aligned currents (FACs).

Spaced receiver observations of amplitude scintillations on a 244 MHz signal, at an equatorial station, have been used to study random temporal changes associated with the scintillation-producing irregularities and the variability of their motion. The computed drift of the scintillation pattern shows the presence of velocity structures associated with equatorial bubbles in the early phase of their development. The power spectra of the most highly correlated scintillations recorded by spaced receivers indicate that the associated irregularities are confined to a thin layer on the bottom side of the equatorial F region. In an other study, it was found that during the high solar activity period (1989-1991), an increase in geomagnetic activity suppressed the occurrence of scintillation activity at Trivandrum and Mumbai stations, whereas the electrojet strength is found to have no association on the occurrence of scintillations.

Space weather affects the distribution of plasma in the ionosphere and plasmasphere through which radio waves used for communication and navigation propagate. On some occasions, only large scale (>10 km) structures in the propagation medium are encountered by the radio waves, while at other times small scale variations in ionospheric electron density give rise to scintillations on trans-ionospheric radio waves.

The occurrence of L-band scintillations on trans-ionospheric signals, due to plasma density irregularities in the nighttime equatorial ionosphere, may have a significant impact on the use of Global Positioning System (GPS) signals for navigation, particularly in the present phase of solar cycle maximum. Using spaced receiver observations of a 250 MHz signal at a location close to the equatorial anomaly crest, it is seen that the presence of strong L-band scintillations is closely associated with large decorrelation between the 250 MHz signals recorded by spaced receivers. This generally happens in the pre-midnight period when equatorial plasma bubbles rise rapidly to the topside of the *F* region and become highly structured.

An airglow monitoring station has been operating at Kolhapur to study various characteristics of F-region irregularities using an all-sky camera, tilting photometers, scanning photometer and VHF scintillation experiment. A large number of equatorial ionospheric plasma bubbles or depletions are characterized by the development of strong equatorial ionization anomaly. Analysis of the airglow data obtained during the ISTEP-II campaign period of March 12-21 and

April 10-22, 1999, showed north-south aligned intensity depletions, which are the optical signature of large scale ionospheric F-region plasma bubbles, on most of the nights.

The night airglow observations were carried out from Kolhapur (16.8^0 N, 74.2^0E) and Panhala (17.0 ^{0}N, 74.2 ^{0}E), India which is situated at 3200 feet above the sea level during February, 2001 using tilting photometers (OI 630 nm and OH) and an all-sky imager on clear and moonless nights. From these data, the gravity waves were detected, for the first time in Indian latitude region, showing perturbation in density in the mesospheric region (80-100 km) while the waves were propagating vertically from tropopause to the upper atmosphere. An intense enhancement in OI 630 nm intensity was observed during the main phase of the geomagnetic storm on the night of 7^{th} February 2000.

The importance of studies of ionospheric plasma irregularities grew because of their strong influence on ionospheric and trans-ionospheric communications. The bubbles observed during the different phases of geomagnetic storms show unusual structures (bifurcated and twisting). The continuous movement of the high rise bubbles across the zenith gives rise to strong VHF scintillations.

An analysis of low order mode coupling equations is used to describe the nonlinear behaviour of the Rayleigh-Taylor (RT) instability in order to understand the generation of equatorial spread-F. The nonlinear evolution of RT instability leads to the development of shear flow. It is found that there is an interplay between the nonlinearity and the shear-flow which compete with each other and saturate the RT mode both in the collisionless and collisional regime.

The characteristics of geomagnetic pulsations undergo appreciable changes as they pass through the ionosphere. These changed properties at the low and equatorial stations are distinctly different from those at the high latitudes. It is found that polarization directions of PC3-4 (period 10 to 100 seconds) pulsation changed during the counter electrojet time. The amplitude of these pulsations is enhanced by equatorial electrojet. The response of magnetospheric transverse modes to the solar wind dynamic pressure induced oscillations of the surface current flowing at the magnetopause has been computed based on the technique of spectral representation of the Green's function.

There are very few phenomenon in the upper atmosphere that are as sensitive to the strength and distribution of the earth's core field as the equatorial electrojet. The Oersted initial field model along with the earlier IGRF models have been used to provide insight into the secular changes in the global patterns of the position and strength of the Equatorial Electrojet (EEJ).

The Equatorial Geophysical Research Laboratory (EGRL) at Tirunelveli made good progress during this period. The partial reflection (PR) drifts at 98 km measured by the medium frequency (MF) radar are shown to have the combined effects of mesospheric winds and the equatorial electrojet. Observations of mesospheric winds in the altitude region 84-98 km with the PR radar at Tirunelveli and the ground-based geomagnetic data from the low latitude Indian sector have been used to identify the signatures of the quasi-2-day (QTD) planetary waves in the equatorial electrojet (EEJ). It is found that there is a reasonable correlation between occurrence times of the quasi-2-day oscillation in the EEJ strength and the mesospheric winds.

Second partial reflection radar at the Shivaji University Campus, Kolhapur became operational. The two radars at Tirunelveli and Kolhapur constitute a unique pair for studying structure of tidal mode, planetary scale oscillations and gravity waves. Important results on the characteristics of the mesospheric 3.5-day ultra-fast Kelvin waves, which carry eastward momentum into the upper atmosphere, were obtained and the results presented in the PSMOS workshop. It is planned to set up some new atmospheric electricity experiments.

Examination of the Tirunelveli PR radar data reveal a relationship between the tidal characteristics and the occurrence of afternoon counter electrojet (ACEJ). A clear anti-correlation is seen between the afternoon electrojet strength and the amplitude of the semi-diurnal tide in the solstitial months of June and July, 1995.

Magnetospheirc Phenomena

Boundary layers, commonly encountered in space and astrophysical plasmas, are the site where energy and momentum are exchanged between two distinct plasmas. Broadband plasma waves spanning a frequency range of a few mHz to 100 kHz and beyond have been observed in the Earth's magnetopause boundary layer, the Jovian magnetopause boundary layer, the plasma sheet boundary layer, and the Earth's polar cap boundary layer. The most intense waves are detected coincident with the strongest magnetic field gradients (field-aligned currents). The rapid pitch angle scattering of energetic particles via cyclotron resonant interactions with the waves can provide sufficient precipitated energy flux to the ionosphere to create the dayside aurora at Earth and a weak high-latitude auroral ring at Jupiter.

Polar cap boundary layer waves are ELF/VLF electric and magnetic waves detected on field lines just adjacent to the polar cap. Intense waves are present at this location essentially all (96%) of the time. The wave latitude-local time distribution is shown to be the same as that of the Feldstein auroral oval, a distribution centered at ~75^o at local noon and ~65^o at local midnight. The most intense waves are detected coincident with the strongest magnetic field gradients (field-aligned currents).

A fully electromagnetic linear theory for the generation of broadband plasma waves observed in the low latitude boundary layer by POLAR has been developed. It is shown that electron acoustic wave instability can offer a possible generation mechanism for the broadband electrostatic noise (BEN) observed in auroral acceleration region, plasma sheet boundary layer, and polar cusp region. A theoretical model for the large amplitude electrostatic ion – cyclotron modes in an auroral beam – plasma system is developed. The numerical solutions of the non-linear evolution equation could reproduce several essential features of the observed waveform by FAST and POLAR satellite.

Recent exciting high time resolution results coming from Geotail, Viking, Polar and FAST show that broadband plasma wave emissions consist of bipolar and monopolar solitary structures. A model for the nonlinear evolution of electron-acoustic waves into solitary structures has been developed. The predicted properties of the electron acoustic solitons are found to be in good agreement with the observation of spiky electric field structures by the spacecraft. Further, an analytical model of the coupled nonlinear ion cyclotron and ion-acoustic waves has been developed to explain the strong spiky waveforms in the parallel electric field in association with ion cyclotron oscillations observed by FAST satellite.

Interplanetary medium

A direct mechanism for the generation of waves in the intermediate frequencies between the water-group and the proton gyrofrequencies in cometary environments is suggested in an unstable wavelength band when the solar wind is sufficiently mass-loaded by cometary material. The mirror mode structures at comet Giacobini-Zinner are detected in a region just adjacent to the magnetic tail, and they have scale sizes of ~ 12 H_2O group ion cyclotron radii. It is shown that nonlinear evolution of Alfvén waves, propagating in streaming solar wind plasma with non-uniform densities and inhomogeneous magnetic fields, is governed by the modified derivative nonlinear Schrödinger (MDNLS) equation.

Analysis of Ulysses magnetometer data revealed the presence of magnetic field decreases (MDs) over the heliospheric polar regions. The MDs have minimum spatial scale sizes of 25 proton thermal gyroradii, and are typically bounded by tangential or rotational discontinuities. Charged particle interactions with the MDs can lead to particle guiding center displacements and hence particle cross-field diffusion.

It is shown that interplanetary shocks impingement upon the Earth's magnetosphere can cause dayside near-polar auroral brightenings. The aurora first brightens near local noon and then propagates toward dawn and dusk along the auroral oval. Significant charged-particle precipitation occurs in the dayside auroral zone during and after these shock impingements. The total energy deposition rate may be considerably greater (□ an order of magnitude) than nightside energy rates.

Simulation studies

The resistive hydromagnetic equations are solved numerically in a two dimensional box to simulate the dynamics of geomagnetic tail during substorm events by applying the Flux Corrected Transport (FCT) code. Three different widths for the initial current sheet are investigated. For wider current sheet the reconnection starts later than the case of narrower current layer. It is found that pre-substorm earthward flows deduced from satellite data could be explained by the wider current sheet case. However, these simulations are able to reproduce the onset of reconnection and formation of magnetic island - like structures called plasmoid as observed.

Solid Earth Geomagnetism (SEG)

Wide Band Magnetotelluric studies of Indian Lithosphere

Magnetotelluric studies in the Himalayan region have shown an anomalously high conductivity in the Indus suture and the Tso Morari dome extending from the shallow levels to depths of about 25 km. Studies in the granite-greenschist region of the Dharwar craton have delineated a high conductive zone beneath the west Dharwar crust at depth of about 60 km and beyond, corresponding to the lithospheric mantle. Studies over the NW Indian shield of Rajastan have delineated clear signatures of the Bundelkhand granitic mass subducting beneath the Aravalli block along the great boundary fault.

Deep Electromagnetic Imaging of the Indian Shield

A new program of long period magnetotelluric (LMT) measurements has been initiated at the Institute to determine and establish deep electrical character beneath cratons, mobile belts, and collision zone. The LMT studies across the Dharwar craton have revealed lithosphere-asthenospheric boundary at a depth of 220 km confirming well with the heat flow and seismic data. The studies in the NW Himalaya have provided new insight on the depth extent of the high conductivity zone beneath Tso Morari and shown evidence of anisotropic layer at a depth greater than 100 km LMT survey across the thermally active Kutch rift to decipher deep geodynamics and possible thermal manifestation of Deccan volcanism along the western continental margin, has brought out evidence on the presence of a moderately conducting layer between 10-17 km.

An electrical conductance model has been evolved to account for the geomagnetic induction anomalies in peninsular India and Bay of Bengal, The model showed that South India Offshore Conductivity Anomaly and its coincidence with the seismic low velocity zone and MAGSAT low magnetization anomaly, all centered near the southern tip of India, indicate these geophysical anomalies to be the manifestation of the interaction of the Marion plume with Indian Lithosphere. The nature of conductivity distribution beneath the Nintyeast and 85^{o} E ridges, inferred from transient geomagnetic data recorded by ocean bottom magnetometer, does not favour presence of partial melt but does not rule out localized magmatic intrusion into the crust.

Studies of Indian Lithosphere Through Magnetic Anomalies

Aeromagnetic data over Peninsular India (8 to 24 degrees N) have been analysed for the first time to throw light on the various tectonic blocks of the region. From the aeromagnetic anomaly, its analytical signal and Euler solutions, the subsurface structure of the region is brought out which redefine the edge of the craton and the tectonic elements of the area especially in regions with large surface cover. The Charnockites and the iron ore series are identified as the main magnetic sources. A very striking feature is the long arcuate shaped shear that extends for over 1000 km in Central India across the Peninsula from west to east to mark the edge of the Eastern Ghat block, the Bastar craton and possibly the Dharwar craton. This has been termed as the Main Peninsular shear.

Palaeomagnetic studies

The Palaeomagnetism Group has been very active in establishing the precise age, duration and extent of the Deccan Traps magmatism by carrying out palaeomagnetic studies on the dykes swarms intruded into the Deccan basalt flows along the west coast and also in the central part of the Deccan volcanic Province. The results on the Deccan Traps associated dykes indicated that the Deccan eruptions took place around 65 Ma back with the span of less than 1 Ma and affected the entire Bagh Group sediments of Narmada region. Palaeomagnetic investigations have been successfully used in differentiating the dykes of Dharwar Craton based up on their characteristic remanent directions. Precambrian dykes of Dharwar Craton were distinguished into 5 generations, viz., 1100 Ma, 1650 Ma, 1800 Ma, 1900 Ma and 2300 Ma, and traced the apparent movement of the Dharwar Craton during 2000 Ma to 2300 Ma by fitting the polar wander curves. Palaeomagnetic studies on Oddanchatram anorthosites, Tamilnadu indicated that this body was emplaced during the Eastern Ghat orogeny (~1000 Ma) and may be seen as the western extension of the string of massif type anorthosites in the Eastern Ghat Mobile belt.

The low field AMS studies on the clastic sediments of a 5.5 km thick section in the Assam-Arakan basin yielded well defined magnetic lineation directions which are parallel to the bedding strike directions, suggesting the sediment supply to the studied area was from the Mishimi Hill mountains, which rests at the northeastern margin of the studies section.

Environmental mineral magnetism in palaeoclimate and environmental reconstructions

The Institute has established a group for environmental studies that has made rapid growth and generated quality data on the Indian lake, delataic and deep sea sedimentary records. Sedimentary litho units, grain size parameters and magnetic susceptibility differences from four mangrove regions namely Mahanadi, Krishna, Godavari and Cauvery have revealed marked changes in recent climate, i.e. high hematite content due to warm climate conditions around 2000 cal yr BP (before present). Mineral magnetism of Iskapalli lagoonal sediments documented a drier climate (~ reduced monsoons) leading to more frequent fire disturbances around 3700 cal yr BP. Global significance of rapid climate oscillations during the last glacial period (~ 70 ka) over the continent is inferred for the first time from a newly generated continental record from western tropical India using variations in percentages of grain size, magnetic susceptibility, carbonates and minerals.

GPS studies in estimating the strain field

Many GPS campaigns have been undertaken in various earthquake prone zones of India viz. Western Maharashtra, Bhuj region of Gujarat, Chamoli region in Uttaranchal, North Eastern Indian region. Magnitude of the average horizontal velocity of Deccan trap region in ITRF96 is 51 mm/yr in N47^{o} E. The estimated dilatational strain is about 0.4 micro strain/yr in average. An extensional strain regime is observed along the west coast transcending into a region of compressive strain towards the interior of the shield area. The extensional strain regime coincides with the West Coast Geothermal Province. The Murbad region in Thane district of Maharashtra is under E-W compression and N-S expansion regime. Intra-plate movements are detected around Amberji. The East-West, North-south and vertical components of the baseline Lodai-Ratanpar (passing through the epicentral area) show no co-seismic displacements associated with 26^{th} January 2001 Bhuj Earthquake. N-S compressional strain of about 0.1 micro strain/yr found in between Ratanpar and Dhamdkapir

Instrumentation Division

A PC controlled PPM and a new Barker Coil System , for a newly designed Vector Proton Magnetometer were fabricated. The PC Controlled Proton magnetometer has a sensitivity of 0.1 nT and can be used in Magnetic Observatories for Calibration of other Magnetometers.

A portable/field use microcontroller based Proton Magnetometer that works on batteries and has internal memory to store data was designed. This magnetometer was tested against international commercial models in a Symposium organized by IAGA at South Africa. The model showed a good match with the standard at Hermanus Magnetic Observatory at South Africa.

The Indian Institute of Astrophysics, Bangalore

The regular sunset enhancement of upward drift of equatorial *F* region plasma is observed to be abnormally large on certain quiet days (Sp. □ 5) as manifested by an anomalous increase of *F* region height. It is found that on the days with an unusually large dusktime increase of *F* region height over Kodaikanal, the diurnal profile of the equatorial electroject (EEJ) strength is severely distorted (with a shift in some cases, of *Sq*(H) phase from the usual time interval, characteristic of the abnormal quiet days, AQD0 with enhanced EEJ conditions in the postnoon period (13000-1600 LT). This is accompanied, near the magnetic equator, by higher values of *F* layer peak height (*hpF2)* and lower values of peak electron density (*f0F2*) in the early evening period (1600-1800 LT), compared with the monthly median/quiet day mean values. These changes in EEJ and *hpF2/f0F2* are consistently seen in all cases studied. We interpret that the perturbations in plasma density distribution of equatorial F region, increase the thermospheric zonal wind and its local time gradient as well as the ratio of flux-tube-integrated Pedersen conductivity of the *F* to *E* region. These modifications just prior to sunset, prompt an efficient *F* region dynamoaction, resulting in the observed abnormally large dusktime increase of *F* region height. The study strengthens the view that the postsunset behaviour of the equatorial ionosphere is sometimes predetermined by the properties of the thermosphere-ionosphere system in the early evening hours.

In-depth case studies are made to characterize the features of the dynamics of the ionosphere-thermosphere system that favour the occasional postsunset onset of range spread-F at Fortaleza, Brazil (dip latitude 1.8 S) during the June solstice. This is the season in which frequency spread F is typically seen while range spread F is remarkably inhibited at Fortaleza. The onset of range spread-F studied is thus an exception to the rule and has relevance to the topic of day-to-day variability of equatorial spread F of much current research. It is found that an impulsive and large F layer vertical drift (20 – 60 m/sec) prevails in the early evening hours on days of range spread F, in contrast to the average pattern of a slowly varying vertical drift of moderate amplitude (15 – 18 m/sec). There is no significant change in the pattern or magnitude of low-latitude meridional winds between the days of range and frequency spread F at Fortaleza. This suggests that meridional wind variability does not play a important role in creating favorable conditions for range spread F on a day-to-day basis in the June solstice. The prerequisite for the occasional occurrence of range spread F is the presence of an impulsive and large vertical plasma drift, a condition favourable for destabilization of the bottomside F layer through Rayleigh-Taylor (RT) instability mechanism. Evaluation of the generalized RT growth rates for the specific events supports the interpretation. The anomalously large F layer vertical drift seen on range spread F days is associated with moderately disturbed geomagnetic conditions as well as quiet conditions. Short-lived prompt electric field disturbances due to auroral substorm activity are ascertained to be the cause of the large F layer uplifts under disturbed geomagnetic conditions.

Electrodynamic Coupling of High Latitude-Low Latitude Ionospheres

The geomagnetic and ionospheric manifestations of DP2 activity that occurred on April 7, 1995 were studied using the high time resolution measurements of F layer vertical drift, Vz over Kodaikanal, India with the HF Doppler radar and magnetometer data of IMAGE network in Scandinavia and at Alcantara, Brazil. Quasi-periodic fluctuations in dusktime (1730-1900 LT) F layer vertical drift occurred over Kodaikanal *coherent* with DP2 type magnetic fluctuations (period ~ 25 minutes) at the dayside dip equator (Alcantara) and auroral/subauroral latitudes (IMAGE network stations). The DP2 – associated vertical plasma drifts are upward (amplitude 13-33 m/sec) implying eastward electric field disturbances. These first ever observations of ionospheric plasma motions due to DP2 electric fields at the duskside dip equator are in agreement with the two-cell equivalent current system proposed for Dp2. The results demonstrated that the transient component of the magnetospheric electric field responsible for DP2 magnetic fluctuations penetrates, through the polar ionosphere on the duskside as on the dayside. An additional observation is that the amplitude of the plasma drift fluctuations increase towards the nightside – suggesting a contribution of sunset electrodynamics to the observed signature of DP2 electric fields.

The F-layer of the ionosphere above the dip equator is known to develop "spread – F" conditions around midnight during summer. Earlier, this was thought to be due to instabilities manifested as an increase in the mean height of the F-layer. An analysis of the ionogram database of Kodaikanal showed however that the F-layer elevation occurs irrespective of spread – F conditions. This finding requires a drastic revision of the earlier ideas about the phenomenon.

The first ever evidence for DP2 electric field in the midnight dip equatorial ionosphere was obtained from careful analysis of quasi-periodic fluctuations in F-layer vertical plasma motions recorded by the HF Doppler sounder at Kodaikanal. Complex patterns of the latitudinal variation of the solar flare effect in geomagnetic field was seen from a study using data from the Indo-USSR chain of magnetometer stations.

The STP group participated in the observational equatorial spread – F (ESF) campaign held in April 1998 and March 1999 under the activities of Working Group (WG) 3 of Indian Solar Terrestrial Energy Programme (I-STEP.)

The STP group of the Institute participated in the *Equatorial Spread F* (ESF) campaign held during April 1999 under the I-STEP. Regular data acquisition in the monitoring mode continued with the experimental facilities (IPS42 digital ionosonde, HF Doppler Radar and Magnetometer) at Kodaikanal Observatory.

A comprehensive study of the ionospheric storm of November 4, 1993 in the Indian equatorial region was undertaken in the Institute because of the absence hitherto of an assessment of the response of equatorial upper atmosphere to this magnetic storm. The study, based on data from the ionosonde and magnetometer networks in the country, brought to light several new facets of the storm-time behavior of the equatorial ionosphere, indicating, in particular, a significant electrodynamic coupling between high – and low latitude ionosphere.

Work is continuing in the Institute on the inter-relationships between solar wind, magnetosphere and ionosphere. The global manifestation of the waveform of the geomagnetic storm sudden commencement (SC) of November 18, 1993 has been evaluated using high time resolution data of several magnetometer networks coupled with HF Doppler Radar measurements at Kodaikanal. The work revealed that the dip equatorial appearance of the preliminary reverse impulse (PRI) of the SC deviated quite significantly from the pattern established by previous statistical studies as well as the one predicted by currently available theoretical models of SC.

Institute's scientists are also involved in detailed study of the effects of meteor showers on the ionosphere. In particular, the effect of Leonid meteor showers during the years 1996 through 1998, on the characteristics of sporadic-E layers at equatorial latitudes, has been studied using data of rapid ionospheric soundings at several stations in the country. The results showed an increase in the occurrence of Es layers at altitudes in the range 100-140 km throughout the equatorial region at the times of peak shower activity. The finding underscores the need for further studies to ascertain the origin of the observed changes in Es behavior, in particular the relative roles of deposition of metallic ions due to shower activity and the physical mechanism(s) that cause ion-convergence and lead to Es layers.

Case studies are done to investigate the nature of transient disturbances (duration ~ 2 hr) in the equatorial electrojet current during the different phases of isolated substorms triggered by directional changes in the interplanetary magnetic field, IMF. Data from the Indian magnetometer network spanning the dipole latitude range 1.2 S-13.5 N are used. A positive bay-like perturbation is found to prevail during the growth phase of the substorm, followed by conspicuous negative-by perturbation precisely with the onset of the expansion phase. The amplitude of both the positive bay and the subsequent negative bay is markedly enhanced in the equatorial electrojet region compared to stations outside the electrojet. This repeatable response pattern is strongly indicative of the occurrence of short-lived disturbances in the ionospheric zonal electric field with both the growth phase and expansion phase onset of isolated substorms, a feature that has never been reported before. The evidence electric field perturbations are suggested as signatures of prompt penetration electric fields associated with rapid changes in magnetospheric convection brought about by swift transitions in IMF Bz/By components during substorms.

Solar wind-magnetosphere-ionosphere coupling

A halo coronal mass ejection (CME) left the Sun around 1054 UT on July 14, 2000 and the CME-driven shock wave impacted the Earth's magnetosphere at 1437 UT on July 15, 2000 and produced a severe magnetic storm the largest such event in nearly a decade. This magnetic storm which has come to be popularly known as the *Bastille day* storm. IPS42 digital ionosonde measurements at Kodaikanal, Waltair and Trivandrum showed an anomalous and extremely rapid decrease in F layer height (maximum value close to dip equator, 215 km/hr) simultaneously at all the stations around local midnight during the storm main phase on July 15, 2000. Careful analysis of the geomagnetic and ionospheric data showed that the abnormal midnight descent of equatorial F region indicative of a short-lived westward electric field disturbance (peak amplitude □ mV/m) is due to prompt penetration of convection electric fields associated with impulsive injections of the magnetospheric ring current. This is the first time evidence for the occurrence of such a large amplitude westward penetration electric field around local midnight, in an environment under the influence of eastward electric fields due to the 'disturbance dynamo' mechanism. The case study highlights the profound manner in which the equatorial F region plasma dynamics can get modified during the main phase of severe magnetic storms. This result has important practical implications for telecommunications.

Ionospheric Oscillations

Global scale oscillations in the earth's magnetosphere-ionosphere system were found to follow the impulsive increase in the solar wind dynamic pressure from 1.5 nPa to 4.0 nPa over the interval 1002-1008 UT on November 9, 1997. This evidence was obtained from simultaneous measurements with multiple spacecraft and groundbased instruments. The magnetospheric compression affected by the solar wind pressure pulse generated drift echoes in the outer radiation zone, with the strongest echoes from electrons in the energy range 100-200 keV. Ground based magnetometers registered periodic enhancements of ionospheric currents with a period of 60-70 min, the same as of the drift echoes. The study suggests a new source of ionospheric oscillations in association with magnetospheric drift echoes generated by solar wind pressure pulses.

Storm Sudden Commencements

The geomagnetic storm sudden commencement (SSC) of July 8, 1991 was characterized by a reduction (enhancement) of X/H-component at midlatitudes in the noon (midnight) sector in the 1-hr period after its start at 1636 UT. This distinctive feature was seen even after accounting for the effects of Chapman-Ferraro currents in the magnetopause. The HF Doppler radar measurements of F region vertical plasma drift over Kodaikanal revealed that, over the same 1-hr period after the SSC on July 8, 1991, an eastward electric field disturbance grew up and decayed near the premidnight magnetic equator. The eastward electric field is interpreted as the signature of the penetration of the dawn-to-dusk electric field associated with an enhancement of region-1 field-aligned currents (FACs) driven by the solar wind.

Developmental work

Preparations are nearing completion for the installation of the DMI digital fluxgate magnetometer as the replacement for the aged La Cour Variometer which has been in round-the-clock operation in Kodaikanal Observatory since 1949. The DMI fluxgate system is on par with IAGA standards and provides geomagnetic data with high sensitivity and time resolution to address several problems in STP that was not possible before.

National Physical Laboratory, New Delhi

SROSS-C2 satellite RPA results:

Retarding Potential Analyser (RPA) aeronomy payload on board SROSS-C2 Indian satellite, which was launched in May 1994 remained in orbit till July 2001 thereby covering the period from solar minimum to solar maximum. It generated huge amount of data over the Indian region at F region heights from 400 km to 620 km. during this period. Some very interesting results have been observed during the mission. During high solar activity there is a occurrence of very large scale plasma density depletions at F region heights during pre-midnight hours. These depletions were found to be 3 to 4 decades down as compared to normal densities and contain large latitudinal gradients. Smaller scale irregularities are also found embedded within such depletions (Garg et al., 2003). The results on temperatures and densities showed some very interesting results during magnetically disturbed conditions, Electron temperature showed substantial rise and latitudinal variation during such events. Leonid meteor shower events during 1998 & 1999 were intercepted by the payload. This showed presence of heavy metallic ions (Fe+) during meteors.

GPS observations for TEC measurements

Observations of total electron content (TEC) of the ionosphere were carried out for the first time at the Indian station Maitri in Antarctica from Jan. 12, 1998 to Feb. 5, 1998 during 17^{th} Indian scientific expedition to Antarctica. For this purpose signals from Global Positioning System (GPS) orbiting satellites were monitored. A software for deriving TEC from GPS observations has been developed at NPL. The values so derived for Maitri do not show large diurnal variations, however the signatures of large scale disturbances are seen superimposed on the diurnal variations of TEC.

A new software has been developed which estimates the Faraday rotation suffered by the em wave at 6.6 GHz from sea surface to the orbiting satellite at a height of 800 km. above the earth based on total electron content observed by GPS satellites. In this scheme GPS TEC is used to optimize the IRI model and then IRI model is used to get faraday rotation.

Ionospheric Scintillations

Signals from FLEESAT satellite were monitored to study the effects of ionospheric irregularities on trans ionospheric propagation. The data was analysed to study the role of neutral winds and electric fields on generation and sustenance of equatorial ionospheric irregularities. The results have shown the importance of electric fields as evidenced from ionospheric heights variations at the geomagnetic equator in producing the scintillations at a location like Delhi. The study was also taken up as part of nationally coordinated program on equatorial ionospheric irregularities. Observations have also been started at two satellite earth stations Chengleton (12.7^{O} N, 79.9^{O} E) and Sikanderabad (28.5^{O} N, 77.7^{O} E) at 4 GHZ. These observations were carried out using C-band pilot carrier of Thaicom geostationary satellite at 94^{O} E. A study conducted using Sikanderabad data showed that there was good correlation between the day time equatorial electrojet strength and nighttime scintillation intensity.

Anomalous Ionospheric Electron Temperatures

Study conducted using electron temperature data from HINTORI satellite has revealed certain anomalous variations in the ionospheric electron temperatures at 600 km altitude by way of, exceptionally large increases as compared to background value in ± 30^{o} latitude range. These ionospheric temperatures enhancements (T_{en}) have been observed in a wide range of longitudes including the Indian zone with distinct seasonal and local time bias. On a large no. of occasions they have been found to occur on either side of the geomagnetic equator coinciding with the well known equatorial ionisation anomaly. The results are explained in terms of zonal winds, winter anomaly in electron density and electrodynamic drifts (Dabas et al., 2000). The RPA payload data from SROSS-C2 satellite also supports HINTORI observations.

Improvements in IRI

About 1500 electron density (Ne) profiles observed with the Arecibo Incoherent Scatter Radar were used to obtain the thickness parameters of the bottomside F layer (B0 and B1 parameters) by fitting the observed profiles to the IRI profile function. The relative between the best fit profiles and the observed IS profiles were also examined. The error was found to be very large during the day especially at times when the F1 layer was present which happened for about 30 % of the total population. The B0, B1 values obtained for the remainder 70 % of the cases showed large variability and were different from the IRI model values. The B0, B1 were modelled and suitable changes were suggested to be included in IRI model (Mahajan and Sethi, 2000; Sethi et al., 2000; Sethi and Mahajan, 2002) . The studies were carried out on the variability of equivalent slab thickness.

The studies have been made on foF2 for a no, of stations for period from IGY to 1990. This data was obtained in the form CDs from World Data Centre, Boulder. It was revealed from these studies that the noon time foF2 shows a linear variation with sunspot no. (R12) at mid-latitudes. However, at low latitudes it is no more linear at high values of R12.

The comparison of IRI model values with obtained for Delhi using digital ionosonde shows a fairly good agreement with observed median foF2 values for the daytime, during all the seasons. Discrepancies between the two exist during nighttime, when the percentage deviations of the IRI model with respect to observed values fluctuate between 10 to 25 % especially during winter and equinox months. This digital ionosonde facility was established in 1999 at NPL, New Delhi.

Rain Attenuation Studies on GHz radio links

To study the effect of rain on microwave signals at GHz frequencies, experiments are being conducted to derive (a) rain characteristics using an X-band radar of the Indian Meteorological Department located at Kolkatta, (b) rain attenuation by monitoring simultaneously a LOS radio link operating at 18 GHz and (c) rain condition by mounting rain gauges at nearby locations. The horizontal and vertical extents of rain cells were deduced from radar reflectivity measurements. The link was operating between Sonarpur and Jadavpur covering a distance of 8 km. The signals were attenuated by as much as 18 dB even under moderate rain fall conditions of 55 mm/hr. intensity. Based on the observations, rain intensity vs rain attenuation curves have been obtained which can be used for designing high reliability links at frequencies > 10 GHz which are capable of large data transmission rates.

RWC AND Forecast services

Short term forecasting and data exchange activities of Indian RWC operating from NPL is a continued effort. Forecasts on solar and magnetic activities were provided to a no. of user agencies Indian Navy, Space, IMD etc. Spatial ionospheric predictions were also provided to the Indian Defence Services to aid in planning of HF links. NPL has also been providing HF prediction for links operating in certain strategic region to Indian Army and Air Force.

Prediction of the size of cycle 23 using Multivariate relationships

A new technique based on multivariate analysis is developed for the prediction of the size of maximum amplitude of present sunspot cycle 23. The importance of the technique lies in its ability to predict the size of forthcoming cycle even before the start of the cycle that was not possible with traditional statistical techniques. The no. Of geomagnetic disturbances at selected times in the declining phase of cycle 22 are used as precursor to predict the size of the cycle 23. The observed values are found to be within 5%. The technique has predicted the size of present cycle 23 to be 152.

Planetary Ionospheres

The aeronomy experiments on the Pioneer Venus Orbital (PVO) established three characteristic features of the nightside ionosphere of Venus, (1) the disappearing ionospheres (2) the large spatial/temporal variability of ion densities and (3) the plasma holes. The studies on the temporal/spatial ion density variability and the plasma holes, were carried out by analyzing O+ density profiles measured by the ion mass spectrometer experiment on the PVO. It was found that most of the variability in the central nightside ionosphere was related to PSW which was seen to control the O+ peak density and the height of the nightside ionopause. The plasma holes were found to occur above the nightside ionopause when PSW was generally moderate. It was demonstrated that there were not real holes in the main ionosphere but were ionospheric structures seen above the nightside ionopause. The plasma in these structures was generally found to be disturbed and it is proposed that the source of these structures is the plasma clouds/ detached plasma transported from above the dayside ionopause. The strong radial (sunward/ anti-sunward) magnetic fields, which have been reported to exist in the holes, were quiet similar to the ones, which were generally seen in the nightside ionopause.

Centre for Earth Science Studies, Tiruvananthapuram

Radioactivity and Atmospheric electrical conductivity:

Simultaneous measurements of radioactivity using a gamma ray intensity meter and atmospheric electrical conductivity using a Gerdien condenser were made in the south-western coast of India, a region of one of the world's richest radioactive deposits. The measurements were used to relate the strength of radioactivity and atmospheric electrical conductivity. The data set was used to derive the effective recombination coefficient. The derived values agree with the model values. Thus, qualitatively and quantitatively the effect of radioactivity in enhancing atmospheric electrical conductivity has been established. It also points to the fact that enhanced conductivity can be used to identify radioactive deposits.

Distribution of currents in an abnormal Equatorial Electrojet

A number of rocket magnetometer measurements of the Equatorial Electrojet (EEJ) have been carried out from Thumba, India. Most of the flights were conducted on quiet days close to noon when the electrojet strength was very high. At the time of these flights, the geomagnetic field variations at Thiruvananthapuram (a EEJ station) were larger than those at the non-EEJ station like Alibag. However, the geomagnetic field variations were quite unique at the time of a launch of a particular flight. The vertical distribution of current measured in this flight is compared with the average profile obtained from the results of a number of flights from Thumba, India. It is observed that on a day when the geomagnetic field variation in the H-component at Thiruvananthapuram is very close to that at Alibag, the vertical extent of the electrojet current seems to have been reduced.

Raindrop size distribution at Thiruvananthapuram

Raindrop size distribution was measured at Thiruvananthapuram using a Joss-Waldvogel type disdrometer. Two types of distribution were observed. Much of the rainfall showed distributions similar to that of the Marshall-Palmer (MP) model, N(D) = N_0*exp(-_D) with _ = 4.1 $R^{-0.21}$, where R is the rate of rainfall, N(D) is the number per cubic metre of drops of diameter D, and N_0 corresponds to the asymptotic value for the number of drops of zero diameter. In certain particular instances, the distribution deviated significantly from the MP model. Here, better fits were obtained with the gamma distribution function, particularly for the drops above about 0.5 mm diameter.

In subsequent analyses, the lognormal function was fitted to the drop size distributions, and good fits were obtained in all cases. The lognormal fit uses three fit parameters that can be related to the size distributions, namely the total number of drops, N, the geometric mean, x_g, and the standard geometric deviation, □. These parameters were found to depend on the rate of rainfall. This is being carried out under a programme sponsored by the Dept. of Science & Technology, Govt. of India.

Study on the widespread "colour rain" phenomenon

The state of Kerala, India, experienced several instances of coloured rainfall during the months July to September 2001. Rain samples were collected from a few sites and the detailed analysis was done at one site (Changanassery: Lat: 9.45°, Long: 76.55°). The rain sample from Changanassery was found to contain spores of a lichen-forming alga identified as belonging to the genus *Trentepohlia*. The red colour of the spores was due to the presence of haematochrome. The other samples examined also contained similar spores in sufficient quantities to give colour to the water. Analysis of samples from the surface at Changanassery showed that the area was covered with lichens in a large number. Culture of these samples showed that they also belong to the same genus. It indicated that the spores seen in the rainwater could be of local origin and would have come from the surface itself. (part of rainfall studies supported by DST, Govt. of India)

Lightning monitoring

To understand the distribution of lightning incidents over Kerala, a programme to collect and collate the past data on lightning incidences has been taken up. Data is collected from Revenue records, newspapers and other establishments like Telecom that are affected by lightning. This data will be used to get a lightning activity map of the state and also to help in understanding the reasons for the activity to happen more frequently in certain areas. Along with the data collection, an electric field meter is being used to monitor atmospheric electric field. The movement of thunderclouds and their effect on electric field is being studied with this data. The lightning events as recorded by the meter and the actual area where lightning struck are being studied to evaluate the usefulness of the electric field data.

Facilities Established

An electro-mechanical (Joss-Waldvogel type) Disdrometer to measure rain drop size spectrum (funded by DST). Intensity rain gauges to measure the rainfall intensity are being established at four different altitudes in the western ghats (funded by DST)

University of Pune, Pune

Measurements of optical properties of naturally occurring and anthropogenic aerosols and their distribution are needed to evaluate their climatic impact and monitor their climatology. Atmospheric aerosols arise from a variety of sources, which include both natural and anthropogenic processes. They play important role in the radiation balance and energetics of the earth-atmosphere system. In atmospheric chemistry they provide the base for heterogeneous chemical reactions some of which play a vital role in the ozone depletion phenomenon in the stratosphere. Aerosols also act as condensation nuclei in the formation of clouds. By virtue of these interactions atmospheric aerosols constitute important climate forcing due to their radiative effect and their influence on cloud properties. Optical properties of aerosols depend on the aerosol size distribution as well as on refractive index and the shape of the particles. In order to understand the above features and their climatic implications on regional and tropical scale, multiple wavelength radiometer (MWR) studies are continued from Pune University (18° 32’ N, 73° 51’ E, 559 m MSL) under the sponsorship of UGC, CSIR and ISRO-GBP.

Instrument Development

A sun-tracking MWR having wide spectral range from 380-1020 nm has been indigenously developed for measurement of direct solar irradiance at the ground. The instrument consists of a sun-tracked plane mirror, which is clock driven. It is deployed on the open terrace of the laboratory. The primary mirror reflects the image of the solar disc on to the entrance aperture of the integrating sphere of the MWR. Homogeneous light beam entering the MWR passes through optical interference filter and is incident on a solid state detector whose electrical output is recorded on a PC with the help of data acquisition card. The output is proportional to the ground reaching solar flux in the wavelength band of the filter. Eleven narrow band (~10 nm) Optical filters covering the above spectral range are mounted on a filter wheel that is rotated by a stepper motor to effect a change of filter. From the data, columnar total optical depth of the atmosphere is determined following the Langley technique. Columnar aerosol optical depth (AOD) is deduced from the total depth by subtracting contribution due to Rayleigh scattering and ozone absorption.

The Diurnal Variation of AOD

Two-segment Langley plot is a special feature at Pune and it occurs throughout the observation period from December to May, although it is more prominent during winter (Dec – Feb) when precipitable moisture provides a strong source of haze particles.

The linear segments, one for the forenoon (FN) and the other for the afternoon (AN), define corresponding AODs. Usually $□_{p□}$ (FN) > $□_{p□}$ (AN) during winter. This is regarded as the diurnal variation of AOD. Cases of $□_{p□}$ (FN) < $□_{p□}$ (AN) occur on some occasions during summer.

The difference between $□_{p□}$(FN) and $□_{p□}$(AN) is large in December–February and becomes less from March to May. Also the difference is large in the wavelength range 400-600 nm and is less at higher wavelengths.

The occurrence of $□_{p□}$(FN) and $□_{p□}$(AN) is found to be due to processes in the ABL. The ground gets warmer around the local noon causing vertical mixing and boundary layer growth.

About an hour after local noon, convection builds up carrying aerosols vertically upwards in the cooler environment that is high in RH due to adiabatic cooling. Aerosol swelling results causing increase in particle size and about 30-40% reduction in their extinction efficiency at shorter wavelengths and hence in their $□_{p□}$ (FN) in the spectral range 380-600 nm. The reduced AOD is $□_{p□}$ (AN). Determination of size of aerosols separately during FN and AN shows growth.

In the daily measurements of solar irradiance, the changeover from $□_{p□}$(FN) to $□_{p□}$(AN) is marked by a small enhancement in the intensity of ground reaching direct solar flux at shorter wavelengths in the spectral range 380-600 nm within an hour after the local noon.

Monthly and Spectral Variation of AOD

AOD is high at 400 nm and low at 800 nm. In April AOD values range from 0.93 at 400 nm to 0.70 at 800 nm (summer Maximum) and in Dec-Jan from 0.54 at 400 nm to 0.33 at 800 nm. (Winter minimum).

Spectral variation has different characteristics during 1998-2001.During 19998-99 and 200-2001 the curves display at least two peaks between 400 and 600nm. The data for 1999-2000 show that AOD is high at 400-500 nm and decreases at higher wavelengths attaining low value at 1020 nm. The shape of the monthly spectral variation is decay type in different months during 1999-2000.

The monthly average aerosol size distribution is mostly decay type during 1999-2000 and is bimodal from December to March and is decay type in May during 1998-99 and 2000-2001. April appears like a transitional month, with the distribution curve a mixture of bimodal and decay types.

It is plausible that the source of primary mode aerosols is the atmospheric haze while the secondary mode particles are of anthropogenic origin. The latter dominate in April and May.

Upper air circulation at the top of the ABL exerts strong influence on $□_{p□}$ either through influx of marine aerosols and moisture (in February-March) or through their confinement (in April), or by controlling the dispersal of aerosols (in May-June).

Angstrom turbidity parameters (□,□) show monthly variation. □ has small positive values during December – April showing prevalence of small size particles which is confirmed by the size distribution analysis. Large size particles prevail in May when □ is negative. □ is minimum in winter and maximum in summer.

Results are used for evolving climatology of aerosol optical depth for the tropical urban environment at Pune.

Indian Institute of Tropical Meteorology, Pune

Atmospheric Electricity

Data on atmospheric electric field and electric conductivity obtained at Maitri during XVI Indian Scientific Expedition to Antarctica showed a peak in electric field at 1300 hrs and a secondary peak in electric field at 1900 hrs. The electrical conductivity did not show any significant variation during the period of measurement at Maitri, Antarctica. The results have been analyzed to study the relative contributions of different generators to the Global Electric Circuit. The atmospheric electric conductivity was measured over the Indian Ocean on different cruises of ORV Sagar Kanya during the INDOEX. Results showed a north-to-south positive gradient of conductivity extending up to the ITCZ in the southern hemisphere. Results have been used to study the large-scale transport of aerosols.

Maxwell current density, electric field, precipitation current, space charge density and conductivity were measured below thunderclouds. The results showed that the recovery curves of electric field after positive lightning were much different from that of the negative lightning when the value of pre-discharge electric field was very high.

The vertical profiles of the atmospheric electrical parameters close to the ground were computed for different conditions of the vertical stability and different values of the surface electric field. The effect of surface radioactivity was also included. The atmospheric stability of the lower atmosphere was found to have a very prominent effect on the profiles. A comprehensive experiment to understand the atmospheric electrical state of atmosphere close to the ground was carried out at the Atmospheric Electricity Observatory, Pune. Simultaneous measurements of different atmospheric parameters viz., atmospheric electric field, conductivity, space charge, air-earth current, ion concentration, atmospheric temperature profile and radioactivity were carried out.

Five a.c. field mills and five conductivity apparatus were fabricated for the measurements of electric field and conductivity in the DST project of Indian Institute of Geomagnetism (IIG) on Global Electric Circuit. The instruments were calibrated, tested and handed over to IIG for measurements.

Stratosphere-Troposphere Energy Exchange

Association between daily values of zonal winds in the lower stratosphere and upper troposphere vis-à-vis solar activity was investigated using the MST Radar special observations of winds collected at Gadanki (13.5°N, 79.2°E) during 14 May – 14 June 1995. The study suggested that the day-to-day variations in the zonal winds in the upper troposphere or lower stratosphere were not correlated with the sunspot number peak values of 10.7 cm solar flux. But zonal winds in the stratosphere showed good positive correlation with solar magnetic field variation.

The variations in the total ozone, and characteristics of the winds and wave activity in the region extending from the lower troposphere up to the middle atmosphere during the occurrence of high latitude stratospheric warmings were investigated by using the data regarding occurrence of stratospheric warmings in the high latitudes, rocketsonde wind and temperature data for the period 1970-1992 and the total ozone data for 1°-67°N latitude belts for the period 1970-1997. The total ozone was found to be increased in the high latitudes and decreased in the equatorial regions during the period of major high latitude stratospheric warmings. Cooling in the tropical mesospheric and tropospheric regions followed by wind reversal from easterly to weak westerly was also observed.

The daily data of geomagnetic activity (characterized by Ap index) and temperature and wind (from rocketsonde and radiosonde) at 30 hPa level over Volgograd and Heiss Island during January-February 1986 were examined to study the possible relationship between the geomagnetic activity, temperature and wind over mid and high latitude stations.

A statistically significant (< 5% level) negative correlation (r=0.38) between temperature and Ap index over Volgograd, while a positive correlation (r=0.37) between zonal winds and Ap index over Heiss Island was revealed. The results can be explained on the basis of interactions between generation and development of planetary wave activity (due to wind and temperature fields) and geomagnetic activity.

A study of the influence of an Index (geomagnetic activity) on the mean structures of wind and temperature of the tropical middle atmosphere during the winter and summer seasons of 1979-1987 was carried out by utilising the structure of the winds and temperatures derived from rocketsonde wind and temperature data for Thumba (8.5ºN, 76.9ºE) of the Soviet M-100 rockets and aa Index anomalies calculated from the aa Index 30-year mean (1957-1986). The cold/warm temperatures at 14 km and associated negative/positive Index anomalies during summer were found to be responsible for the phase reversal of wind from easterly to westerly in the lower stratospheric levels during winter (December).

The association between the space-time evolution of radar tropopause (sharp enhancement in the radar backscattered signal strength) and vertical wind was investigated by conducting special experiments at the Indian MST Radar Facility at Gadanki (13.47°N, 79.1°E), Tirupati, Andhra Pradesh over three diurnal cycles on 17-18, 22-23 and 24-25 November 1994. The results indicated that the atmosphere was more turbulent around midnight, which resulted in the weakening of the tropopause. The height averaged vertical wind velocity was maximum preceding and following the occurrence of tropopause weakening. Smaller vertical wind velocity gradients were found to be associated with the stability conditions in the tropopause.

A study relating to long-term temperature trends in the middle atmosphere vis-à-vis possible global change was undertaken utilizing radiosonde and M-100 rocketsonde data collected over Thumba (8°N) in the 20-80 km altitude region for the period 1971-1993. An annual negative temperature trend of 1 - 2.5° K/decade was noticed from 20 to 45 km and of 2 - 3°K/decade in the lower mesosphere, and a rise in cooling up to 5°K/decade in the upper mesosphere. A variation in trend pattern was observed in different seasons. A multiple function regression analysis of the Rocketsonde data showed a significant solar cycle component in the mesospheric temperature, magnitude of which increases with height. A negative correlation in the entire stratosphere and a positive correlation in the mesosphere were found to exist. Solar coefficients fell off with height above 70 km and the value touched as high as 4°K/100F at 75 km.

Effect of Stratospheric Changes on Climate

A study of the tropospheric and lower stratospheric parameters associated with Mediterranean cyclones suggested that the cyclonic activity in the Mediterranean region could be associated with (i) the low latitude surface pressure and (ii) the zonal winds at 100 hPa level and reversal in the meridional winds in the stratospheric levels at high latitudes.

From superposed epoch analysis of daily winds and temperatures during 1971-1987 for the summer and winter seasons for the stations Madras, Hyderabad, Kolkata and Thiruvananthapuram, increase in wind speed from -3.7 to +3.8 and increase in temperature from 23°C to 28.1°C in the troposphere following the geomagnetic storms were observed with a lag up to 3 days. Also, a 15-day periodicity and a high correlation between geomagnetic activity and temperatures/winds over a period of 15 days were observed from the spectral analysis of k-indices and temperatures/winds (daily values).

A study was carried out to examine the relationship between total ozone and southern oscillation index (SOI) during both the phases of quasi biennial oscillation (QBO) by using total ozone data for 0° - 20°N latitude and 70° - 100°E longitude during 1950-1992 for three months (June-August) as well as SOI data. It was observed that SOI-ozone relationship depends on the QBO, i.e. during the periods when the QBO and SOI are in phase decrease in total ozone was observed.

The relationship between the frequency of cyclonic storms, genesis potential (GP) and temperatures in the lower stratosphere at 60°N in the easterly and westerly phases of QBO for a 36-year period (1964-1998) was investigated. GP values were calculated by subtracting the values of relative vorticity at 850 hPa from those at 200 hPa. To calculate GP values, radiosonde data at 00 and 12 GMT were utilized. GP was found to be greater for developing synoptic scale disturbances in the westerly phase of QBO than in the easterly phase of QBO. Also, cold temperatures in the lower stratosphere at 60°N in the westerly phase of QBO were found to be associated with more number of cyclonic storms over Indian seas.

Saurashtra University, Rajkot

Monitoring of satellite radio beacon signal strength fluctuations characterized by some form of scintillation index provides a simple method to study ionospheric irregularities. The VHF (250 MHz) scintillation observations made at a chain of stations in India under AICPITS was continued during the period under report. The data during 19-20 February, 1993, when an extensive "ionization hole campaign" involving other experiments were also carried out, showed that, on average, the scintillation onset was nearly simultaneous at the equatorial stations up to about 20^{o} magnetic dip angle while a systematic time shift that progressively increased with dip angle was observed. The vertical rise velocity of the plasma depletions estimated from the time delays was found to range from 40m/s to 420 m/s in the altitude range 300 to 1350 km.

Applying power spectral analysis to the digital scintillation data recorded at Rajkot for an extended period , 1991 to 1993 , quantitative parameters such as S4 index, fade rate, upper roll off frequency, spectral slope etc are derived and discussed in terms of the parameters of the causative plasma irregularities. The effect of the irregularities on communication systems in terms of signal statistics such as cumulative amplitude distribution functions, fade rate, message reliability and bit error on a typical communication system are computed.

The association between the equatorial electrojet strength and ionospheric scintillation at the anomaly crest station, Rajkot is investigated. The EEj strength is low on days of weak premidnight scintillations and high on days of strong premidnight scintillations. This in turn is consistent with a good correlation between the post sunset enhancement in F region vertical drift and EEJ. Thus a positive correlation between daytime E-region dynamo and nighttime f region dynamo can be inferred.

Nocturnal, seasonal and solar activity variations of VHF scintillation occurrence at the equatorial and anomaly crest locations in India are presented and compared with corresponding variations in spread F occurrence. At equator, scintillation and range spread F occur predominantly in the pre midnight period of equinoxes and increase with solar activity. At anomaly crest, scintillation occurrence is always less than at equator with similar patterns in equinoxes. Post midnight scintillations are generally associated with frequency spread F, predominant in summer and decreases with solar activity. Comparison of spread F occurrence in Indian and Brazilian equatorial locations brings out the magnetic declination control.

These scintillation characteristics are modeled empirically using the cubic-spline technique and good agreement between the observed and modeled values of scintillation occurrence percentage and their latitudinal and local time pattern is obtained.

Multitechnique investigations of ESF phenomena using GPS spaced receiver scintillations, ionosonde spread F, VHF radar and air glow photometer over the equatorial and low latitudes in Brazil are carried out to bring out interesting features of the equatorial ionospheric plasma bubble phenomenon and its dynamics.

Studies using the Interplanetary scintillation array at Rajkot.

Using the interplanetary scintillation (IPS) observation at 103 Mhz at Rajkot , solar wind velocity estimate using IPS technique at 327 MHz at Nagoya, Japan, ionosonde observations at Ahmedabad, enhanced interplanetary scintillation index (plasma turbulence) and a reduced solar wind velocity during the passage of the interplanetary disturbance consequent to a solar flare on 12 May,1997 were observed . The D-region ionization increase due to the x-rays emitted during the flare was inferred from the ionosonde data.

Using a novel radio astronomical technique, the presence of Traveling Ionospheric Disturbances (TID) are detected from observations of radiostar signals by the IPS system at Rajkot for the first time. To study the ionospheric TIDs, signals from different radio stars are recorded daily using the radio telescope. When TID is present, the radio wave passes through undulated ionosphere causing ray deviation by refraction leading apparent position shift of the source and corresponding intensity variation at the receiver. The measurements at two receivers looking at two different sources whose ionospheric crossover points are spaced horizontally, show consistent time shift of similar features due to the passage of TID across the line of sight. From the time shift and estimating the horizontal distance between the ionospheric cross over points, the speed of the TID is estimated. Observed TID periods are 20-24 minutes and the north –south component of their speed ranges from 66-273 m/s. This is characteristic of medium scale TID originating from atmospheric gravity waves.

MST radar studies of atmospheric dynamics in the tropical atmosphere

Study of dynamical phenomena such as tides and waves and their role in coupling between the different regions in the middle atmosphere have been continued. Seasonal differences of diurnal tidal oscillations in zonal and meridional winds using Indian MST radar located at Gadanki (13.5^o N, 79.2^{o}E) have been brought out. Diurnal tidal amplitudes vary from 2-3 m/s at lower heights to 8-10 m/s at higher heights. The vertical wavelength also varies from 3-4 km in the lower troposphere to 5-7 km in the upper troposphere. The observed amplitudes and phases in different seasons are consistent with numerical simulations of non-migrating tides. These tides with amplitude ~10m/s observed in the month of august over Gadanki may be associated with latent heat released by deep convective activity in this thunderstorm season.

Our earlier studies had identified the presence of Kelvin waves with period ~12-14 days and mixed Rossby gravity waves with period of ~4-5 days in this tropical middle atmosphere. The momentum flux carried upward by these waves have been estimated now and found to be significant to contribute to the mean flow changes. The presence of gravity waves of periods 15-35 minutes and their propagation characteristics have been inferred from both MST radar and LIDAR observations from the same location.

Physical Research Laboratory, Ahmedabad

Space weather studies

Using IPS observations of 103 MHz made at Rajkot, a few events were investigated with a view to understand the solar terrestrial relationship, these are Earth directed CMEs and the so called solar wind disappearance event. For the investigation we also used the satellite data (ACE) of solar plasma parameters and find a good corresponds in the in-situ and the IPS measurements. It is seen that properly oriented relatively weak CME event could cause a reasonable effect on the terrestrial environment. One of the most Geoeffective coronal mass ejection (CME) has been that of April 4, 2000. As seen in SOHO/LASCO images a halo CME with a bright front began on April 04, 2000 at about 1632 UT. This appeared to be associated with C9 flare in AR 8933. With IPS observations at 103 MHz, we detected the effect of this CME at the line of sight of 3C459 two days later and at the line of sight of 3C2, 3C119 and 3C122 three days later. At the line of sight of 3C48 there appeared a very feeble or no effect of the passage of this CME. This could be due to the projection effect of the CME or along that direction the interplanetary disturbance associated with the CME is absent. The CME of April 4, 2000 produced a shock which was detected by ACE solar wind velocity measurement (the radial velocity increased from 375 km s^{-1} to 575 km s^{-1} at 16 UT on April 6, 2000). This shock led to a very large drop (~ 300 NT) in equatorial Dst and produced one of the largest geomagnetic storm of this century. This CME appears to be very geoeffective where as there are several others not so effective in producing disturbances in the terrestrial environment. In fact this poses a serious problem for the prediction of geomagnetic storms and substorms. This work is done in collaboration with SU Rajkot.

Study of solar rotation

Investigations of the solar coronal rotation using radio emissions probes were made. It was possible to find unique features one of these has been the discovery of differential rotation as a function of height in the solar corona. Recently this method was extended to chromospheric emission Lyman Alpha whose measurements are available over many years 1947 – 1999. The auto and cross correlation analysis is used for this. We found that the rotational modulation is highly variable. In several years it is very high up to 60% and in some others the evidence of rotational modulation is negligible. The rotational modulation shows evidence of longer period (> 100 years) in Lyman Alpha which is not so evident from sunspot numbers. The cross correlation coefficient of the sunspot number and solar Lyman α irradiance has a peak positive value of 0.12 at a lag of 5 years and a peak negative value of -0.18 at a lag of -1 year. Thus rotational modulation is highly variable and seems to be almost independent of the phase solar activity cycle. The synodic rotation period is also found to be variable with maximum as much as ~ 32 days. The rotational modulation appears to be very different during the year 1979. This peculiarity is differently present in both the Lyman Alpha emissions as well sunspot number. The modulation index is reasonably large in both, but the period is ridiculously small. The cross correlation of Lyman Alpha and sunspot number is almost zero.

Ionospheric studies

Ionospheric data over Ahmedabad for 1955-1996 were examined for long-term changes due to the cooling of the mesosphere and thermosphere by increased green house gases. F layer peak decreases by about 10 km in 40 years. The critical frequency of the F_2 layer decreases by 1 MHz in this period but of the F_1 layer increases by 0.3 MHz. The results are consistent with the predictions of Rishbeth and Roble.

Enhanced sporadic-E occurrence associated with Leonid meteor showers starting from 1996 and peaking in 1998 was noticed from ionosonde data. Multiple traces between 100 and 150 km appear on some occasions for both the years 1998 and 1999, which lend support to the association of meteor shower with the sporadic-E observed.

VHF scintillations at 244 MHz at Calcutta during the night of 16-17 November 1998 are shown to be associated with the sporadic-E layer generated by meteoric ionization. Two examples of scintillations corresponding to the peak period of Leonid meteor shower are transient and quasi-periodic in nature with much shorter duration (30-100S) than normally observed. Critical frequency of the sporadic-E layer over Ahmedabad also shows two isolated spikes. Observations are validated using the diffraction theory from a series of one-dimensional irregularities

VHF (244 MHz) scintillations at a chain of 20 stations in India during AICPITS campaign (February-March 1993), were used to estimate the vertical velocity of large-scale plasma depletions associated with equatorial spread-F from the mean time delays between the onset times of scintillations. The velocities of 40-420 m/s with maximum at altitudes of 400 to 800 km are consistent with the in-situ electric field measurements from satellites.

Simultaneous in-situ measurements of the fluctuations in electron density and electric field during strong spread-F were made for the first time in India. Strong irregularities were seen at 160-190, 210-257 and 290-330 km regions. Intermediate scale vertical electric field fluctuations showed spectral index of –2.1 below the F-layer base as compared to –3.6 in the valley region and –2.8 below the F-layer peak.

Detailed analysis of 630 nm and 777.4 nm images from SHAR showed that on highly disturbed magnetic epochs, the inter-depletion distance increased by a factor of about 2 and became as high as 1600 km. This is the first experimental evidence that the gravity waves of auroral origin are responsible for modulation of the bottom side of the F region. During magnetically quiet periods, gravity wave with origin in the lower atmosphere were responsible for perturbing the F region

Two rocket-borne experiments were conducted from SHAR, on 18 and 20 November, 1999 during morning hours to investigate the effects of Leonid meteor storm. The ion composition measurements reveal presence of ions in the range of 55 to 60amu presumably Fe^{+} ions associated with Leonid storm. Electron density data do not show any thin layer of or irregularities in scale size of 100 m down to 3 m. The result reveals the significance of electrodynamical processes at 6^{o} away from dip equator.

A coordinated campaign was conduced during March, 1998 and 1999 to study equatorial F region irregularities. The MST radar was operated in ionospheric mode for mapping structure (RTI maps) and dynamics of the F region irregularities. 630 nm night airglow intensities using a photometer in a bi-directional scanning (zonal) mode provided zonal drifts from identifiable features. Similar patterns were seen in the airglow intensities and MST radar maps. Downward moving structure recorded in MST radar was identified to be an enhancement in 630 nm intensities corresponding to the enhancements in the ambient ionization. The high altitude enhancements in electron densities during ESF are shown to be due to the interaction of two long wavelength modes as a seed perturbation in the non-linear evolution of ESF.

Electric field perturbations with scale sizes similar to those of the gravity waves are required to initiate large-scale structures in the ESF. It is shown that when the E layer is thin, the perturbation electric fields produced through Hall conductivity are much larger than those produced through the Pedersen conductivity. The perturbation electric fields produced through Hall conductivity transmitted to the F region via the geomagnetic field lines were shown to be more suitable for triggering of the ESF than those produced through Pedersen conductivity.

From rocket-borne measurements of ionospheric current and ground geomagnetic data in the equatorial region, linear relation are found between the peak current density and range in H for Indian and American longitude sectors to convert the long series of geomagnetic data into peak current density. Electron drift velocity is estimated using E-region peak electron density. Ionospheric currents and electron drift velocity, show strong equinoctial maxima. The solar cycle variation of electrojet is primarily due to electron density while seasonal variations are due to electric field. The currents are stronger in the American sector (24 %) caused primarily by the larger electron drift velocity (33 %).

2 RH 300 Mark II rockets were launched on 18^{th}, 20^{th} November 1999 from SHAR, during Leonid shower activity. High frequency Langmuir probe reveals an experimental evidence for the first time for the presence of sub-meter scale size plasma waves during Leonid meteor storm with maximum amplitude of these about 4% of ambient at 105 km on both the days. Evidences are obtained that the causative mechanisms for the generation of the plasma waves are different from gradient drift and two stream plasma waves. The association of the sub-meter waves with the activity of Leonid meteor storm is also obtained

Evolution of equatorial spread F structures with perturbation consisting of a single wavelength mode and superposition of two modes was studied. Depleted region always moves up with a single wavelength mode while the superposition of two modes gives rise to low level plasma depletion which moves downward even when the ambient plasma motion is upward, in addition to well developed upward moving plasma bubbles and down drafting enhancements. Well-developed plasma bubbles with scale size corresponding to smaller wavelength mode is possible even with very small (0.5%) perturbation when it rides over a long wavelength mode with large perturbation (5%). The longer wavelength mode develops to form a lower envelop over which multiple plumes with varying degree of depletions ride over, plumes separation decided by the short wavelength. The rising multiple plumes and the descending structure along with downward moving streak observed by the MST radar is explained.

Satellite observations of ESF revealed the presence of molecular ions (NO^+) in the topside ionosphere and enhancements were collocated with the depletions in atomic oxygen (O^+). To understand the presence of short-lived molecular ions at higher altitude, two fluid model is used to investigate the nonlinear effects of molecular ions. It is shown that the plasma transport processes associated with the plasma instability bring the plasma from the base of F-region. Depletion in O^+ is collocated with the enhancement in molecular ions similar to satellite observations. The variations in NO^+ at higher altitudes are associated with the variations of the relative concentration of NO^+ and O^+ at the base of the F-region.

The rotational temperatures in the daytime mesopause region obtained by the multi-wavelength dayglow photometer observations at Tirunelveli showed diurnal and day to day variabilities. Derived temperatures were significantly different from the MSIS-90 model temperatures.

DE-2 satellite data were examined to understand the Equatorial temperature and wind anomaly (ETWA) and a plausible explanation was given on the basis of chemical heating due to exothermic reactions and the frictional heating due to ion-drag. Temporal variation in the integrated E-region conductivity and its subsequent loading effect on F-region dynamics over low latitudes during day was considered to account for the iondrag associated heating at all local times.

Studies on Dusty Plasma

New results have come out of the work on dusty plasmas. The concept of the dust fugacity has been introduced and dusty plasmas have been classified into tenuos, dilute or dense types. A new kind of dust wave mode driven by Coulumb pressure has been found in dense regime. This mode can be considered as the electrostatic analogue of the hydromagnetic (Alfven) waves in ordinary plasmas. Dust plasmas are shown to be governed by a new kind of length scale, which plays a fundamental role in the dense regime, like the Debye length of the tenuos regime.

Indian Institute of Technology, Kharagpur

200km long magnetotelluric traverse was completed from Khorda to Keonjhar in Orissa during this period which cuts across Mahanadi graben, major faults near river Brahmani, Sukinda thrust(an Archaean-Proterozoic contact between the northern margin of the high grade granulitic terrain and the Singhbhum craton) and Singhbhum granite batholith(SBG-A)It is a part of the work under Chilka –Gangtok geotraverse program of DST.

100km long magnetotelluric traverse was completed from Khandwa to Barwaha in Madhya Pradesh during this period which cuts across the Khandwa Lineament and Narmada –Son Lineament. This programme was sponsored by Geological Survey of India.

Salient features of results

Lower crust is highly conducting and remarkably horizontal below Eastern Ghat Mobile Belt(EGMB) from Khorda to the northern margin of the Eastern Ghat. Higher conductivity from MT and higher ductility from DSS (Kaila, NGRI, 1985) matched. Presence of plenty of biotites, graphites, banded iron formations(BIFs) and magnetite quartzites in Khondalites are responsible for higher conductivity when they got mixed with the percolated meteoric water through the major faults and graben type structures near river Mahanadi and Brahmani. Higher conductivity of the lower crust made the detection of Moho possible here. Because the olivine dominated ultrabasics in the upper mantle is less conductive than lower crustal conductive mixture at Moho temperature. Model experiment has shown that the probability of detection of Moho increases when the structure is nearly 1D.Estimated depth of the Moho is 38km from MT and 34 km from DSS.

The property 'Static Shift' can be qualitatively used for detection of faults/ fractures/sutures/lineaments. Both amplitude and phase of the horizontal components of the magnetic field show sharp changes across a fault. Therefore major faults can be detected by examining the horizontal components of the magnetic fields.

In general the thickness of the lithosphere along the Chilka-Gangtok geotraverse varied from 90 to 120 km. This estimate roughly matched with the estimate of lithospheric thickness of the northern India given by IIG, Mumbai.

Rotation invariant apparent resistivities and phases, viz. (rho_determinant and phi_determinant), (rho_average,phi_average) and (rho_central,phi_central) generate much more closer and more consistent earth models than those generated by (rho_TE,phi_TE) and (rho_TM,phi_TM). Plots of rotation invariant apparent resistivities and phases are more stable with smaller error bars.

TE and TM mode models are never same for real field conditions. Therefore to trust a geoelectrical model inversion should be done with different MT parameters and different inversion softwares. And the common features of all the models should be taken with greater confidence level although the geometrical shapes of the Common features may be different.

Mathematical modeling revealed that TM mode MT resolves the subsurface with greater clarity than that done by TE mode MT specially to resolve vertical contacts. For lithospheric studies, it is always advisable to search for granite windows or hard rock areas for field observation.

Repeatable observation should be given greater weightage. Since data weightage varies inversely with error bar, uncertainty level in the parameter estimation increases with error bar.

Survey of India, Dehradun

Surface data acquisition and analysis during the period under report: Observations of Declination, Horizontal force and Vertical force and 138 repeat stations, 104 profile stations and 15 field stations were carried out in various parts of the country for preparation of

Isomagnetic charts for Declinations, Horizontal Force and Vertical Force for epoch 2000.0 chart of Magnetic Declination of epoch 2000.0 is in final stage The 104 Nos. of Profile stations were observed in connection with seismotectonic studies.

Madras Institute of Magnetobiology, Chennai

The Institute founded in 1984 as a registered non-profit scientific Society of Tamil Nadu, has been engaged in fundamental and applied research and development of Pulsed Magnetic Field (PMF) technology. Given below is an outline of the R&D activities engaged in by the Institute during the period Jan 1998 to Dec 2002.

Clinical applications of PMF for the cure/palliation of a variety of human ailments/functional disorders such as arthritis (rheumatoid and osteo), spondylosis, non-uniting fractures, festering wounds of various aetiologies like post-surgical non-healing wounds, diabetic ulcers, burns etc, spasticity in children and epilepsy.

The Institute has a separate therapy and clinical division where PMF treatment is being offered to out patients with these ailments. During the reporting period a total number of 850 cases have been handled by the division. The division also has ongoing projects in collaboration with other Institutes.

Based on a few earlier pilot studies, an experiment was carried out in collaboration with the Central Sericulture Research and Training Institute (CSRTI), Mysore on application of PMF to silk worm eggs. The results showed a strong enhancing effect of PMF on the cocoon weight and tensile strength of the silk filament besides also showing a decrease in the mortality of the worms.

A series of pilot studies were carried out (as an intramural effort) on the possible control of PMF in the biodegradation of effluents from sugar distilleries and tanneries. The efficacy of bacterial cells exposed to PMF in treatment of the effluent was compared with that of unexposed cells.

The first results of these pilot experiments have been highly promising and await further detailing as to the specific frequency-intensity-dose duration combinations of PMF which would show the most optimal performance in the biodegradation.

Instrumentation

The Institute has been from the beginning supported by an Instrumentation group since none of the CMF enclosures for the specialized studies, can be procured from any market and also the calibration procedures are not conventionally known/ practised.

All the CMF coil enclosures like Fransleau-Braunbeck type, Reuben cubic lattice system, Helmholtz coils and solenoid enclosures were all designed, fabricated, erected and calibrated by the Magnetic Standardization Lab of the Institute. Foir calibration a "La Cour Declinometer" assembled to operate as a null field system and also the Askanian Field Balance and the Danish Zero Balance Magnetometer (BMZ) are being used.

Barkatullah University, Bhopal

At Space Science Laboratory, Barkatullah University, Bhopal, the emphasis has been to understand the dynamics of ionosphere and magnetosphere via radio beacon experiments and VLF wave observations. Study of the ionospheric scintillation is being carried out from VHF-receiver system. This system is monitoring Radio Beacon Signal at 250 MHz from FLEETSAT Satellite situated at equator around 73 degree East longitude. Analysis of the data will give morphological details of ionosphere at low latitude (Bhopal).

TEC measurement are being done through Faraday rotation method and data are being taken from different satellites by Indian Space Research Organization, India and World Data Center, USA. . The group is collaborating Trieste, Italy with Prof. S.M.Radicella on the problems of ionospheric modeling and its variability at low, mid and high latitudes.

The GPS satellite navigation system is affected in two ways, namely, Ionospheric Delay Errors (proportional to Total Electron Content) and Scintillations. To study above two effects we use GPS data for detecting ionospheric irregularities, which affect the navigation and communication. Rapid phase and amplitude variations on the GPS signals causing GPS receiver to loose lock. The effect of Seismo electromagnetic signal related to the ionospheric perturbations during Earthquake with the help of GPS receiver are also being investigated..

The study of Whistler at Bhopal, a low latitude station and at Antarctic, a high latitude station are being carried out. Using an improved antenna and VLF-receiver system. Analysis of VLF- signal reveals the occurrence of Whistler, which are useful in the diagnostics of Ionospheric parameter such as : density, temperature, etc. Modified version of VLF receiving system along with digital tape recorder interface with Computer is being used for VLF analysis.

The detail linear and non-linear analysis of electromagnetic and electrostatic cyclotron instabilities has been taken up. The stability criteria for various wave modes such as electron cyclotron (Whistler), Ion cyclotron, magnetospheric, etc. have been studied. Application of these studies are incorporated in explaining satellite data for plasma Waves and Electric fields from ISSE 1 and 2. The existence of electric fields and electric currents (field aligned currents) have significantly changed the electrodynamics, energization, precipitation and acceleration of charged particles in the magnetosphere. A detailed theoretical study is being undertaken to understand the structure of field and current in the magnetospheric region, microscopically. The effect of electric field on the wave generation in magnetospheric is being categorically studied.

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Hydrological Sciences

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Introduction

India, being a vast country, is characterized with a variety of climatic environment ranging from Thar desert of Rajasthan in Western India to the region of world's heaviest rainfall i.e., Cherapunjee in Eastern India; snow covered peaks of Himalayan mountains in the North to the arid/semi arid regions of southern Plateau. The demand of water supply is increasing day by day to meet the pace of developments in domestic, agricultural and industrial sectors. It has to support the needs of 16% world's population with merely 4% of world's water supply. Vagaries of monsoon and withdrawal of groundwater in excess to replenishment of aquifer system in many parts of India result into continuous declining of water table, causing reduction in water supply and deterioration of its quality. The problem is many folds in hard rock regions where the water table has gone down below the weathered zones and is available only in fractured zones. The aquifer systems in many hard rock as well as alluvium areas have been over exploited. Therefore, to ensure the sustainable water supply for different uses several governmental and non-governmental organizations have carried out investigations and researches for assessment, development and management of surface and groundwater resources. This report presents a brief account of the works in different disciplines of hydrology which includes groundwater assessment and development, water quality, groundwater recharge, rainfall-runoff, flood, sedimentation and glacier's hydrology.

Groundwater resources assessment & development:

Assessment of groundwater potential in different parts of the country has been carried out by using geophysical methods, remote sensing techniques and GIS. Identification of fractures/lineaments and hydro-geomorphological units are prerequisite for undertaking groundwater assessment and development in any region. Aeromagnetic data have been interpreted to delineate ground water bearing structures in the form of lineaments in a hard rock region at the junction of two river basins, viz. Marvanka basin and Chitravati basin covering a total area of 400 sq. km. A new electrical tomography technique is tested in the hard rock regions of Dindigul in Tamil Nadu to locate the suitable borehole sites. This technique involves series of traverses with the electrode spacing being increased with each successive traverse. The measured resistivity is used to construct a contoured section displaying the variation of resistivity both laterally and vertically over the section. It provides a detailed view of subsurface structure than by other geophysical techniques. Geophysical surveys comprising deep electrical resistivity soundings, gravity and magnetic surveys were carried out in Sivaganga area, a part of Cauvery sub basin in Tamil Nadu, to delineate deeper aquifers. Electrical survey has been carried out to delineate the groundwater potential zones in an area of 224 sq. km. located in the southern part of Chandrapur district of Maharashtra. Hydrogeological and geophysical investigations have been carried out in other parts of the country such as Maheshwaram watershed situated 30 km south of Hyderabad, Sonbhadra district of Uttar Pradesh, Kandivalasa river sub basin in Vizianagaram district of Andhra Pradesh, parts of Alwar district and Shahabad block of Baran district in Rajasthan, north western part of Cuddapah basin in Andhra Pradesh, Kerala/Idamalayar lineament covering parts of Palghat and Trichur districts in Kerala, Pageru river basin in Andhra Pradesh, a watershed covering Indian

Aluminum Company Ltd. near Belgaum city in Karnataka, in and around Dhenkanal town in Orissa, Gujarat Refinery area in Vadodara district of Gujarat, National center for Plant Genome Research campus of JNU, New Delhi, M C Tanda watershed located in granitic terrain in Anantapur district and Kallugotla watershed located in sedimentary terrain in Kurnool district of Andhra Pradesh. Artificial Neural Network (ANN) approach has been used to interpret the DC resistivity data from Puga valley in Ladakh district of Jammu and Kashmir state. The ANN approach has been found to be fast method for layer thickness and layer resistivity estimation.

Exploratory drilling is the most effective means of exploration for locating, assessing and evaluating the groundwater potential. Central Groundwater Board (CGWB) has been conducting groundwater exploration studies in many parts of the country by the construction of exploratory wells, observation wells, slim holes and piezometers. From a network of about 15000 stations, the CGWB monitors the positions of groundwater levels four times in a year in the month of January, April/May, August and November. In Andhra Pradesh alone the CGWB, till 2002, has drilled 1927 bore holes, 926 exploratory wells, 891 observation wells, 14 slim wells and 265 piezometers. The maximum depth of exploration carried out in this state so far is 750 m in the soft rock areas piercing Tertiary and Gondwana formations. In the hard rock areas maximum depth drilled was 300 m.

A software package is developed on Fox Pro version 2.5 to evaluate the Ground Water Potential Index (GWPI). The package has the facilities to declare the titles of the parameters that influence the ground water potential, to create data base, to create a model by performing the statistical and regression analyses, to draw a graph and to predict the groundwater potential of a given area. The computer package has been developed such that each time when the ratings and weights given to each of the parameters of a given site according to their importance in groundwater exploration are suitably modified by the user during the model calibration, the program performs all the necessary operations and gives the end results accordingly. It is demonstrated that the results obtained with the help of this computer software package are tallying with the results obtained through manual processing.

Field observation and analysis of pumping test data of dug wells in parts of Nasik district show that dykes act as potential aquifers when they are jointed/fractured. An integrated geophysical approach has been applied to identify structural features such as fractures, weak zones and intrusive dyke bodies which can control and host potable groundwater at greater depth in an area of about 8 sq. km along the east coast of Tamil Nadu which has been identified as a major rain shadow zone.

Water quality

The quality of water is of vital concern to the mankind, as it has direct link with human health. Therefore, pollution of surface/ground water is another major problem, which has attracted the attention of scientists, engineers and planners. Groundwater pollution has been growing incessantly in several parts of the country, particularly in areas of intensive industrialization. Many industries discharge their untreated waste in the immediate neighborhood or in some near by low lying areas mostly in open channels which join various surface water bodies such as large ponds, streams, rivers etc. The pollutants of these waste materials seep down to the groundwater system along the entire course of fluid flow. The Ganga alluvial plain is one of the largest groundwater repositories of the Earth. For several decades the drainage basin of the Ganga plain has been used for the disposal of domestic and industrial wastes which has adversely affected the quality of water, sediments and agricultural soil of the plain. A study has been carried out to know the status of anthropogenically induced metal pollution in the Kanpur – Unnao industrial region of the Ganga Plain. This study indicates that the water and soil of this region is highly polluted by various metals.

Based on hydrochemical investigation of water samples from northwestern parts of Ranga Reddy district in Andhra Pradesh (A.P.) the water is characterized as hard to very hard class. The hardness is due to presence of Ca and Mg carbonates. Similar hydrochemical investigations have been carried out in different problematic regions of the country to quantify groundwater quality. Examples can be cited from a portion of Ghataprabha left bank canal command area in the Belgaum and Bagalkot districts of Karantaka, Hardwar district of Uttaranchal, Sakri and Panchana rivers basins in Newada district of Bihar, suburban areas of Hubli in Karnataka, Rewa region in Madhya Pradesh, Pageru river basin in Cuddapah district and Enumula Vagu sub basin under Dindi river basin in Mahaboobnagar district of A.P., Salem magnesite area in Salem district of Tamil Nadu, Patancheru industrial area in A.P., Ganga Alluvial plain in Etah district of U.P., Krishna Delta in A.P., catchment area of Rajghat dam in Lalitpur district of Madhya Pradesh, Jammu district of Jammu and Kashmir state, Kodaganar water shed in Dindigul district of Tamilnadu, in and around Dindigul Town, Erode district of Tamil Nadu, Maheshwaram water shed in Ranga Reddy district of A.P. , Palar basin in Tamil Nadu, Gujarat refinery in Gujrat, Potharlanka island of Krishna delta in A.P. Water quality monitoring and aquaculture impact on coastal tracts of West Godavari district of A.P. have been carried out. The study area lies between Godavari and Krishna rivers. Origin and distribution of Nitrate in groundwater from different part of the country have been investigated by CGWB. Some of the major findings of the above mentioned hydrochemical investigations are given below:

- Fluoride content ranging from 0.08 to 2.8 mg/l are found in the study area of Newada district with higher values restricted in Rupan-Kankol belt.
- In Rewa region, the groundwater from shallow zones is suitable for drinking, and industrial purposes.
- Groundwater of Pageru river basin is good either for drinking or for agricultural purposes.
- In Enumula Vapu basin, the high fluoride rich zones of dug wells localized around Kondareddy palli and Tippareddy villages.
- Water in and around the Patancheru industrial area is contaminated showing very high concentration of heavy toxic metals than that of permissible limit prescribed by WHO.
- The groundwater in parts of Etah district is alkaline, hard and moderately mineralized. The heavy metals concentration in the shallow aquifers is above the permissible limit whereas in the deeper aquifers concentration is well within the limits.
- Groundwater of north Krishna delta is more polluted than the south delta and in this region 24% dug wells and 18% hand pumps have exceeded the limits. The possible source of high nitrate level in groundwater has been identified as excessive utilization of nitrogenous fertilizers, insecticides and pesticides for agricultural purposes.
- Water samples from in and around Dindigul have shown very high values for Na, Cl, Ca, So_4 and NO_3 indicating the influence of the effluents of the tanneries. Groundwater from an area of about 50 sq. km around Dindigul has became unfit for drinking and irrigation.
- The water quality monitored in 45 wells in the region of Gujarat refinery indicates groundwater contamination from anthropogenic sources. TDS, sodium and chloride concentration are found to be high and show a consistent spatial variation.

Pollution potential index for the Musi river sub basin from Amberpet to Nallacheruvu in Hyderabad city has been evaluated. From the analysis it is found that when we face downstream of the Musi near Amberpet, all along the left bank of the Musi is more susceptible for pollution. This has been ably confirmed by hydrogeochemical investigations carried out in the study area. Major ion concentration including fluoride were analysed from 92 samples collected in and around the twin cities of Hyderabad and Secunderabad during June 2000. The results show that more than 60% of samples have fluoride exceeding 1.5 mg/l, the higher limit prescribed by WHO including a few that cross even 2.5 mg/l. In general, the deep aquifers are potable, but since they are connected to shallow aquifers as well as surface water bodies and also due to indiscriminant pumping, migration of pollutants to these aquifers cannot be ruled out.

Studies carried out on trace elements (Cu, Fe, Zn, Mn and Pb) geochemistry of groundwater from Behedi basin in Nasik district of Maharastra have shown spatial as well as temporal variations of these elements. Weathering of rocks and the human activities have been identified as the main sources of trace elements in the groundwater. Intensive use of micronutrient fertilizers in association with the use of pesticides have lead to higher concentration of trace elements under irrigated agriculture than the other land use types. This study suggests chemical fertilizers as potential source of trace element pollution of groundwater. In an attempt to evaluate the impact of irrigation on quality of groundwater, 136 samples from Sangamner area in Ahmedanagar district of Maharashtra have been analyzed. The investigations suggest that excessive use of fertilizers and irrigation water in a terrain characterized by low flushing rates, presence of alluvium and flat topography have caused deterioration of groundwater quality. Similar studies have been carried out to quantify the groundwater quality deterioration caused by improper agricultural practices, mainly due to excessive use of fertilizers and pesticides in other parts of the country. Geophysical investigations carried out in the Mettupalyam industrial state in Pondicherry have revealed a number of contaminated zones due to indiscriminate discharge of effluents from the chemical, paper and metal industries in the open drains or on the ground. These effluents, which have found their way into groundwater region, started migrating along with ground water flow. Groundwater quality characterization and pollution vulnerability in Ghaziabad urban area of U.P. has been investigated. Protection strategies to mitigate the pollution problems of the area on long-term basis have been suggested. The occurrence of high concentration of fluoride in groundwater (1.5 mg/l) in the villages of Singpur Sagarajan in the Nayagarh district of Orissa and its relation with the fluoride rich hot spring water (10mg/l) located near by have been studied. The topography of the area has exerted a control on the aerial extent of fluoride contamination. Concentration of heavy metals (Cd, Fe, Cr, Mg, Pb and Zn) have been evaluated at nine spring water and eight surface water sampling locations near the limestone mining area of Sirmour district of Himachal Pradesh during pre and post monsoon seasons. This study shows that the water in this region is not polluted with respect to heavy metals despite the prolific growth of limestone mining in this region.

An analysis of groundwater flow and transport processes of arsenic in the flow domain of Yamuna sub basin located in West Bengal is carried out. The study indicates that the occurrence of arsenic at a location has no correlation with the transport of arsenic from other sources; rather it indicates that there is spreading at a localized scale due to transport of in-situ activation. Capture zone analysis does not show encouraging results for removing arsenic through a specific set of clean up wells. Geochemical properties of groundwater from Nadia district in West Bengal have been analyzed to interpret arsenic contamination of groundwater. The appearance of arsenic and chemical extent of the deterioration in groundwater quality of the Rajnandgaon district of M.P.

has been reported. Total arsenic concentration obtained in the analysis ranged between 0.01 – 1.01 mg/l. The number of people at risk is 10,000. Contamination of groundwater due to fluoride is reported from many places of Andhra Pradesh, Tamil Nadu, Karnataka, Gujrat, Rajasthan, Punjab, Haryana, Bihar and Kerala. A high concentration of 5.2 mg/l has been reported in Medak district of A.P., 15 mg/l in Nawabganj block, Uttar Pradesh and 18 mg/l in Jaipur, Rajasthan as against the critical limit of 1.5 mg/l in drinking water. The incidence of very high level of fluoride is in the eastern and southeastern belt of Karnataka, covering districts of Gulbarga, Raichur, Bellary, Chitradurga, Tumkur and Kolar.

An attempt has been made to study the progression of seawater intrusion into coastal aquifers of Vakadu mandal in Nellore district of A.P. The degree of contamination due to saline intrusion was estimated before and after the monsoon. Due to the increase of aquaculture in and around west Godavari district, quality of groundwater has been a problem in coastal tracts of west Godavari district of A.P. For a better understanding of this problem integrated surveys, which include hydrochemical studies and statistical modeling technique, have been applied in the region of Kolleru lake. This study reveals that the indiscriminate and illegitimate expansion of aquaculture in Kolleru lake and its environ drastically reduced the inflows into Upputern river. Reduction in the inflow resulted into ingression of seawater. A study has been carried out to investigate groundwater quality in order to generate baseline information on groundwater resources in developing urban area of Guntur district in A.P. In accordance with the domestic and industrial water quality standard ground water is not suitable for uses.

Groundwater recharging (natural/artificial)

Harvesting and storage of runoff and recharging of aquifers in a framework of integrated land water development on a watershed basis with community participation is emerging as a new paradigm due to the recent efforts of both government and non-government organizations. Under the supervision of workers of Tarun Bharat Sangh, a nongovernmental organization, Arvari river in Alwar district of Rajasthan state has been revived by mean of storage of rain water in percolation tanks and Johads constructed along the bank of the river. Johads are simple concave shaped barriers built across the slope to arrest rainwater with high embankment on three sides while the fourth side is left open for the rain water to enter. For this purpose 4500 Johads in 1050 villages has been built. As a result of this water table in this region has been raised by 5 to 8 meters. Apart from Arvari river four more streams have been revived. Similar experiments of groundwater recharging through rainwater harvesting have been executed at some other places. The average natural recharge to the aquifer of Kongal river basin located in Nalgonda district of A.P. due to 1993-94 monsoon is estimated by Kriging and Thyson polygon methods. The estimated recharge is 5% of the rainfall.

Recharge measurements using Tritium (tracer) injection technique were carried out in 16 study areas located in granite terrain. It indicates annual recharge varying from 25 mm/y to 159 mm/y with an average annual recharge of about 80 mm/y or about 10% of the seasonal rainfall. A linear relation between rainfall and natural recharge is observed for several watersheds/basins. Two percolation ponds, one at Karthikeyapuram and another at Santhan Venu Gopalapuram in Tamil Nadu were observed for three years to assess their potential influence zone. An artificial recharge structure has been constructed on a granitic terrain to augment and improve the groundwater quality by diluting the fluoride rich aquifer of the Jawalgera village in Raichur district of Karnataka. The scheme has brought down the fluoride levels from 1.9 to 1.1 mg/l within a year. A subsurface dam was constructed across a stream in a small watershed measuring 2.34 sq. km at Gaurelli village of R.R. district in A.P. The impact assessment study indicates that the construction of the dam enabled to conserve additional groundwater. Also there was considerable reduction in fluoride concentration in the groundwater.

A pilot project on developing a groundwater sanctuary for drinking water in wasteland at Gurukanipalle village in Chittoor district of A.P. was executed. Estimation of recharge using Tritium tracer technique indicates that 13.6% of seasonal rainfall percolates down to replenish the shallow groundwater regime. Another project was executed in Dhanauti Badi village in Churu district of Rajasthan to harness the surplus runoff for artificially recharging the groundwater to create a potable groundwater source and to improve the groundwater quality by dilution of fluoride content.

To evaluate the efficiency of Kalwakurty percolation tank situated in granitic area of Mahaboobnagar district in terms of its contribution to the groundwater regime, the technique of environmental chloride mass balance in tank water as well as in downstream well water is employed. Through this technique it is estimated that the tank contributes about 21000 Cu. m. of impounded water to the groundwater with an efficiency of 44% artificial recharge. The environmental chloride profiling is carried out at six sites in Maheshwaram watershed near Hyderabad in A.P. to estimate the recharge. The total recharge is estimated to be 10% of the annual recharge. Hydrogeological and geophysical investigations have been carried out in 44 villages of Pakur districts in Jharkhand state to select suitable sites for the construction of check dams/percolation tanks. Based on these investigations sites were selected for construction of these structures. Percolation tanks and check dams have been constructed in many parts of the country for the replenishment of aquifer.

For the entire Ranga Reddy district of A.P. an integrated study has been undertaken on the basis of drainage network, surface topography, structural geological features and surface storage source (tanks). Thematic maps for all these aspects have been prepared and overlapped using GIS to arrive at their interrelationships in terms of groundwater distribution. The present study has clearly brought out distinct groundwater mounds, signifying areas of potential recharge. The present study brought out a correlation between the lineaments and groundwater mounds. This study indicates that Ghatkesar, Hayatnagar, Ibrahimpatnam, Marplace, Moinpeta, Vikarabad mandals are the best areas for the development of recharging activities.

Modeling of groundwater flow and mass transport

Mathematical models play key role in assessing the dynamic behaviour of a groundwater system to various schemes of recharging/pumping and other stresses and in selecting an appropriate one out of many proposed schemes for sustainable development of groundwater systems. Knowledge of the dynamic behaviour of groundwater flow is also essential to assess the extent of spreading of hazardous substances from the source of contamination. Such knowledge helps in finding out some ways and means to prevent or at least minimize the spreading of pollutants. In the last four years both the numerical and analytical mathematical models have been developed to understand the dynamic behaviors of groundwater flow and pollutant transport in different parts of the country in order to suggest remedial measures to protect the regional water balance and quality of groundwater/surface water bodies. Numerical mathematical models have been developed to understand the nature of groundwater flow and pollutant migration in the region of Gujarat refinery. Distributions of hydraulic head and combined concentration of sodium and chloride have been computed for the year 2000. The prediction of pollutants transport has been made for the year 2005 and 2015.

Groundwater flow and mass transport numerical model of the Mettupalyam Industrial Estate and its environ covering

Muttarpalyam well field has been developed. The computed values of sulphate concentration are matching closely at all the observation wells. To assess further migration of contaminants towards the Muttarpalayam well field, it is suggested to drill some more wells along the southern boundaries of the industrial estate for abstraction and treatment of the contaminated groundwater for industrial use. This may help in containing spread of the contaminant plume towards the Muttarpalayam well field. Numerical mathematical model has been developed to study the impact of Bansagar reservoir on groundwater seepage to Kuteshwar limestone mines in Jabalpur district of M.P.

A numerical model combining the transport with the equilibrium aqueous geochemistry is developed for simulating hydrogeochemical behaviour observed in groundwater system. The model is capable of considering ion exchange, precipitation, dissolution, redox and acid-base reactions occurring in groundwater. The model is applied on three field problems to demonstrate it's applicability in analyzing groundwater system influenced by transport and geochemical reaction. The first problem corresponds to an ion exchange case; the second pertains to the chemical concentrations pattern evolving from complex changes in chemical compositions resulting from precipitation and dissolution of carbonate minerals. The third problem deals with the oxidation of pyrite in the Vadose zone of mines tailing which result in acidic drainage conditions along with associated leaching of dissolved metals into the groundwater system.

Groundwater in the Palar basin is getting deteriorated due to indiscriminate disposal of wastes from tanneries and industries. Mathematical modeling has been carried out to estimate the variation of groundwater heads for various proposed schemes of groundwater resources development in order to know the direction of flow of pollutants. A numerical mathematical model has been constructed to gain a comprehensive understanding of the groundwater system behaviour in Vattigudipadu watershed in Krishna district of A.P. Numerical results indicate that there will be decrease in groundwater storage because of continuous over exploitation of groundwater.

A numerical mathematical model has been developed for inverse modeling of groundwater systems using the Generic Algorithm (GA) approach. The model can be successfully applied for aquifer systems where data available may be sparse and with errors. The developed model is useful for parameter estimation with little available field information. A groundwater flow model of the aquifer system of Kanchanapally watershed spreading over 11 km in Nalgonda district of A.P. was calibrated under transient conditions using monthly recharge estimates of the water balance model. The average groundwater recharge is found to be 86.7 mm/y for an average annual rainfall of 759.6 mm/y. The output of the recharging process model was found very useful to simulate dynamic variations of recharge in a groundwater flow model while giving input at monthly intervals.

Based on the Galerkin Finite Element numerical formulation, a computer program, named FEMTRAN is developed to describe the groundwater flow and mass transport. After verification against the results of 1-D and 2-D analytical solution, the program is applied to a field problem to analyze the contamination of the groundwater due to discharge of effluent from Mulla sugar factory located in Ahmednagar district of Maharashtra.

Simulation of seawater intrusion in a section of Ernakulam coast through saturated unsaturated (SUTRA) model has been carried out to examine the impact of increased pumping scenario on the extent of seawater intrusion. This study reveals that the sensitive zone (salinity more than 500 mg/l) in this area is between 440 m to 2000 m from the high tide line. Therefore, any groundwater development activities in this area need to be carefully planned with remedial measures to contain further intrusions.

A 2-D solute mass transport model with vertical cross section of the Kavaratti island in the Arabian sea off the western coast of India was constructed by using computer code SUTRA. The model analysis shows that the salinity of groundwater continues to increase unless pumping is kept below a certain rate. Groundwater potential can be augmented by reducing the subsurface outflow to the sea and by raising the water table by a subsurface dam.

Numerical models are mostly used to solve the real field problems. However, before application to field problems, their validity has to be checked either by comparing the numerical results with the observed data or with the results of analytical models. Mostly analytical models were developed to describe water table fluctuation in response to constant rate of recharge. However, the rate of recharge like infiltration rate is known to vary with time due to several factors. Initially swelling and dispersion of the soil particles beneath the recharge basin reduces the infiltration rate for a short duration and then it increases to a maximum value due to release of entrapped air in soil pore. After that the infiltration rate decreases again due to sediment and biological clogging. The rate of recharge follows approximately a similar pattern of variation but with less intensity and some time lag. By considering such variation in recharge rate as well as in pumping rate analytical models have been developed to predict the water table fluctuation in different flow systems characterized by different kinds of initial and boundary conditions. The rate of recharge/pumping is approximated by a number of linear elements of different lengths and slopes depending on the nature of variation in the recharge and/or pumping rates. In this scheme recharging/pumping can be considered from any number of basins/wells of any dimensions located any where within the flow domain but away from the boundary. Analytical models have also been developed to describe the water table variation in response to exponentially decaying recharge rate in leaky aquifer and to describe the nature of stream - aquifer interaction. Analytical models have been developed in stochastic framework to describe water table fluctuation by taking into account the random nature of aquifer parameters. Analytical models have been also developed to describe the spreading of pollutants from the source regions.

Rainfall-runoff, Flood, Sedimentation and Glacier's Hydrology:

Rainfall data are measured at more than 3000 stations spread over different part of the country by the Indian Meteorological Department (IMD). The Central Water Commission (CWC) operates a network of about 877 hydrological observation stations for collection of gauge discharge, silt and water quality data for planning and management of water resources projects. CWC also operates 132 flood-forecasting stations to cover most of the flood prone rivers. An analysis is made to study winter rainfall pattern in the southern Indian region and its relation to the cyclonic storms in the Bay of Bengal. For this purpose, data for the year 1901 – 2002 have been analyzed. This analysis shows that in winter the highest seasonal rainfall is recorded in Tamil Nadu and the least rainfall is in coastal Karnataka and north interior Karnataka. The variability of rainfall is the highest in the subdivisions of Karnataka and the least is in Tamil Nadu, Kerala and Lakshaweep.

Runoff is the most basic and important data needed for planning water control strategies/practices, such as storage facilities, erosion control structures etc. The most popular method used for runoff estimation is SCS runoff curve number method. An attempt has been made to compute runoff for the Neeralipallam watershed located in Nilgiri district of Tamil Nadu by using the daily rainfall data, estimated runoff curve number and remote sensing imageries. From the rainfall and runoff values it is noted that the study area is influenced by both the monsoons i.e. southwest and northeast. The northeast monsoon (Oct. – Dec.) is dominated over the southwest monsoon (June – Sept.), as there is more runoff in this season. These values of rainfall-runoff are very useful for the proper management of watershed.

A study was undertaken to compare composite and distributed curve number (CN) techniques for estimation of runoff to a medium size agricultural watershed, namely Tarafeni (138.06 km^2), located in West Bengal. The pertinent observations from the study revealed that the percent increase in runoff is very high for small events, moderate for medium and low for high rainfall events. This study recommends the distributed CN Technique with initial abstractions (I_a) = 0.2S (s is the maximum potential retention). Gurpur river basin of Dakshin Kannada district of Karnataka State has been chosen as a test site to demonstrate the capabilities of Geographical Information System (GIS) coupled with Remote Sensing (RS) data as input for SCS model in estimating the volume of runoff. Runoff is computed for few rainfall events both by conventionally derived CN and GIS derived CN. The results are agreeable thus providing GIS to be a preferred alternative to conventional methods. GIS and Remote Senescing data have been successfully applied in the development of proposed urban storm water management for Kolkata city in West Bengal. By using an integrated approach of Remote Sensing (RS), GIS and Soil Conservation Service (SCS) model, an attempt has been made to estimate runoff for the Remi watershed situated in the East Siang district of Arunachal Pradesh. The total average annual runoff yield of the watershed is 347.37 mill. m^3. If this much amount of water can be harvested properly, then it can be used for irrigation, domestic and other uses. In another study an attempt is made to use RS and GIS techniques to identify suitable sites for water harvesting structures in Nagulaty forest range of Kurnool district of A.P. Runoff potential map is prepared based on curve number criteria. Runoff estimation has been made for the Peddapandyal watershed in Warangal district of A.P. using RS and GIS techniques.

Complexity of the nature of Indian rainfall record has been studied using the Artificial Neural Network (ANN) model. As an example annual rainfall data spanning over a period of 1900 – 1986 was trained using the concept of ANN and their predictability was made successfully for a period from 1987 to 1998. The predicted values have almost a perfect match with the actual data.

The frequencies of floods at gauge/discharge (G/D) sites of Indian rivers have been examined using 14 years data of 1986 to 1999. Only the data of such G/D sites have been considered which have experienced more than 50 floods during this period. It is found that such frequent floods do not occur in the central and peninsular rivers but only in northeast and north Indian rivers. In northeast India such floods have occurred in 8 rivers including Brahmaputra at 12 G/D sites while in north India 9 rivers including the Ganga at 20 G/D sites have registered more than 50 floods. The worst flood prone sites have been found on the Brahmaputra at Dibrugarh and on the Beki River at Road Bridge and on the Kosi River at Baltara. The magnitude of flood deviation at different sites has also been examined. This study has shown that enormous water resources are available in this country, which can be used in deficient rainfall regions through a network system of reservoirs and canals.

A proto-type space-based disaster management system (DMS) has been organized with comprehensive data base design, space based near real time monitoring/mapping tools, modeling frame works, networking solutions and multi-agency interfaces. With the appropriate synthesis of these elements, a system-definition of the frame work of a DMS has been arrived at in terms of developing a methodology towards damage assessment due to 1998 Brahmaputra floods. The limited validation experiments carried out in consultation with local level functionaries reveal that the experimental results on damage to agricultural crops due to floods are in conformity with field condition.

The Himalaya, covering about 17% of total mountainous area of the Indian subcontinent, comprises several important glacier systems. Himalayan glaciers form a unique reservoir of fresh water, which support mighty perennial river systems such as the Indus, the Ganges and the Brahmapurta. Their combined annual runoff amounts to about 1.19 X 10^3 km^3 and the total suspended sediment load nearly 1.8 Gt. The Himalayan proglacial streams carry about 70-85 % of the total annual river flow, which is derived from snow and glacier ice melt, which in turn is related to the radioactive energy input, variation in air temperature etc.

Apart from being the source of freshwater, Glaciers have been recognized as significant agent of erosion and deposition. Discharge and suspended sediments were measured throughout the ablation seasons between May and October 1999 and 2000 in the proglacial stream that drains the Gangotri Glacier into Ganges river basin. During the observed periods, the total discharge volume was estimated to be 581.87 and 547.47X$10^6$$m^3$ respectively, and the total suspended sediment was 165.62 and 104.99 X 10^4 t, respectively. A large part of the total discharge volume and suspended sediment was contributed between July and September when solar radiation is strong. This study indicates that the suspended sediment load exhibits a positive correlation with the discharge volume on a seasonal scale. However, different sediment rating relationships were found for different years under the influences of changing patterns of snow and glacier ice melts.

The average contribution of snow and glacier melt runoff in the annual flows of the Satluj River at Bhakra Dam is estimated about 50%, the remaining 40% being from rain. Remote sensing through its spatial, spectral and temporal attributes provides synoptic and repetitive information on the water spread area of a reservoir. Using satellite data of various years, it is found that on average about 14998 km^2 (65% of the total drainage area) of the Indian part of Satluj river basin up to Bhakra Dam is covered by snow in the month of March. After the snowmelt season in September, about 4528 km^2 (20.3% of the total drain area) remains covered by perpetual snow and glaciers. As such, an area of about 9970 km^2 becomes snow free during the melt season.

Sediment particles originating from erosion processes in the catchment are propagated along with the river flow. When the flow of the river is stored in a reservoir, the sediment settles in the reservoir and reduces its capacity. Reduction in the storage capacity of a reservoir beyond a limit hampers the purpose for which it was designed. Thus, assessment of sediment deposition becomes very important for the management and operation of such reservoirs. In a study, remote sensing approach has been attempted for assessment of sedimentation in Bhakra reservoir. Remote sensing data (IRS-1B-LISSII) provided the information on the water-spread area of the reservoir, which was used for computing the sedimentation rate. The loss in reservoir capacity due to deposition of sediments for a period of 32 years (1965-1997) was determined to be 807.35 Mm^3, which gives an average sedimentation rate of 25.23 Mm^3 per year.

An index based approach, based on the surface factors mainly responsible for soil erosion is used to assess the vulnerability to the river Tapti in Surat district of Gujarat state using remote sensing data and GIS. Two watersheds were identified as being the most susceptible to soil erosion. Based on the integrated index, a priority rating of the watersheds for soil conservation planning is recommended.

Suspended sediment concentration in the melt water of Pindari Glacier located in the Almora district of Uttaranchal state in Central Himalaya was determined at regular intervals in four ablation seasons. The sediment chemistry of the Glacier is dominated by Si, Al, K, Fe and Mg together constituting > 70% of the elemental abundance. The X-ray diffraction study showed that quartz is the most dominant mineral followed by Mica/Illite, Feldspar and Kaolinite. Coarse and medium silts predominant in the size distribution while clay constitutes about 7% of the total size population. By use of remote sensing data in conjunction with GIS, assessment of sediment deposition in Bargi Reservoir, Madhya Pradesh state has been made. The resulting sedimentation rate in the zone of study is about 229 m^3 of catchment area per year.

The water balance of the lake Nainital, located in the Kumaun Himalayan region has been computed. The mass balance results indicate that the groundwater contribution is about 50% of the total annual inflow to the lake. The subsurface out flow is about 55% of the total annual outflow from the lake. The water retention periods for the lake estimated by isotopic mass balance, Chloride mass balance and conventional water balance methods are about 1.93, 1.77 and 1.92 years, respectively.

Water and bed sediment samples collected from the Damodar river and its tributaries were analyzed to study elemental chemistry and suspended low characteristic of river basin. The suspended sediments show a positive correlation with discharge and suspended load, reach their maximum value during the monsoon season. The geo-accumulation values calculated for Fe, Mn, Zn, Ni and Cu are well below zero, suggesting that there is not pollution from these metals in Damodar river sediments.

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METEROLOGY AND ATMOSPHERIC PHYSICS

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Introduction

This report gives an outline of the work done by the scientific organizations of India in the field of Meteorology and Atmospheric Physics during the period 1998- 2002. In this field more than 30 organizations including Universities, Institutes, other Government agencies are involved in research, capacity building, observational and data base development work etc. In this report, the work done during 1998-2002 is broadly summarised under the following headings:

1. Monsoon studies
2. Atmospheric modelling and Dynamics
3. Climate studies
4. Air-sea Interaction
5. Atmospheric Physics, Chemistry, Cloud and Radiation
6. Atmospheric Boundary layer
7. Satellite Meteorology
8. Experimental studies.

Inputs were requested from over 30 organizations. A selected list of organizations those who have contributed to this report within the requested time frame are given in the report. A selected bibliography of papers, supplied by the contributing organizations as well as collected from the literature is also given at the end of the report.

Monsoon studies

Impact of monsoon dominates in many spheres of national activities including the socio- economic sector. In view of this, the study of monsoon remained to be the major area of research in India. Various aspects of monsoon and its systems, including their interactions, inter-annual and intra-seasonal variability, global teleconnections, prediction on various scales, numerical impact assessment and diagnostic studies- were given great importance. Herein after the word monsoon is used for Southwest Monsoon. Major research programmes for understanding the variability of monsoon, the oceans and the coupling of ocean and atmosphere were also carried out. Some of the results of such major programmes like INDOEX (Indian Ocean Experiment), BOBMEX (Bay of Bengal Monsoon Experiment), and ARMEX (Arabian Sea Monsoon Experiment) are summarised in section (8) under Experimental studies.

Studies on advance phase of monsoon showed that the establishment of mid-tropospheric subtropical ridge over north India and Tibetan plateau after mid June was found to be a key factor in maintaining monsoon trough over the country. The warming of Tibetan plateau by the middle of June was found to be conducive for the establishment of Tibetan anticyclone and advance of southwest monsoon. In its absence, the westerly trough propagated equatorwards and hindered the progress of monsoon.

The north Indian Ocean becomes the warmest area of the world oceans prior to the onset of southwest monsoon in June. During this period, a zonal band of high sea surface temperature (SST), the "thermal equator" (TE), moves over this region concurrently with the Intertropical Convergence Zone (ITCZ). Using a weekly SST data set, it was shown that another SST high developed off southwest India in the Lakshadweep Sea in March, well before the TE moved in to the area, and that it continued to retain its identity until the onset of monsoon. By, May, when the thermal equator and ITCZ moved over the region, the high could be seen embedded in the TE. It was speculated that, at this time the high helped in producing conditions that were conducive for the genesis of the monsoon onset vortex.

Study of rocket wind data over Thumba (India) and upper wind data in the lower stratosphere over Singapore, behaviour of equatorial stratospheric and mesospheric zonal winds in governing monsoon rainfall over India indicated that the westerly winds/light- easterly winds during phases of QBO in preceding January and May were favourable for good monsoon while easterlies were non conducive for good monsoon. The inverse relationship of SST Anomaly over Nino 3 area and Indian seasonal monsoon rainfall was found to be significantly enhanced during the easterly phase of QBO. This probably explains why every EL Nino is not associated with the drought over India.

The Indian monsoon rainfall (IMR) showed epochal behaviour with the periods 1895-1930 and 1963-1990 characterised by below normal rainfall with high frequency of droughts while the periods 1871-1895 and 1930-1963 characterised by above normal rainfall with very few droughts. It was seen that the impact of El Nino was more severe during the below normal epochs than the above normal epochs. Further analysis revealed that probably IMR is tending towards an epoch of above normal rainfall with a turning point around 1990. This may be another possible reason for India not experiencing a drought during the 1991-94 and 1997 El Nino episodes.

Analysis of the 140-year historical record suggested that the inverse relationship between El Nino - Southern Oscillation (ENSO) and the Indian monsoon broke down in recent decades. Two possible reasons emerged from the analyses. A south- eastward shift in the Walker circulation anomalies associated with ENSO events could have resulted in reduced subsidence over the Indian region, thus favouring normal monsoon conditions. Additionally, increased surface temperatures over Eurasia in winter and spring, which were a part of the mid-latitude continental warming trend, might have favoured the enhanced land-ocean thermal gradient conducive to a strong monsoon. These observations raise the possibility that the Eurasian warming in recent decades could help to sustain the monsoon rainfall at a normal level despite strong ENSO events.

Rain over northern parts of India and position of 500 hPa ridge in the month of April showed significant correlation with subsequent SST anomalies of eastern Pacific Ocean (Nino-3 region). As the relationship was stronger during El-Nino years, it could be used for prediction of peak warming which usually occurs during October to December months.

In the light of the global warming scenario, the inter-annual and decadal variability of the IMR was examined by using observed data for the period 1871-2001. There was no clear evidence to suggest that the variability of the IMR was affected by the global warming. Connections between the ENSO phenomenon, Northern Hemisphere temperature, and Eurasian snow cover revealed that the correlations were weak and changed signs in the 1990s suggesting that IMR was de-linked not only with the Pacific but the Eurasian continent also. The fact that NH temperature / snow relationships with IMR were weak suggested that the global warming could not be a cause for the recent ENSO-Monsoon weakening. The analysis of Northeast monsoon rainfall data for the period 1901-1997 revealed that ENSO years were generally associated with enhanced northeast monsoon precipitation.

Century-long observations provided evidence for an interesting out-of-phase variability between the first principal component of Baiu rainfall over the Japanese archipelago and the monsoon rainfall over India during the early summer season (June and July). It was suggested that the circulation near the subtropical region of the west Pacific Ocean tended to vary in-phase with that over the Indian subcontinent, so that an intensified (weakened) west Pacific subtropical high was accompanied by an intensified (weakened) Baiu circulation over Japan and a weakened (intensified) monsoon circulation over India. A pattern consisting of an anomalous low over the Caspian and Aral Sea regions, a high over Mongolia and an anomalous low over Korea and Japan, tended to be associated with increased Baiu rainfall over Japan and decreased monsoon rainfall over India.

Studies focused on the Eurasian sector snow depth revealed that there were localized regions over Russian sector, where the snow depth variations during January had a substantial impact on the subsequent IMR. One of the important findings of this study was that the coherent areas of significant relationship shifted southward as time progressed from winter to spring and non-El Nino related droughts over India were associated with snow depth variations over the above localized regions.

Studies on the energetics of monsoon for its various stages were carried out. Analysis of monthly momentum transport of zonal waves at 850 hPa between 30°S and 30°N for January to April showed a positive correlation between IMR and the momentum transport of wave zero over latitudinal belt between 25°S and 5°N during March. Northward (Southward) momentum transport of wave zero observed in March over the belt subsequently led to a good (drought) monsoon season over India which was found to be true even when the year was marked with El Nino event.

In order to understand the intra-seasonal and inter-annual variability of the monsoon circulation, global energetics during the early monsoon months were examined. Computations showed that the maximum amount of kinetic energy (KE) was clustered around 250 hPa level in the atmospheric region between 1000–100 hPa. The maximum fluctuations in the KE were also observed at 250 hPa level during the period of the study. The 1st peak of KE was seen to occur during 1st week of June, which was just after the onset of monsoon over India and neighbourhood. The 2nd peak was observed after a period of about 45 days. This probably reflected the 40-60 days oscillation.

Temporal variation of kinetic energy of wave number 1 showed a steep decrease prior to the formation of depressions/cyclonic storms in the Bay of Bengal. The kinetic energy of wave number 1 weakened (strengthened) when the depression/cyclonic storm in the Bay of Bengal strengthened (weakened). After the decay of the cyclonic system, wave number 1 received the kinetic energy. The study suggested a signal about the formation of the depression / cyclonic storm in the Bay of Bengal.

A diagnostic mathematical model was used to understand the dynamics of low frequency intra-seasonal oscillations during the contrasting monsoon years at 850 hPa and 200 hPa. Latitude-frequency distributions of nonlinear energy interactions over Indian region and global tropics at 850 hpa showed strong energy transfer to low frequency oscillations on Madden- Julian time scale to the north of the Equator up to 20°N. Strong non-linear triad energy interactions among large scale monsoon circulations, low frequency transients on Madden Julian time scale and seasonal mean flows were found to be viable dynamical mechanism for good summer monsoon over Indian region and global tropics.

North Atlantic Oscillation (NAO) and Southern Oscillation (SO) were found to be inverse oscillations and just before the beginning of monsoon season, the relationship between them was found to change sharply. The behaviour of these two oscillations was in phase in the excess monsoon years while it was out of phase in the deficient monsoon years. Simultaneous impact of NAO and SO on monsoon activity over Indian sub-continent was expressed as an index called effective strength index (ESI) and was defined on the basis of monthly NAO and SO indices. ESI in the month of April showed an inverse association with Indian summer monsoon rainfall. The relationship was statistically significant. It was also seen that during the positive phase of ESI the easterly over the central equatorial Pacific Ocean intensified and due to which there was a shift in the

Walker circulation towards the Indian subcontinent. This ultimately increased the convergence over Indian region, which led to higher monsoon rainfall activity.

The analysis of the duration of breaks in the month of July and August, with North Atlantic Oscillation (NAO) indices indicated that during the negative phase of NAO there was either less duration of breaks or no breaks in the monsoon activity while during positive phase of NAO the break monsoon condition prevailed significantly. The study helps to understand the dynamical aspect of breaks in monsoon condition over Indian region and also the tropical- extra tropical interactions.

The inter-annual variations of SSTs in the Indian Ocean (IO-SST) in summer and autumn appeared to have some connection with winter circulation anomalies over the Eurasian region during the period, resulting in warmer than normal surface temperature conditions in the recent decades. Keeping in view the fact that the surface temperatures over Eurasia in winter and spring played a dominant role in determining the strength of the monsoon over India, the enhanced Eurasian temperatures in recent decades, both as part of the general global warming and through IO-SST induced mid-latitude circulation response, might be a plausible mechanism for the recent long-lead correlations between IO-SSTs and IMR. May wind stresses over Arabian Sea were also found to be statistically significantly related with ensuing IMR.

Decadal scale variability in Indian monsoon rainfall seems to be forced by global scale SST anomalies. The analysis of SST Index (Southern Hemisphere minus Northern Hemisphere ocean temperature anomalies) for the months July to September showed that the two periods 1901 to 1920 and 1965 to 1990, in which India witnessed frequent droughts broadly corresponded with warm SST index.

Studies, addressing the Indian summer monsoon teleconnections and long range forecasting of Indian summer monsoon, identified new teleconnections of IMR with global surface air temperatures, Indian Ocean sea surface temperatures, winter surface pressure over Eurasia and Sea Surface Temperature (SST), Out going Long-wave Radiation (OLR) over Atlantic Ocean. Some of these teleconnections are being used as predictors in the operational Long Range Forecast (LRF) model of India Meteorological Department. Models for long range forecasting of All India summer monsoon rainfall and broad homogeneous regions rainfall using new techniques like artificial neural network, principal component, discriminant and Power Transfer analysis have also been developed.

Spochal changes in relationship between various predictors and the All India Monsoon Rainfall, which are mainly responsible for long range, forecast errors, as in 2002, were analysed in detail. To tackle this problem at least partially, prediction by time series using an Artificial Neural Network (ANN) technique with error-back propagation algorithm was attempted. Though results for IMR forecast appeared to be satisfactory, but for monthly scales they were very poor. To tackle the problem of changing relationship, a new technique was developed to analyze the spochal changes of predictor-IMR relationship. Based on this technique a hypothesis was proposed which states that the resultant association between a predictor and monsoon rainfall can be expressed as a sum of basic climatic (long period) association and perturbed climatic (very short period) association and if both of these associations between the predictor and predict and are used, the accuracy of the forecast would be greater than that could be achieved with the existing long range forecast models. The hypothesis was validated by formulating a new model, termed as Power Transfer Model.

Atmospheric Modelling and Dynamics.

Modeling of atmospheric and oceanic processes, and their interactions remained another thrust area of research. Simulation and sensitivity studies helped in the better understanding of atmospheric phenomena and circulation. Studies were carried out to incorporate different physical parameterisation schemes and initialization schemes in models of various scales.

Utilizing radiosonde and M-100 rocket-sonde data, collected over Thumba (8°N) in the 20-80 km altitude region for the period 1971-1993, a multifunctional regression model was developed to study the long-term temperature trends in the middle atmosphere vis-à-vis possible global change. Results of the study indicated an annual negative temperature trend of 1 to 2.5° K/decade from 20 to 45 km, 2 to 3°K/decade in the lower mesosphere and a higher cooling up to 5°K/decade in the upper mesosphere.

A pure baroclinic 16- layer quasi-geostrophic numerical model was applied to determine the baroclinic structure of a severe cyclonic storm that formed during June 1994. It was found that the baroclinic structure of preferred wavelength was comparable to that of the observed structure of the cyclonic storm. By inclusion of surface friction, the perturbation field was slightly enhanced but the vertical extension remained unchanged. The model was found useful in understanding the occurrence of transient disturbances, which led to the onset of South West monsoon.

Results obtained from a set of atmospheric general circulation model (AGCM) experiments indicated that the Indian Ocean SSTs generally had much less impact on the monsoon variability compared to the Pacific Ocean. Besides, the impact of ENSO on the Indian monsoon was found to be much less in the presence of strong continental warming, suggesting that the enhanced land-sea gradient and an enhanced monsoon due to general warming could counter the negative impacts of El Nino on the monsoon to a large extent and thereby might have weakened the connection between these two important global climate phenomena.

Diagnostic analysis of observations and a series of ensemble simulations, using an AGCM were carried out with a view to examine the wide-spread suppression of the seasonal summer monsoon rainfall over the Indian subcontinent in 2000. During this period, the equatorial and southern tropical Indian Ocean were characterized by warmer than normal sea surface temperature (SST), increased atmospheric moisture convergence and enhanced precipitation. The findings of this study revealed that the strengthening of the convective activity over the region of the southern equatorial trough played a key role in inducing anomalous subsidence over the subcontinent and thereby weakening the monsoon Hadley cell.

A six-member ensemble Atmospheric General Circulation Model (AGCM) runs, made with observed global SSTs were analysed to examine the model's ability to simulate various global climatic features such as the Indian summer monsoon, North Atlantic Oscillation (NAO) etc. and their inter-annual variability. The results were also utilized to study the predictability aspects of various global meteorological variables such as the precipitation, surface temperature, sea level pressure etc.

Climate Studies

Climate has far reaching consequences on long- term socio- economic environment and sustainable developments. The roles of trends, periodicities, variabilities of climate and those parameters related to climate change have a very important place in the current research activities. Analysis of various factors that affect climate and the simulation studies are engaging the attention of many scientists.

A project, Climate Related Environment Monitoring (CREM), which aims at establishing a network of stations in India to generate primary data on green house gases and aerosols on a long-term basis was under taken. Such data are of vital interest to our country with regard to climate change studies and to create a sound database, which can be used in future climate change negotiations in the United Nations framework and also for understanding different aspects of climate change.

Climate variations and teleconnections over South and East Asia were investigated by using monsoon rainfall data for a period of 1881-1998 over India, Mongolia, China, Korea and Japan. The interconnections between the monsoon-related events (rainfall over South Asia, rainfall over East Asia, northern hemisphere circulation, tropical Pacific circulation) appeared to strengthen (or weaken) around the same time, implying that monsoon-related events over geographically separated regions got linked (or delinked) around the same time.

Simulation of climate using a simple diagnostic model, based on moisture and energy budget, which could demonstrate the seasonal variation of monsoon rainfall with the seasonal variations of evaporation, net radiation at the top of the atmosphere and precipitable water vapour engaged the attention of scientists. Results threw some light on the difficulty in simulating the climate.

A few epochal decreasing and increasing trends in the frequency of cyclonic disturbances over the Indian Seas were found during past hundred years. The frequency of cyclonic disturbances in the monsoon season was also found to show the typical epochal trends. It was observed that the genesis potential (GP) was greater for developing synoptic scale disturbances in the westerly phase than in the easterly phase of QBO. Also, cold temperatures in the lower stratosphere at 60°N in the westerly phase of QBO were found to be associated with more number of cyclonic storms over Indian seas.

In order to reconstruct the variations in the intensity of summer monsoon precipitation during the late Quaternary, the analyses of two sediment cores from the southwestern continental margin of India was made. It indicated that the summer monsoons in general were weaker during the late glaciation, with distinct events of intensification of approximately 28 000 and 22 000 yr BP.

Recent trends in the tropospheric temperatures were studied by using objectively interpolated upper air and surface data of Indian stations on a 2° x 2° grid. The analysis of all India mean monthly and seasonal temperature series indicated warming at the surface levels and cooling at upper levels. Seasonal variations in tropopause height and temperature over Indian stations indicated that on annual and seasonal scales there was a significant increasing trend in the tropopause height over almost all the stations south of 20°N.

Studies of trends in rainfall and radiation over smaller spatial scales over India indicated that all India rainfall did not show any trend, but showed epochal decreasing and increasing trends. In recent years a decreasing trend in rainfall was noticed over most of the hilly areas. Most of the stations did not show any trend in global radiation. However, a slight increasing trend of tropospheric ozone and a decreasing trend in stratospheric ozone were observed.

In recent decades an increasing trend in the number of poor visibility days (less than 2000 metres) in winter season, particularly in morning hours was noted. One of the reasons could be the degradation of air quality due to significant increase in anthropogenic pollutants in the urban areas. On seasonal and annual scale, a decreasing trend in heavy rainfall events was noted over most of the stations of the country in recent years.

Air Sea Interaction

The large-scale atmospheric circulation is greatly influenced by the ocean interactions. The location and intensity of the convection and diabetic heating of the atmosphere are greatly influenced by ocean parameters like SST. An important question in the tropical dynamics is the exact role of SST in the genesis of the observed spectrum of oscillations. SST, as the major lower boundary forcing with substantial variability at different scales, is known to be important for the atmospheric processes like onset and maintenance of convection. However, its role in range and quality of atmospheric simulation needs to be quantified at various scales. In particular, it is not clear how the higher frequency variability of SST affects the atmospheric processes. Recent observations and theoretical studies emphasised intra-seasonal variability of SST with significant amplitudes. It is expected that these SST intra-seasonal oscillations will have significant effect on the simulated atmospheric systems.

Simulation of two contrasting monsoon years by a GCM indicated very significant influence of temporal structure of SST on precipitation. Contrary to the general belief, it was found that use of daily SST could substantially influence and improve the monsoon simulation. This in turn emphasized the need for quality forecasts of the SST field and in particular, need for reliable ocean-atmosphere coupled models.

A parameterization of ocean atmosphere coupling in the tropics was developed using the concept of convective relaxation time scale, known as convective ocean atmosphere coupling. It was found that the sea surface temperature affected the low level atmospheric circulation only indirectly, by modulating the column moisture and hence the column precipitation. Since precipitation was a threshold process, the convective ocean-atmosphere coupling also became a second order threshold process. These works showed that such a formulation of ocean atmosphere coupling, in addition to being conceptually appealing, could explain the genesis of a broad spectrum of atmospheric and oceanic variabilities. Both moist feedbacks and the basin geometry played crucial roles in understanding and modeling the low frequency variabilities over the Indian Ocean region.

An examination of the trend in SST and total cloud amount over the Indian Ocean for the period 1951 to 1998 showed that the cloud cover over Bay of Bengal was modulated by the ENSO events. On inter decadal scale, the amount of low cloud significantly increased after 1980 which might be associated with the corresponding inter decadal changes of SST over north Indian Ocean that were observed during late 1970s.

The air-sea interaction processes over the tropical Indian Ocean region are studied using sea surface temperature data from the Advanced Very High Resolution Radiometer sensor onboard the NOAA series of satellites. The analysis of columnar water-vapour content, low-level atmospheric humidity, precipitation, wind speed, and back radiation obtained from the Special Sensor Microwave Imager on board the U.S. Defense Meteorological Satellite Program for two contrasting monsoon years, 1987 (deficit rainfall) and 1988 (excess rainfall) indicated that the evaporation rate over the south Indian Ocean and the low-level cross-equatorial moisture flux seemed to have exerted considerable influence on the ensuing monsoon activity over India while the evaporation over the Arabian Sea exerted a little influence.

An analysis of the heat budgets of the near-surface Arabian Sea and Bay of Bengal showed significant differences between them during the monsoon. In the Arabian Sea the winds associated with the monsoon were stronger compared to Bay of Bengal and favoured the transfer of heat to deeper layers owing to overturning and turbulent mixing. As a result, the sea surface temperature in the bay remained higher than 28 °C, thereby supporting large-scale deep convection in the atmosphere during the monsoon.

Atmospheric Physics and Chemistry, Cloud and Radiation

In the light of anthropogenic impact on climate, research in the field of atmospheric Physics, Chemistry and radiation remained another thrust area amongst Indian Scientists. Effects of the increased emission of green house gases, stratospheric ozone depletion, occurrence of acid rain, reduction in visibility due to smog formation, the changing characteristics of troposheric and stratospheric aerosol, cloud physics, electricity and weather modification were given great importance. On these aspects, a good number of observational as well as modelling studies were carried out.

To monitor the characteristics of upper tropospheric and stratospheric aerosol including the influence of winds and atmospheric stable layers such as tropopause on aerosol characteristics, experiments were carried out using Nd: YAG lidar system, available at National Mesosphere-Stratosphere-Troposphere Radar Facility. Simultaneous observations of atmospheric stable layers and 3-Dimensional vector winds also were carried out using MST radar. The results helped in understanding radiative properties of cirrus clouds and their influence on tropopause thereby stratosphere - troposphere interaction. An analysis of Argon-ion lidar and polarization lidar data indicated that the lidar has the capability to capture the multi-layer cloud structures, interface between cloud condensation nuclei in the sub-cloud layer and in the vicinity of cloud-base and anisotropy of aerosol scattering.

The analysis of multi-filter solar radiometric observations of aerosols and trace gases indicated significant inter-annual variability of columnar aerosol optical depth, aerosol size distribution, ozone and precipitable water content. All the parameters were found to show a decreasing trend with varying magnitude.

An analysis of tropical tropospheric column ozone (TCO) data, derived by Nimbus7 and Earth Probe -total ozone mapping spectrometer (TOMS) during the period 1979-2002 over the tropics (12.5°S to 12.5°N), revealed statistically significant linear trends widely believed to be of anthropogenic origin. An increase in TCO by 23 (±10) % in the past two decades was found. That means a radiative forcing of climate might be up by about $0.3 Wm^{-2}$. If sustained, it could have serious climatic implications.

A two- dimensional interactive model of radiation, dynamics and chemistry was used to reconstruct the annual vertical distribution of thermal structure and trace gas concentrations of the lower and middle atmosphere for the period extending from last ice age to the present, with ice core air data of the forcing parameters like CO_2, CH_4 and N_2O as input. Model results showed that the considerable reduction in the greenhouse gas content for the last ice age resulted in cooling of troposphere and a warming by about 10°K to 15°K in the upper stratosphere as compared to present. The variation in temperature was found closely related with the water vapour content. The percentage change in ozone concentration for the last glacial period was to a maximum of 50% near the poles in the upper stratosphere and about 10% in the tropics.

Studies were undertaken, using the coupled neutral-ion photochemical model to demonstrate that gas-phase sulfur chemistry played a vital role in perturbations of the stratospheric ion composition following the Pinatubo eruption. Model calculations indicated that immediately after the eruption, the large amount of SO2 injected directly into the tropical stratosphere produced additional sulfuric acid vapour, which increased the abundance of heavy negative ion family by several orders of magnitude over the ambient. The perturbation (now weaker) in ion composition continued to be unabated even after one year of eruption but settled down to background level after 2 years.

Data on atmospheric electric field and electric conductivity, obtained at Maitri during XVI Indian Scientific Expedition to Antarctica showed a peak in electric field at 1300 hrs and a secondary peak in electric field at 1900 hrs. The electrical conductivity did not show any significant variation during the period of measurement at Maitri, Antarctica.

Aerosol size distribution obtained during the onward and return journeys of the XVI expedition to the Antarctica showed large aerosol concentrations and their north to south positive gradient over northern Indian Ocean. The results also indicated the transport of air pollutants from northern to Southern Hemisphere with cross-equatorial flow. Some pockets of very high aerosol concentrations were observed in and around the Inter Tropical Convergence Zone. Some peaks in aerosol concentration associated with the low-pressure systems were observed around the continent of Antarctica. These observations strongly demonstrated the effect of wind direction on the land-to-ocean transport of the atmospheric aerosols. The total aerosol concentrations were normally observed between 800 and 1200 partciles/cm^3 at the coastal stations at Antarctica in summer. Aerosol size distributions were found to be generally tri-modal and a pen-ended with a peak between 75 and 133 nm and two minima at 42 and 420 nm size distributions remained almost similar for several hours or even days in the absence of meteorological disturbances.

The atmospheric electric conductivity was measured over the Indian Ocean on different cruises of Ocean Research Vessel Sagar Kanya during the Indian Ocean Experiment. Results showed a north-to-south positive gradient of conductivity extending up to the Inter Tropical Convergence Zone in the Southern Hemisphere. Special observations of maritime aerosols, total column ozone and precipitable water content using multi-band solar radiometers were carried out onboard ORV Sagar Kanya over Bay of Bengal as part of the Bay of Bengal Monsoon Experiment-99. The results indicated interestingly lower aerosol optical depths and size distributions with abundance of coarse-mode particles as compared to those aerosols of typical land origin which depicted day-to-day variation in aerosol optical depth at different wavelength of the radiometer. When a low-pressure area was present, great optical depth near the coast and sudden fall in optical depth during 13-19 August 1999 due to cloud scavenging and associated rainfall were also noted.

To study the effect of vertical electric field on the rate of evaporation of water drops, a laboratory experiment was conducted by suspending drops in vertical wind tunnel under vertical electric field. The result showed that the rate of evaporation of charged drops was found to be slower than that of uncharged drops. Also at the cloud base, a charged drop is required to be smaller in size as compared to an uncharged drop in order to reach the Earth's surface with the same size. The distortion of water drops suspended in a small vertical wind tunnel was also studied by taking their photographs with a 16-mm movie camera. Results showed that the deformation of the drop increases with the size of the drop and also with the increase in the horizontal electric field.

Studies using International Satellite Cloud Climatology (ISCCP) and Earth Radiation Budget Experiment (ERBE) data showed that among deep convective regions of the tropics, only in the Asian monsoon region, the net cloud radiative forcing was large negative, exceeding 30 Wm^{-2} during the monsoon season. The combination of presence of large amount of high clouds and high optical depth of these clouds was attributed to it.

Anthropogenic emissions over the Asian region have been growing rapidly with the increase in population and industrialization. This probably led to a brownish haze over most of the North Indian Ocean and South Asia during winter and spring. The haze is known to reduce the surface solar insolation by about 10% (-15 W/m^2) and nearly double the lower atmospheric solar heating. To study the effects of absorbing aerosols with competing radiative forcing on the atmosphere and the surface, an analysis of observed surface-temperature variations over the Indian subcontinent was carried out. The analysis revealed that the absorbing aerosols led to a statistically significant cooling of about 0.3°C since 1970s.

Under the Arabian Sea Monsoon Experiment Phase-I, cruise observations were undertaken on board ORV Sagar Kanya. Surface ozone was monitored with the help of UV photometric ozone analyser at 254 nm wavelengths. Hourly analysis showed no prominent diurnal variation of surface O_3 over the ocean. Mass size distribution of aerosols showed a bimodal distribution with a small peak in fine size (0.65 μm) and a major peak in coarse (4.7 μm) indicating a dominance of coarse size sea-salt particles and less anthropogenic influence over the sea.

Nitrous oxide (N_2O) is an important greenhouse gas that plays a crucial role in the stratospheric ozone and thereby in the radiation budget. Analysis of seasonal and annual N_2O concentration fields for the Arabian Sea surface layer using a database containing more than 2400 values measured between December 1977 and July 1997 showed that N_2O concentrations were highest during the southwest (SW) monsoon along the southern Indian continental shelf. It was seen that annual emissions range from 0.33 to 0.70 Tg N_2O was dominated by fluxes from coastal regions during the SW and northeast monsoons. Arabian sea is an important site of bio-geo-chemical ocean- atmosphere transfers and plays a crucial role in regulating the atmospheric chemical composition and the climate. Due to a delicate bio-geo-chemical balance, the Arabian Sea is expected to be among the first to react to potential anthropogenic perturbations.

A general increase of turbidity at all Global Atmospheric Watch (GAW) stations in India except Kodaikanal was observed in recent years. These stations also showed anomalously high values of atmospheric turbidity in 1982-83 and 1991-92 following the eruptions of volcanoes El-Chichon, Mexico, in April 1982 and Mt. Pinatubo, Philippines, in June 1991. The increase in atmospheric turbidity values following these eruptions was discernible for 1.5-2 years after the eruption. pH values from Indian stations were around 7.0 or even higher up to 1980. But by 1990 large number of pH values ranged between 5.0 and 6.0, indicating a severe negative change. This can be attributed not only to increasing sulfate concentration but also even more to increasing nitrate concentration. Studies addressing the climatic effects of anthropogenic aerosol highlighted the role of sulphate aerosols in modulating the radiation budget and thus cooling of surface temperatures also.

The precipitation chemistry data showed that local effects seem to be more important for chemical wet deposition than large- scale geographical influences. Comparison of pH and other wet deposition data showed that India is much better compared to many other countries as far as acid rain situation is concerned.

Estimation and prediction of the ground level concentration of the air born effluent that might be discharged under normal operating conditions of the nuclear power plant or under a hypothetical accidental condition is a challenging task. As it happens, most of the nuclear power plants are located at coastal or hilly terrain where the meteorological condition influencing the air pollution dispersion is non-homogeneous and non -stationary. The sea – land breeze circulation and development of internal boundary layer greatly influence the trajectory and diffusion of the pollutants at a coastal site. The terrain undulations, mountain – valley circulation and the varying land cover influence the dispersion under a mountainous terrain. Some of these aspects were also investigated during the period. Field experiments and modeling studies were conducted in meso and long - range atmospheric dispersion. The data collected routinely and under field experiments were found useful for studying land, atmospheric and coastal processes during different seasons. The modeling study can be used for the development of a generic numerical code for emergency impact assessment for any nuclear/ non -nuclear effluent releases.

Atmospheric Boundary Layer

The exchange of mass, momentum, heat and water vapour from the earth's surface to the air above is important and is taking place through the lowest layer of the atmosphere, known as Atmospheric Boundary layer (ABL). The thermodynamic structure of the marine boundary layer over Bay of Bengal was studied using Radiosonde measurements made during the Phase II of the BOBMEX-99. The observational area was divided in to region I (87°-85° E), region II (85°- 82° E) and region III (82°-80° E) depending upon the surface pressure distribution and total cloud amount. The results of the analysis of the radiosonde data showed relatively dry air near the ocean surface between 1000 to 950 hPa and persistent low cloud layers between 900 and 700 hPa. The lifting condensation levels of the region I were above 963 hPa whereas they were below 963 hPa over region II and III.

Aerological observations collected over six coastal stations when a low-pressure area was observed during Bay of Bengal Monsoon Experiment-99 were analysed. The stations in the vicinity of the system were found to be associated with more convective instability in the lower layers, less mixed layer heights and Convective Boundary Layer tops reaching up to higher levels as compared to stations away from the system.

A number of studies related to atmospheric boundary layer, convection and precipitation, winds, waves and turbulence, cirrus cloud, tropopause using the Mesosphere-Stratosphere-Troposphere (MST) radar, Lower Atmospheric Wind Profiler (LAWP), Rayleigh/ Mie Lidar, Optical Rain Gauge (ORG), Disdrometer, automatic weather station (AWS), radio-sonde /GPS-sonde and rocket borne experiments were carried out. During monsoon and post monsoon seasons strong turbulence was observed at the height range of 16-20 km and a minimum in the height range of 12-16 km. This strong turbulence was noted to be closely associated with vertical shear of horizontal winds that were observed to occur at the upper edge of the Tropical Easterly Jet winds.

Satellite Meteorology

For monitoring weather systems over land and ocean, like tropical cyclones, monsoon depressions, western disturbances etc., satellites act as effective observing platform. The availability of satellite-derived data was of enormous help in understanding the atmosphere and different weather systems. Satellites also played important role in air- sea interaction studies and in mapping of aerosol optical depth over land regions, associated with different geographical, terrain, meteorological and environmental conditions.

Analysis of satellite derived out- going long wave radiation (OLR) data over the Indian Ocean (30°N to 30°S and 40°E to 100°E) showed that the OLR of two regions appeared to be strongly related with the Indian Monsoon Rainfall (IMR). One of the regions was located over the Bay of Bengal during May (Index one) and the other one over the Indian Ocean during April (Index two). The multiple regression model developed using these indices gave encouraging results.

The sea surface winds obtained by SSM/I by DMSP satellite of USA were compared with the initial winds and the model forecast (T80 L18) winds at 1000 hPa over the broad region of Indian summer monsoon for the onset phase of summer monsoon. Though a speed difference of 4 mps in general was observed, a good quality, dense data over data sparse oceanic regions of Indian sub-continent was available by using the satellite data for resolving synoptic scale weather systems.

A useful system was developed for assimilation of humidity profiles, estimated from INSAT infrared cloud imagery and also temperature, moisture and geopotential height data derived from NOAA satellite in the limited area forecasting system. Cloud motion vector winds derived from the major geostationary satellites (INSAT, GMS, METEOSAT, GOES) were subjected to quality checks and were successfully used in 6 hourly data assimilation cycle. The analysis and forecast fields generated using ATOVS & SSM/I data were compared with corresponding operational archives. Results of these studies suggested that the SSM/I measured Total Precipitable Water Content was useful to estimate the moisture content not only in the initial state of atmospheric circulation but also in forecasts.

Experimental studies.

The analysis of the data, collected during BOBMEX-98 pilot showed that the Bay of Bengal was comparatively warmer than the Arabian Sea. An abnormal high value of SST recorded coincided with a maximum global solar radiation at the same time on that day. During BOBMEX-99 many unknown features came to focus such as continuous southeast shift of the eastern end of the monsoon trough into the Bay, a sudden change in the surface circulation pattern within a day due to a sudden change in the circulation pattern of the mid-troposphere etc. The large impact of aerosols in the Arabian Sea in radiative budget was demonstrated. First measurement of the aerosols over Bay of Bengal was made. A large gradient of aerosol optical thickness was found across the inter-tropical convergence zone. Both natural and anthropogenic aerosols were found to be important in the Arabian Sea during the period April to June. The effect of clouds and surface reflection and sea surface winds on aerosol radiative forcing was also demonstrated during these experiments.

Surface meteorological parameters acquired during field phase of the Bay of Bengal Experiment (BOBMEX-99) for the stationary periods of the ship ORV Sagar Kanya over Bay of Bengal were used to estimate the fluxes of sensible and latent heat and momentum at the air-sea interface. Large-scale aspects of the atmospheric conditions over Indian Sub-continent and local meteorological parameters over Bay of Bengal were studied. The surface and the boundary layer fluxes of moisture, sensible heat and momentum exhibited a large amplification as waves in the Madden -Julian Oscillation (MJO) time scales, interacting with synoptic time scales of 2 to 7 days. The data sets for this study were derived from a coupled Ocean-Atmosphere model that was able to resolve a robust MJO in its simulations.

From the meteorological observations recorded onboard ORV Sagar Kanya during the post-monsoon season of 1999, the fluxes of sensible heat and momentum showed smooth variation during open sea condition but they showed an increase, as the vessel moved towards the coast. The standard deviations of the fluctuations of wind velocity components and temperature that were computed when normalised with the respective scaling parameters, were found to obey the Monin- Obukhov similarity theory. The correlation coefficients for heat and momentum fluxes showed dependence on atmospheric stability. The drag coefficient was found to vary with wind speed and stability. Drag coefficient under neutral condition agreed closely with the range of value quoted in the literature for the sea/ocean environment.

Under the Arabian Sea Monsoon Experiment, a national field experimental programme, observations on wind (speed and direction), air temperature, relative humidity, short wave and long wave radiation (incoming and outgoing), 5m. height turbulence measurements on wind components, and virtual temperature were under taken. Measurements on CO_2 and H_2O were also taken. The data are being studied and fruitful results are expected in near future.

The report is based on the contributions from several organizations in the country.

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PHYSICS AND CHEMISTRY OF THE OCEANS

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Introduction

Studies in the Physical and Chemical oceanography in India encompass all aspects of the disciplines. Over 150 organizations participate in the studies. These could be viewed by way of their research outputs in the form of publications.

In all, 276 Indian publications (list enclosed), during the period 1998-2002, on the above mentioned disciplines were downloaded from *IndOcean: A database of abstracts* (compiled at NICMAS, National Institute of Oceanography, Goa, India). The break-up of these is as follows. It needs to be mentioned that many of them are multidisciplinary and an effort has been made to class them in only one most relevant category. The ASFA (Aquatic Sciences and Fisheries Abstracts) scheme of categorization has been used.

Topic	**No of items**	**Progressive total**
Physics: General	4	
Regional Studies	6	
TSD distribution, Water masses	15	
Air-water boundary layer	23	
Ocean circulation & currents	35	
Benthic boundary layer	2	
Tides, surges and sea level	26	
Wind waves	10	
Near shore dynamics	8	
Ocean acoustics	3	
Ocean optics	7	139
Physics and chemistry of water	8	
Composition of water	37	
Organic compounds	12	
Chemistry of suspended matter	4	
Geochemistry of sediments	41	
Atmospheric chemistry	35	137
Total	276	276

Almost equal number of references have been published in both the major disciplines (physical and chemical oceanography) under analysis. Among the Physical Oceanography, the significant number of contributions are in the areas such as: TSD distribution, water masses; Air-water boundary layer; Ocean circulation and currents; Tides, surges and sea level; and Wind waves. Whereas in Chemical Oceanography, the Composition of water; Organic compounds; Geochemistry of sediments; and Atmospheric chemistry take front seat. The mission oriented projects acted as catalyst in increasing the number of research contributions. The JGOFS, BOBMEX, INDOEX, etc., are some of such examples during the period of analysis.

The work was carried out in many organizations. The prominent ones (alphabetical order) are: Andhra University, Annamalai University, Centre for Earth Science Studies, Cochin University, Geological Survey of India, Indian Institute of Science, Indian Institute of Technology Delhi, Indian Institute of Tropical Meteorology, National Centre for Medium Range Weather Forecasting, National Geophysical Research Institute, National Institute of Oceanography, Physical Research Laboratory, Space Applications Centre, Vikram Sarabhai Space Centre. Of these National Institute of Oceanography at Goa alone had about 100 contributions.

For the items listed in the report or the *IndOcean: A database of abstracts* to view other research contributions in this geographic area, contact: murari@darya.nio.org

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General

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SEISMOLOGY AND PHYSICS OF THE EARTH'S INTERIOR

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Introduction

Seismological research in India, during the last quadrennium has undergone radical transformation due to the availability of high fidelity digital broadband seismological data and enhanced computing capabilities. The Department of Science and Technology, New Delhi, has launched an ambitious program of funding projects to several research institutes, government departments and universities in the country to enhance the detection capabilities of intra and inter-plate earthquakes and to study the source characteristics of earthquakes and seismic structure of the Indian plate.

With the up-gradation from analog to digital broadband seismometry in the country during the last one-decade, understanding about the structure and dynamics of the earth has changed dramatically. Indian scientists are now in a position to understand the seismic structure and the source in a better way. The techniques used for oil exploration are now being extended to probe the lithospheric structure in greater detail. The lithospheric architecture deduced from velocity images is integrated with complex surface geology to understand the evolution of the Indian continental masses. The improved characterization of earthquake sources for large and moderate earthquakes in Koyna region in western India, in terms of fault geometry and rupture dynamics has opened up new vistas for tectonic studies. Although, long-term forecast of earthquake potential now appears to be a possibility, medium and short-term predictions are still a distant reality. In this scenario, major thrust has been shifted from earthquake forecasting to earthquake hazard assessment and mitigation. From this point of view strong motion and ground amplification studies are being taken up to provide inputs in designing safer earthquake resistant critical structures like dams and nuclear power plants in the country. Under the GSHAP programme, a seismic hazard map has been prepared for the Indian plate region, comprising the Himalaya, Northeast India, the Indian shield, South China, Nepal, Burma and Andaman regions. This effort has led to delineation pf eighty-six potential seismic source zones, the highest risk being in the Burmese arc, the Northeastern India and the Hindukush regions with Peak Ground Acceleration (PGA) values of the order of 0.35-0.4g.

The significant contributions in seismology from India during the past four years are in areas such as i) understanding reservoir triggered earthquakes, ii) structure of the peninsular and extra-peninsular India from controlled source and passive seismological experiments like body wave and surface wave modelling and tomographic inversion studies, iii) studies of the source mechanism and moment tensor solutions along with numerical modelling of the stress fields to comprehend the active tectonics of the Indian plate margins and the shield region, iv) multi-disciplinary geophysical studies in the source region of damaging earthquakes.

The achievements in seismology research have been made possible through intensive research under various time-targeted projects at different organizations. The Government of India's current emphasis on research and development to create wealth and improve the quality of life has led to the formulation of projects relevant to the present day needs of the country. This report provides information on the contributions made by the Indian researchers in the field of seismology during1999-2003.

Bhuj Earthquake

The most important seismological event in the beginning of the third millennium that dominated research activities in the country was the occurrence of Bhuj (Mw 7.7) earthquake on January 26, 2001. This was a great intraplate earthquake with a maximum intensity MMI of X+ in Zone V of the seismic zoning map of India. The focal mechanism of the main shock from waveform inversion of the regional data and the aftershocks indicate that the main shock and the most of the aftershocks have occurred along a E-W trending and south dipping hidden fault with reverse thrust motion. The focal depth of this earthquake was estimated to be around 20 km. The earthquake claimed several thousand lives and caused widespread damage in the Kutch region of Gujarat, western India. High stress accumulation in Kutch is attributed to the proximity of the triple junction and pivotal point for anti-clockwise rotation of the Indian plate.

The aftershocks study of the 2001 Gujarat, India earthquake reveal the seismically active fault dips toward the south at about 50° and is interpreted as the fault plane of the main shock. The depth distribution of aftershocks is from about 10 to 35 km and does not extend to the surface. This is important for evaluation of seismic hazard in continental areas. Large damaging earthquakes can occur on buried faults, which show no displacement or topographic features at the surface. Earthquakes, such as the 2001 Gujarat event leave very little surface evidence of faulting that can be used to identify past earthquakes.

The most interesting feature of this earthquake was the widespread deformational features on the ground caused mainly by secondary tectonic features due to strong ground shaking in the meizoseismal area of 40 km x 20 km. The features mainly include prominent development of extensional cracking of near surface ground and liquefaction. The earthquake provided an opportunity to study a range of liquefaction and plastic deformational features in soft unconsolidated sediments and the phenomenon of lateral spreading, especially where there was no surface expression of coseismic rupture. Evidence of intense lateral spreading was observed in the vicinity of the epicentral area where it has consummated into ubiquitous cracking in the agricultural fields. The patterns of cracks striking almost E-W are the normal faults associated with the extensional regime, with general trend of down throw due north. The field investigations indicated that none of the active faults seems to have moved during the earthquake, suggesting that in all probability the movement took place on a blind thrust and the rupture did not reach the surface. Soil-gas helium emanometric studies in the meizoseismal area reveal no significant helium anomaly along surface ruptures suggesting seismic fault must have ended blindly in the subsurface.

Studies of satellite imageries have shown several traces of active faults in the pediment zones along the northern margins of Katrol Hill Range and Northern Hill Range correspondingly. The comparison of pre and post earthquake data from Indian remote sensing satellite IRS 1D LISS-III and IRS P4 clearly brought out emergence of a paleochannel. Resistivity soundings in the epicentral region have shown presence of shallow water table at the liquefaction sites where buildings sunk into the ground. Along the coast emergence of land and activation of the channels were also clearly evident.

The 3-D seismic velocity and Poisson's ratio structures of the source area (60X40 sq km) was carried out to understand the probable cause of triggering the devastating earthquake at Bhuj using 1948 P and 1865 S-waves high quality arrival times from 331 Bhuj aftershocks recorded at a temporary seismic network consisting of 12 seismic stations. Significant velocity variations up to 5% and Poisson's ratio up to 10% are revealed in the aftershock area. The Bhuj mainshock is located in a distinctive zone, which is characterized, by high P-wave velocity (high-Vp), low S-wave velocity (low-Vs) and high Poisson's ratio. In contrast, areas with high aftershock activity are mainly associated with low Poisson's ratio. The low-Vs and high-Poisson's ratio anomaly at the Bhuj mainshock hypocenter is visible in the depth range of 22 to 30 km and extends 10 to 15 km laterally. The anomaly may be due to a fluid-filled, fractured rock matrix, which might have contributed to the initiation of a big and killer earthquake, at Bhuj, western India.

Shear-wave splitting studies were done for some aftershocks of Bhuj earthquake. Two patterns in polarization direction in fast shear-wave are found, regardless of the hypocenter location of the individual events. The NNE-SSW direction in fast azimuth coincides with the direction of the maximum horizontal compressive tectonic stress in the region.

Source Studies

The Indian plate has diverse tectonic environments along the plate boundaries, comprising a continent-continent collision in the Himalaya-Tibetan plateau region, an oblique subduction in the Burmese arc and a nascent plate boundary zone in the northeastern Indian Ocean deformation zone. The Indian shield within the plate is a mosaic of cratonic blocks sutured by paleo-rift valley zones, and is known to be a Stable Continental Region (SCR). In the last quadrennium numerous studies have been undertaken to understand the source processes for earthquakes, which have occurred within the plate interior and along the collision zone in the north and subduction zone in the northeast.

Intraplate Earthquakes

The most active seismic regions of the Indian shield are the Koyna-Warna region on the west coast of the Indian peninsula, which is a classic example of Reservoir Induced Seismicity (RIS), and the Narmada-Son lineament (NSL) zone cutting EW across Central India, the only active lineament on the Indian shield with at least 5 earthquakes of M > 5.5 and continue to interest the earth scientists in trying to understand the seismo tectonics of these regions.

Koyna-Warna region

Koyna, located near West Coast of India is known to be the most significant site of artificial water reservoir triggered seismicity, starting soon after initiation of filling of the lake in 1961. Reservoir triggered earthquakes have been occurring uninterruptedly in a small crustal volume of 30 x 5 x 10 km3 in the Koyna - Warna seismic zone. Till date, 18 earthquakes of M(5.0 (including the 1967 main shock of mb 6.3), over 180 earthquakes of M(4 and several thousands of M(3 have occurred in the region. It is observed that earthquakes of M (5) occurred when certain conditions are met e.g. water level in Koyna and/or Warna reservoir exceeding the previous maxima (Kaiser Effect), rate of loading exceeding 12 m/week and the retention time of high water level exceeding 90 days. The cross-correlation analysis between time series of the Koyna reservoir levels and the strain factor (Energy 1/2) calculated for earthquakes of M (3.0 suggest that the initial seismicity in the Koyna region during 1963 was triggered after the region attained steady state pore pressure by diffusion processes, particularly occurred along vertical strike-slip faults. Subsequently, major episodes of earthquake energy release till 1999 show a periodic behavior related to the annual filling of both the Koyna and Warna reservoirs. Two stages of earthquake energy release are evident till 1996 coinciding with annual filling and draining of the reservoirs. Since 1996, the energy release episodes correlate mostly to the draining cycle of the reservoir levels indicating a shift in the present day earthquake activity in the region, which may be due to a combined effect of both the Koyna and Warna reservoirs. Modeling of pore pressure front diffusion shows that water level change of the order of 1 m in 5 days in the surface potential can propagate 5-15 % of pore pressure front, corresponding to 0.75-2.25 bars, to the hypocentral depth of 6-8 km. This kind of stress perturbations are sufficient to trigger seismicity on pre-existing critically stressed faults in the Koyna-Warna region.

Space-time studies of epicenters in few selected time windows for moderate size earthquakes have shown that the fracturing processes initiates at shallow depths (< 1 km) and then gradually deepens to cause the main shock near the base of the seismogenic layer at about 8-11 km. This nucleation process preceding the main shock can thus, be considered as an immediate earthquake precursor for Koyna-Warna earthquakes.

With a view to understand the role of pore fluids in triggering earthquakes, twenty-one bore-wells of 90 to 250 m depth were drilled in the Koyna-Warna region. These bore wells instrumented with pressure transducers capable of measuring 1 mm change in water levels. Most of these wells are sensitive to tidal signals and thus acts as strain meters reflecting pressure changes in the medium. These studies have shown five cases of anomalous changes in well water levels due to local earthquakes (within 25 km) of 4.3 (M (5.2). The epicenters of all these earthquakes are located within the network of wells. These wells also found to respond to aseismic events and to transient changes due to the passage of seismic waves. The response of wells is categorized in three types, viz., co- and pre-seismic, aseismic and transient changes. The co-seismic steps are understood as sudden pore pressure changes related to an alteration in in-situ volume strain caused by the redistribution of stress in the brittle crust. These co-seismic steps are found to be preceded by persistent water level drops from 2 to 23 days prior to the earthquake. Some anomalous water level fluctuations were observed which were not associated with local or teleseismic earthquakes. In one case water level fluctuations were also found to be associated with passing seismic waves due to the M 7.9 earthquake at distance of about 800 km. All these observations indicate that the wells in the network respond to local/regional strain changes caused by the redistribution of stresses in the shallow brittle crust to different forcing functions.

Narmada-Son and Godavari rift valley earthquakes. The earthquakes along the Narmada-Son Lineament (NSL) are deeper as compared to most of the Indian shield earthquakes and there are at least 2 events along NSL whose depths have been determined at lower crustal levels - the 1938 Satpura earthquake at 40 km depth (37 - 44 km) and the 1997 Jabalpur earthquake at 35 km depth. Moment tensor solutions for the 21 May 1997, Jabalpur earthquake, using the regional Indian broadband data show reverse fault mechanism with the preferred fault plane striking ENE-WSW. This is also seen to coincide with the local strike of the Narmada South fault cutting across the Indian shield in the same direction. Investigation of the source process revealed a complex rupture process involving a sub-event 2 km above the main event, delayed by about 1 second. The lower crustal depth of the Jabalpur earthquake was also studied by modelling the sPn phase. The occurrence of such deep lower crustal earthquakes has been explained by the presence of possibly serpentenised elliptical intrusives near Moho, as the probable locales of stress concentration.

A mechanism to explain Godavari rift valley earthquakes has been attempted. Using moment tensor inversion of broadband waveform data a strike-slip fault for 03 February 1999 (Mw 3.6) earthquake has been obtained. Based on correlation of the slip vectors of the 1969 Bhadrachalam earthquake and the 1999 Godavari earthquake with faults inferred from LANDSAT images, the possibility of block rotation in the faulted paleo-rift valley zone is inferred.

Interplate Earthquakes

The Chamoli earthquake, which occurred in 1999, has generated considerable interest and various studies have been undertaken to understand the seismogenesis of this earthquake. Studies on the Indo-Burmese convergence zone in NE India tried to address whether the eastward Subduction of the Indian plate is active or not?

Chamoli earthquake

The Chamoli earthquake (M 6.6) of 29 March, 1999 in the Garhwal Himalaya has been studied extensively and a thrust fault along the detachment surface below the

MCT, at a depth of about 15 km has been inferred. One of the source models proposed for this event indicates the earthquake nucleated at the intersection of a transverse fault with westward rupture propagation along the detachment surface whilst another study shows the earthquake had a southward propagation based on the isoseismal mapping.

Mathematical modeling of Himalayan earthquakes

The coeval development of the South Tibetan Detachment (a regional-scale normal fault in Tibet) and the Main Central Thrust together with the observed dominance of thrusting in the Himalayas is modeled using stress simulation analysis. 2D non-linear elastic and homogeneous wedge models, representing cross-sections of the Himalayas and Tibet are used. Simulated stresses for a set of boundary conditions in which the stress magnitudes are sufficient to cause failure along the wedge base (lower boundary) and reverse faulting at its toe (up dip end of the base), invariably lead to the simultaneous development of intra-wedge normal faults. Further, a decrease in shear strength of the wedge base relative to its interior favors the development of normal faults and/or reduction in the magnitude of thrusting stresses within the wedge. These results suggest that the presence of a relatively strong Main Himalayan Thrust, the plate boundary fault below the Himalayas, would have favored the occurrence of thrusting in the wedge. Moreover, a weak Main Himalayan Thrust below Tibet along with initiation of the Main Central Thrust can explain coeval development of the South Tibetan Detachment. Thus, a relatively strong Main Himalayan Thrust below the Himalayas would have favored the occurrence of thrusting whilst a weak Main Himalayan Thrust below South Tibet along with the initiation of the Main Central Thrust would have been responsible for the coeval development of the South Tibetan Detachment.

A new measure of seismic activity in a region is defined, which is based on the concept of integrated fault surface area of earthquakes in the region. Using this concept, we analyze the Harvard CMT data of the Himalaya-Tibet-Burma seismic belt to estimate the relative proportions of seismic activity corresponding to reverse, strike-slip and normal faulting in the region. Further, strain rates are computed through summation of moment tensor elements of earthquakes. The study indicates that the deformation patterns of the Himalaya and the adjoining Tibetan plateau regions are distinct. For instance, the seismic activity of the reverse fault category changes from 93 % in the Himalaya to a mere 2 % in Tibet, which is dominated instead, by strike-slip faulting (59 %). Strain rate computation indicates predominant crustal thickening in the Himalaya with a clear transition to crustal thinning in the Tibetan plateau region, just across the Indus-Tsangpo suture zone where EW extension is the predominant mechanism. A model of a thinning seismic upper crust in the EW direction decoupled from a thickening aseismic lower crust, both in equilibrium, in the Tibetan plateau, is proposed. In the Burmese arc region, crustal thickening is indicated, but coupled with NS compression. The observed seismic activity is predominantly of the strike-slip type (56 %), uncharacteristic of subduction zones, which generally display up to 75 % of seismic activity of the reverse fault category. This has implications for Indian plate motion along the Burmese arc, rather than in the direction of the subducted slab.

Indo-Burmese convergence zone and Andaman Arc Analysis of all available seismicity/CMT data from the Indo-Burmese convergence zone and Andaman Arc reveal interesting results. The Burma-Andaman arc region is the eastern margin of the Indian plate, where an oblique subduction of the Indian plate under the Burmese plate, is believed to be taking place.

A detailed study of the Centroid Moment Tensor (CMT) solutions in the Burma-Andaman arc region indicates a distinct segregation of strike-slip and reverse fault types of earthquakes in the upper and lower parts of the eastward subducted slab, and P axis orientations nearly along the arc, rather than across it. It is inferred that the Indian plate, along with its eastward subducted Indian slab is shearing past the Burmese plate in the NNE direction. Based on the predominantly down-dip oriented T axis directions an active subduction in the region has been suggested. However, a comparative study of major subduction zones in the world brings out the uniqueness of the Burmese arc region and provides evidence for cessation of subduction at present. Nevertheless, subduction in this region remains a puzzle and the debate is far from settled.

Crust and Mantle Structure of the Indian Plate. The origin and growth of the Archean crust has been a subject of intense investigation leading to inferences that a fundamental difference existed in the evolution of early and mid-Archean crust than the late Archean crust. Numerous studies have been carried out in the last four years with broad band experiments initiated in the South Indian Peninsular shield which is comprised of Archean Dharwar Craton, South Indian granulite terrain which is Archean in age, Proterozoic Cuddapah basin, Godavari graben which has Proterozoic ancestry and Cretaceous-Tertiary Deccan Volcanic Province located in South India. Using broadband data from 32 seismic stations, which were, located on the Archean and Proterozoic terrains of south India the crustal thickness and Poisson's ratio from receiver function analysis has been determined. The crustal thickness in the late Archean Dharwar craton varies from 34-39 km where an earlier study using broad band data from 10 Permanent stations in Indian Peninsular shield have obtained the similar crustal thickness through receiver function approach. However, the most significant result is the presence of anomalous present day crustal thickness of 42-51 between beneath the mid Archean segment of Western Dharwar Craton. Also, the crustal thickness beneath the southern granulite terrain varies between 42-60 km. The Poisson's ratio ranges between 0.24-0.28 beneath the Precambrian terrains indicating the presence of intermediate rock type in the lower most crust. The variation in crustal thickness between Archean and Proterozoic terrains has been explained in terms of their contrasting evolutionary mechanism of the continental crust during Archean and Proterozoic times.

Local earthquake tomographic studies of Shillong Plateau and Assam Valley in north east India has revealed strong lateral velocity variations in P and S wave velocities with the major seismically active faults being associated with low velocity Zones.

Using the receiver function approach the mantle discontinuities in the Indian Peninsular shield have been mapped. The presence of a seismic discontinuity in the subcrustal lithosphere at 90 km depth has been observed. The SV response of the deep upper mantle indicates a prominent signal corresponding to the 410-km discontinuity, which appears at a delay time of 43.6 s and can clearly be traced over the whole slowness range. In contrast, the P660s at 67.8 s appears less clear, probably due to the interference with signals other than PDs conversions. The delay times of P410s and P660s are close to the global averages, corresponding to conversion depths of 406 and 659 km, respectively. No evidence is found for a discontinuity around 520 km depth.

A correlation of mantle transition zone (MTZ) thickness (temperature) and distribution of major continents and oceans was claimed and disputed as well, in few seismological reports. Most of the studies carried out in this direction mainly use the SS precursor or Ps conversion data. However, both on local and global scale, significant disagreements based on these two observations do exist in regard to the MTZ thickness distribution over continents and oceans and the anti-correlated behavior of the 410 and 660-km discontinuities. Broadband Ps conversion data from oceanic hotspot regions and numerous continental stations (stable and tectonically active areas like subduction zones) were compared with SS precursor results. The MTZ thickness varies in a tight bound between 220 and 280km in both the data sets with the ocean and old continents as the lower and higher end members that deviate from a global average of 250km. Though the expected negative correlation between MTZ thickness and the apparent 410-km depth becomes obvious in both the data sets, the slope of this correlation is significantly different for Ps conversion data in contrast to the similar slope from SS data. As the apparent depth of 410-km depends strongly on the upper mantle velocity structure and in light of similar image of the MTZ by these two techniques, the observed discrepancy mainly arises due to the significantly different view of the average upper mantle velocity by Ps conversions and SS precursors as a consequence of their different ray paths and Fresnel zones.

Seismic Hazard

The scientists have addressed the issue of seismic hazard in India as early as 1953 when a three-zone (Severe, Moderate, Minor hazard) Seismic Zoning map of India was brought out. This map was based on a broad concept of earthquake distribution and geotectonics. The severe hazard zones are roughly confined to plate boundary region i.e. the Himalayan Frontal Arc in the north, the Chaman fault region in the northwest and the Indo-Burma border region in the northeast. The minor hazard zone is confined to Indian shield region in the south and the moderate hazard zone confined to the transitional zone in between the two. Since then, many versions of the seismic zoning map of India have been brought out. A new seismic hazard map for the Indian plate region was prepared under the Global Seismic Hazard Assessment Program (GSHAP), as a part of the International Lithospheric program (ILP).

For the Indian region, 86 potential seismic source zones were delineated based on the major tectonic features and seismicity trends. The Peak Ground Accelerations (PGA) were computed for 10% probability of exceedance in 50 years, at locations defined by a grid of 0.5o X 0.5o in the region 0oN-40oN and 65oE -100oE. A majority of the Indian plate boundary regions and the Tibetan plateau region have hazard levels of the order of 0.25g with prominent highs of the order of 0.35-0.4g in the seismically active zones like the Burmese arc, Northeastern India and North-west Himalaya / Hindukush region. In the Indian Shield region, the regional seismic hazard covering a major area is of the order of 0.1g whereas some locales like Koyna depict hazard to the level of 0.20g. The Bhuj region, which is the site of the recent deadliest intraplate earthquake, indicates PGA values of the order of 0.20-0.25g.

Landslide Hazard Zonation (LHZ) is carried out to rank different parts of a region according to its potential hazard from landslides and requires different causative factors to be analyzed simultaneously. The Landslide Hazard Zonation maps are used to identify and delineate hazard prone areas, so that environmental regeneration schemes can be initiated adopting suitable mitigation measures. If such multi-purpose terrain evaluation maps are used as basis of preliminary planning and development schemes, it will help in selecting geo-environmentally sound sites that may pose minimum hazard of instability.

Catalog for Himalaya and Northeast India
Global and regional catalogs for the historical, early instrumental and modern instrumental periods has been compiled and assessed for the completeness of reporting and accuracy in estimation of magnitudes. A relationship between surface wave magnitude (Ms) and Scalar Moment (M) has been established for northeast region. Moment estimates from the available Centroid Moment Tensor solutions for the period 1977-1996 and the moments estimated from spectral amplitudes of long-period (90-110s) Love and Rayleigh waves have been used to derive this relationship for magnitude range 4.5<=Ms<=8.6. Such a log Mo vs. Ms relation could be an important link for relating the modern instrumental period catalogs and the early instrumental catalog. This relationship was used to convert the early instrumental period (1900-1964) earthquake magnitudes to moment magnitudes. This conversion is an essential

step towards establishing a uniform magnitude scale for the entire period of the catalog (about 1900-present).

Paleoseismology

In Paleoseismology the work primarily focused on understanding the earthquake processes in the Indian SCR (Stable Continental Region) and along the Himalayan collision zone. The efforts were directed in understanding the seismotectonic environment in the SCR and interplate regions, in understanding the nature of deformation, evaluation of past seismicity using historic and paleoseismologic data and to develop earthquake chronology based on dates of past movements. All these provide useful inputs for regional seismic hazard evaluation.

Study of the 1819 Rann of Kachchh earthquake revealed a 4.3 m of coseismic uplift occurred during the 1819 earthquake whilst 1m of uplift was created by the past earthquakes. This was inferred using digital theodilite studies. Trenching excavations led to identification of one past earthquake, which was dated to have occurred about 800-1000 years ago. Studies in Killari, Jabalpur and other locations in the peninsular India conclude that the reactivation interval on specific faults in these regions could be of the order of several thousands of years as the dates for some faults indicate that they have not moved during the last 400 thousand years. Based on the detailed studies on seismites like old thrust sheets, fault gouge and obsequent fault scarps in addition to the archaeological artifacts in Latur lead to the identification of a paleosiesmic event of 2200(200 year BP, which is supposed to have affected the area.

The paleoseismological studies in the Shillong Plateau area, which was affected maximum by the Great Assam Earthquake of 1897 have brought out some interesting results. By documenting many liquefaction/deformation features such as sand dykes, slump structures, sand blows etc and 14C dating of the organic samples collected from these features located around the Chedrang Fault and Krishnai/Dudhnai river sections of the Assam -Meghalaya border region located in the North West portion of the Shillong Plateau, three paleoseismic events prior to 1897 have occurred.

Paleoseismic studies carried out in the meizoseismal area of the great 1934 earthquake which affected the Bihar-Nepal region have resulted in finding of approximately half a dozen liquefaction/deformation features despite unfavourable conditions like flash floods prevailing in North Bihar for preservation of such features. Based on geological evidence for at least two paleoseismic events to occur (i) between 1700-5300 yrs BP and (ii) 25000 yr BP in addition to the well-documented great events of 1833 and 1934 in this region have been inferred.

Heat Flow Studies

Thirty new heat flow values determined in the Southern Granulite Province (SGP) and heat production estimated from radio-elemental measurements at more than 1000 sites in the Dharwar greenstone-granite-gneiss province (DP) and the SGP, together with the existing data, bring out contrasting crustal and sub-crustal thermal characteristics between the two Precambrian provinces in south India. A new approach to heat flow studies has been adopted by undertaking drilling of boreholes in areas best suited for heat flow determination. The DP has a heat flow range, 25 to 50 mW m-2, with a mean of 36±8 (s.d.) mW m-2. The western part of the province has marginally lower heat flow than the eastern part, consistent with the lower levels of heat production of the major crustal litho-units. The heat production of the gneisses constituting the basement to the supracrustal rocks west of Closepet Granite range from 0.5 to 1.8 μW m-3. In the eastern part, heat production of the gneisses ranges from 1.6 to 2.9 μW m-3 and that of the granitoids from 1.6 to 4.5 μW m-3. The data confirm that heat production values can be highly variable both laterally and vertically, even within a single craton and does not necessarily follow any unique model of heat production distribution with depth, as has been often assumed in thermal modeling of the continental crust.

A two-layer granulite crust of Late Achaean charnockites and gneisses characterizes the northern block (NB) of the SGP. Overall, the range of heat flow values in the SGP is similar to that in the adjacent Achaean Dharwar greenstone-granite-gneiss province (DP) in south India. Mantle heat flow in the NB, deduced in the light of heat production and heat flow data, ranges from 23 to 32 mW m-2, which values are distinctly higher than 11 to 16 mW m-2 for the DP. The higher mantle heat flow in the NB of the SGP appears to be a consequence of higher heat production in the subjacent mantle. The temperatures estimates at the Moho range from 285o to 410o C for the DP, and 580o to 660o C for the two scenarios in the northern block of the SGP.

Climate change in India inferred from geothermal observations for the first time in India, borehole temperature records have been analyzed for deciphering surface ground temperature (SGT) changes that have taken place during the past few centuries. The data set fills the gap for the under-represented low latitude regions ~12-28o N in geothermal climate-change studies.

Seventy temperature-depth profiles covering five major climatic provinces of the country have been analysed. The climatic provinces studied are: (1) North-west, (2) North-central, (3) North-east, (4) Interior peninsula and (5) East coast. The analysis revealed an average ground warming in India of 0.9o±0.1o C over the last 150 years, an outcome consistent with changes in surface air temperature (SAT) gleaned from data of 48 meteorological stations in the vicinity of the borehole sites. Individual climatic provinces however show large variations. A combined analysis of borehole temperatures and meteorological SAT records yielded a long-term pre-observational mean (POM) for the SAT, 0.8o±0.1o C lower than the 1961-1990 mean. When the most recent decade is included directly in the analysis, the average total warming in India from the early 1800s to the late 1990s is about 1.2o C. These observations constitute a clear pointer that the warming trends observed in the SAT records do represent significant increases from the pre-instrumental (19th century) conditions.

GPS derived velocity and deformation in the Indian subcontinent GPS measurements were carried out at 90 sites in the Indian subcontinent. Leh, Hanle, Almora, Bangalore, Hyderabad and Kodaikanal are permanent stations, which run 24hrs a day and 365 days a year. Delhi, Jamanagar, Bhopal and Shillong are reference stations where more than 10days GPS measurements are available every year. Rest of the sites are campaign style sites with 3 days of measurement every year. The velocities of South India are not significantly different from the Indian plate velocity of 58±4mm/yr Motion of GPS sites in South India in the Indian reference frame as well as relative to IISc station are not significant considering the error bars. This implies that South India moves as a rigid plate with velocity approximately equal to Indian plate velocity. No significant observations can be made from the motion of GPS sites in Gujarat as the two epochs of measurement were made soon after Bhuj 2001 earthquake so the velocity vectors are more indicative of post seismic deformation due to Bhuj earthquake. Motion of sites in Ladakh show that the ITRF velocities of Ladakh are 10mm less than the motion of Gharwal sites and the direction of motion is more towards the East. Motion of the sites in the Indian reference frame and relative to IISc give the convergence between the Indian subcontinent and Ladakh at 14 to 20mm/yr. Convergence rates in Gharwal-Kumaon Himalayas are 10 - 18 mm/yr. ITRF velocities in the Gharwal Kumaon Himalayas are slightly higher when compared to Ladakh and the motion is more towards North. Motion of Sikkim sites is significantly different from that of Ladakh, Gharwal Himalayas. Convergence rate in the Sikkim region is 10-12mm/y. Velocity of Shillong in N.E India is 54±6 mm/yr. Significant conclusions that arise from GPS studies are Southern peninsula and Delhi moves as a rigid plate with the velocity approximately equal to Indian plate velocity.

All the convergence occurs in the 2500 km stretch of the Himalayan arc from Kashmir to Arunachal and the convergence rates vary significantly from west to east. This study also brings out the Himalayan arc can be divided in to 10 regions with lengths roughly corresponding to those of great Himalayan ruptures (~220km).

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VOLCANOLOGY AND EARTH'S INTERIOR

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Introduction

New data, evidence and thoughts on magmatic aspects of the Indian lithosphere culled from literature 1998-2002 are presented. Reference to a few earlier publications was inadvertent. Few references could not be reached out, but are added in the reference list.

Himalayan region

Episodic mafic and acid volcanism during late Archaean, Paleoproterozoic, Neoproterozoic and early Paleozoic are reported from different parts of the Higher Himalayan (HH) and Lesser Himalayan (LH) region (Ahmed et al., 1999; Bhat et al., 1998; Miller et al., 2000; Singh et al., 2002). The oldest intrusives (2.51± 0.8 Ga, Sm-Nb whole rock) of the Garhwal/Bhowali mafic volcanics in the Kumaun LH and Rampur - Mandi volcanics in Larji-Kullu-Rampur window show distinct low-Ti tholeiite trend with negative anomaly in Nb, Sr, Pb, Ti and high positive ε_{Nd} (+5) (Bhat et al., 1998). The trace element variations especially in ε_{Nd} is attributed to early depletion and re-enrichment of LREE in the mantle source. These volcanisms are deemed chemically equivalent to the basal 2.5 Ga Aravalli volcanics and arguably fed by a single mantle plume (Bhat et al., 1998). $^{207}Pb/^{206}Pb$ ages (Miller et al. 2000, 2002) of zircon grains using single grain evaporation technique yield considerably lower ages (1800±13 Ma) for the Rampur metabasalts (quartz tholeiite). However, the trace and rare earth element distribution is in unison with the observation of Bhat et al (1998) and thought to be derived by moderately high degree of partial melting in shallow mantle. Ti/V ratio in the range of 20-50 closely resembles continental flood basalt chemistry with the incorporation of the crustal component either by crustal contamination or by recycling of the older crust (Miller et al., 2000). Paleoproterozoic (1800 –2000 Ma using whole rock Rb-Sr data with initial $^{86}Sr/^{87}Sr$, 0.7022±0.008) mafic volcanics in the HH and LH Garhwal and Himachal region (Ahmed et al., 1999) despite their temporal equivalence show distinctly different trace element compositions in these two units. While the LH volcanics show enrichment in LILE and LREE and negative anomalies in Nb, Pb and Ti, the HH volcanics are less enriched and lack any negative anomalies but shows distinct positive anomaly in Sr. The authors suggested involvement of an enriched mantle with subsequent assimilation for the genesis of the LH volcanics. The HH volcanics, on the contrary, are considered to originate from asthenospheric mantle with minimal crustal assimilation.

In the Ladakh plutonic complex (Ahmed et al., 1998) andesitic-basaltic enclaves, enclosing metamorphosed mafic volcanics (amphibolites) and meta-aluminous to slightly per-aluminous acidic volcanism of dominantly granodiorite – quartz monzonite – granite affinity are considered to represent different stages of arc-maturation related to the subduction and final closing of the Neo-Tethyan ocean. While the enclaves and the mafic volcanics show distinct low-Ti tholeiite trend, the acid volcanics characterize a calc-alkaline trend with enrichment of LILE-LREE and depletion of HFSE. Per-aluminous Chor granitoid (quartz monzonite with high Rb: 200-260 ppm, Th: 30-50 ppm and U: ~10 ppm) in the lesser Himalaya (Singh et al., 2002) is dated to be Neoproterozoic (825±5 Ma, Pb-Pb ages in zircon). The rocks showing distinct enrichment in LREE and negative Eu anomaly are thought to be a product of anatexis of older Proterozoic crustal rocks.

Granites of younger ages (Dhaoladhar granite whole rock 511.4 ± 9.8 Ma, Vijan et al., 2002), and Kaplas granite (553 ± 2 Ma

(2□) using single zircon U–Pb date, Miller et al., 2001) represent temporally equivalent granitoids in the Himalaya are correlated with Pan African orogeny related magmatism. Trace element distribution in these granites indicates derivation from crustal source. Per-aluminous S-type leucogranites of Cenozoic age, derived primarily from crustal anatexis (Singh et al., 2002) are ubiquitous in the Higher Himalayan zone and are related to the Himalayan orogeny.

Andaman Ophiolite

The geochemical character of plagiogranites from the Andaman Ophiolite Suite is consistent with its derivation from an oceanic crust (Shastry et. al. 2002). All elements when plotted on the primordial mantle normalized multi-element spidergrams show enriched patterns. The Fe-Ti enriched mafic rocks associated with oceanic plagiogranites are deemed to have formed by late stage liquid immiscibility.

The Deccan Province

Deccan flood basalt province (DFBP) spread over 500,000 Km^2 excluding sub-aqueous portion below the Arabian Sea represents fissure-type eruptive that appeared during the well-known K-T transition period and followed into the Tertiary. The Deccan Flood Basalt Province (DFBP) overlies three major rifts initiated at different time in Mesozoic as marginal-marine basins, e.g. the Narmada-Tapi-Son Rift, the Cambay Rift and the West Coast Rift that converge at the Cambay triple junction (Chandrasekharam, 1985; Sheth and Chandrasekharam, 1997). The northerly drift of the Indian subcontinent at the Late Cretaceous passed over the Reunion hot spot causing activation of the plume and rifting (Morgan, 1981). Basu et. al. (1993) suggest the Reunion hot spot incubated below the Indian subcontinent for at least ~ 3 Ma prior to the main tholeiitic eruption. Alkaline rocks free from any crustal contamination show a depleted HREE and enriched LREE pattern (Mundwara Complex; Basu et. al. 1993, 1995). A ~14 times higher $^3He/ ^4He$ compared to atmosphere measured in pyroxenes comply well with ocean island basalts (OIB) and a diagnostic of deep mantle source with relict pristine mantle-reservoir characteristics.

Sheth and Chandrasekharam (1997) raise several important arguments on the relationship of rifting and volcanism, keeping plume activity as the central theme. They suggest 'pre volcanism extension' evident from several uncontaminated alkaline complexes reported from the northern end of the Cambay Rift and presumably emplaced along 'translithospheric pathways'. Controversy persists over the mode of plume generation and its upward progress. In the plume impact model it takes a very short time for the residence of the plume-head below the lithosphere prior to ascent, and eventually the degree of melting is low. But emplacement of early contamination free alkaline rocks followed by the tholeiitic suite suggests considerable time lapse during which incubation of the voluminous plume took place. This probably suggests that the plume impact model is not a realistic model. Instead, the plume incubation is possibly the model of choice. It invokes several millions of years of plume residence below the lithosphere, thinning it slowly and hence generating an initial low degree of alkaline melt, depleted in HREE at greater depth.

Intrabasaltic variants found within the DFBP are late fractionates of the tholeiitic eruptives, and show evidence for metasomatic and related alterations. Sethna et. al. (1999) report spotted spilitic basalts from Daman. These rocks are characterized by the typical pillow structure and their spotted appearance is due to the presence of basaltic remnants incorporated by matrix of spilitic rocks. A sub-aqueous type of eruption accompanied by metasomatic alteration is suggested for their occurrence. Major element analysis of some of the variants of this kind shows high TiO_2 content (1.93-3.92 %) as similar to oceanic basalts. Chondrite normalized LREE patterns show elevated peaks for basalts relative to spilites, where as MORB normalized HFSE distribution shows marked depletion trend in spilites than basalts (Sethna et. al., 1999). Some of the late fractionates have formed ignimbrites after collapse of the vents as in the north of Mumbai (Sharma et. al. 1998). These are probably indicative of the waning phases of eruption. Yet, another interesting phenomenon is the occurrence of ferro-enstatite orthopyroxene in basaltic dikes reported from Narmada-Tapi rift zone by Chandrasekharam et. al. (2000). These basaltic dikes contain clusters of quenched, prismatic ferro-enstatite crystals hitherto unreported from any other flood basalt province in the world. The An enrichment trend in plagioclase phenocrysts An_{60-61} (+ orthopyroxene) relative to the groundmass (An_{43-46}) suggests their late stage development from a contaminated melt that became enriched in excess silica, Al_2O_3 and CaO as a result of early fractionation. Since a dry magma is unable to produce orthopyroxene due to thermodynamic restrictions, a semi-aqueous magma (containing not enough H_2O that can produce amphibole) probably took part in the later reaction to produce orthopyroxene. This, however, strongly suggests a shaly crustal contaminant for the resulting assemblages (Chandrasekharam et. al., 2000).

Aravalli Fold Belt

The late Proterozoic Malani bimodal volcanics (745±10 Ma; Bhushan, 1999) constitute the largest suite of anorogenic acid volcanics in India succeeding the granitic activity of Abu pluton. Volcanics of the first stage are basalts with minor andesite/trachybasalts. This was followed by hypersolvus and subsolvus granite intrusion that ceased with ash flow deposits. The initial basaltic magma was possibly generated at deeper depth by hot spot activity (Bhushan and Chittora, 1999). Krishnakanta and Vallinayagam (2002) suggest based on LREE and HREE enrichment with large negative Eu anomaly and ancillary geochemical data a crustal origin for the felsic suite. The volcanism following cratonization of the Aravalli-Delhi mobile belt is ascribed to geothermal elevation and spasmodic mafic emplacement in an extensional regime. Significantly, the pre-Malani basement represented by biotite-trondhjemite and hornblende-granodiorite (Pandit et.al. 1999) is presumably of Archaean age. A deep-seated origin for hornblende granite is suggested by the presence of magmatic epidote, and its incomplete dissolution suggests rapid uplift (cf. Zen and Hammerstrom, 1984). Barker (1979) contends that the biotite trondhjemite suite is derived from deep-seated low-K tholeiite.

Continental tholeiites similar to the Mesozoic continental flood basalt (CFB) have been reported from Bayana basin in the northeastern part of this region. (Ahmad and Rajamani, 1991; Ahmad and Tarney, 1993; Raza and Khan, 1993; Abu-Ramatteh et.al,. 1994). Relationship between incompatible element concentrations including REEs suggests subcontinental lithospheric source(s) for the tholeiites. The source region was enriched following mantle metasomatization by fluids and/or melt phase enrichment (Raza et.al., 2001). Interestingly, lamprophyres intruding meta-volcanic rocks of Ajabgarh Group of Delhi Supergroup are argued to originate from a less metasomatized mantle, the geochemical signatures being more consistent with crustal contamination during ascent and/or emplacement of melts parental to the suite (Kirmani and Fareeduddin, 2000).

Central India

Geochemical data on volcanic rocks from different parts of Central India provide an outline for mantle evolution through time. Metamorphosed pillow basalts of late Archean-early Proterozoic age from Bijawar Group of rocks document flat REE pattern with weakly positive Eu anomaly (Pati and Raju, 2001). The available data indicate a slightly enriched asthenospheric mantle with moderate Th/Ta, low La/Ta and relatively high Sr/Ce ratio as source of the metabasalts generated in an extensional tectonic setting (Pati and Raju, 2001). A homogeneous melt, derived from a single source, was possibly erupted in a shallow sea due to decompression melting in a zone of extension marginal to the Bundelkhand

Granitoid Complex. The mafic dyke swarms in the Archean to Palaeoproterozoic Bundelkhand massif basement shows much lower Nb/La ratios compared to the primitive mantle (Mondal and Ahmad, 2001). The geochemical data suggest the basement to represent a subduction related juvenile crust that experienced lithospheric extension and rifting in response to mantle plume activities.

Western Dharwar Craton

The Sandur schist belt, a part of the western Dharwar craton, and correlatable with the Chitradurga schist belt (2.7 Ga; SHRIMP U-PB data after Nutman et al 1996) is a classic greenstone belt (Manikyamba and Naqvi, 1998; Naqvi et al. 2002). The metabasic rocks comprise thloeiitic and high-Mg basalts and komatiitic ultramafics. The metavolcanics are characterized by MgO between 6-30 wt%, Al_2O_3/TiO_2 ~ 10-21 (11-23 for komatiites) and CaO/ Al_2O_3 ~1 (0.5-2 in komatiites). REEs spectra (2-12 times chondrite) are flat with small +ve/-ve Eu anomalies; ε_{Nd} (+ 0.8649±).00024) resemble CHURT. Ti/V, Ti/Zr, Zr/Y, Sc/Y, Nb/La, Nb/Th, Nb/U, MgO-TiO_2, MgO/FeO and Al_2O_3/TiO_2 ratios are also near chondritic. Based on the exhaustive data set, Naqvi et al (2002) suggests a mantle plume derived from an enriched mantle was causal to the origin of the oceanic volcanic sequence of Sultanpura block. The compositional heterogeneity especially in HFSE and REE signatures is attributed to dynamic plume melting during ascent. According to the authors, "entrenchment, mixing of AORB, crustal contamination and subduction of such a plume-fed slab may have generated the compositional heterogeneities observed in the Sultanpura block".

Eastern Dharwar Craton

There have been several attempts to characterize Archaean-Proterozoic volcanism in the Dharwar craton. Significant among these is the high Mg granitoid (Qtz-monzodiorite) xenoliths reported from within the Archaean granodiorite and granite of eastern Dharwar craton. The rocks are characterized by high mg# (44-57), show Ba and Cr enrichment, and moderately sloping chondrite-normalized REE patterns (LREE enrichment and HREE depletion). Sarvothaman (2001) interprets the rocks to have been derived from a LREE depleted and high Mg- source such as a mantle peridotite. The author argues that this finding and its interpretation establish the involvement of mantle magmatism in the formation of pre-Archaean crust of the Dharwar craton.

Giriritharan and Rajamani (1998) present data on amphibolite facies mafic volcanics from the Hutti-Maski schist belt. The rocks are Fe-rich tholeiites with flat to LREE enriched rare earth patterns. Trace element modeling indicates that the tholeiitic protoliths were formed from mantle sources variably enriched by partial melts at pressures > 25 kbar.

The intracratonic Cuddapah Province in the East Dharwar craton is a host to profuse mid-Proterozoic kimberlite pipes and lamprophyre dykes along its eastern and western margins. The lamprophyres are potassic in nature, nepheline and/or leucite normative, characterized by highly fractionated chondrite normalized REE patterns, with initial $^{87}sr/^{86}Sr$ varying between 0.703-0.705. (Madhavan et al.1998). The authors contend that the geochemical signature of the ultra-potassic magmas is consistent with derivation from a mantle source or a source near the crust-mantle boundary. But on a cautionary note the authors state "As a deviation, Ravipadu lamprophyre fails to record substantial degree of mantle enrichment whereas the Kellampalle lamprophyre magma lying to the west of Ravipadu, appears to have differentiated from a mantle derived magma by olivine fractionation". Madhavan et al (1999) reports the occurrence and geochemistry of mid-Proterozoic alkaline and non-alkaline inrtusives in and around the Cuddapah basin. Based on major and trace element (enriched in Sr, Ba, Nb, Zr) variations and highly fractionated enriched rare earth element spectra (La_{cn} ~ 100; Lu_{cn} ~ 10), the authors suggest the intrusives underscore the importance of mid-

Proterozoic intraplate alkaline magmatism in Eastern Dharwar.

The Uppalapadu alkaline plutonic complex (1348 ± 41 Ma) to the east of the Cuddapah Basin along the western margin of the Eastern Ghats Mobile Belt comprises tholeiitic gabbro and ferrosyenite representing a subalkaline series. The tholeiitic and calc alkaline suites formed prior to emplacement of the alkaline complexes (Ratnakar and Sharma 1994, Vijayakumar and Ratnakar 1995a). At Uppalapadu, it is inferred that a higher degree of partial melting of mantle has produced the subalkaline (tholeiitic) basaltic liquids, whereas a lower degree of melting of enriched garnet-lherzolite mantle and segregation at relatively deeper levels formed the alkaline basaltic liquids (Krishna Reddy et al. 1998).

The Ravipadu Gabbro Pluton is an intrusive within Precambrian crust (composed of amphibolite and granulite) in the Prakasam igneous province. It is sandwiched between the Eastern Ghats Mobile Belt and the Cuddapah basin. The texture of the Ravipadu gabbro indicates its formation by crystal-liquid fractionation of subalkaline tholeiitic magma under anhydrous conditions. Petrogenetic model designed in support of its formation suggests that the parental liquid is derived by low degrees of melting of late Archaean underplated komatiite/basaltic komatiite crust; crustal melting being induced by a mantle plume (Vijayakumar and Ratnakar, 2001). 23 km North of Anantapur is an east-west trending body, the Ramdaspeta Gabbro-Anorthosite, intrusive into tonalite-granodiorite-adamellite suite of Peninsular gneiss of east Dharwar craton. It is a composite layered body comprising melanocratic cumulus gabbro, porphyritic gabbro and anorthositic gabbro. Differentiation of tholeiitic magma, as suggested by Ashwal (1993), may be responsible for the evolution and emplacement of Ramdaspeta intrusive into a thickened crust (Suresh et al. 1998).

The mid Proterozoic metabasic rocks from the Khammam schist belt separating the Dharwar craton from the Eastern Ghats Mobile Belt are tholeiites, cluster in the ferrobasalt field of Jensen (1976), and are depleted in incompatible elements, especially HFSEs relative to MORB. Chondrite-normalized REE patterns are disc shaped (characteristic of boninite) or are weakly fractionated La_N/Yb_N ~ 1.66. Overall, the Khammam metabasites indicate bonninitic rather than a komatiitic affinity, and formed by process similar to those producing present day bonninites from depleted upper mantle source in a supra-subduction region (Bose and Moulick, 1999). In sharp contrast to the inference of Bose and Moulick's (1999), Hari Prasad et al (2000) based on immobile element (Zr – Y – Ti) signatures advocate an ocean island arc or continental margin island arc settings for the Khammam metabasites.

Chatterjee and Bhattacharji (1998, 2001) present new data and provide a detailed account of the petrology, geochemistry and geochronology of mafic dykes and sills within and along the margins of the Cuddapah Basin. According to the authors, the igneous activity around the basin was intermittent beginning at 2400Ma, peaked at around 1200-1400 Ma and continued till 800 Ma after sedimentation ceased. The Cuddapah basin dykes and sills are mostly tholeiites characterized by enrichment of incompatible elements relative to MORB. The authors argue that the tholeiites were formed via fractional crystallization (5 kbar, 1000-1100°C) of locally heterogeneous mantle derived melts reflected by variations in Ba/Rb, Ti/Zr, Ti/Y Zr/Nb and Y/Nb ratios.

South Indian Craton

In the high-grade granulite region in South India, Proterozoic mafic dyke swarms show LILE and LREE enrichment, and Nb, Ta depletion (Radhakrishna and Mathew, 1998). Dolerite dykes in the Tiruvannamalai and Dharmapuri area is explained by crustal contamination and derivation from an enriched lithospheric mantle, developed much earlier than dyke intrusions during a major crust building event in Archaean (Radhakrishna and Mathew, 1998). Dehydration melting induced by decompression and lithospheric attenuation or impingement of partial melts from plume heads at the base of the lithosphere is cited to be the cause for dyke emplacement.

Geochemical data from Proterozoic alkaline carbonatite complex of Samalpatti in Tamil Nadu suggest their origin by liquid immiscibility from carbonated nephelinitic magma generated from an enriched mantle source (Shrivastava, 1998)

Singhbhum Craton

Minor rhyolite intrusives spatially associated with granophyric granites occur along the eastern and southwestern fringe of the Archaean Singhhum Granite batholith in the eastern Indian Craton. These have intruded Archaean mafic-ultramafic rocks that form the basement over which unconformably overlies the granites of Proterozoic age. It is inferred that the rhyolites were generated by partial melting of Archaean continental crust (Sengupta et al. 1998).

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