



Climate Change Studies Using Space Based Observation

Ranganath R. Navalgund · Raghavendra P. Singh

Received: 25 October 2010 / Accepted: 21 February 2011
© Indian Society of Remote Sensing 2011

Abstract Climate change is associated with earth radiation budget that depends upon incoming solar radiation, surface albedo and radiative forcing by greenhouse gases. Human activities are contributing to climate change by causing changes in Earth's atmosphere (greenhouse gases, aerosols) and biosphere (deforestation, urbanization, irrigation). Long term and precise measurements from calibrated global observation constellation is a vital component in climate system modelling. Space based records of biosphere, cryosphere, hydrosphere and atmosphere over more than three decades are providing important information on climate change. Space observations are an important source of climate variables due to multi scale simultaneous observation (local, regional, and global scales) capability with temporal revisit in tune with requirements of land, ocean and atmospheric processes. Essential climatic variables that can be measured from space include atmosphere (upper air temperature, water vapour, precipitation, clouds, aerosols, GHGs etc.), ocean (sea ice, sea level, SST, salinity, ocean colour etc.) and land (snow, glacier, albedo, biomass, LAI/fAPAR, soil moisture etc.). India's Earth Observation Programme addresses various aspects of land, ocean and atmospheric applications. The present and planned missions such as Resourcesat-1, Oceansat-2, RISAT, Megha-Tropiques, INSAT-3D, SARAL, Resourcesat-2, Geo-HR Imager and series of Environmental satellites (I-STAG) would help in

understanding the issues related to climate changes. The paper reviews observational needs, space observation systems and studies that have been carried out at ISRO (Indian Space Research Organization) towards mapping/ detecting the indicators of climate change, monitoring the agents of climate change and understanding the impact of climate change, in national perspectives. Studies to assess glacier retreat, changes in polar ice cover, timberline change and coral bleaching are being carried out towards monitoring of climate change indicators. Spatial methane inventories from paddy rice, livestock and wetlands have been prepared and seasonal pattern of CO₂, and CO have been analysed. Future challenges in space observations include design and placement of adequate and accurate multi-platform observational systems to monitor all parameters related to various interaction processes and generation of long term calibrated climate data records pertaining to land ocean and atmosphere.

Keywords Earth observation · Climate change · Green house gases · Glacier retreat · Biomass burning · Climate change Indicator

Introduction

Increasing human population and industrialization including unsustainable consumption pattern, particularly by rich industrialized nations are major causes of concern related to climate change. The impact of climate change on food security, water security, sea

R. R. Navalgund (✉) · R. P. Singh
Space Applications Centre, ISRO,
Ahmedabad 380015, India
e-mail: director@sac.isro.gov.in

level rise leading to submergence of coastal areas and increased frequency of extreme events (drought, flood) pose serious threat to India. The capacity to detect and track the course of climate changes and model the effect of these changes is the most important present global environmental challenge. Measurements acquired from the space platforms provide vital information related to long term changes in atmospheric composition, glaciers, sea level rise, hydrology and biospheric activities.

Space based remote sensing data help in mapping earth resources, monitoring their changes and deriving bio-geophysical parameters. All this information helps in identifying the indicators and agents of climate change. The space-based inputs can also be integrated with physical simulation models to predict the impact of climate change. It provides information related to three aspects (i) the indicators of climate change (ii) assessment of agents of climate change, such as greenhouse gases and aerosol, their sources and distribution pattern and (iii) modeling the impact of climate change in various fields and natural resources that would be of help in planning towards adaptation measures and preparedness.

The far-reaching consequences of climate change are inevitable as demonstrated by the simulation models using various projection scenarios. However, accuracy of the projection is still a challenge at the present time. Therefore, attempts are being made towards calibrating and validating these simulation models using remote sensing and ground observed parameters for Indian condition. These studies have been carried out in the fields of agriculture, hydrology, and ocean productivity, impact on coastal zone due to sea level rise, regional climate model and global water cycle. The paper reviews the research conducted mainly at Space Applications Centre, ISRO, Ahmedabad in mapping the indicators of climate change such as glacial retreat in Himalaya, change in polar ice cover, vegetation in alpine zone and bleaching of coral reefs. It also reports the current status on assessment of methane emission and variability of other trace gases (CO₂, CO, NO₂ etc.) over India carried out using satellite data. The experience and knowledge gained from these studies would be useful in specifying the trend in climate change impacts and suggesting corresponding adaptation measures.

Observational Needs

The broad observational needs to address the issues of climate change cover parameters related to atmospheric compositions; ocean surface topography; precipitation; and land-surface observations. In the area of measurements to monitoring atmospheric composition encompass CO₂, water vapour, ozone, aerosols etc. On ocean topography, monitoring sea level rise, as well as providing ocean temperature and chemistry trends is necessary. In the area of precipitation, tracking the seasonal progression of rainfall and attempting to better understand development, movement and impact of severe storms, as well as improving the understanding of water cycles is an important area of concern. Terrestrial monitoring systems are required to observe changes in croplands, coastlines, deserts and forests, and to track short-term threats to climate change, such as wildfires, floods and volcanic activity. Present and planned global satellite missions play an important role in providing synoptic atmospheric, terrestrial and oceanic environmental data from space to address these observational requirements. These data promotes multidisciplinary research in the Polar Regions and can be instrumental in furthering our understanding of the Earth as a System. The important area of climate variables which is being measured using space platform are as follows,

- Radiation, clouds, water vapor, precipitation, and atmospheric circulation;
- Ocean circulation, productivity, and exchange with the atmosphere;
- Troposphere chemistry and greenhouse gases;
- Land ecosystems and hydrology;
- Snow, ice, and glacier extent;
- Ozone and stratospheric chemistry; and
- Volcanoes and climate effects of aerosol.

Earth Observation Systems for Monitoring Climate Variables

The goal of space based global change observation, together with other observations and studies, is to provide a sound scientific basis for developing national and international policy relating to natural

and human induced changes in the Earth system. Some important programmes are described below

Earth System Science Pathfinder (ESSP) Program

The ESSP of NASA addresses unique, specific, highly focused mission requirements in earth science research. The ESSP program is an innovative approach for addressing Global Change Research by providing periodic 'Windows of Opportunity' to accommodate new scientific priorities. ESSP missions are capable of supporting a variety of scientific objectives related to earth science, including the atmosphere, oceans, land surface, polar ice regions and solid earth.

The ESSP mission comprises analysis/retrieval of parameters from the host of satellites viz., Gravity Recovery and Climate Experiment (GRACE), Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), CloudSat, and Aquarius. NASA has developed a strategy for long-term monitoring of some key parameters needed to bring us closer to the answers we need regarding climate change and its relation to social systems. This technology consists of a group of satellites that can make a suite of earth observations referred to as the 'A-Train'. CloudSat and CALIPSO, Aqua, PARASOL, and Aura are important satellites in A-Train formation. The satellites fly in a nearly circular orbit with an equatorial altitude of approximately 705 km.

Living Planet Programme

European Space Agency (ESA) launched Living Planet Programme, which includes the Earth Explorer missions, and the Earth Watch element designed to facilitate the delivery of Earth Observation data for the eventual use in operational services. Earth Watch includes the well-established meteorological missions with the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) and also new missions focusing on the environment and civil security under GMES (Global Monitoring for Environment and Security) a joint initiative between the European Commission and ESA.

As part of the Living Planet Programme, the Earth Explorer missions encompass a new strategy for observing the earth from space where missions are designed to address critical and specific issues that

have been raised by the science community. The family of Earth Explorer missions is a result of this strategy. Currently there are six missions in this category and a further six undergoing assessment study as follows:

- GOCE (Gravity field and steady-state Ocean Circulation Explorer)
- SMOS (Soil Moisture and Ocean Salinity):
- ADM-Aeolus (Atmospheric Dynamics Mission)
- CryoSat-2
- Swarm
- Earth CARE (Earth Clouds Aerosols and Radiation Explorer)

Indian Earth Observation System (EOS)

The Indian EOS has emerged as a strong constellation of geostationary and polar orbiting satellites (Tables 1 and 2) to provide the data for mapping and monitoring of ecosystems, detecting the changes in various temporal and spatial scales and retrieval of land, oceanic and atmospheric parameters for calibrating and validating the circulation models (Navalgund 2006; Navalgund et al. 2007). The current remote sensing satellites consist of theme-specific polar orbiting satellites, with a constellation of satellites in operation (IRS-1 C, IRS-1D, IRS-P3, OCEANSAT-1/2, Technology Experiment Satellite - TES, RESOURCESAT-1, and CARTOSAT-1 & 2/2A/2B). The polar orbiting satellite RESOURCESAT-1 provides multi-spectral data at 5.8 m (LISS-4); 23.5 m (LISS-3); and 56 m (AWiFS) spatial resolution with a few days to a few weeks revisiting capability, thereby offering a better scope for resources management. CARTOSAT-1 provides high-resolution (2.5 m spatial resolution) panchromatic data in the stereo mode, making it possible to generate Digital Terrain Model (DTM) for various applications. The latest remote sensing satellite CARTOSAT-2/2A/2B is designed to provide much higher resolution data (0.8m spatial resolution) for cartographic mapping. Oceansat-1 and Oceansat-2 both carried 8 band Ocean Colour Monitor (OCM). Passive microwave radiometer (MSMR) was flown on Oceansat-1 satellite, which provided important information on polar ice cover. The Ku band Pencil beam Scatterometer and Radio Occultation for Sounder for the Atmosphere (ROSA) are flown in Oceansat-2 mission.

Table 1 Essential Climate Parameters, required parameter accuracies and Satellite sensors with associated instrument accuracies (Adapted from NIST Report (2004))

Parameters	Req. accuracy	Satellite instrument	Accuracy
Solar Irradiance	1.5 W/m ²	Radiometer	1.5 W/m ²
Precipitation	0.125 mm/hr	MW Radiometer/Radar	1.2 K
Cloud Optical Thickness	10%	Vis. Radiometer	5%
Cloud top temperature	1 K/Cloud Emissivity	IR Radiometer	1 K
Atm. Temperature	0.5 K	MW/IR Radiometer	0.5 K
Water Vapour	5%	MW/IR Radiometer	1 K
Ozone (total column)	3%	UV/Vis Spectrometer	2%
Aerosols (AOD)	0.01	Vis Polarimeter/LIDAR	Radiometric 3% Polarimetric 0.5%
Carbon dioxide	10 ppmv	NIR/IR Spectrometer	3% (Ambient CO ₂)
Ocean Colour	5%	Vis Radiometer	5% (Radiance)
Sea Level	1 cm	Altimeter	2.8 cm
SST	5%	IR Radiometer	0.1 K
Albedo	0.01	Vis. Radiometer	5%
LAI	0.5	Vis Radiometer	0.5
Soil Moisture	3% (v/v)	Active/Passive MW	5% (soil moisture)

Table 2 Present and planned Indian earth observation satellites

Satellite	Sensors	Launch Date
Bhaskara-1	TV camera, SAMIR**	7 June, 1979
Bhaskara-2	TV camera, SAMIR**	20 Nov., 1981
IRS-1A	LISS-I, LISS-II	17 Mar., 1988
IRS-1B	LISS-I, LISS-II	29 Aug., 1991
IRS-P2	LISS-II	15 Oct., 1994
IRS-1 C	LISS-III, PAN, WiFS	28 Dec., 1995
IRS-P3	MOS A,B,C, WiFS	21 Mar., 1996
IRS-1D	LISS-III, PAN, WiFS	29 Sep., 1997
INSAT-2E*	CCD, VHRR	03 Apr., 1999
IRS-P4 (Oceansat-1)	OCM, MSMR**	26 May, 1999
Kalpana-1*	VHRR	12 Sept, 2002
INSAT-3A*	CCD, VHRR	10 April, 2003
IRS-P6	LISS-III, LISS-IV, AWiFS	17 Oct., 2003
IRS-P5 (Cartosat-1)	PAN (Fore, Aft)	05 May, 2005
Cartosat-2	PAN	10 Jan. 2007
Cartosat-2A	PAN	28 April, 2008
IMS-1	Hysi, Mx	28 April, 2008
Oceansat-2	Scatterometer***, OCM, ROSA	23 Sept. 2009
Cartosat-2B	PAN	12 July 2010
RISAT	SAR***	Planned
Megha Tropiques	MADRAS**, SAPHIR**, ScaRaB, GPS Occ.	Planned
INSAT-3D*	Imager, Sounder	Planned
SARAL***	Altika. ARGOS	Planned

*INSAT-2E/3A/3D are geo-stationary satellites, others are polar orbiting satellites

**SAMIR, MSMR, MADRAS, SAPHIR are multifrequency passive microwave radiometers

***SAR, Altika and Scatterometer are active microwave sensors

India has also launched geostationary satellites i.e., INSAT series (viz., INSAT 1, 2 and 3) and METSAT (Kalpana-1) for meteorological applications. INSAT series deployed in orbit comprises of Very High Resolution Radiometer (VHRR) with imaging capability in visible (0.55–0.75 micron), thermal infrared (10.5–12.5 micron) and water vapour channel (5.7–7.1 micron) and provides 2×2, 8×8 and 8×8 km ground resolution, respectively. The satellite METSAT (Kalpana-1), which carries VHRR and Data Relay Transponder (DRT) payload, provides meteorological services.

Periodic inventory of natural resources, generation and updation of large-scale maps, disaster monitoring and mitigation, improved weather forecasting at better spatial and temporal scales, ocean-state forecasting, facilitating infrastructure development and providing information services at the community level for better management of land and water resources continue to be the thrust areas of applications for the Indian Earth Observation (EO) program. In order to address these thrust areas, the following Indian EO missions with different thematic goals have been planned, viz., operational polar orbiting RESOURCESAT-2, CARTOSAT-2/3 series, OCEANSAT-2, and RISAT; experimental polar orbiting SARAL and low-inclination orbit Megha Tropiques in cooperation with CNES. These will be augmented with the geostationary INSAT systems with Imagers and Sounders and a Geo-HR-Imager. In addition, it is planned to have microwave remote sensing satellites with mutli-polarisation and multi-mode capabilities in L, C, and X-bands. It is also planned to use the complementary and supplementary data from the other international missions to augment the data sources for climate change research in India. A brief description of forthcoming satellites for atmosphere, oceanography and meteorology follows:

- INSAT-3D will carry 6 channel Imager covering visible, infrared and water vapour channels and a 19 channel Sounder with bands in infrared and visible region.
- Megha Tropiques is an ISRO-CNES joint mission with three payloads viz., a five frequency (18, 23, 37, 89 & 157 GHz) imaging microwave radiometer—MADRAS (Microwave Analysis and Detection of Rain and Atmospheric Structures); a 6 channel humidity sounder—SAPHIR (Sounder

for Atmospheric Profiling of Humidity in the Intertropics by Radiometry) and a radiation measurement instrument—SCARAB (Scanner for Radiation Budget).

- I-STAG (Indian SaTellite for Aerosols and trace Gases) is planned under ISRO's Small Satellite Programme, and will carry three payloads viz., MAPI (Multi-Angle Polarisation Imager); MAVELI (Measurement of Aerosols by Viewing Earth's Limb); and MAGIS (Measurement of Atmospheric Gases using Infrared Spectrometer).
- SARAL (Satellite with ARGos and ALtika) is a joint mission of ISRO and CNES with the main objective of monitoring the ocean state. The payloads included are a ka-band radio altimeter called Altika and an ARGOS space segment.

Space Based Climate Change Studies in India

It has been fairly established that climate change happenings are real, and these are further evident from recent increase in extreme events. With a view to understand the underlying science aspects, ISRO on its part, through its focused ISRO Geosphere Biosphere Programme (ISRO GBP), has been pursuing a climate research programme over the past two decades with specific focus on studying atmospheric aerosols, trace gases, GHGs, paleoclimate, land cover change, atmospheric boundary layer dynamics, energy and mass exchange in the vegetative systems, National Carbon Project (NCP) and Regional Climate Modeling (RCM). ISRO has also carried out extensive campaigns with integrated satellite, aircraft, balloon and ground-based measurements, jointly with many sister institutions in the country, to study quantitatively the above aspects, and has brought out many scientific findings in many reputed international peer reviewed journals.

Many studies have been carried out towards mapping and monitoring of climate change indicators, which include glacier retreat (Kulkarni et al. 2005; 2006; 2007), changes in polar ice cover (Vyas et al. 2003), timberline change (Panigrahy et al. 2007) and coral bleaching (Bahuguna, 2008; Bahuguna et al. 2008). There have been some pioneering efforts to map the global change forcing agents. Spatial methane inventories from paddy rice (Manjunath et al. 2009),

livestock (Chhabra et al. 2009) and wetlands (Garg et al. 2005) have been prepared. Trends and seasonal pattern of Aerosols (Singh et al. 2004; Prasad et al. 2004), CO₂ (Singh et al. 2008b), CO (Singh et al. 2008a) and NO₂ (Ghude et al. 2008) have been analyzed. All these, information along with land surface parameters may help in improving the accuracy of regional climate models and their projections for India.

Long-term impact assessment requires simulation models for forecasting. Attempts have been made towards calibrating and validating these simulation models using remote sensing and ground observed parameters for Indian condition. These studies have been carried out in the fields of agriculture, hydrology, ocean productivity, impact on coastal zone due to sea level rise, regional climate model and global water cycle. The experience and knowledge gained from these studies would be useful in forecasting the climate change impacts and suggesting adaptation measures. Salient findings of these studies have been discussed in the following sections.

Space Based Indicators of Climate Change

Glacial Retreat in Himalaya

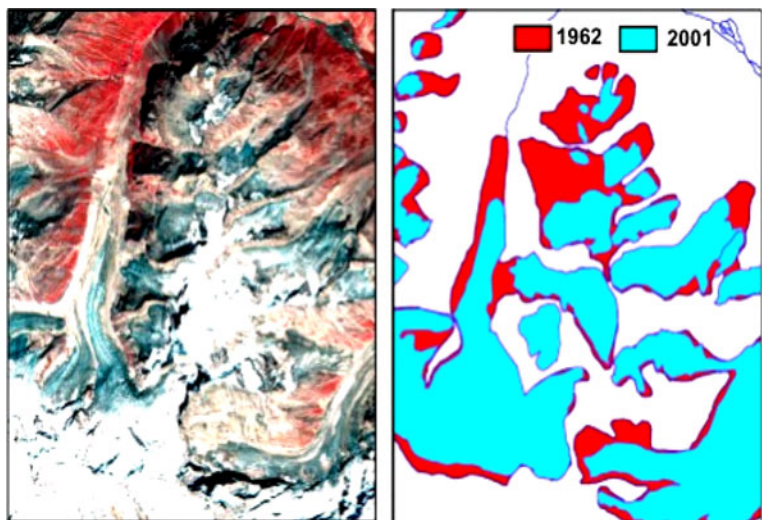
Glaciers are normally described as mass of ice slowly moving down a gradient. A glacier consists of ice crystal, water and rock debris. Out of these, ice is an essential part of the glacier. Climate change is

expected to change the ice cover and glacier extent. Satellite remote sensing data has been used to map and monitor the Himalayan glaciers. Glacier inventory of Indian Himalaya was completed at 1:250,000 scale using IRS-1A LISS-II data. 1702 glaciers covering an area of 23,300 sq km were mapped. Glacier inventory at 1:50,000 scale was carried out in the Satluj, Tista, Dhauli Ganga and Chenab basins.

Initial studies on monitoring of glacial retreat and estimation of loss in glacial area carried out for two glaciers viz. Samudra Tapu (Kulkarni et al. 2006) and Parbati glaciers (Kulkarni et al. 2005) in Himachal Pradesh using satellite images show that these glaciers are presently retreating at the rate of 26 m and 38 m per year, respectively (from base year 1962).

A model based on accumulation area ratio has been developed to estimate glacial mass balance. The model suggests an annual loss of 84 cm of ice in Baspa basin. This study is now expanded to 10 sub-basins in the Indian Himalaya. Glacial retreat in Chenab, Parbati (Fig. 1) and Baspa basins suggests an overall reduction in glacier area by 21% and mean of glacial extent has reduced from 1.4 to 0.32 km² (Kulkarni et al. 2007). Small glaciarets and ice fields having, less than 1 sq km area have shown retreat of 38% from 1962, possibly due to small response time. In addition, many glaciers are having no accumulation area. These glaciers are expected to face terminal retreat, due to lack of formation of new ice. Seasonal snow cover monitoring in the Baspa river basin suggests a large retreat in December and

Fig. 1 Retreat of Glaciers in Parbati river basin, Himachal Pradesh, studied using high resolution LISS-IV images of Resourcesat satellite. (Source: ISRO Report (2008))



average stream runoff of the month has increased by 75%. The observations such as glacial retreat, negative mass balance, early melting of seasonal snow cover and wintertime increase in stream runoff suggest an influence of climate change on the Himalayan cryosphere.

Similarly, change in snow cover is also expected as an indicator of climate change. Snow cover monitoring algorithm was used to monitor seasonal snow cover in 28 sub-basins in the Indus and Ganga river basins using AWiFS data from Resourcesat-1. Initial results show significant change in snow cover. Further study is planned that will provide snow cover atlas of 28 sub-basins in Indian Himalaya, glacier retreat in 6 sub basins, and glacial inventory covering Indus, Ganga and Brahmaputra basins.

Change in Polar Ice Cover

The Earth's Polar Regions play a critical role in the Earth System. In polar oceans, sea ice forms a blanket over ocean during winter that melts in the summer. During the winter this blanket acts as a barrier between underlying ocean and incident solar energy. By reflecting incident solar energy and radiating to space the earth's long-wave energy, the Polar Regions help to keep the planet cool. Satellites in near-polar orbit can provide consistent spatial and temporal coverage necessary to document the changes in Polar ice. Microwave remote sensing has greater role to play in sensing polar ice change because the changes in dielectric properties of ice due to growth and aging can be exploited in ice retrieval algorithms. Polar sea ice has been monitored quasi-continuously over the last 30 years using Passive Microwave Radiometers (PMR), namely SSMR (Nimbus-7) and SSM/I (DMSP). Space Applications Centre (SAC), in collaboration with National Centre for Antarctic and Ocean Research (DOD), Goa, India, has also contributed significantly in the use of MSMR data for monitoring the Antarctic region.

Vyas et al. (2003), have assessed the potential of MSMR observations for analyzing the sea ice extent. Bhandari et al. (2005), have carried out relative calibration of MSMR using independent SSM/I measurements for Sea Ice Concentration (SIC). These studies developed the confidence on use of MSMR data for polar ice studies. Vyas et al. (2003), have analyzed the intra-annual variation and inter-annual trends of SIC over Antarctic using MSMR data (from

1999 to 2001) and SSMI data (from 1979 to 1998). It was observed that sea ice extent is minimum in February, whereas in August it is maximum. Even in August, significant variations in SIC was observed between 2000 and 2001 that highlights the presence of inter-annual variations in Antarctic parts of Polar region. Relatively moderate rate of long term increase of sea ice extent (2.6% per decade) was reported in the results of trend analysis using SMMR, SSM/I and MSMR observations. However, decreasing trend of -1.1% per decade was observed in the Weddell Sea Sector. For the Arctic region, brightness Temperature mapping (at 18 GHz) has been carried out using MSMR data from 1999–2001.

Upward Shift in Timberline and Vegetation in Alpine Zone

High altitude/mountain ecosystems defined by low temperatures are considered sensitive to climate warming. Simulation studies show that climate change impact will result in invasion of vegetation to higher altitudes. Study has been carried out in high altitude Central Himalayan ranges in a part of the World Heritage site (the Nanda Devi Biosphere reserve) using temporal satellite remote sensing data. Data of March 1986 (Landsat TM), March 1999 (Indian Remote Sensing satellite—IRS LISS III) and March 2004 (IRS LISS III and LISS IV) were used in conjunction with the topographic map of Survey of India at 1:50,000 scale (based on 1960 aerial photographs). Digital elevation data derived from remote sensing was used to analyze the terrain parameters, mainly elevation to study the regions above 3000 m (above sub-alpine zone).

Analysis of survey map of 1960 showed that glaciers, snow and scrub, were the dominant land cover types of the area. Vegetation was reported in the form of scrub and scattered trees. The timberline was at 3900 m AMSL in 1960. Analysis of remote sensing data of March 1986 showed no significant deviation from the baseline information obtained from topographic map. The 1999 data showed indications of reduction in snow/ice cover and increase in vegetation cover in areas above 4000 m. Data of 2004 showed significant increase in vegetation cover in alpine zone. It occupied 23% of area in comparison to around 0.5% in 1986. Vegetation regeneration was in areas that were snow/ice in 1986. This is so far highest reported vegetation ingress in mountainous regions

within a span of two decades. On the other hand, the snow/glacier class reduced to 35.0% in 2004 compared to 90.5% in 1986, while scrub area increased from 9.0 to 42%. The elevation contours overlaid on the image showed that now the timberline is at 4300 m AMSL, the scrub line is at 4900 m AMSL and the tundra vegetation line is at 5300 m AMSL. The vegetation ingression and timberline shift can be used as indicators of climate change (Fig. 2). Recently Thapliyal et al. (2009) has reported systematic increase in vegetation greenness (in terms of NDVI) in Garhwal Himalayan region using three-decade remote sensing data (Landsat MSS (1976) and IRS LISS III (1999 & 2006)).

Bleaching of Coral Reefs

Recent assessments suggest that a significant fraction (10–16%) of the historical extent of coral reef coverage has been lost worldwide. Coral bleaching, or the separation of coral algal symbionts (zooxanthellae) from a host coral, is a process that was first described over 75 years ago, but which has become a pervasive and frequent phenomenon over the past 20 years. The major factor causing coral bleaching is increased ocean

temperature. It is apparent that the major causes of bleaching events are unpredictable and uncontrollable, and probably are linked to climatic conditions that may become more stressful in future.

There are four major reef regions in India, and they have been mapped using satellite data at the SAC, Ahmedabad, for their extent and ecological condition. These are currently being zoned at eco-morphological level. Bahuguna et al. (2008) have developed the indicator-based approach for monitoring health of reefs. The leading indicators give an early idea of the reef environmental condition and have led to the development of 'Warning Index'. The co-incident indicators tell about the current ecological state of reef and lead to the Ecological Index and the Lagging indicators indicate the damage that has already occurred (Damage Index). These three indicators help in giving a statement on the health of the reef. The warning index is primarily dominated by, the sea surface temperature (SST) anomaly. The effect of increased SST on the coral reefs has been well studied. Increased SST leads to coral bleaching followed by increasing cover of macro-algae (Fig. 3) and therefore a classic case of phase shift (coral dominated to macro-algae dominated habitat) (ISRO Report (2008)).

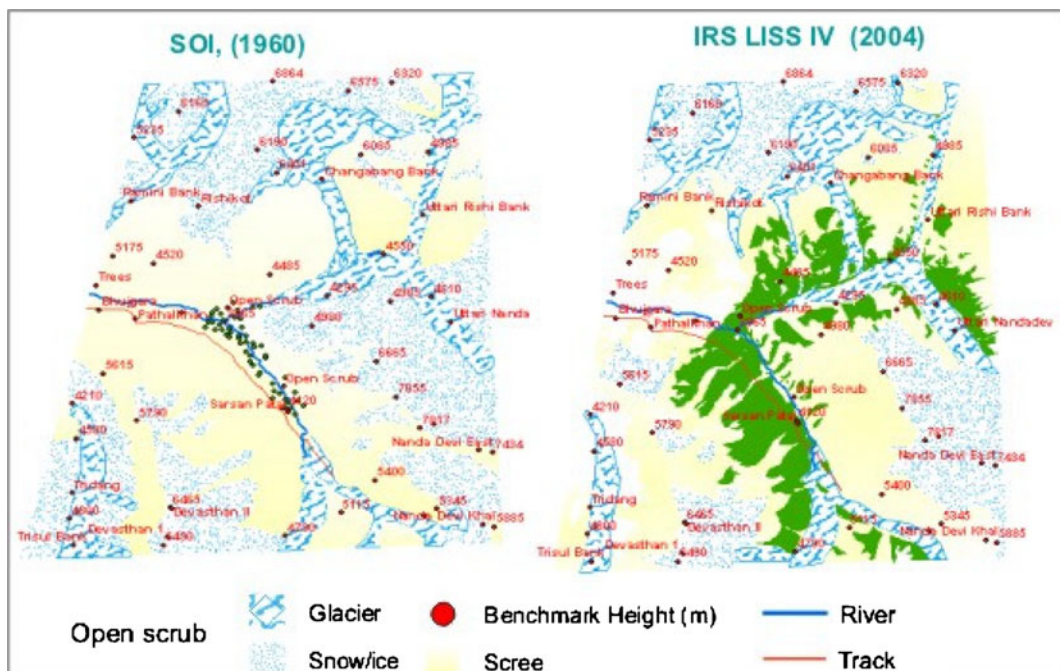
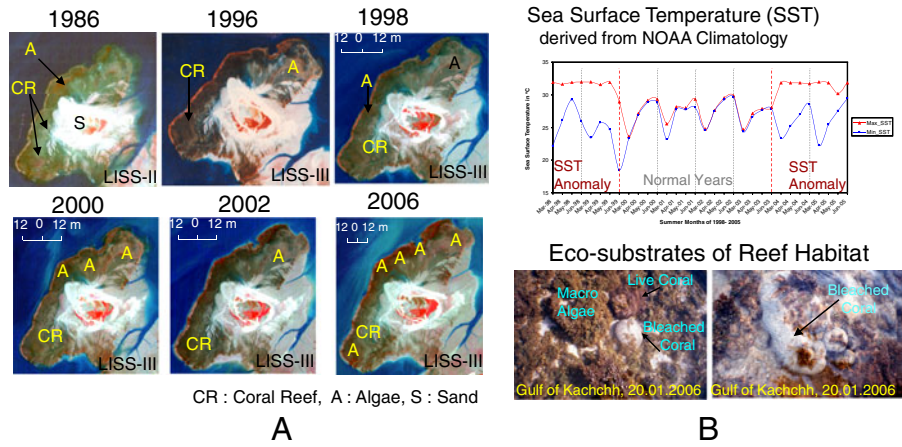


Fig. 2 Increased vegetation cover (Green colour) in alpine zone and decrease in snow & glacier cover, and upward shift in timberline from 1960 to 2004. (Source: ISRO Report (2008))

Fig. 3 Coral reef habitat (Pirotan) and its degradation as a result of Temperature Anomaly in 1998 and 2004. (Source: Bahuguna et al. 2008)



A : Sequential Temporal Changes in PIROTAN Coral Reef habitat (Gulf of Kachchh, India) is observed in the IRS images over 20 years period :1986-2006.
B : NOAA Climatology SST (Sea Surface Temperature) showing Anomaly Period 1998-99 and 2004-05.

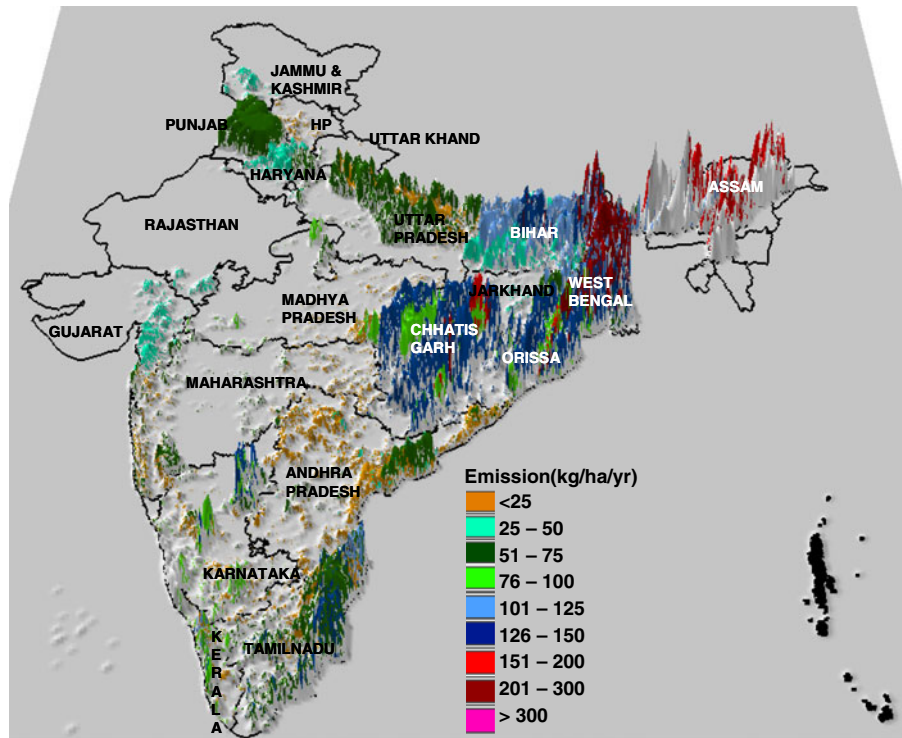
Mapping and Monitoring Agents of Climate Change

Methane Emission from Rice Lands

Space Applications Centre has carried out a national inventory of methane emission using an

integrated approach (Manjunath et al. 2009). Satellite remote sensing data was used to derive the rice area, crop-growing calendar (duration, growth stages) and digital elevation. These have been used to model the hydrological regime of rice lands. These inputs along with collateral data on soil and irrigation were used to stratify the rice

Fig. 4 Perspective view of methane emission from rice lands in India. (Source: Manjunath et al. 2009)



lands (as per IPCC guidelines) and designing a sampling scheme. About 471 sampling locations were identified across the country, where emission was measured during different crop growth stages. Soil and plant parameters were also measured. These measurements were used for up-scaling of emission in each strata. The strata level estimates were used to derive country level emission (Fig. 4). The seasonal integrated flux (SIF) for the dry season was 78.3 kg/ha with SD of 33.3 kg/ha. The emission from the rice ecosystems of India ranged from 1.557 to 5.21 Tg with a mean of 3.383 Tg (Manjunath et al. 2009). The peak emission was observed during September month.

Methane Emissions from Indian Livestock

Livestock is another major source of methane emission with global contribution of about 37%, mostly from enteric fermentation by ruminants. Livestock constitutes an integral component of Indian agriculture. India possesses the world's largest total livestock population of 485 million, which accounts for ~57% and 16% of the world's buffalo and cattle populations, respectively. A detailed state/district-level methane emission inventory for different livestock categories was made using the country-specific and Indian feed standard based methane emission coefficients, which are based on IPCC guidelines, and the latest available livestock census. The total methane emission including enteric fermentation and manure management has been estimated as 11.75 Tg for the year 2003 (Chhabra et al. 2008). Enteric fermentation accounts for ~92% or 10.65 Tg of the total, while manure management contributes only 8% or 1.09 Tg. Uttar Pradesh, Rajasthan and Madhya Pradesh are the top three livestock methane emitting states.

Methane Emission from Wetlands

SAC has also carried out the first wetland inventory using remotely sensed satellite data (of 1992–1993) for the entire country at 1: 250,000 scale. Later, the same has been updated with the AWiFS data of 2004–2005. This has evolved into a national wetland information system for the country. The total area under various wetland categories (24 classes) was estimated to be 78,48,427 ha in 1992–1993, while it

has shown an increase and accounted for 88,28,685 ha in 2004–2005. Preliminary analysis of potential methane emission from Indian wetlands was carried out using published values from international study. The wetland database was used to compute annual emissions from the wetlands in India. Results showed that the potential emission may vary from 1.27 Tg/year to 2.31 Tg/year, with national annual mean emission of 699 kg/sq. km (ISRO Report 2008). Efforts are needed to generate the country specific coefficients for methane emission from Indian wetland using the in situ measurements.

Space Based Monitoring of Greenhouse Gases

The concentration of Greenhouse Gases (GHGs) in the atmosphere is of significant importance in the context of climate change. These are varying with time and place. SAC has taken initiatives in this direction by analysis of the satellite based trace gases concentration over India. Studies are being carried out to arrive at optimal sensor parameters for greenhouse gas detection and develop remote sensing technique to monitor the GHGs under Pracriti program. The salient findings are discussed in the subsequent sections.

Carbon Monoxide

The concentration of atmospheric Carbon monoxide (CO) plays an important role in the troposphere chemical system. CO, produced mainly from incomplete combustion, is both direct and indirect precursor for numerous trace gases including several greenhouse gases. It is a primary component of the biomass burning and produced by burning of fossil fuels in urban and industrial areas. Major sink for the carbon monoxide is its reaction with OH radical present in the atmosphere.

Spatial and seasonal variation in column CO concentration over India was observed (Singh et al. 2008a) from EOS-TERRA MOPITT (Measurements of Pollution In The Troposphere) sensor, an instrument on board the NASA Earth Observing System (EOS) Terra satellite (Fig. 5). MOPITT is a nadir Infra Red (IR) radiometer, in which measurements of upwelling IR radiation are collected by using the principle of correlation spectroscopy at

wavelengths 4.7 μm and 2.3 μm with a near global coverage within 3–4 days. It was observed that the Indo-Gangetic plain was associated with highest annual average columnar CO concentration ($>2.5 \times 10^{18}$ molecule/cm²), whereas hilly terrain of J&K showed lowest concentration ($<2.0 \times 10^{18}$ molecule/cm²). The systematic seasonal cycle was observed in the concentration of CO, in all the years. It was found that CO concentration is higher during the pre-monsoon period (January–April) with a peak in March–April ($\sim 2.5 \times 10^{18}$ molecule/cm²). In summer and monsoon period (May–September) CO levels tend to decrease ($\sim 1.5 \times 10^{18}$ molecule/cm²), which again increase in post monsoon (October–December) months. It was observed that average CO concentration over India is increasing $\sim 1.7\%$ per year (Fig. 6)

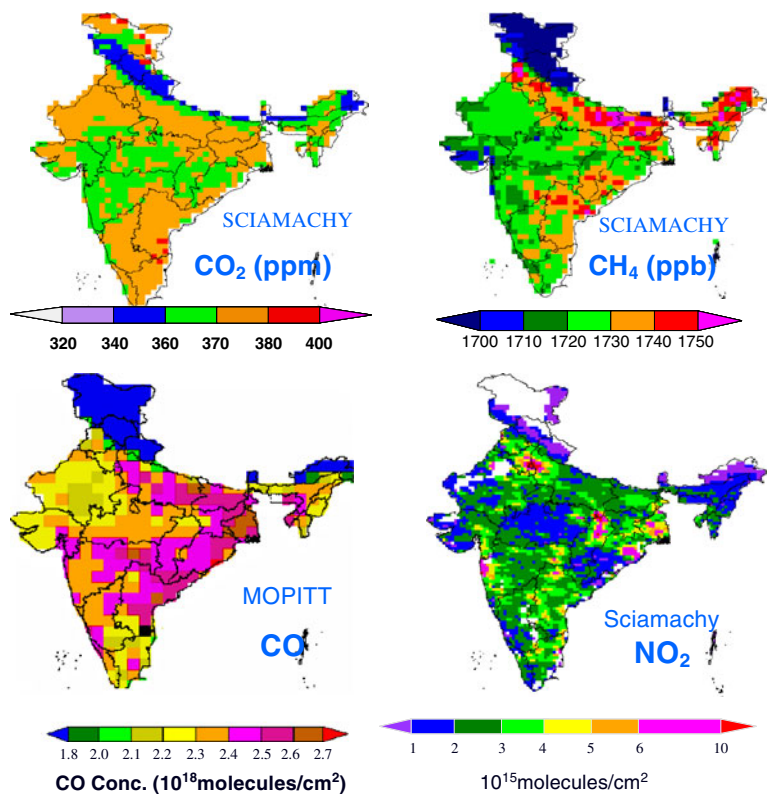
Carbon Dioxide

The rapid increase in atmospheric concentrations of carbon dioxide over years is linked with

combustion of fossil fuels, conversion of forested land to agricultural use and changes occurring in various carbon pools and fluxes. There has been growing concern in recent years that these high levels of greenhouse gases may not only lead to changes in the earth’s climate system, but may also alter ecological balances through effects on vegetation. Terrestrial ecosystems can act as both source and sink and large uncertainty exists in understanding the current carbon status and its spatial and temporal variability.

Satellite based estimation of atmospheric CO₂ is an emerging technique which provide information on the spatial variability. Spatial and seasonal variability of the CO₂ was estimated using ENVISAT-SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY) sensor (Singh et al. 2008b; Singh 2008). SCIAMACHY is an imaging spectrometer whose primary mission objective is to perform global measurements of trace gases in the troposphere and in the stratosphere. The solar radiation trans-

Fig. 5 Spatial variability of atmospheric CO₂, CH₄, CO and NO₂ over India estimated using SCIAMACHY and MOPITT sensor data



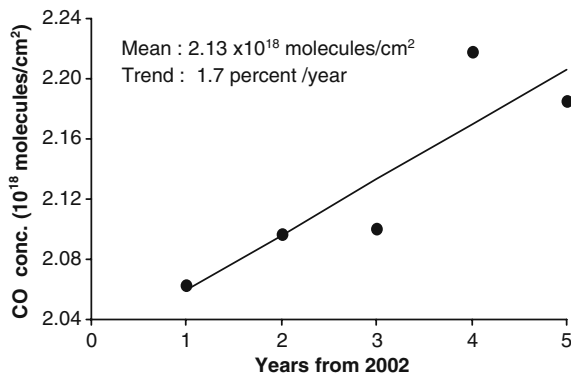


Fig. 6 Inter annual variability in carbon monoxide over India estimated using MOPITT sensor data

mitted, backscattered and reflected from the atmosphere is recorded at relatively high resolution (0.2 nm to 0.5 nm) over the range 0.24 μm to 1.7 μm , and in selected regions between 2.0 μm and 2.4 μm . The high resolution and the wide wavelength range make it possible to detect many different trace gases despite low concentrations. It is observed that vegetated region such as forests of Himalaya and Kerala are associated with relatively low CO_2 concentration (~ 350 ppm) as compared to arid region of Rajasthan (~ 375 ppm). Terrestrial vegetation acts a sink of CO_2 and uses it for primary production. The inter annual increasing trend of CO_2 associated with seasonal cycle of vegetation estimated using SCIAMACHY data is shown in Fig. 7.

Methane

Methane is the second most important greenhouse gas after carbon dioxide and contributes $\sim 15\%$ to the global warming. Rice cultivation has been accredited as one of the major source of anthropogenic methane. With the intensification of rice cultivation to meet the growing global food demand, CH_4 emission from this important ecosystem is anticipated to increase. It was observed that all India monthly average atmospheric concentration of methane ranges from 1693 ppb to 1785 ppb. A systematic seasonal pattern was observed in methane concentration, which was mostly influenced by rice growth characteristics. It was found that January to June is associated with relatively lower concentration of methane (1699 ppb–1708 ppb)

in India, which characteristically increase from July to September (1747 ppb–1785 ppb) with further gradual decline from October to December (1768 ppb–1704 ppb). The spatial distribution of methane over Indian region is associated with agricultural practices particularly rice cultivation. It was observed that Indo gangetic plain including North East region, parts of Chhatisgarh, Orissa and Andhra Pradesh showed higher methane concentration (>1730 ppb) as compared to hilly regions of Jammu and Kashmir (<1710 ppb).

Atmospheric NO_2

Nitrogen oxides play a central role in tropospheric chemistry. An improved knowledge of the global tropospheric distribution of NO_x ($\text{NO} + \text{NO}_2$) is important for climate change studies. NO_x and volatile organic compounds are emitted in large quantities due to human activities such as vehicles and industry. The knowledge of the ozone distribution and its budgets is strongly limited by a severe lack of observations of NO and NO_2 in the troposphere. The technique used to retrieve total slant columns of atmospheric trace species from Satellite (GOME, SCIAMACHY) measurements is the Differential Optical Absorption Spectroscopy (DOAS). The DOAS technique allows the determination of concentrations of atmospheric species, which leave their absorption fingerprints in the spectra. Spatial distribution of tropospheric NO_2 concentration was analyzed over India. It was observed that high concentration of NO_2 distribution is associated with coal-mine and thermal

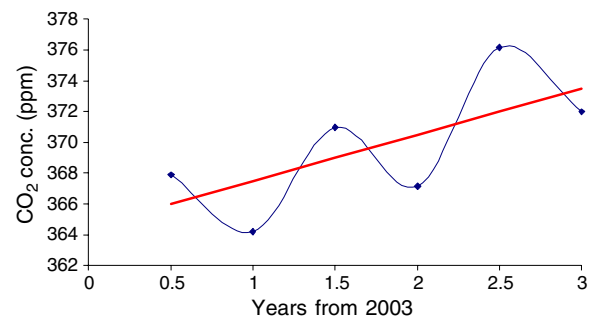


Fig. 7 Inter annual variability in carbon dioxide associated with biospheric seasonal signal over India estimated using SCIAMACHY sensor data

power locations as well as major metropolitan cities of India (Fig. 5).

Biomass Burning/Forest Fire

Biomass burning including forest fire is an important source of greenhouse gases and has substantial impact on climate. The frequency of forest fires is expected to increase in India as a result of global warming. Decoupling the fire due to human-induced climate change and natural climatic variability is not certain. However, fire frequency is expected to increase with human-induced climate change, especially where precipitation remains the same or is reduced. Several researchers suggest that climate change is likely to increase the number of days with severe burning conditions, prolong the fire season, and increase lightning activity, all of which lead to probable increase in fire frequency and areas burned. Space-borne remotely sensed data play a crucial role in observing fire events spatially as well as temporally (Singh et al. 2009).

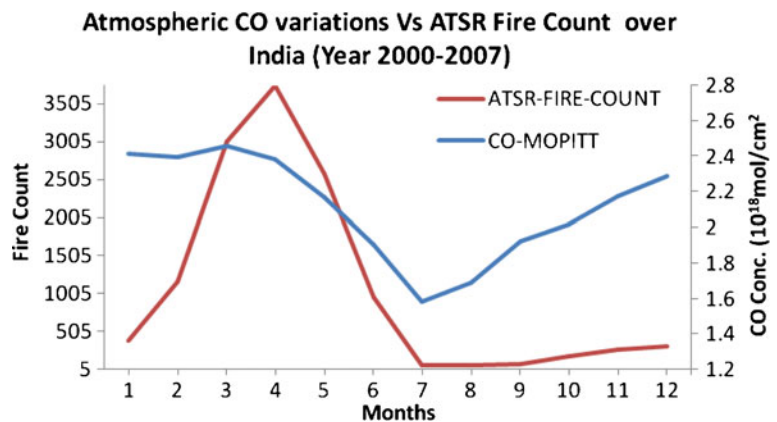
ISRO/DOS Centres, over the years, have been carrying out work regarding the detection of fire, burnt area mapping using various satellite sensors like IRS and MODIS. SAC has studied month wise fire events (counts) using ATSR over India (includes forest fires, agricultural and other biomass burning events), and yearly variations were also studied using ATSR fire atlas data (source: <http://dup.esrin.esa.int/ionia/wfa/index.asp>).

Results show that March and April are the months, when fire events are high, while July is the least fire event month (Fig. 8). Analysis of fire events in relation to land use/cover showed that more than 80% events are from two classes: (i) tree cover, broadleaved, deciduous, closed forest, and (ii) well managed agricultural lands.

Conclusion and Future Direction

Evolving a coherent research program and selecting research priorities is a major challenge in a broad scientific domain such as climate change that crosses over a number of different disciplines, each evoking many scientific questions. Developmental needs of the country place enormous demand on its resources. The challenge lies in balancing the competing demands placed on its limited resources and development processes relevant to national policy issues by use of Technology. Space technology of earth observation provides important inputs in addressing the climate change issues in India. Studies discussed in the paper are some examples of utilization of space technology in climate change studies. The experience and knowledge gained from these studies would be useful in specifying the trend in climate change impacts and suggesting corresponding adaptation measures. There is need to strengthen these studies further covering many other new areas. Summary of some of the important direction and future action plans in these fields are as follows,

Fig. 8 Atmospheric CO variations from MOPITT Vs ATSR based Fire Count over Indian region for year 2000–2007. (Source: Singh et al. 2009)



- Developing benchmark sites at different ecological regions of the country to regularly monitor the indicators of climate change.
- Long-term monitoring of atmospheric composition using flux towers and satellite observations.
- Use of simulation models to study the long-term impacts on agriculture, hydrology, coastal land-use, ocean productivity, desertification etc. (PRACRITI 2008).
- Development/adaptation of Regional Climate Models (RCM) for generation of India-specific climate scenarios - using detailed observations, RCM and coupled ocean-atmosphere-land-ice model.
- Facilitating in situ observational networks for weather and climate, comprising of indigenously developed Automatic Weather Station (AWS), AGROMET Tower, Doppler Weather Radar (DWR), Boundary Layer LIDAR (BLL) and GPS Sonde.

Design and development of series of satellite missions (Manjunath 2006; Singh et al. 2007; Singh and Shukla 2008) to make global measurements of greenhouse gases and establish necessary calibration sites.

The climate change studies would need integrated effort with extensive measurement campaigns involving collaboration with the concerned national and international scientific organizations.

Acknowledgment All the studies mentioned are being carried out involving teams from a large number of organizations/institutions within the country viz., Ministry of Environment of Forest (MoEF), Ministry of Earth Sciences (MoES), Indian Council of Agricultural Research (ICAR), Indian Institute of Technology (IITs), State Remote Sensing Applications Centres, and Academic Institutions etc., along with ISRO/Dept. of Space. One of the Author (RPS) gratefully acknowledge, Dr. J.S. Parihar, Dr. (Mrs.) S. Panigrahy, Dr. A.V. Kulkarni, Dr. N. K. Vyas, Dr. S.S. Ray, Shri K. R. Manjunath, Shri C.P. Singh, Dr. (Mrs.) Abha. Chhabra, Ms N. Roychaudhary, Shri S. K. Goroshi and other scientists at Space Application Centre, Ahmedabad for suggestions and inputs in preparation of the manuscript.

References

- Bahuguna, A. (2008). Impact of climate change on coral reefs. Indian Society of Geomatics (ISG) Newsletter, 14 (1–4), December, 2008.
- Bahuguna, A., Nayak, S., Choudhury, R., Sharma, N., Bhandari, S., Wafar R. J., et al. (2008). Assessment of coral reef health using satellite data. Scientific Note, Space Applications Centre, Ahmedabad, SAC/RESA/MESG/MCED/SN/62/2008.
- Bhandari, S. M., Vyas, N. K., Dash, M. K., Khanolkar, A., Sharma, N., Khare, N., et al. (2005). Simultaneous MSMR and SSM/I observations and analysis of Sea Ice characteristics over the Antarctic region. *International Journal of Remote Sensing*, 26, 3123–3136.
- Chhabra, A., Manjunath, K. R., Panigrahy, S., & Parihar, J. S. (2008). Methane emission inventory from Indian livestock, Scientific Report, Space Applications Centre, Ahmedabad, SAC/AFEG/AMD/EIAA/SN/01/08, p 51.
- Chhabra, A., Manjunath, K. R., Panigrahy, S., & Parihar, J. S. (2009). Spatial pattern of methane emissions from Indian livestock. *Current Science*, 96(5), 683–689.
- Garg, J. K., Patel, J. G., & Singh, T. S. (2005). Methane emission from wetlands in India, Scientific Report, Space Applications Centre, Ahmedabad, SAC/RESIPA/FLPG/SR/03/2005, p 131.
- Ghude, S. D., Fadnavis, S., Beig, G., Polade, S. D., & Vander, A. R. J. (2008). Detection of surface emission hot spots, trends and seasonal cycle for satellite retrieved NO₂ over India. *Journal of Geophysical Research*, 13, D20305. doi:10.1029/2007JD009615.
- ISRO Report (2008). Space Technology Applications for Climate Change, ISRO Technical Report, ISRO/DOS/TR/01/2008.
- Kulkarni, A. V., Rathore, B. P., Mahajan, S., & Mathur, P. (2005). Alarming retreat of Parbati Glacier, Beas basin, Himachal Pradesh. *Current Science*, 88(11), 1844–1850.
- Kulkarni, A. V., Dhar, S., Rathore, B. P., Govindharaj, K. B., & Kalia, R. (2006). Recession of Samudra Tapu glacier, Chandra river basin, Himachal Pradesh. *Journal of the Indian Society of Remote Sensing*, 34(1), 39–46.
- Kulkarni, A. V., Bahuguna, I. M., Rathore, B. P., Singh, S. K., Randhawa, S. S., Sood, R. K., et al. (2007). Glacial retreat in Himalaya using Indian Remote Sensing Satellite data. *Current Science*, 92(1), 69–74.
- Manjunath, K. R. (2006). Sensor for estimating concentration of atmospheric gases, Scientific Report, Space Applications Centre, Ahmedabad, SAC/RESIPA/ARG/SR/01/2006, pp. 70–89.
- Manjunath, K. R., Panigrahy, S., Addhya, T. K., Beri, V., Rao, K. V. & Parihar, J.S. (2009). Methane emission inventory from Indian Rice ecosystem using remote sensing, GIS and field observations. Scientific Report, Space Applications Centre, Ahmedabad, SAC/AFEG/AMD/EIAA/SN/03/08, p. 131.
- Navalgund, R. R. (2006). Indian Earth observation system: an overview. *Asian Journal of Geoinformatics*, 6, 17–25.
- Navalgund, R. R., Jayaraman, V., & Roy, P. S. (2007). Remote Sensing Applications: An Overview. *Current Science*, 93 (12), 1747–1766.
- NIST Report (2004). Satellite instrument calibration for measuring global climate change, Report of a workshop at University of Maryland Inn and Conference Centre, College Park MD, November 12–14, 2002.
- Panigrahy, S., Anitha, D., Kimothi, M. M. & Singh S. P. (2007). Climate change indicators in alpine ecology of central Himalaya: An analysis using satellite remote sensing data. Tropical Ecology Congress 2007, 2–5 Dec. 2007, Dehradun, INDIA.

- PRACRITI (2008). Programme on Climate Change Research in Terrestrial Environment (PRACRITI), Project Proposal Report, Space Applications Centre, Ahmedabad.
- Prasad, A. K., Singh, R. P., & Singh, A. (2004). Variability of aerosol optical depth over Indian subcontinent using MODIS data. *Journal of the Indian Society Remote Sensing*, 32, 313–316.
- Singh, R. P. (2008). Variability of atmospheric and land surface biophysical parameters retrieved using satellite based measurements over India, Proc. of 15th United Nations/Austria/European Space Agency Symposium on “Space Tools and Solutions for Monitoring the Atmosphere and Land Cover” on 9–12 September 2008, Graz, Austria.
- Singh, R. P. & Shukla, M. V. (2008). Development of technique for estimation of atmospheric carbon dioxide using radiative transfer model, Presented at National Seminar on Advances in Remote Sensing technology and applications with special emphasis on Microwave Remote Sensing, Annual Conf. of Ind. Soc. of Remote Sensing, Dec. 18–20, 2008, Nirma University, Ahmedabad, India
- Singh, R. P., Dey, S., Tripathi, S. N., Tare, V., & Holben, B. (2004). Variability of aerosol parameters over Kanpur, Northern India. *Journal of Geophysical Research*, 109, D23206. doi:10.1029/2004JD004966.
- Singh, R. P., Pandya, M. R., Panigrahy, S. & Parihar, J. S. (2007). Analysis of Tropospheric Emission spectrometer (TES) observed hyperfine thermal radiance and emissivity spectra over India. International Symposium on Aerosol-Chemistry-Climate Interactions, 20–22 Nov. 2007, Physical Research Laboratory, Ahmedabad, India
- Singh, R. P., Sobhan, K. K., Panigrahy, S. & Parihar, J. S. (2008a) Study of carbon monoxide using remote sensing data, Proc. of technical Hindi Seminar on Jan. 29, 2008, Space Applications Centre, Ahmedabad.
- Singh, R. P., Sobhan, K. K., Panigrahy, S., Buchwitz, M., & Parihar J.S., (2008b). Variability of atmospheric carbon dioxide concentration over India derived using ENVISAT-SCIAMACHY measurements, Presented at National Seminar on Advances in Remote Sensing technology and applications with special emphasis on Microwave Remote Sensing, Annual Conf. of Ind. Soc. of Remote Sensing, Dec. 18–20, 2008, Nirma University, Ahmedabad, India.
- Singh, C. P., Singh R. P., & Panigrahy, S. (2009). Assessment of biomass burning & CO emission over India using Space borne measurement. Geomatics 2009, National conf. on Geomatics and impact of climate change with specific reference to mountain ecosystem, Feb. 4–6, 2009, Dehradun, INDIA.
- Thapliyal, A., Singh, C. P., Kimothi, M. M., Panigrahy, S. (2009). Satellite based change detection of vegetation in 3 decade over Garhwal Himalyas in relation to climate change. Geomatics 2009, National conf. on Geomatics and impact of climate change with specific reference to mountain ecosystem, Feb. 4–6, 2009, Dehradun, INDIA.
- Vyas, N. K., Dash, M. K., Bhandari, S. M., Khare, N., Mitra, A., & Pandey, P. C. (2003). On the secular trend in sea ice extent over the Antarctic region based on OCEAN-SAT—1 MSMR Observations. *International Journal of Remote Sensing*, 24, 2277–2287.