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Use of satellite data in the Geosphere-Biosphere Programme

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सार – इस शोध–पत्र में भूमंडल और जीव मंडल कार्यक्रम (जी.बी.पी.) के उपग्रह सुदूर संवेदी आंकड़ों के उपयोग के कुछ मामले प्रस्तुत करने का प्रयास किया गया है, जिसमें मुख्य रूप से, भारतीय अध्ययन किये गए हैं क्योंकि अंतर्राष्ट्रीय क्षेत्र अत्यंत व्यापक होने के कारण उनका संक्षिप्त अध्ययन करना कठिन है।

कुल मिलाकर, ग्रीन हाउस गैस अंतर्क्षेपण की समस्याओं में से, संश्लेषण द्वारा स्थलीय और समुद्री पारिस्थितिक तंत्र दोनों में कार्बन की सीमा निर्धारित करना एक महत्वपूर्ण प्रश्न है। कार्बन निर्धारण से गहरे रूप से संबद्ध स्थलीय नेट प्राइमरी उत्पादकता का आकलन करने के लिए भारतीय सुदूर (आई.आर.एस.) उपग्रह पर आधारित "वाइड फील्ड क्षेत्र (डब्ल्यू.आई.एफ.एस.) और लैंड सेट "थीमेटिक मैपर (टी.एम.)" नामक संवेदी का उपयोग किया गया है। संपूर्ण वन क्षेत्र और प्राचलों तथा जैव विविधता का भी मानीटरन किया जा रहा है। डब्ल्यू. आई.एफ.एस. का उपयोग करते हुए भारतीय वनस्पति के जीवोम स्तर की विशेषताओं का पता लगाया गया है। पिछले कई वर्षों से चल रहे दीर्घकालिक अध्ययन में भारतीय क्षेत्रों के स्थलीय पारिस्थितिक तंत्र के कार्बन पूल और चक्र का भी कार्बन डाइऑक्साइड और मीथेन बजटिंग दोनों के साथ आकलन किया जा रहा है ; इन मूलभूत आंकड़ों में स्वस्थाने और उपग्रह सेट दोनों सम्मिलित हैं। डब्ल्यू.आई.एफ.एस. और डी.एम.एस.पी. ओ.एल.एस. आकड़ों से जैवभार दहन के अध्ययन किए गए हैं।

इसी प्रकार, अरब सागर और बंगाल की खाड़ी के विशेष संदर्भ सहित समुद्री और पारिस्थितिक तंत्र में कार्बन के निर्धारण का आकलन करने के प्रयास किए गए हैं। ओशनसेट –1 के हिंद महासागर रंगीन मानीटर (ओ.सी.एम.)' संवेदी से लिए गए उत्पादकता / क्लोरोफिल मानचित्र प्रमुख निवेश हैं।

जी.बी.पी. के अंतर्गत तटीय क्षेत्र पर स्थल महासागर अन्योन्यक्रिया के महत्वपूर्ण घटक के रूप में उड़ीसा के चिल्का समुद्रताल का अध्ययन, एल.आई.एस.एस., पी.ए.एन. आदि के साथ डब्ल्यू. आई.एफ.एस. और ओ.सी.एम. से प्राप्त स्वस्थाने और उपग्रह आंकड़ों से विस्तृत रूप से किया गया है। भूमि उपयोग के परिष्करण से संबंधित जलगुणवत्ता और उत्पादकता में परिवर्तनों के अलावा कार्बन के संवहन, सिल्टेशन, लिटोरल अपवाह जैसी सुसंगत प्रक्रियाओं का अध्ययन किया गया है।

भविष्य की जलवायु का पूर्वानुमान करने में जलवायु निदर्शन, विशेषकर धरातलीय विशेषताओं और वायुमंडलीय मिश्रण में होने वाले परिवर्तनों के प्रतिक्रिया स्वरूप हाने वाली वर्षा का जी.बी.पी. के अंतर्गत महत्वपूर्ण अध्ययन प्रगति पर है। इस संबंध में स्वस्थाने और उपग्रह स्रोतों से प्राप्त किए गए समुद्र धरातल तापमान, वनों की कटाई (और एलबीडो पर इनके प्रभाव) जैसे धरातल के कारकों को समाविष्ट किया गया है। अन्य महत्वपूर्ण धरातलीय प्राचल भूमि की नमी/मृदा की आर्द्रता है। भूमि की नमी और उसके भूमंडलीय उपयोग हेतु ओशनसेट –1 पर भारतीय भूचैनल स्कैनिंग सूक्ष्म तरंग रेडियो मीटर (एम.एस.एम.आर.) द्वारा प्रेक्षित किए गए सही तापमान को संबद्ध करने के लिए कदम उठाए गए हैं।

उपग्रह के आंकड़ों से हिमालय के हिमनदों में हुए परिवर्तनों का अध्ययन किया गया है। इसमें हिम संवेदी चैनल सहित डब्ल्यू. आइ.एफ.एस. के अलावा स्टीरियो स्कोपिक पी.ए.एन. का उपयोग किया गया है। जलवायु के महत्व की एक अन्य धरातलीय विशेषता ध्रुवीय क्षेत्रों (आर्कटिक/अंटार्कटिक) में समुद्री हिम है जिसका मौसम के अनुरूप चित्रण भी किया गया है और यहाँ तक कि इंडियन ओशनसेट–1 एम.एस.एम.आर. से विभिन्न खंडों में प्राप्त पहले के निम्बस–एस.एम.एम.आर.पर आधारित प्रवृत्तियों का अब तक विस्तार हो चुका है।

अन्य मानव जनित अव्यवस्था, उद्योगों, वाहनों, घरेलू ईधनों आदि से उत्पन्न होने वाले वायुविलयों के कारण होती है। पहले आई.आर.एस. – पी. 3 'एस. के जर्मन पेलोड मल्टी स्पेक्ट्रल ऑप्टो इलैक्ट्रानिक स्केनर (एम.ओ. एस.)' और अब इंडियन ओशनसेट–1 ओ.सी.एम. न केवल चित्रण के लिए बल्कि वायुविलयों के आकार/स्रोत की विशेषताओं का विश्लेषण करने के लिए उपयोगी पाए गए हैं। बदले में ये निदर्श के परिकलनों में सहायक पाए गए हैं।

गुप्त उष्मा (वाष्पोत्सर्जन के द्वारा) के महासागरीय वायुमंडल विनिमय ओशनसेट – 1 एम.एस.एम.आर. जैसे उपग्रह आँकड़ों से आकलित किया जा रहा है जो निदर्शों के नेदाानिकी में सहायता दे रहा है।

विकिरण बजट जलवायु का संकेतक होने के साथ ही साथ एक महत्वपूर्ण वाहक भी है। विभिन्न उपग्रहों/संवेदकों से विकिरित फ्लक्सों की तुलना एन.ओ..ए.ए.–ए.वी.एच.आर.आर., आई.एन.एस.ए.टी.–वी.एच.आर.आर., ई. आर.बी.एस.ए.टी. – ई.आर.बी.ई से की गई हे। इन्हें मानकीकृत किया गया है और जलवायु निदर्शों का अनुकूलन/चयन करने में इनका उपयोग किया जाता है। इस प्रकार के अध्ययनों से भारतीय क्षेत्र में मेघ तंत्रों की विशेष विकिरण विशेषताओं का भी पता लगाया गया है।

ABSTRACT. This review paper attempts to present a few cases of the utilization of satellite remote sensing data in the Geosphere-Biosphere Programme (GBP), mainly confined to Indian studies, as the international field is too wide to be covered in a brief review.

In the overall greenhouse gas injection problem, one of the important questions is the extent of carbon fixation in both, terrestrial and marine eco-systems by photosynthesis. Indian Remote Sensing (IRS) satellite based sensor called 'Wide Field Sensor (WiFS)' and Landsat 'Thematic Mapper (TM)' have been used, to estimate terrestrial net-primary productivity, closely linked to carbon fixation. Overall forest area and parameters and biodiversity, are also being monitored. The biome-level characterisation of Indian vegetation is being done using WiFS. The carbon pool and cycle of the Indian regions' terrestrial ecosystems, are also being estimated in a secular study over a number of years, including both carbon dioxide and methane budgeting; the basic data include both *in-situ* and satellite data sets. Studies on bio-mass burning are being done from WiFS and DMSP OLS data.

Similarly, attempts have been initiated to estimate the carbon fixation in marine ecosystems, with special reference to the Arabian Sea and the Bay of Bengal. Productivity/Chlorophyll maps from Indian 'Ocean Colour Monitor (OCM)' sensor on Oceansat-1 are the key inputs.

As an important component of 'Land Ocean Interaction at the Coastal Zone' under GBP, the Chilika lagoon, Orissa, has been extensively studied with *in-situ* and satellite data from WiFS and OCM, along with LISS, PAN etc. Relevant processes such as transport of carbon, siltation, littoral drift are being studied, besides changes in water quality and productivity related to landuse modifications.

Climate modeling to predict future climate, particularly rainfall in response to changes in surface characteristics and atmospheric composition, is a vital study under GBP, in progress. In this context, surface factors like sea surface temperature, deforestation (and its effect on albedo), obtained from *in-situ* and satellite sources, are being incorporated. Another important surface parameter is ground wetness/soil moisture. Steps are initiated to relate brightness temperature observed by Indian 'Multi-channel Scanning Microwave Radiometer (MSMR)' on Oceansat-1 to ground wetness and use this globally.

Changes in Himalayan Glaciers are being studied from satellite data. In this, besides WiFS with snow-sensitive channel, stereoscopic PAN is used. Another surface feature of climatic significance is sea-ice at polar regions (Arctic, Antarctic), which too has been mapped seasonally and even, the earlier Nimbus-SMMR based trend extended to present day, from the Indian Oceansat-1 MSMR, in different segments.

Another human disturbance occurs in the form of aerosols from industry, vehicles, domestic fuel etc. Indian Oceansat-1 OCM now, and earlier, IRS-P3's German Payload 'Multi-spectral Opto-electronic Scanner (MOS)' are found useful for not only mapping but analysing size/source characteristics of aerosols. These in turn are being incorporated in model calculations.

The ocean-atmosphere exchange of latent heat (*via* evaporation) is being estimated from satellite data such as Oceansat-1 MSMR, which is assisting in diagnostics of models.

The radiation budget is an important driver as well as indicator of climate. Radiative fluxes from various satellites/sensors have been compared – *e.g.* NOAA-AVHRR, INSAT-VHRR, ERBSAT-ERBE. These have been standardized, and utilised in tuning/selecting climate models. Also, special radiative characteristics of the cloud systems in the Indian region have been brought out from such studies.

Key words – Geosphere biosphere programme, Satellite observations, Remote sensing, Climate change, Global warming.

1. Introduction

The Geosphere-Biosphere Programme, both internationally and in India, was initiated in the light of a realisation, through scientific investigations, that several human activities have the potential to disturb the global and regional climates – which in turn, can affect the biosphere including food security. An urgent need was therefore felt, to attempt to understand the Interactive earth system and the quantitative impact of anthropogenic perturbations therein, so that mitigative measures could be taken where appropriate. Some prime examples of human effects on climate could be: (*i*) large or regional scale land use changes, including deforestation, biomass burning etc., which can impact climate in a variety of ways such as albedo and friction changes, decreased fixation of carbon dioxide etc. (Charney, 1975; Sud and Smith 1985); (*ii*) emission of greenhouse gases-notably carbon dioxide through fossil fuel combustion, methane from wetlands, rice paddies, cattle etc. chlorofluoro-carbons used in refrigeration, air-conditioning, fire-fighting equipments etc. – which can shift the short-wave long-wave radiative balance towards higher surface/low-level global temperatures accompanied by stratospheric cooling (Ramanathan *et al*., 1985); this may be partially compensated by aerosols which can reflect some short wave radiation (Kiehl and Briegleb, 1993); still the net effect being towards global warming, major changes in rainfall patterns, food production and also a sea-level rise can be expected (Wigley and Raper, 1987; Zwally, 1991); (*iii*) release of chlorofluorocarbons leading to ozone depletion in the stratosphere – this is more alarming from the ultraviolet transmission to surface, but even climatic effects of decreased stratospheric ozone and increased tropospheric ozone created by industrial pollution are expected (Kiehl *et al*., 1999); (*iv*) marine pollution and man-induced disturbances in nutrient outflow to oceans, which can reduce carbon fixation in marine biological productivity (photosynthesis) and thereby keep larger percentage of anthropogenic emission of carbon-dioxide in the atmosphere, exacerbating the greenhouse warming (Sarmiento *et al*., 1998).

In terms of observational sources, paleoclimatic research depends on proxy data such as tree-rings, sediments etc.; micro-level investigations obviously need *in situ*/field data, but they can also benefit from satellite data at fine scale; whereas global level studies benefit most from satellite data which are generally global, besides from a network of meteorological, trace gas and other *in situ* observations spread over the globe. Satellite data are particularly useful in otherwise relatively data sparse regions such as oceans, polar regions, etc. and to get synoptic view in the stratosphere. Indeed, space agencies, realising the value of archived satellite data, are piecing them together in uniform mutual calibration, to create medium-duration satellite data sets for climate/GBP studies (NOAA-NASA,1994). There are also elaborate plans to place series of satellites with sensors geared towards global change observations (CEOS, 1997; Hansen *et al*., 1995; Desai and Joseph, 1994). Readers wishing to understand imaging sensors may see Joseph, 1996.

The Indian scenario on GBP too, is quite active with many agencies/groups addressing different aspects thereof. Some of the investigations are using satellite data as integral component of the projects. In the present review paper, attempt is made to bring out such cases of utilization of satellite remote sensing data in GBP, mainly confined to Indian studies, as the international field is too wide to be covered in a brief review (barring a few instances). Even the Indian coverage may be representative, not exhaustive. Some of the work can be found in a book reflecting the GBP Programme of the Dept. of Space (ISRO, 1998).

2. Terrestrial ecosystems

2.1. *Biome mapping*

Physical and physiological status of vegetation govern critical land-atmosphere interaction processes like carbon transfer, biomass accumulation, sensible and latent heat transfer, albedo, friction etc. In this context, mesoscale classification of vegetation into quasi-homogeneous units called 'biomes' is of great significance for further aggregation of eco-physiological process and outputs. A few states are initially selected for such a classification using 4 to 8 months satellite data and extensive field observations with the aim to generate mesoscale vegetation class map of the whole of India.

The satellite data found most useful for this purpose are the 'Wide Field Sensor (WiFS)' on the Indian Remote Sensing Satellites (IRS) – 1C, P3 and 1D launched in 1995, 1996 and 1997 respectively. The spectral channels on WiFS are Red and Near-Infra-Red similar to 2 channels of NOAA-AVHRR which are used to arrive at a Normalised Difference Vegetation Index-NDVI, as a measure of the extent and health of vegetation. On IRS P3 only, a third short-wave-infrared channel more useful in ice/snow, aerosol and other application is also available. Specifically : the channels are centered around 0.65, 0.81 and 1.62 microns, with a spatial resolution of 188 m (*vs* NOAA 1 km), and a swath of 800 km; typical repeat cycle is 5 days. Effect of viewing geometry on WiFS data is significant (Pandya *et al*., 2000). Radiometric, atmospheric and geometric corrections were applied to such WiFS data, and image-to-image registration, map projection were first achieved. Then NDVI (mean, maximum, minimum, amplitude, integrated based on maxima) and raw near-infrared band merged with integrated NDVI to enhance vegetation, were mapped. These were then classified by hybrid algorithm on time series sets. A mosaic of the entire country for 9 months (barring July-September : cloud covered) was generated and stratification within the above mentioned states was carried out (Roy *et al*., 2000). Earlier, a more 'macro' level study of vegetation cover and dynamics (seasonal patterns in 6 different agro-climatic zones) had also been carried out over India, using NOAA data base (Jayaseelan and Thiruvengadachari, 1998) of global and local vegetation indices at 4 and 1 km resolutions respectively from 1982 onwards. The peak NDVI provided significant contrasts *e.g.* 0.13 in arid and 0.30 in humid zones, indicative of photosynthesis activity.

2.2. *Regional forest productivity*

An important role of forests in the context of greenhouse warming and global change, is the capture and fixation of carbon from atmospheric CO_2 *via* photosynthesis. Thus, regional net primary productivity is an important parameter. A satellite remote sensing based approach for its estimation at landscape level is presented by Roy and Jain (1998), using Landsat Thematic Mapper T.M. data at a tropical dry decidous forest site in Shivpuri, M.P. in October 1989-January 1990. This sensor also had red and near-infra-red bands suitable to derive NDVI, besides a middle-infra-red band. The authors cited above, experimented with various combinations of these spectral reflectances, in exponential relations with ground-measured NPP, *i.e.* net (above-ground) primary productivity (incremental biomass corrected for litterfall, decomposition, grazing etc.) as well as growth stage-wise CO_2 uptake efficiencies measured by infrared gas analyzer combined with satellite-based linear estimation of Intercepted Photosynthetically Active Radiation (IPAR) from spectral indices – *i.e.* the first method is a purely statistical correlation approach between spectral index and NPP, whereas in the second elaborate method, physical meaning is assigned to spectral index in terms of radiation, and a weighted average conversion efficiency, based on stagewise field measurements, is combined with this radiation, to estimate NPP. They found that integrated NDVI (also derivable from WiFS) is the most suitable spectral index in both the approaches, with typical *r*-square 80%.

2.3. *Terrestrial carbon pools and cycle*

The overall carbon cycling and sequesterisation (fixation or removal from the atmosphere – which can partially mitigate the greenhouse warming), through the terrestrial ecosystems, has several components. Forests, referred in the previous subsection, are just one of them. Agro-ecosystem, including crops and livestock also help fix some carbon if there is an increasing trend in their pools. Soil organic carbon is an important pool, feared to be a source due to land use changes and global warming. Wetlands, marshes, rice fields, cattle, present sources of methane (CH_4), another carbon-based greenhouse gas. While ecosystem level exchange rates need field-based measurements, satellite remote sensing has a significant role in regional assessments. Forest Survey of India's biennial regular surveys, now (since 1980) routinely use remote sensing as an integral additional source besides field observations, to make national forest maps (FSI, 1995).

The effort also covers field inventories of growing stock volumes. Recently, this data base (a combination of satellite and field data) classified in a matrix of 4 forest types at 3 crown densities, for 1992-93, was utilized along with biomass expansion factors, by Chhabra *et al*., 2002a, to estimate the total standing (above plus below ground) biomass in Indian forests, at about 8700 mt (80% : 20% shoot : root). This is a refinement over previous estimate of 8150 mt for 1991 which accounted for fewer (2) crown density classes. The widely varying biomass density was also brought out (27 t/ha:Punjab to 252 t/ha : J&K). Such density estimates coupled with remote sensing based land use changes, can help estimate C fluxes. Case of deciduous forest, for carbon flux from satellite data, is addressed by Prasad *et al*., 2000.

Another use of remote sensing based forest inventory is to estimate soil organic carbon pool in Indian forests. Forest typewise soil organic C densities estimated from published database were combined with the above forest inventory, to arrive at soil organic C pools by major forest types in India (Chhabra *et al*., 2002b) which can form as vital inputs in estimating C release from forests by deforestation. The present total soil organic C pool in Indian forests is estimated as 4.1 PgC in top 50 cm and another 2.7 PgC in the next 50 cm depth. Another important pathway in the forest C cycle is litterfall. Combining these various sub-components, the carbon cycle for the Indian forest component is quantified by Dadhwal *et al*., (1998).

The direct use of satellite data for estimating forest biomass, either by relating satellite spectral reflectances with canopy cover or by defining forest types for further field surveys, is being investigated and evaluated with encouraging success (Tiwari, 1994; Roy and Ravan, 1996). Forest biodiversity mapping is also being done (Srivastava and Oza, 1994; Tiwari, 1998; Roy and Tomar, 2000). The human adverse impact in Vindhyan biodiversity has been studied from satellite data (Jha *et al*., 2000).

The Indian Agro-ecosystem presents a favourable scenario of increasing carbon fixation. There is an intensification of C-cycling in the Indian agro-eco-system, and a small incremental sinking of C. A specific focus on the Indo-Gangetic plain is placed in the study by Dadhwal and Chhabra (2002). As for wetlands and rice fields from the viewpoint of methane flux estimation, again optical and microwave satellite maps along with field emission measurements are found useful. The overall district-level Indian greenhouse gas emissions have been assessed by combining satellite and *in-situ* data (Garg *et al*., 2001).

2.4. *Forest fires and biomass burning*

The specific practice of biomass burning for domestic use (fuel wood) or agriculture, (forest clearing and shifting cultivation) leads to emission of several trace gases, including CO_2, H_2O, CO, CH_4, NO_2 and NMHC's, besides aerosols (particulate carbon). All these constituents play an important role in the radiation budget. The aerosols and NO_2 also lead to surface ozone and hence reduction in UV-B. The natural fire risk has been modeled using remote sensing data by Jain *et al.* (1996). To quantitatively understand the environmental impact of large scale biomass burning, a campaign was conducted in east Godavari District (A.P.) in February 1999, where shifting cultivation was in progress. Besides *in situ* measurements with chemi-luminiscent analyser, infrared gas filter, correlation analyser, CO_2 IR gas analyser, UV-B biometer, ozone analyser, steel canisters (for CH_4) and 5-channel sunphotometer for aerosol optical depths (340 to 1020 nm), satellite data of IRS-P3 WiFS, IRS-IC LISS-III, Defense Meteorological Satellite (DMSP)-Operational Line Scan System (OLS) and NOAA-AVHRR were also collected in ambient (pre-burning) and active biomass-burning phases. The IRS-P3 WiFS data could capture the vegetation dynamics during the shifting cultivation operations-for example, deciduous vegetation, its leaf shedding phase, and fire affected patches (initially detected in NOAA-AVHRR and night-time DMSP-OLS data) are clearly marked out in WiFS imagery of the relevant phases (Prasad *et al*., 1999a; 1999b; Kant *et al*., 2000b). The overall integrated study of biomass combustion and emission inventory, using remote sensing, geographical information system and ground based measurements is presented by Prasad *et al*., 2001; 2002. The related increase of carbonic aerosol optical depth from NOAA-AVHRR and simultaneous decrease in UV-B is discussed by Kant *et al*., 2000a.

2.5. *Thermal and humidity aspects of land covers*

Land surface also plays shorter term roles in weather/climate, besides the longer term effects through carbon, nitrogen cycles discussed in the previous two subsections. The exchange of heat and water-vapour between the land and atmosphere fall in this category. In as much as water vapour itself is a strong greenhouse gas, the "biospheric aspects of the hydrological cycle" (BAHC) is also an important GBP project.

The NOAA-AVHRR thermal infrared data are normally used for sea surface temperature mapping. On land surfaces, the variations in emissivity have to be accounted for, hence it is not operationally feasible to map land surface temperature. However, as a research approach, the same AVHRR(Visible/NIR channels) has been used to first obtain NDVI, and then relate the thermal emissivity to it linearly. In fact first, the broadband (8-14 micron) thermal emissivity is found in terms of fractional vegetation cover in the pixel (assuming values 0.92, 0.986 for soil, vegetation). Then the split-window technique is used on land pixel with the modeled emissivity (from NDVI). The method is found viable to get land surface temperature (LST) to an accuracy of about 1 degree (average over 1 km × 1 km pixel) even in heterogeneous terrains (Kant and Badarinath, 2000). Gupta *et al*., (2000) discuss sensible heat flux, roughness parameter, LST from AVHRR data.

The estimation of evapotranspiration (ET), *i.e.* the moisture input from vegetation (and surrounding soil) into the atmosphere, is probably the most vital yet challenging aspect of BAHC. Satellite derived surface temperature, as discussed above, along with satellite derived albedo – as a measure of fractional vegetative cover – are used to model evapotranspiration (Kant and Badarinath, 1998). Regional scale estimation of Leaf Area index (LAI) and evapotranspiration (ET) from a tropical wet evergreen forest − case of Western Ghats − is attempted through conjunctive use of remote sensing and ground measurements, wherein the satellite sensor is Landsat TM; reasonable maps of LAI and ET could be obtained (Gharai *et al*., 1998).

Soil moisture itself is an important climatic parameter. Estimation of soil moisture on a climate-compatible scale (on 1.5 degree grid), but on a global coverage, from satellite sensors is still an investigative topic. One approach is to relate soil moisture to thermal inertia, as indicated by the rate of rise of surface temperature in the forenoon – either INSAT-VHRR or a pair of NOAA-AVHRR's could be used, at 8.30 and 11.30 IST or so. The greater this rise in temperature, the less the thermal inertia and hence soil moisture : an empirical relation could be established; however this worked better in arid/semi-arid zones like Gujarat/Rajasthan, and a complexity of accounting for the presence of vegetation, *via* NOAA-AVHRR NDVI, was encountered (Pathak *et al*., 1993). As infrared sensors are constrained by cloud cover problem, and because soil emissivity in the microwave range is a sensitive function of soil moisture, it is now customary to explore microwave sensors for soil moisture. Whereas for agricultural application high resolution radars are used, here for global climate study and modeling, lower resolution sensors like microwave radiometers and scatterometers (typical spatial resolution 100 km and 25 km respectively) are more suitable. The Indian satellite IRS-P4 launched in 1999 has a Multichannel Scanning Microwave Radiometer (MSMR) with frequencies 6.6, 10.7, 18 and 21 GHz, at both H and V polarisations, all at an observation angle of about

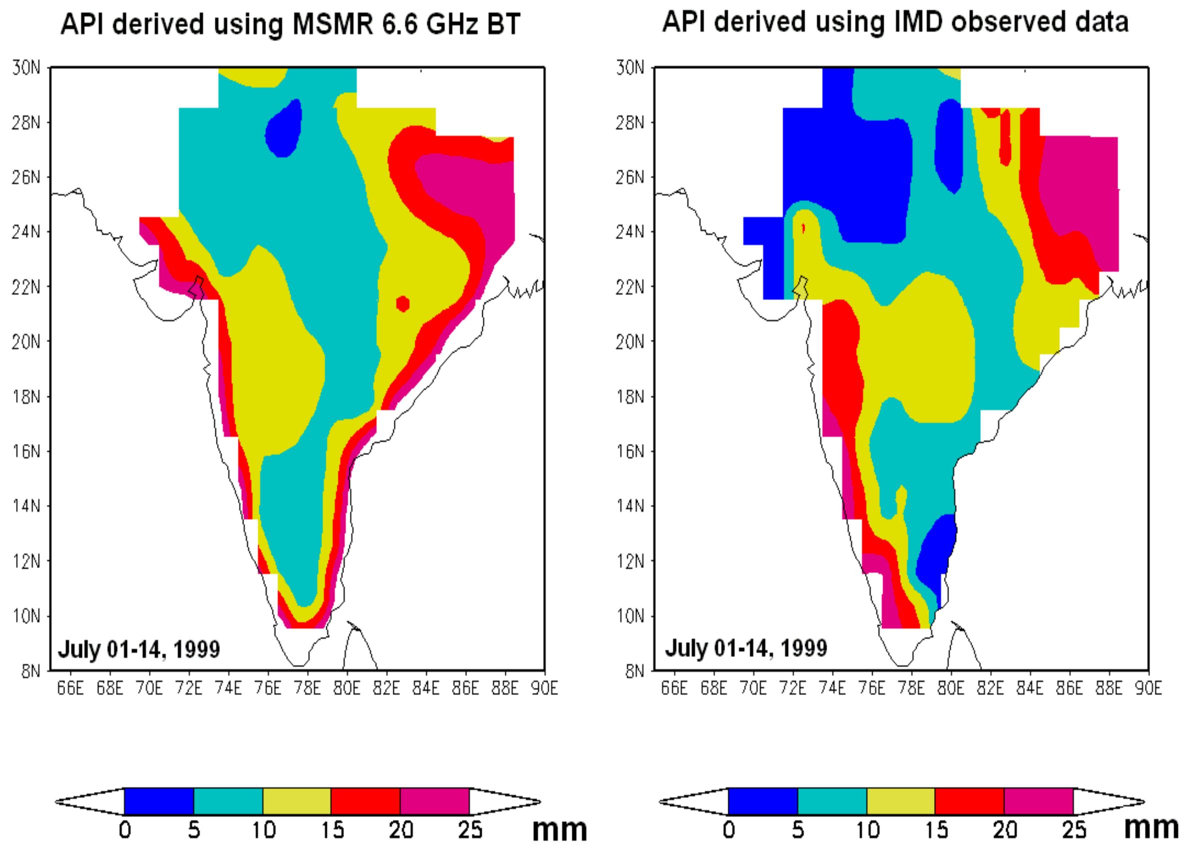

Fig. 1. Comparison of IRS-P4 MSMR derived Antecedent Precipitation Index (API, proxy soil moisture estimate) with the API derived using observed rainfall and surface temperature data for 1-14 July, 1999

50 degrees. Of these, the 6.6 GHz (H) brightness temperature is found to be a good indicator of large scale soil moisture; it also affords a global coverage as fast as once in 2 days (Rao *et al*., 2001; Pal *et al*., 2000).

Fig. 1 shows MSMR ground wetness index *vs* anticedent rainfall index (Rao *et al.*, 2001).

2.6. *Coastal zone*

The coastal zone has a unique role in the overall bio-geo-chemical cycle. Recognising this, a separate component called 'land-ocean interaction in the coastal zone' (LOICZ) is defined under GBP. Satellite sensors with fairly high spatial resolution and multiple spectral channels are desirable, to capture the relatively finer coastal features and water quality variations (Nayak *et al.*, 1996), for example the LISS and PAN (panchromatic 5.8 m resolution) sensors on Indian Remote Sensing Satellites. However, for large water bodies like Chilika lake and for offshore marine water-quality (chlorophyll, sediment and yellow substance), sensors with higher 'gain' (sensitivity to low reflected radiation) and several narrow spectral channels to distinguish such water constituents, are required. The IRS-P4, also called Oceansat-1 has such a sensor called Ocean Colour Monitor (OCM) with 8 narrow spectral channels (412 to 865 nm).

In the context of GBP and global warming, one issue in the coastal zone (and islands) is the expected impact of future sea level rise. A typical case study of such a likely impact on the Gujarat Coast, of an assumed 50 cm – 100 cm rise in sea level, has been carried out using IRS LISS-I data base at 1:2 m scale (Nayak, 1994). The spatial resolutions of LISS-I, II, III respectively are 72, 36, 23 meters. Another concern is that of human land-use changes exerting ecological pressures on lakes. In this connection, a case study of and around the Chilika lagoon

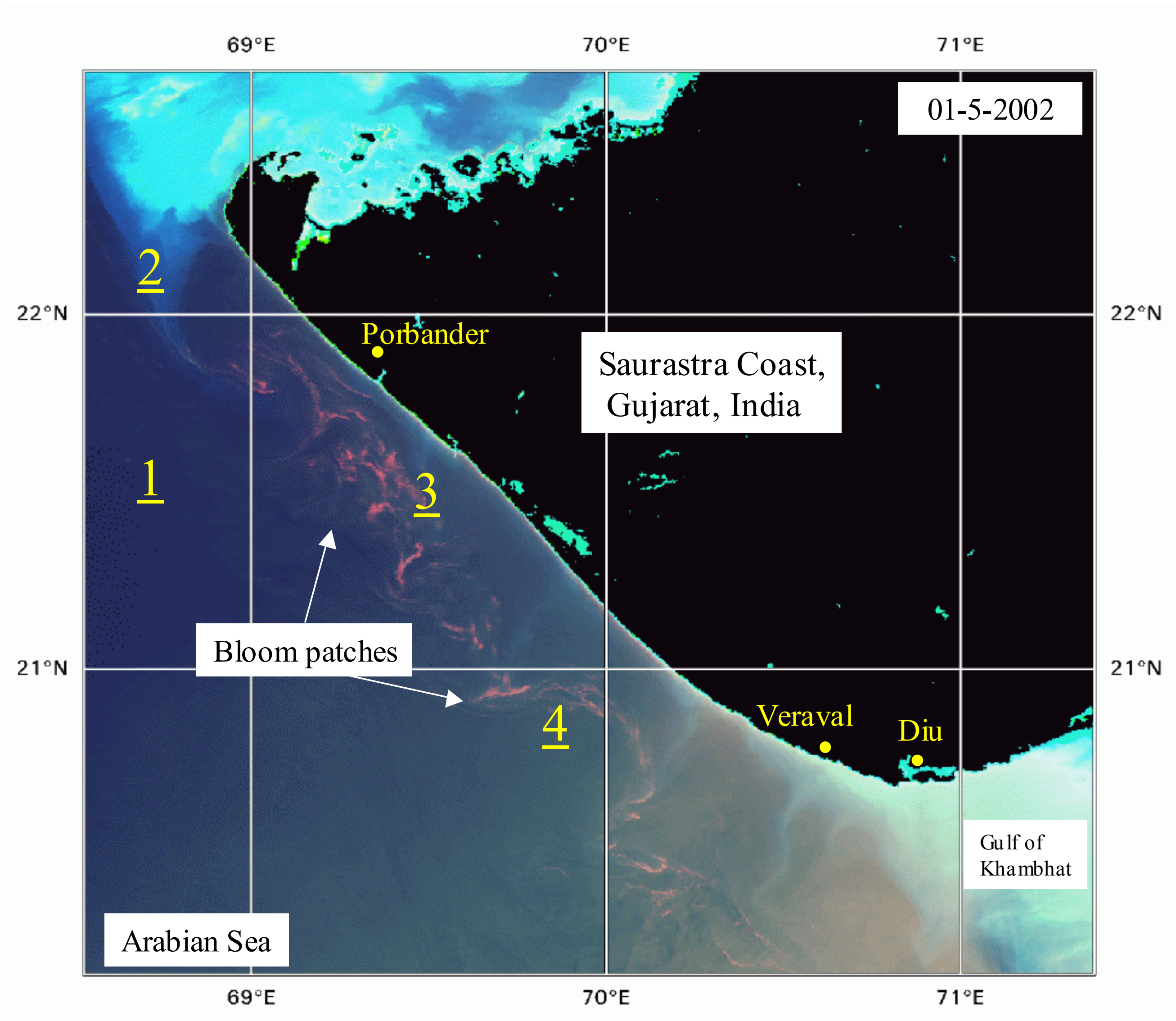

Fig. 2. Detection of Algal bloom around Saurashtra coast, Gujarat, India

(Orissa) has been carried out, combining several sensors data, *viz*. IRS-P4 OCM, IRS-P3 WiFS and MOS (Multispectral Optoelectronic Scanner, similar to OCM in function, provided by German Space Agency), IRS-1C and 1D PAN, LISS-III, WiFS, IRS-1A and IB LISS-II, and earlier Landsat TM and MSS (Multispectral Scanner) besides topographic maps and field surveys, to relate landuse changes (since 1929) with increase in siltation, weed growth, near-shore sediments, yellow substance (degraded biological matter) and littoral drift (resulting in adverse shoreline changes -–for example, reduced number of inlet openings from sea to lake, which used to be 3 until about 1980, but now there is only one opening – resulting in decreased salinity and hence fishery productivity as well). Further study of transport of terrestrial carbon to the coastal region is in progress (Nayak *et al*., 2000). Kolleru Lake (in A.P.) has also been studied for changes, using Landsat, IRS (Rao *et al*., 2000a).

3. Marine ecosystems

3.1. *Carbon fixation*

As in case of terrestrial productivity, marine photosynthesis too, represents a sink for atmospheric CO_2 – which is beneficial from greenhouse viewpoint. The specific satellite sensors alluded to above which are sensitive to marine chlorophyll, *viz*. IRS-P3 MOS and IRS-P4 OCM, and a few international ones like Sea Star satellite's Sea WiFS (Sea-viewing Wide Field Sensor) and

ADEOS satellites' OCTS (Ocean Colour & Temperature Sensor) and EOS/TERRA satellite's MODIS (Moderate Resolution Imaging Spectrometer) help in estimation of biological primary productivity in the ocean, related to CO_2 fixation.

The primary productivity along the east coast of India is being attempted to be estimated from ocean colour sensors (of the type listed above). *In situ* underwater radiometer data as well as chlorophyll measurements, at a test site near Paradip (Orissa) are used to benchmark satellite estimate of chlorophyll. Then primary productivity is estimated from non-spectral photosynthesis-*vs*-irradiance (PI) model from literature, adjusted by *in situ* measurements for local conditions. The results indicate the heavy effect of atmospheric aerosols which introduce path radiances in the selected spectral channels. Thus, this is an active developmental topic (Rao *et al*., 2000b). In a similar manner, another test site, this along the west coast of India (off Gujarat) is being studied, again resorting to site-specific non-spectral PI model. The satellite inputs in this model are : the chlorophyll concentration and the diffuse attenuation co-efficient. Further, a regional factor or fraction 'f' is applied to the total primary productivity, to arrive at the 'new' primary productivity (using upwelled nitrogen rather than recycled urea, ammonia and dissolved organic carbon *i.e*. a true measure of fresh atmospheric CO_2 fixed in ocean). Remote sensed parameters could be having an influence on this fraction 'f', (Watts *et al*., 1999; Morrison *et al*., 2000). But at present this is found from ship's observation of new and recycled production or obtained from literature, in biologically homogeneous domains. Finally, maps of 'new primary productivity' are prepared combining satellite and *in situ* data; algal blooms stand out prominently as patches of higher 'new' production in such maps (Dwivedi *et al*., 2000). It is noted that beyond the above, another factor called export 'e' is to be finally applied, representing 'raining out' of carbonate pellets from the mixed layer into deeper ocean – that is the ultimate removal (barring long-term recycling on a millennial scale) of the fixed carbon. This too is to be regionally determined (in the Arabian Sea it is about 0.25), or modeled in terms of oceanic parameters, some of which could be remotely sensed.

Fig. 2 gives an example of algal bloom (Nayak, S.R., Priv. Comm.).

A few random international examples will be helpful, to indicate the further potential role of satellite data in the marine carbon fixation problem. The rather unexpected role of an oceanic sensor called altimeter (a nadir looking microwave radar wherein the time of return of a pulse from the ocean surface back to the satellite is used to map relative ocean surface topography to about 10 cm) in studying inter-annual and basin scale variations of biological new production in the tropical Pacific Ocean during 1992-1999, covering an El-Nino and a La-Nina event, is demonstrated by Turk *et al*., 2000. Their method is indirect : new production is related (negatively) to the 20° C isotherm depth (from *in situ* data) which in turn, is related to the sea level anomaly or sea surface height, SSH (combining *in situ* with altimeter data of satellite called TOPEX/POSEIDON). Another approach towards new production estimate, is based on inferring first, surface nitrate due to wind driven upwelling (in summer) or thermal convection (in winter), from a combination of chlorophyll and sea surface temperatures from satellites (Goes *et al*., 2000).

However, some authors point out that nitrate alone is not sufficient to induce productivity; iron deficiency creates what are known as HNLC (High Nitrate, Low Chlorophyll) zones. But there is a good scope for positive feedback : any initial high abundance of chlorophyll can trap more solar heat, thinning and warming the mixed layer while cooling the subsurface, which in turn can encourage lower level nutrients to mix into the upper layer *via* cold core upwelling and turbulent mixing, giving a positive feedback. Model results and observations in the Arabian Sea and Pacific Ocean corroborate this line of thinking. Here, the use of remote sensed chlorophyll is made not only directly, but also in judging the vertical distribution of solar heating of the upper ocean layer, which is then fed to a thermodynamic ocean model to predict sea surface and lower layer temperatures and thence future productivity (Nakamoto *et al*., 2000). Methods of estimating primary productivity by combining satellite maps of chlorophyll and sea surface temperature are still evolving (Asanuma *et al*., 2000).

Some authors have taken recourse to 'physical' oceanographic data, to understand 'biological' production. Presented below are gists of 3 examples : (*i*) Rodriguez and Stuardo (2000) have studied the relation of winds and wind-induced upwelling, with chlorophyll concentration in the Panama Basin. They used data of microwave scatterometer (NSCAT) and ocean colour/temperature sensor (OCTS) from the Japanese satellite ADEOS. Monthly average oceanic Ekman pumping (vertical velocity) map, estimated from NSCAT wind stress, showed that strong upwelling (March-April 1997) was associated with substantial increase in chlorophyll and a decrease in sea-surface-temperature, as expected. (*ii*) In the Arabian Sea, the south-west monsoon season offers similar upwellings; but in north-east monsoon, a different mechanism, *viz*. convection induced by surface cooling, brings or mixes nutrients into the upper layer, leading to higher biological productivity; such inverse relation of sea-surface-temperature and cholorophyll in winter on the Arabian Sea, is found from OCTS (Jadhav *et al*., 2000). Sasmal and Somasundar (2000) used NOAA AVHRR and Nimbus CZCS to study these phenomena. (*iii*) The case of Indonesian Archipelago is presented by Moore and Marra (2000). As contrasting epochs, the late 1997 El-Nino and the late 1998 La-Nina show : Southern Oscillation Index rising from –2.5 to +1, the sea surface height anomaly (off Java, as seen in TOPEX/POSEIDON/ERS altimetric product) going from –22 cm to +20 cm (the sharpest protracted rise in that whole decade), indicative of upwelling and downwelling, analysed wind anomaly in November 1997 still easterly favouring the upwelling, sea-surface temperature (from NOAA-AVHRR 1 km local area coverage provided by Australia) being low 24° C in October 1997 and high 29° C in end 1998, and chlorophyll concentration (from Sea WiFS at 9 km) abruptly rising from 2 mg/cu m in October 1997 to 14 mg/cu m in mid November 1997, then falling back to near zero by early 1998 and staying low.

3.2. *Carbon dissolution*

Before closing this section, it is in order to point out that biological photosynthetic fixation of carbon dioxide is not the only mechanism for CO_2 uptake from the atmosphere by the ocean. In fact, inorganic exchange by diffusion and (at high winds) bubbles caused by wind-wave breaking – the latter being drastically high at gales (Bortkovskii, 2000) – is also to be accounted for. Indeed, the Arabian Sea, despite its high overall biological productivity which helps it to take up CO_2 emits inorganic carbon, and acts as a net source of CO_2 to the atmosphere, estimated at 250 TgC (Sarma, 2000). Monahan (2000) has suggested the use of satellite microwave radiometers (which respond to bubbles' high emissivity) to judge the foam covered fraction of the sea, to which the air-sea gas transfer co-efficient is proportional. In normal, placid times when bubbles are not dominating, the usual diffusive equation for CO_2 flux is used involving product of an exchange co-efficient (function of SST and wind speed), solubility (function of SST and salinity) and differential partial pressure of CO_2 (sea *vs* air). Of these factors, SST, wind speed are amenable to satellite remote sensing (salinity is an experimental topic). Further, an empirical quadratic regression is proposed, for estimating oceanic partial pressure of CO_2, involving SST, chlorophyll and salinity by Osawa *et al*., (2000) – again, herein 2 out of 3 input parameters are amenable to remote sensing. However, in the above simplistic discussion, we have taken the exchange co-efficient to be a function of 'wind speed' along with SST. Actually it is a function of friction velocity at the sea surface. Fortunately satellite wind sensors such as microwave scatterometer, radiometer are indeed responding to the friction velocity or wind-stress (not wind speed) *via* scattering or emission of microwaves. But in practice, empirical relations called 'model functions' are obtained between back scattering and wind speed at some height like 10 meters due to the experimental arrangement. In that case, one has to use 'satellite U-10' to find the drag co-efficient. Now this relation is not unique but it is a family of curves varying with 'wave age', represented *via* sigma-*p*, the angular frequency of wind wave spectral peak. By painstakingly determining relation of roughness-length with such sigma-*p* (a negative slope obtained indicating positive dependence of wind stress on wave age/growth) in varied laboratory and field conditions, a family of drag co-efficient curves is obtained by Suzuki *et al*., 2000. So in the end, our round about approach lands us in the additional problem of finding wave age from remote sensing or otherwise – a function of fetch or duration of wind. Either 'Analysed Wind Field History' of past many hours, or advanced microwave sensor like Synthetic Aperture Radar which can give wave set up (slope, spectrum) would be needed. Perhaps we should rethink, why not directly relate backscatter with wind-stress by field experiments.

3.3. *Ocean-atmosphere heat exchanges*

A global role of oceans in the atmospheric circulation, is the exchange of sensible and latent heat between the ocean and the atmosphere. Methods of estimating these from satellite observations are evolving. As in the CO_2 gas transfer problem, H_2O transfer also requires consideration of variable exchange co-efficient as per the environment. Further, the near-surface air humidity and temperature are to be estimated. While satellite sounders do not have the fine vertical resolution required to provide these directly, some indirect methods are being attempted. The total integrated water vapour column of the atmosphere, amenable to remote sensing by microwave radiometers having channels near the 22 GHz water-vapour absorption line (U.S. Defense Meteorological Satellite Programme's Special Sensor Microwave Imager DMSP SSM/I and Indian Oceansat – 1 MSMR) is climatologically related to the near-surface humidity; refining such relation regionally and seasonally, variability of latent heat and water vapour flux divergence over the Indian Ocean region has been studied by Vinayachandran and Ramesh Kumar (1990), Ramesh Kumar and Rao (1990) and Nair *et al*., (1995). Another approach is to use 3 layer moisture from NOAA sounder (Simon *et al*., 1995). Gautier *et al*., (1998) study seasonal and inter-annual variability of air-sea interaction over the Indian Ocean using satellite data sets (SST, LHF, SW Rad., Precip.) in novel ways.

A recent trend is to bypass the bulk aerodynamic formulation (with satellite derived parameter inputs), and rather relate the heat exchanges directly to the brightness temperatures; such an attempt with Oceansat-1 MSMR data is presented by Singh *et al*., (2001), giving a better accuracy; such estimates help in diagnosing and refining atmospheric models. A multi-angle sensor, Along Track Scanning Radiometer on the European Remote Sensing Satellite is used, to study latent heat in relation to monsoon, by Mathur *et al*., (1999), besides near-surface-humidity. Akin to El-Nino/La-Nina, Indian Ocean dipole in SST/SSH/Chlorophyll is found from satellite data, by Saji *et al*., (1999).

4. The cryosphere

4.1. *Polar sea-ice*

The polar ice-caps and the adjoining sea-ice, besides seasonal variation, may also have a secular trend in their area, thickness, temperature, etc. If there is global warming, the polar sea-ice, ice-shelf are expected to have relatively rapid impacts; the latter would also contribute significantly to a general sea-level-rise by both melting and sliding or shelf separation effects. Conventional monitoring being difficult and perhaps incomplete, satellite observations are being explored (Gloersen and Campbell, 1988). Recently after the launch of Oceansat-1 MSMR, Vyas *et al*., (2001), analysed its data over the Antarctic and the southern Polar Ocean. Further details can be found in a separate article in the present issue of MAUSAM. Satellite derived sea-ice has been studied in relation to NAO, by Dugam (2000).

4.2. *Himalayan glaciers*

Another sensitive component of the world's cryosphere, mountain glaciers are adversely affected by global warming. To quantify the changes in case of Himalayan glaciers, a detailed study using satellite and *in situ* data is undertaken. Interested reader may see Kulkarni (1991), and Kulkarni (2001), Kulkarni and Bahuguna (2002), Kulkarni *et al*., (2002) and also, for overall snow-cover monitoring aspects, their separate article in the present issue of MAUSAM.

5. The Atmosphere : Constituents, Radiation, Modeling

5.1. *Atmospheric aerosols*

Aerosols have important radiative, chemical and cloud-condensation microphysical roles. Besides natural aerosols, now man-made aerosols are also getting injected in the atmosphere.

Considering that parallel articles on aerosol monitoring are included in the present issue of MAUSAM, here much discussion thereof is not given. An earlier Review by Subbaraya *et al*., (2000) may also be seen.

A novel use of an ozone sensor on satellite, *viz.* Nimbus-7 Total Ozone Mapping Spectrometer (TOMS), by attributing the deviations of 340 *vs* 380 nm radiance differences from theoretical expectation, to aerosols, is given by Moy *et al*., (1999) over the Indian monsoon region.

In the context of GBP and global change, the aerosols may present an opposite (negative) forcing to that of the greenhouse gases in the troposphere *i.e*., aerosols may decrease the tropospheric warming; in the stratosphere on the other hand, they may enhance the cooling caused by greenhouse gases. This is the broad outcome of a model study of non-cloud radiative forcing, and its heating rate impact, due to anthropogenic sulphate aerosols: however the author of it (Rajeevan 1998) has rightly pointed out that there are uncertainties in the computed sulphate concentration fields by various chemistry-transport models, and hence satellite observations of aerosols are desirable. Raj and Devara (1997) studied satellite observed aerosols after volcanoes.

5.2. *Trace gases from satellites*

Internationally this is a vast and active topic. Limiting ourselves to retrievals and utilizations in South Asia, Joshi and Ramesh (1994) have used the infrared 9.6 micron channel on NOAA sounder, to estimate ozone total column. Begum (1999) utilized TOMS ozone column data of October 1982 – September 1983 in the entrance zone of East Asia Sub-Tropical Jet stream, to infer air transfer from the troposphere to the stratosphere in spring season. In winter, the ozone contour and gradient indicate the wind direction and speed of the jet. The ERS-2 Global Ozone Monitoring Experiment (GOME) derived total ozone data over the Indian subcontinent for 1996-99 have been examined in relation to El-Nino and a significant increase at mid-latitudes found (Sarkar and Singh, 2000). Nimbus TOMS derived total ozone data of northern hemisphere have been examined by Patil and Revadekar (2000). Further details are given in a separate article in the present issue of MAUSAM.

5.3. *Radiation budget components*

This is an important aspect of climate and GBP studies; please see separate article. The use of INSAT OLR to estimate the divergent part of upper-air wind, and its further impact in global model (analysis and forecast) are described by Kulkarni *et al*., (1997). Mahajan *et al*., (1998) analyse satellite derived radiative budgets during different phases of monsoon.

5.4. *Climate model experiments*

A few climate modeling numerical experiments to predict future climate (especially Indian regional monsoon) have been undertaken. While in principle, these are only thought experiments, in practice they introduce realistic boundary conditions, be they natural (snow-cover, SST) or by human perturbation (deforestation, greenhouse gas injection). In most cases, satellite observations play a vital role in providing realistic input data or even future trends. For example, Thomas *et al*., (1999) simulate global winter and summer circulation with their model, forced only with solar radiation (integrated from rest for 6 years). Here, seasonal land albedo, SST, sea-ice, snow-covered land area etc. are required as boundary conditions. Implicitly these data sets (available from various sources) had used satellite data. Experiments specifically geared towards anthropogenic perturbations in climate are carried out by Pal *et al*., (1994; 2001). In the former study deforestation over South/South-east Asia was represented by increased albedo (both, 'control' and 'experiment' values of land albedos can be traced back to satellite estimates), and reduction in rainfall was obtained. In the latter study, CO_2 was doubled and changes in rain pattern obtained (direction of pattern-changes is matching with recent trend of observation for example, increase on the west coast and decrease in the northeast). Here the 'expected' doubling of CO_2 in about 50-100 years, is really a proxy for a combination of several greenhouse gases (CO_2, CH_4, CFC etc.), wherein all other trace gases roughly equal the effect of CO_2. The trends of various trace gases over the next few decades are extrapolated from current trends (many of them obtained from a combination of satellite data and *in situ* measurements) moderated by international protocols. Thus we see that even numerical thought experiments are based on the foundation of observations, many of them from satellites. In general, satellite data are useful to calibrate photo-kino-chemical models, particularly tuning of uncertain parameters, and for providing boundary conditions.

Lal (2000) also carried out similar future climate simulations, but the added effect of sulfate aerosols was accounted for. Again, satellite data would have helped in trend inputs. Mohanty and Ramesh (1994) studied the energetics of the monsoon, using ECMWF fields of 1979-88, which would have incorporated improved soundings of TIROS-N/NOAA satellites; they found important role of moisture convergence in the seas around India, which such data would have helped in.

6. Concluding remarks

This brief review could address only a few of the studies done or in progress, on the utilization of satellite data in GBP, particularly confined to the Indian scenario. The forthcoming Oceansat-II, Megha-Tropiques and advanced INSAT satellites beside foreign satellite data should help in further progress in GBP (Gopalan *et al*., 1999). Needless to add, it is advisable to be aware of the limitations of satellite data such as : mutual calibration of different sensors, interfering factors in interpretation of satellite observations etc.

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References

Asanuma, I., Matsumoto, K. and Kawano, T., 2000, "Vertically resolved primary productivity model for satellite remote sensing", *Proc. PORSEC*, Goa, India, 5-8 December 2000, 502-504.

Begum, D.A., 1999, "Relation between total ozone and sub-tropical jet stream", *Mausam*, **50**, 2, 197-202.

Bortkovskii, R. S., 2000, "Wind-wave breaking and atmosphere-ocean gas exchange", *Proc. PORSEC*, Goa, India, 5-8, December 2000, 403-407.

CEOS (Committee on Earth Observation Satellites), 1997, Year book, ESA, p145.

Charney, J. G., 1975, "Dynamics of deserts and drought in the Sahel", *Quart. Jour. Roy. Met. Soc.,* **101**, 193-202.

Chhabra, A., Palria, S. and Dadhwal, V. K., 2002a, "Growing stock based forest biomass estimate for Indian forests", *Biomass and Bioenergy,* **22**, 3, 187-194.

Chhabra, A., Palria, S. and Dadhwal, V. K., 2002b, "Soil carbon pool in Indian forests", *Forest Ecology and Management*, **5877**, 1-13.

Dadhwal, V. K. and Chhabra, A., 2002, "Land-use/cover changes in the Indo-Gangetic plain – Cropping patterns and agro-eco-system carbon cycle", Ch. 9 in: *Land-Use-Historical perspectives-Focus on Indo Gangetic Plain*" (Book) Eds: Y.P. Abrol, S. Sangwan and M.K. Tiwari, Allied Pubs., 249-276.

Dadhwal, V. K., Pandya, N. and Vora, A. B., 1998, "Carbon cycle for Indian forest ecosystem-A preliminary estimate", in : *Global Change Studies*, (vide ISRO 1998 Reference), 411-429.

Desai, P. S. and Joseph, G., 1994, "Satellite observation for the study of global change", *Ind. Jour. Radio & Space Phys.,* **23**, 101-124.

Dugam, S. S., 2000, "Satellite derived sea-ice in the Arctic region, North Atlantic Oscillation, and monsoon variability", (Abstract), *XI National Space Science Symposium*, Puri, India, 1-4 March, 2000, Abst. No. DS-1-1, p1.

Dwivedi, R. M., Raman, M. and Singh, S. K., 2000, "Estimation of transport of atmospheric CO_2 to the Arabian Sea through modeling new primary production", in : *ISRO-GBP : WS-III,* (vide ISRO 2000 Reference), 111-115.

FSI, 1995, "Extent, composition, density, growing stock and annual increment of India's forests", Forest Survey of India, Ministry of Environment and Forests, Govt. of India, Dehra Dun, p128.

Garg, A., Bhattacharya, S., Shukla, P. R. and Dadhwal, V. K., 2001, "Regional and sectorial assessment of greenhouse gas emission in India", *Atmosph. Environ.*, **35**, 2679-2695.

Gautier, C., Peterson, P. and Jones, C., 1998, "Variability of air-sea interaction over the Indian Ocean derived from satellite observations", *Jour. Clim.,* **11**, 1859-1873.

Gharai, B., Murthy, M. S. R., Lakshmi, V. U., Nemani, R. and Dutt, C. B. S., 1998, "Regional scale estimation of evapotranspiration in tropical wet evergreen forests : Western Ghats, India", in : *Global Change Studies*, (vide ISRO 1998 Reference), 253-300.

Gloersen, P. and Campbell, W. J., 1988, "Variation in the Arctic, Antarctic and global sea-ice covers during 1978-1987 as observed with the Nimbus-7 SMMR", *Jour. Geophys. Res.*, **93**, 10666-10674.

Goes, J. I., Gomes, H. D. R., Limsakul, A., Balch, B. and Saino, T., 2000, "El-Nino mediated changes in biological productivity in the sub-Arctic Pacific Ocean-Results from Satellite and ship data", *Proc. PORSEC*, Goa, India, 5-8 December, 2000, 537-542.

Gopalan, A. K. S., Desai, P. S., Narayanan, M. S., Joshi, P. C. and Manikiam, B., 1999, "Indian scenario of satellite data for monsoon and climate studies", *Vayu Mandal*, (Bull. Ind. Met. Socy.), **29**(1-4) – Sp'l Issue : Asian Monsoon and Pollution, Guest Eds: S.K. Dube, U.C. Mohanty, K.J. Ramesh and A. Gupta, 383-386.

Gupta, R. K., Vijayan D. and Prasad, T. S., 2000, "Estimation of land surface processes and parameters from satellite data", (Abstract), *XI National Space Science Symposium,* Puri, India, 1-4March, 2000, Abst. No. DS1-3-9, p77.

Hansen, J., Rossow, W., Carlson, B., Lacis, A., Travis, L., Del-Genio, A., Fung, I., Cairns, B., Mishchenko, M. and Sato, M. 1995, "Low-cost long-term monitoring of global climate forcings and feedbacks", *Climatic Change,* **31**, 247-271 (conveniently available as reproduction in the Book: 'Long-term climate monitoring by the global climate observing system' Ed: T.R. Karl, 1996, Kluwer Acad. Pubs, p117-147).

ISRO (Indian Space Research Organisation), 1998, "Global change studies" (Book) on scientific results from the ISRO geosphere biosphere programme, (Eds) B.H. Subbaraya, D. P. Rao, P. S. Desai, B. Manikiam, P Rajaratnam; Bangalore, India, p442.

ISRO (Indian Space Research Organisation), 2000, Third workshop on scientific results from ISRO's GBP, 3-4 October 2000, Bangalore.

Jadhav, N. A., Rao, L. V. G. and Panigrahy, R. C., 2000, "Pigment patterns in the Arabian Sea : Spatio-temporal variability as observed by ADEOS", *Proc. PORSEC*, Goa, India, December, 5-8, 2000, 50-54.

Jain, A., Roy, P. S., Ravan, S. A., Singh, R. K. and Das, K. K., 1996, "Fire risk modeling using remote sensing and geographic information system", *Current Science*, **70**, 928-933.

Jayaseelan, A. T. and S. Thiruvengadachari, 1998, "Global vegetation index analysis for macro vegetation dynamics in India", in : *Global change studies*, (vide ISRO 1998 Reference), 191-206.

Jha, C. S., Singh, J. S., Raghubanshi, A. S., Dutt, C. B. S., Goparaju, L. and Tripathi, A., 2000, "Community diversity assessment of Vindhyans using remote sensing and GIS", in : *ISRO-GBP : WS-III,* (vide ISRO 2000 Reference), 99-102.

Joseph, G., 1996, "Imaging sensors for remote sensing", *Rem. Sens. Reviews*, **13**, 257-342.

Joshi, P. C. and Ramesh, K., 1994, "Satellite estimation of ozone using infrared remote sensing", in : *Global Change Studies*, ISRO-GBP-SR-42-94, 15-18.

Kant, Y. and Badarinath, K. V. S., 1998, "Evapotranspiration modeling using satellite derived albedo and surface temperature", *Jour. Ind. Soc. Rem. Sens.,* **26**, 3, 113-120.

Kant, Y. and Badarinath, K. V. S., 2000, "Studies on land surface temperature over heterogeneous areas using AVHRR data", *Int'l. Jour. Rem. Sens.,* **21**, 8, 1749-1756.

Kant, Y., Ghosh, P. K., Sharma, M. C., Gupta, P. K., Prasad, V. K., Sharma, C., Badarinath, K. V. S. and Mitra, A. P., 2000a, "Studies on aerosol optical depth in biomass burning areas using satellite and ground based observations", *Infrared Physics and Tech.,* **41**, 21-28.

Kant, Y., Prasad, V. K. and Badarinath, K. V. S., 2000b, "Algorithm for detection of active fire zones using NOAA-AVHRR data", *Infrared Physics and Tech*., **41**, 29-34.

Kiehl, J. T. and Briegleb, B. P., 1993, "The relative roles of sulfate aerosols and greenhouse gases in climate forcing", *Science*, **260**, 311-314.

Kiehl, J. T., Schneider, T. L., Portman, R. W. and Solomon, S., 1999, "Climate forcing due to tropospheric and stratospheric ozone", *Jour. Geophy. Res.,* **104**, 31239-31254.

Kulkarni, A. V., 1991, "Glacier inventory in Himachal Pradesh using satellite data", *Jour Ind. Soc. Rem. Sens.,* **19**, 3, 195-203.

Kulkarni, A. V. 2001, "Effect of climate variations on Himalayan Glaciers: A case study of upper Chandra River basin", in : Remote Sensing Applications (Ed. M G. Srinivas), Narosa Publishing House, New Delhi, 477-486.

Kulkarni, A. V., Bahuguna, I. M. 2002, "Glacial retreat in the Baspa Basin, Himalayas, monitored with satellite stereo data", *Journal of Glaciology*, **48**, 160, 171-172.

Kulkarni, A. V., Mathur, P., Rathore, B. P., Alex, S., Thakur, N., and Kumar, M., 2002, "Effect of Global warming on snow ablation pattern in the Himalayas", *Current Sciences* (In press).

Kulkarni, P. L., Mitra, A. K., Narkhedkar, S. G., Bohra, A. K. and Rajamani, S., 1997, "On the impact of divergent part of the wind computed from INSAT OLR data on global analysis and forecast fields", *Met. and Atm. Phys.*, **64**, 61-82.

Lal, M., 2000, "Simulation of intra-seasonal and inter-annual variability in Asian Monsoon", in *Global Change Studies*, (vide ISRO 2000 Reference), 1-6.

Mahajan, P. N., Chinthalu, G. R. and Rajamani, S., 1998, "Use of satellite-observed radiative energy budget during onset phase of summer monsoon", *Proc. Ind. Acad. Sci. (Earth & Planet Sci.),* **107**, 19-32.

Mathur, A. K., Gohil, B. S. and Agarwal, V. K., 1999, "ERS-1 ATSR derived surface humidity, Sea surface temperature and latent heat flux variations associated with the 1994 monsoon", *Vayu Mandal* (Bull.In. Met. Socy.), **29**, 1-4 – Sp'l. Issue : Asian Monsoon and Pollution, Guest Eds: S.K. Dube, U.C. Mohanty, K.J. Ramesh and A.Gupta, 396-400.

Mohanty, U. C. and Ramesh, K. J., 1994, "A study on the dynamics and energetics of the Indian summer monsoon", *Proc. Ind. Nat'l. Sc. Acad,* **60**(A1), 23-55.

Monahan, E. C., 2000, "Oceanic whitecaps: Features of the Sea-surface readily detectable *via* satellite remote sensing that are direct indictors of the magnitude of air-sea transfer co-efficient for climate gases such as carbon dioxide", *Proc. PORSEC*, Goa, India, 5-8 December 2000, 408-411.

Moore, T. S. (II) and Marra, J., 2000, "Mechanisms of chlorophyll variability in the Indonesian Archipelago during the 1997-98 El-Nino and the 1998-99 La-Nina : A synergy of remotely sensed ocean colour, SST and altimetry (Invited Paper)", *Proc. PORSEC,* Goa, India, 5-8 December 2000, 122-126.

Morrison, J. M., Kamykowski, D., Datta, D. M., Zentara, S. J. and Switzer, A. C., 2000, "A northern Indian Ocean comparison between nutrient availability dervied from AVHRR SST and phytoplankton biomass productivity based on Sea WiFS", *Proc. PORSEC*, Goa, India, 5-8 December 2000, 354-358.

Moy, L., Herman, J., Hsu, C., Krotkov, N., Larko, D., Seftor, C. and Torres, O., 1999, "Aerosol measurements from TOMS satellite (sensor over the) Indian monsoon region", *Vayu Mandal* (Bull. Ind. Met. Socy.), **29**, 1-4 – Sp'l Issue : Asian Monsoon and Pollution, Guest Eds : S.K. Dube, U.C. Mohanty, K.J. Ramesh and A.Gupta, 406-409.

Nair, N., Pandey, P. C., Simon, B. and Gautam, N., 1995, "Seasonal variability of latent heat fluxes over tropical Indian Ocean using SSM/I and NOAA/AVHRR satellite data", *Int'l Jour. of Climatology (London)*, **15**, 303-312.

Nakamoto, S., Prasanna-Kumar, S., Oberhuber, J. M., Saito, H. and Muneyama, K., 2000, "Chlorophyll modulation of mixed-layer thermodynamics in a mixed-layer isopycnal general circulation model – Examples from Arabian Sea and Equatorial Pacific*", Proc. PORSEC,* Goa, India, 5-8 December 2000, 505-510.

Nayak, S. R., 1994, "Application of remote sensing data for estimation of impact of sea-level rise along the Gujarat coast", in : *Global Change Studies*, ISRO-GBP-SR-42-94, 337-348.

Nayak, S. R., Chauhan, P., Chauhan, H. B., Bahuguna, A. and Nath, N., 1996, "IRS-1C applications for coastal zone management", *Current Science*, **70**, 7, 614-618.

Nayak, S. R., Behera, G., Sahoo, R. K., Rajawat, A. S., Das, N. C., Kumar, P., Nayak, B. K., Panigrahy, P. K., Pradhan, Y. and Anuradha, T., 2000, "Land ocean interaction – A case study around the Chilika lagoon", in : *ISRO-GBP : WS-III,* (vide ISRO 2000 Reference), 116-120.

NOAA-NASA, 1994, "The National Oceanic and Atmospheric Adminstration – National Aeronautics and Space Administration pathfinder program", Univ. Corp. Atm. Res. Publ., August 1994, p23.

Osawa, T., Kuroiwa, D., Ishizaka, J., Suwa, J., Akiyama, M. and Sugimori, Y., 2000, "Study of relationship between TCO_2 & pCO_2 in the North Pacific using Sea WiFS and AVHRR", *Proc. PORSEC*, Goa, India, December, 5-8, 2000, 359-362.

Pal, P. K., Kishtawal, C. M. and Narayanan, M. S., 1994, "Impact of surface albedo changes on Indian monsoon", in : *Global Change Studies*, ISRO-GBP-SR-42-94, 283-296.

Pal, P. K., Thapliyal, P. K. and Kishtawal, C. M., 2000, "Impact of land surface processes on the Indian summer monsoon (soil moisture from MSMR)", in : *ISRO-GBP : WS-III* (vide ISRO 2000 Reference), 127-128.

Pal, P. K., Thapliyal, P. K. and Dwavedi, A. K., 2001, "Regional climate changes due to double CO_2 : Simulation by CCM3", *Mausam,* **52**, 1, 221-228.

Pandya, M. R., Dadhwal, V. K. and Navalgund, R. R., 2000, "Effect of WiFS viewing geometry on crop reflectance : A simulation study using SAIL model", *Int'l Jour. Rem. Sens.,* **21**, 9, 1931-1938.

Pathak, P. N., Rao, B. M. and Potdar, M. B., 1993, "Large area soil moisture estimation using INSAT VHRR IR data", *Ind. Jour. Radio & Space Phys*., **22**, 156-164.

Patil, S. D. and Revadekar, J. V., 2000, "An analysis of TOMS ozone data in the tropics of the Northern Hemisphere", (Abstract) *XI National Space Science Symposium*, Puri, India, March, 1-4, 2000, Abst. No. DS1-3-24, p92.

Prasad, V. K., Kant, Y. and Badarinath, K. V. S., 1999a, "Studies on forest fires using DMSP OLS data", *Jour. Ind. Soc. Rem. Sens.,* **27**, 3, 141-148.

Prasad, V. K., Kant, Y. and Badarinath, K. V. S., 1999b, "Vegetation discrimination using IRS-P3 WiFS – Temporal data set – A case study from Rampa forests (Eastern Ghats, A.P.)", *Jour. Ind. Soc. Rem. Sens.,* **27**, 3, 149-154.

Prasad, V. K., Rajagopal, T., Kant, Y. and Badarinath, K. V. S., 2000, "Quantification of carbon fluxes in tropical deciduous forests using satellite data", *Adv. Space Res*., **26**, 7, 1101-1104.

Prasad, V. K., Kant, Y., Gupta, P. K., Sharma, C., Mitra, A. P. and Badarinath, K. V. S., 2001, "Biomass and combustion characteristics of secondary mixed deciduous forests of India", *Atmosph. Environ*., **35**, 18, 3085-3095.

Prasad, V. K., Kant, Y., Gupta, P. K. and Badarinath, K. V. S., 2002, "Biomass burning emission inventory from remote sensing, GIS and ground-based measurements – A case study from secondary mixed deciduous forests, India", *Geocarto Int'l*., (Accepted).

Raj, P. E. and Devara, P. C. S., 1997, "Seasonal and latitudinal variations in the satellite observed aerosol properties in the stratosphere and upper troposphere during the eruption of Alaid and Pagan", *Ind. Jour. Radio & Space Phys*., **26**, 256-263.

Rajeevan, M., 1998, "Model calculations of non-cloud radiative forcing due to anthropogenic sulphate aerosol", *Mausam,* **49**, 1, 45-58.

Ramanathan, V., Cicerone, R., Singh, H. and Kiehl, J., 1985, "Trace gas trends and their potential role in climate change", *Jour. Geophys. Res*., **90**, 5547-5566.

Ramesh-Kumar, M. R. and Gangadhara-Rao, L. V., 1990, "Annual means statics of the surface fluxes of the tropical Indian Ocean", *Bound. Lay. Met,* **51**, 3, 299-312.

Rao, M. V., Rao, K. H., Ramana, I. V., Sasamal, S. K., Choudhury, S. B. and Bhan, S. K., 2000a, "Change detection study in and around Kolleru Lake using high resolution satellite data", *Proc. PORSEC*, Goa, India, December, 5-8, 2000, 690-694.

Rao, K. H., Dash, S. K., Choudhury, S. B., Ramana, I. V. and Shaw, B. P., 2000b, "Estimation of (marine) primary productivity along East Coast of India", in : *ISRO-GBP : WS-III,* (vide ISRO 2000 Reference), 106-110.

Rao, B. M., Thapliyal, P. K., Manikiam, B. and Dwavedi, A. K., 2001, "Large scale soil moisture estimation using microwave radiometer data", *Jour. Agromet*., **31**, 179-187.

Rodriguez, E. and Stuardo, J., 2000, "A study of the photosynthesis pigments in the Columbian Pacific using ADEOS data*", Proc. PORSEC*, Goa, India, 5-8 December 2000, 44-49.

Roy, P. S. and Jain, A., 1998, "A satellite remote sensing based approach to estimate regional net primary productivity of forest", in : *Global Change Studies*, (vide ISRO 1998 Reference), 139-190;also *Int.Jour.Rem.Sens*. (in press).

Roy, P. S. and Ravan, S., 1996, "Biomass estimation using satellite remote sensing data – An investigation on possible approaches for natural forest", *Jour. Bioscis*., **21**, 4, 535-561.

Roy, P. S. and Tomar, S., 2000, "Biodiversity characterization at landscape level using geospatial modeling technique", *Biolog. Cons.,* **95**, 1, 95-109.

Roy, P. S., Singh, S., Agrawal, S., Joshi, P. K. and Gupta, S., 2000, "Biome level characterisation of Indian vegetation using IRS-ID/IC WiFS data", in : *ISRO-GBP : WS-III,* (vide ISRO 2000 Reference), 17-22. Also in : IGBP in India 2000, 371-387.

Saji, N. H., Goswami, B. N., Vinayachandran, P. N. and Yamagata, T., 1999, "A dipole mode in the tropical Indian Ocean", *Nature,* **401**, 6751, 360-363.

Sarkar, S. and Singh, R. P., 2000, "Inter-annual variability of total ozone and its relation to observed El-Nino of 1997-98", (Abstract), *XI Nat'l Sp. Sci. Symp.,* Puri, March, 1-4, Abst. DS1-3-25, p93.

Sarma, V. V. S. S., 2000, "Seasonal changes in effect of surface pCO_2 and air-sea exchange in the Arabian Sea", *Proc. PORSEC,* Goa, India, 5-8 December 2000, 416-420.

Sarmiento, J. L., Hughes, T. M. C., Stouffer, R. J. and Manabe, S., 1998, "Simulated response of the ocean carbon cycle to anthropogenic climate warming", *Nature*, **393**, 245-249.

Sasmal, S. K. and Somasundar, K., 2000, "Significance of upper ocean dynamics in the bio-geo-chemical processes of the Arabian Sea", *Proc. PORSEC*, Goa, India, 5-8 December, 2000, 804-808.

Simon, B., Joshi, P. C. and Desai, P. S., 1995, "Moisture profiles over tropics from NOAA/TOVS satellite data", *Jour. Geophysc. Res.,* **100**(D1), 1439-1444.

Singh, R., Simon, B. and Joshi, P. C., 2001, "Estimation of surface latent heat fluxes from IRS –P4/MSMR satellite data", *Proc. Ind. Acad. Sci. (Earth & Planet. Sci.),* **110**, 231-238.

Srivastava, V. K. and Oza, M. P., 1994, "Evaluation of species diversity in moist deciduous forest using IRS data", in : *Global Change Studies*, ISRO-GBP-SR-42-94, 227-235.

Subbaraya, B. H., Jayaraman, A., Krishna Moorthy, K. and Mohan, M., 2000, "Atmospheric aerosol studies under ISRO's GBP", *The Jour. of Ind. Geophys. Union*, **4**, 1, 77-90.

Sud, Y. C. and Smith, W. E., 1985, "Influence of local land surface processes on the Indian monsoon : A numerical study", *J. Clim. Appl. Met.,* **24**, 1015-1036.

Suzuki, N., Ebuchi, N., Akiyama, M. and Sugimori, Y., 2000, "Advanced analysis of the relationship between non-dimensional roughness length and wave age using tower-based measurements for study of air-sea CO_2 transfer using satellite data", *Proc. PORSEC,* Goa, India, 5-8 December, 2000, 412-415.

Thomas, B., Kasture, S. V. and Satyan, V., 1999, "Simulation of winter and summer climates with PRL atmospheric general circulation model", *Mausam*, **50**, 4, 391-400.

Tiwari, A. K., 1994, "Mapping forest biomass through digital processing of IRS-1A data", *Int'l. Jour. Rem. Sens.,* **15**, 9, 1849-1866.

Tiwari, A. K., 1998, "Mapping and monitoring of biodiversity using remote sensing - A model study for Central Himalaya", in : *Global Change Studies*, (vide ISRO 1998 Reference), 223-245.

Turk, D., McPhaden, M. J., Busalacchi, A. J., and Lewis, M., 2000, "Basin scale variations in new production in the tropical pacific during 1992-1999 El-Nino and La-Nina events from remotely-sensed observations", *Proc. PORSEC*, Goa, India,5-8 December 2000, 561-564.

Vinayachandran, P. N. and Ramesh- Kumar, M. R., 1990, "Water vapour flux divergence over the Arabian Sea using satellite data", *Bound. Lay. Met.,* **51**, 1&2, 199-209.

Vyas, N. K., Dash, M. K., Bhandari, S. M., Mitra, A. and Pandey, P. C., 2001, "Large scale Antarctic features captured by multi-frequency scanning microwave radiometer on-board OCEANSAT-1", *Curr. Sci.,* **80**, 10, 1319-1322.

Watts. I. J., Sathyendranath, S., Caverhill, C., Maass, H., Platt, T. and Owens, N. J. P., 1999, "Modeling new production in the North-West Indian Ocean region", *Mar. Ecol. Prog. Ser*., **183**, 1-12.

Wigley, T. M. L. and Raper, S. C. B., 1987, "Thermal expansion of sea-water associated with global warming", *Nature*, **330**, 127-131.

Zwally, H. J., 1991, "Global warming : Breakup of Antarctic ice", *Nature*, **350**, 274 (One page).