Developments and achievements in atmospheric sciences and space meteorology in India

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Space research in India began in the early sixties, with the establishment of the Thumba Equatorial Rocket Launching Station. Indigenously developed rocket payloads were carried in foreign rockets and flown for studying various atmospheric parameters, which are unique to the tropics. In the seventies, Indian-made rockets became available. Since then, there has been rapid progress in the technical advancement, which helped the atmospheric scientists in taking up more challenging and contemporary problems, related to mesospheric winds, ionospheric irregularities, stratospheric ozone, role of aerosols in atmospheric radiative transfer, etc. India entered into the satellite era in 1975, with the development of the Aryabhatta satellite, the first Indian experimental satellite, followed by Bhaskara-1 in 1979, which carried a microwave radio meter for retrieval of atmospheric water vapour and cloud liquid water contents. Since then, there have been several satellites, such as the INSAT series for meteorology and communication, Indian Remote Sensing (IRS) satellite series, and Stretched Rohini Satellite System (SROSS) for *in situ* observation of the ionosphere, which are all built in India and launched from Indian soil. High quality data being obtained from these satellite missions are helping scientists in taking up problems that are of regional and global scales and in studying the changes that are taking place in the earth atmosphere system, in a more holistic way. This paper attempts to provide an overview of the scientific developments and highlights some results.

Keywords: Aerosol, carbon fixation, ionosphere, ozone, space meteorology.

THE spectacular growth of space research in India is the result of the competition between the scientific quest for studying the space and the technological growth. For example, it was the need for studying the equatorial electrojet phenomenon that resulted in the establishment of the Thumba Equatorial Rocket Launching Station (TERLS) in Thumba, a location close to the magnetic equator. Also, it was the endeavour to reach the F1 and F2 layers of the atmosphere that resulted in the development of more powerful rockets such the RH560, and the establishment of the high altitude rocket launching station at Sriharikota. These efforts on early rockets helped in building the satellite launch vehicles that propelled the country into the satellite era. Satellites helped the meteorologists to look at the cloud systems from space that made a quantum jump in their weather prediction capability. Satellite remote sensing over the land and the surrounding oceans helped scientists in taking up more challenging and contemporary problems related to global change studies. A brief account of the developments and selected achievements made by Indian scientists in the field of atmospheric sciences and space meteorology is presented. Also, data from Indian Remote Sensing satellite are finding increased usage, apart from earth resources mapping, in tackling contemporary issues of global change. As an illustration, a brief account of a recent study made on the fixation and exchange of carbon in the Indian Ocean using Indian satellite data is presented.

Studies in atmospheric sciences

Study of the vertical structure of the atmosphere is one of the prerequisites for understanding the various processes taking place in it. Particularly, gaining knowledge on the vertical structure of the atmosphere over the tropics is extremely necessary, where the high solar irradiance is responsible for atmospheric processes of different spatial scales, such as the development of deep convective systems, which transport energy and momentum from the low to the high altitudes, higher production rate of ozone molecules in the stratosphere and the formation of the equatorial electrojet in the ionosphere. Systematic exploration of the vertical structure of the upper atmosphere began in India in early sixties, with the establishment of the country's first rocket launching station, TERLS in Thumba (8.5°N, 76.9°E). The first sounding rocket (Nike Apache supplied by NASA) was launched on 21 November 1963, which carried the sodium vapour payload to study the neutral winds in the ionosphere[1]. Later on other payloads like Langmuir and resonance probes, proton precision magnetometer and mass spectrometers were flown for the detailed study of electron concentration and the irregularities within it, altitude profiles of electrojet current as well as ion and neutral compositions[2–6]. Some of these studies were the first of their kind and provided invaluable *in situ* database for modelling various ionospheric proc-

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esses[7]. Several collaborative explorations were carried out from TERLS jointly with scientists from UK, USA, Germany, France, Japan and the erstwhile USSR. Starting from 1970, indigenously developed Rohini (RH) series of sounding rockets became available. Regular wind observations using RH200 were initiated from the Balasore rocket launching site (21.5°N, 86.9°E), initially as a part of the international Monsoon Experiment (MONEX) that continued later, as a regular programme, resulting in a long-term data series[8] over the site. Data from these experiments as well as from the weekly M-100 rocket data from Thumba have helped in making detailed study[8–10] on long period oscillations, such as the quasi-biennial oscillation (QBO), annual (AO) and semi-annual (SAO) oscillations in zonal and meridional winds, which play major roles in the transport of energy and momentum in the tropical lower and middle atmospheres.

With the establishment of the Sriharikota High Altitude Range (SHAR, 13.7°N, 80.2°E, presently known as the Satish Dhawan Space Centre) and the availability of RH-560 sounding rockets, the altitude coverage for ionospheric studies rose up to the F region. Several new and interesting results on the structure and dynamics of the F region came from these studies. A major understanding of the 'equatorial electrojet' and associate plasma instability, an intense electric current in the range of 5–10 amp/km^2 flowing along the east–west direction, in a narrow altitude range of 100–110 km over the dip equator (Figure 1), has come mainly from the *in situ* rocket experiments conducted from India. Another important result[11] of the high altitude rocket experiment is the demonstration of the role of vertical winds in the upper atmosphere in causing irregularities in the vertical profile of electron density in the F region, known as the equatorial spread F.

With the advent of the Indian Middle Atmosphere Program (IMAP) in 1982, the atmospheric region between 10 and 80 km has been brought under the main focus for a detailed study. A number of rocket experiments were conducted from Thumba to study the vertical profiles of the ozone concentration. UV photometers were carried in the rocket to measure the attenuation of the incoming solar UV radiation up to mesospheric altitudes[12]. Special rocket campaigns were conducted to study the effect of solar eclipse on the vertical ozone profile, day–night variation in the mesospheric ozone concentrations, role of dynamics in stratospheric ozone[13,14], etc. Figure 2 shows the average ozone concentration profile obtained over Thumba. For comparison, a typical ozone profile found over the mid-latitude region is also shown. Note that, though the ozone production is maximum over the tropical region, due to higher solar UV irradiance, the column integrated total ozone amount is less, as the ozone molecules produced over the tropics are effectively transported to higher latitude regions. Since the mid-eighties, when ozone-hole was detected over the Antarctic, there are worldwide efforts to monitor the amount of chloroflurocarbons (CFCs) in the stratosphere. As these molecules appear in trace amounts at stratospheric altitudes, it is necessary to collect air samples from these altitudes and transfer them to the laboratory for detailed chemical analysis using gas chromatography and mass-spectrometric techniques. Cryogenic air samplers were flown using the high-altitude balloons from Hyderabad (17.5°N, 78.6°E). The hydrogen filled plastic balloons were capable of carrying payloads weighing up to 1000 kg to about 40 km altitude and the instruments were recovered by detaching the gondola from the balloon and bringing it safely to the ground using a parachute. Some of the first experiments were the result of a collaborative programme between the Physical Research Laboratory and the Max Planck Institute for Aeronomy, Germany. Profiles of various CFCs obtained over Hyderabad helped in studying[15,16] their growth rate at lower altitudes and their photo-dissociation at stratospheric altitudes, which produced free chlorine, and bromine atoms, which catalytically destroy ozone. Later, an indigenously developed balloon-borne cryogenic air sampler was used to study, apart from CFCs, a variety of other gases including N_2O, SF_6, etc. Figure 3 shows the altitude pro-

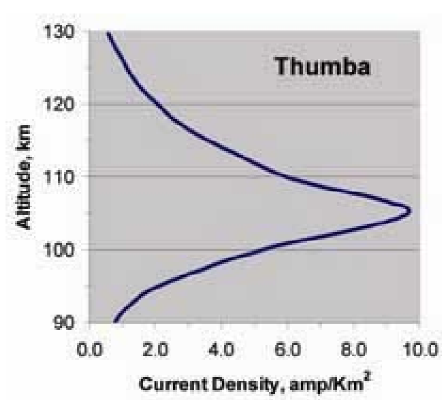

Figure 1. The averaged vertical structure of the electrojet, the intense current that flows over the dip equator, derived from a series of rocket experiments conducted during noon hours over Thumba.

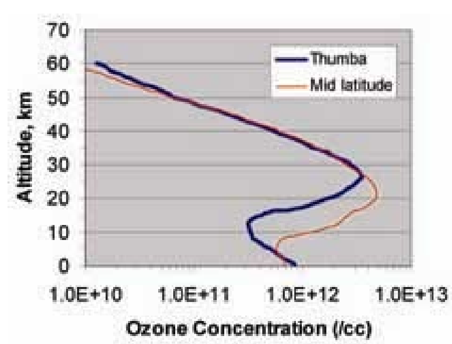

Figure 2. Averaged ozone concentration measured using UV photometers fitted onboard rockets and launched from Thumba. For comparison, typical ozone profile over mid-latitude region is also shown. Note that the column integrated total ozone amount is less over the tropics than over the high latitude regions.

files of SF_6 obtained over Hyderabad during different years[17]. SF_6, the most stable gas, enters the atmosphere entirely due to anthropogenic activities. Study of their vertical profile helps, apart from understanding their growth rate, in validating vertical transport processes in the global 2D models. Only very sparse measurements of this important tracer are available around the globe.

Another important outcome during the IMAP study period is the initiation of detailed studies on atmospheric aerosols, stratospheric conductivity and electric field. The submicron size particles suspended in the atmosphere have different chemical and physical properties and they play a major role in altering the earth's radiation budget, in the formation of clouds, fog, haze, etc. The initial experiments used sun-photometers fitted in rockets to measure the attenuation of direct solar radiation in different spectral bands, and simultaneously measure the angular distribution of the scattered radiation intensity at different altitude levels. The measured values were inverted to obtain the vertical distribution of aerosol concentration and the size parameter[18,19]. Later a balloon-borne sun-tracking and scanning sun-photometer system was developed[20,21] and used routinely from Hyderabad to study stratospheric aerosols. One of the important results obtained is on the formation of stratospheric aerosol layer after major volcanic eruptions. Explosive eruptions inject sulphur dioxide molecules directly into the stratosphere, which are converted into sub-micron size sulphate particles. These particles form a layer in the stratosphere and spread around the globe. In the absence of any other scavenging mechanism, the particles collide with each other and coagulate to form bigger particles of size greater than a micron, and are removed from the stratosphere by earth's gravity. Figure 4 shows profiles of the aerosol extinction coefficient, which is a measure of the attenuation of the radiation due to scattering and absorption processes, obtained from balloon measurements over Hyderabad, and lidar measurements over Mount Abu. The important observation is the stratospheric aerosol layer that formed after the Mount Pinatubo eruption in the Philippines in June 1991. The layer was found[22] to decay gradually till 1994, during which it caused several chemical and physical perturbations, such as the warming of the stratosphere and cooling of the earth's surface. Also, during the IMAP period, a network of multi-wavelength radiometers was established[23] in the country for the regular monitoring of the columnar aerosol optical depth and size distribution over different regions in India. The present focus of the aerosol studies is in determining the aerosol radiative forcing, which influences climate. Several field campaigns are being conducted and environment-monitoring networks are getting established as a part of the ISRO-Geosphere Biosphere Program.

A major advance has been made in the vertical probing of the atmosphere with the establishment[24] of a high power Mesosphere–Stratosphere–Troposphere (MST) Radar at Gadanki (13.5°N, 79.2°E) in 1993. Indian MST radar is a highly sensitive, pulse coded, coherent VHF array

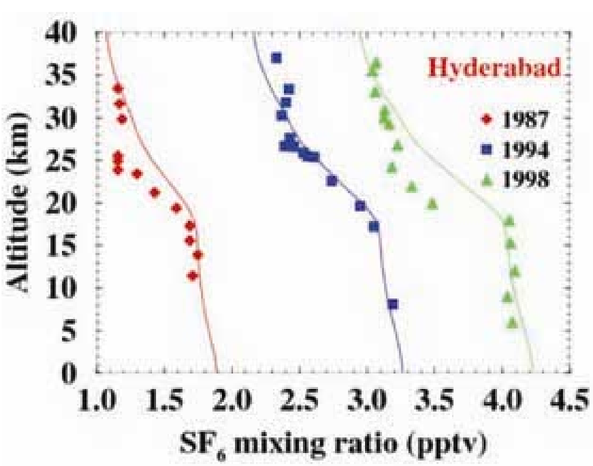

Figure 3. Vertical distribution of the ratio of the SF_6 concentration to air molecules in parts per trillion volume (pptv) obtained over Hyderabad during different years using a cryogenic air sampler. The continuous lines are the model predicted values.

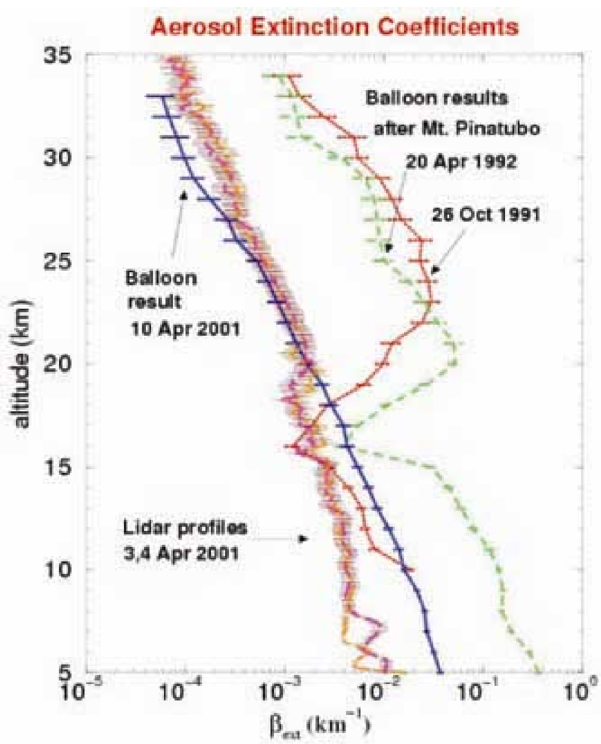

Figure 4. Vertical profiles of aerosol extinction coefficient, which is a measure of the attenuation of the radiation, due to both scattering and absorption and proportional to the amount of aerosol present at that altitude. Note that after explosive volcanic eruptions, the aerosol amount in the stratosphere increases by more than an order of magnitude and the effect lasts for about three years.

radar operating at 53 MHz, capable of studying various atmospheric processes on a continuous basis, with very high altitude resolution up to mesospheric altitudes[25,26]. Also, the coherent backscatter measurements enable study[27] of the ionospheric irregularities above 90 km. There are other supporting and complementary experiments built around the MST radar, such as the Rayleigh, sodium and boundary layer lidars, sodar, lower atmospheric wind profiler, disdrometer for rain drop size distribution, etc.

Atmospheric science studies in India entered the satellite era with the successful launching of SROSS-C satellite (Stretched Rohini Satellite Series – SROSS) in May 1992. The satellite was designed to study the positive ion and electron densities, superthermal electron flux apart from the ambient temperature and the spacecraft potential. During its lifetime, till July 1992, the satellite collected data from the altitude range 200–430 km, over India and the surrounding region, from 30°S to 40°N and 50°E to 90°E. In May 1994 SROSS-C2 was launched, which carried a sensor to detect gamma ray bursts and a Retarding Potential Analyser (RPA) for the measurement of temperature, density and ionospheric characteristics over the low latitudes. Data on electron and ion temperatures and concentration of ionic species were obtained continuously for more than half a solar cycle, till July 2001. Some of the important results obtained from this satellite mission[28] are: (i) the International Reference Ionosphere (IRI) model consistently overestimates the electron and ion temperatures, and the electron density over all seasons, (ii) identification of quasi periodicities in electron and ion temperatures with periods, 14-day, 19-day, 27-day, etc. to 1 and 1.3-year, (iii) detection of heavy metallic ions such as iron, cobalt, magnesium and calcium with concentrations in the range of 100 particles/m^3 in the 200–600 km altitude range etc.

Apart from the above-mentioned satellite experiment, atmospheric science studies in India are mainly confined to rockets, balloons and ground-based observations and the data obtained are highly localized and region-specific. A need for having dedicated satellite programme for atmospheric sciences (climate) has been recognized. A detailed mapping of the changes taking place in the atmospheric composition over the South and Southeast Asian region is essential to understand the short and long term climate variability and its causative mechanisms, based on which necessary mitigation efforts can be undertaken. For example, increase in the amount of greenhouse gases such as CO_2 is known to be the prime reason for the observed global warming. However, aerosols depending upon whether the particles are of scattering or absorbing type, can reduce or add to the warming. As aerosols are produced by a variety of mechanisms, both natural and anthropogenic, and the source regions are unequally distributed around the globe, the large spatial and temporal variations found in their chemical and physical properties make it an extremely challenging task to quantify their impact on climate. Global observations of aerosols properties, their vertical distribution, concentration of absorbing particles and surface reflectivity are needed simultaneously to compute aerosol radiative forcing unambiguously. It is not only the magnitude of the forcing, but even the sign of the net effect, leading to cooling or warming of the earth atmosphere system that critically depends on these parameters besides the vertical distribution of clouds. To address some of these issues, two satellites are being designed, one will be a Space Borne Lidar (SBL) and another is called the Indian Satellite for Aerosols and Gases (I-STAG). While SBL is based on active remote sensing technique by employing an onboard laser, I-STAG is based on the passive remote sensing technique. Both are designed to study the vertical distribution of aerosols, clouds and selected atmospheric constituents such as ozone, water vapour, etc. Similarly for the upper atmospheric studies, though ground-based[29] and rocket-borne measurements[30,31] have contributed significantly in advancing our knowledge of the ionosphere, satellite measurements are fundamental for providing both global coverage and with high resolution of physical processes that are not accessible otherwise. With ISRO providing an opportunity for the availability of small satellite platforms for dedicated science missions, the atmospheric science community has come up with a proposal for a small satellite mission 'SENSE' (Satellite for Earth's Near Space Environment), which will address several issues linked to equatorial ionosphere and thermosphere. Thus the forthcoming satellite missions as well the network of ground stations getting established for providing the necessary ground-truth data are poised to take the Indian atmospheric science programme to new frontiers.

Space meteorology

The era of space meteorology started in April 1960 with the launch of the first meteorological satellite TIROS-1 by USA that provided the first glimpse of the cloud imageries from space. With the advancement in technology, the observational capabilities have enhanced tremendously in terms of spatial, spectral and temporal resolutions. The past two decades have seen the evolution of a global system of space observations from both geostationary and polar orbiting platforms. Currently, several operational meteorological satellite systems provide global and regional observations. In India, applications in meteorology and weather forecasting are one of the thrust areas of the Indian space programme[32]. The first Indian Satellite for Earth Observations (SEO-1, also named as Bhaskara-1) was launched in 1979 carrying a microwave radiometer SAMIR (SAtellite MIcrowave Radiometer) along with a TV camera[33,34]. SAMIR operated at 19 and 22 GHz frequencies and made observations at near nadir angles by spinning the satellite in its orbital plane. Bhaskara-2, launched in 1981, had an additional channel at 31 GHz. SAMIR observations were used for the retrieval of atmospheric water vapour and cloud liquid water contents. Subsequently, a series of multi-purpose geostationary satellites, INSAT, was conceptualized with payloads for meteorology, broadcasting and communications. India has also launched a few polar orbiting satellites with meteorological sensors, and a number of advanced meteorological satellites are in the pipeline. The following sections briefly describe the evolution of the Indian space meteorological programme and a few demonstrative applications.

Geostationary satellites (INSAT)

The INSAT series of geostationary satellites was conceived in the early eighties to meet the operational needs of meteorology and weather services in the country. INSAT-1 series had 4 satellites carrying Very High Resolution Radiometers (VHRR) onboard with two spectral bands for observation: visible (0.55–0.75 μm) and thermal infrared (10.5–12.5 μm). VHRR had spatial resolutions of 2.75 km in the visible and 11 km in the thermal infrared, with the capability of providing half hourly images in normal scan mode. The last satellite in this series, INSAT-1D, provided observations, much beyond its expected lifetime. INSAT-2 series was designed and built indigenously based on user feedbacks, and had 5 satellites to ensure continuity of services. INSAT-2A and 2B were launched in 1992 and 1993 respectively, and carried VHRR with improved resolution of 2 km in the visible and 8 km in the thermal infrared bands. The enhanced imaging capability included three modes, viz. full frame, normal frame and sector mode of 5 min for rapid coverage of severe weather systems. INSAT-2C and INSAT-2D did not carry a VHRR payload. INSAT-2E was launched in 1999, which carried an advanced VHRR payload operating in three channels – visible (2 km), thermal infrared and the water vapour absorption bands (8 km). Observations in the 5.7–7.1 μm band enabled the study of water vapour distribution and flow patterns in the lower troposphere[35]. INSAT-2E also carried a CCD camera with 3 channels – visible, near infrared and short wave infrared with 1 km resolution to map the vegetation cover[36]. CCD also has the capability to estimate atmospheric aerosols over marine environments[37].

Presently, Kalpana (launched in September 2002 and renamed from METSAT-1) and INSAT-3A (launched in April 2003) satellites are available in this series. Kalpana is launched exclusively for meteorological observations[32], having only one payload onboard, i.e. VHRR, whereas INSAT-3A has VHRR and CCD similar to INSAT-2E. The water vapour channel imagery (Figure 5) obtained from Kalpana on 13 December 2002 shows dry air in the middle levels over large parts of the Arabian Sea and the Bay of Bengal. Deep convective clouds can be seen above north of the equator between 60° and 80°E longitudes, with moisture portending from these clouds and spreading into the adjoining areas.

INSAT 3D, to be launched in 2008, will carry an infrared sounder for temperature and water vapour profiles and an imager with split thermal channels for accurate sea surface temperature retrieval. So far, only USA has the GOES satellite in a geostationary orbit with a sounder for the vertical profile of temperature and humidity. INSAT-3D is expected to boost the mesoscale studies and prediction of weather by providing three-dimensional information of atmospheric temperature and humidity, with very high temporal receptivity of a few hours.

Products from INSAT series of satellites

Operational products from INSAT series of satellites are provided by the India Meteorological Department, since the inception of satellites. Various algorithms are developed at ISRO for deriving the meteorological parameters. Atmospheric Motion Vectors (AMV) are estimated from half-hourly INSAT triplet images (Figure 6 *a*). Infrared images are used and the detection and movement of clouds for the estimation of winds at cloud levels, while water vapour (WV) images are used to track moisture patterns. Upper Tropospheric Humidity (UTH) is estimated using brightness temperature observations in the water vapour channel. Figure 6 *b* shows an example of UTH derived from WV channel in Kalpana. Outgoing Longwave Radiation (OLR) is estimated from IR channel observations by converting the narrowband infrared observations into

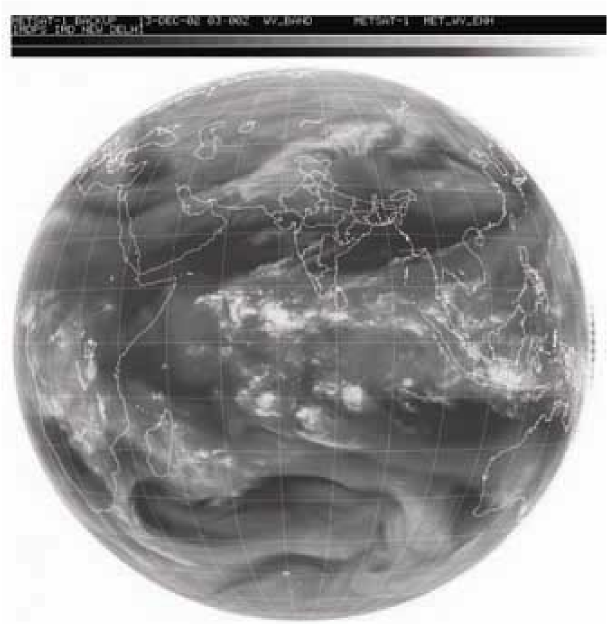

Figure 5. Water vapour imagery from Kalpana obtained on 13 December 2002.

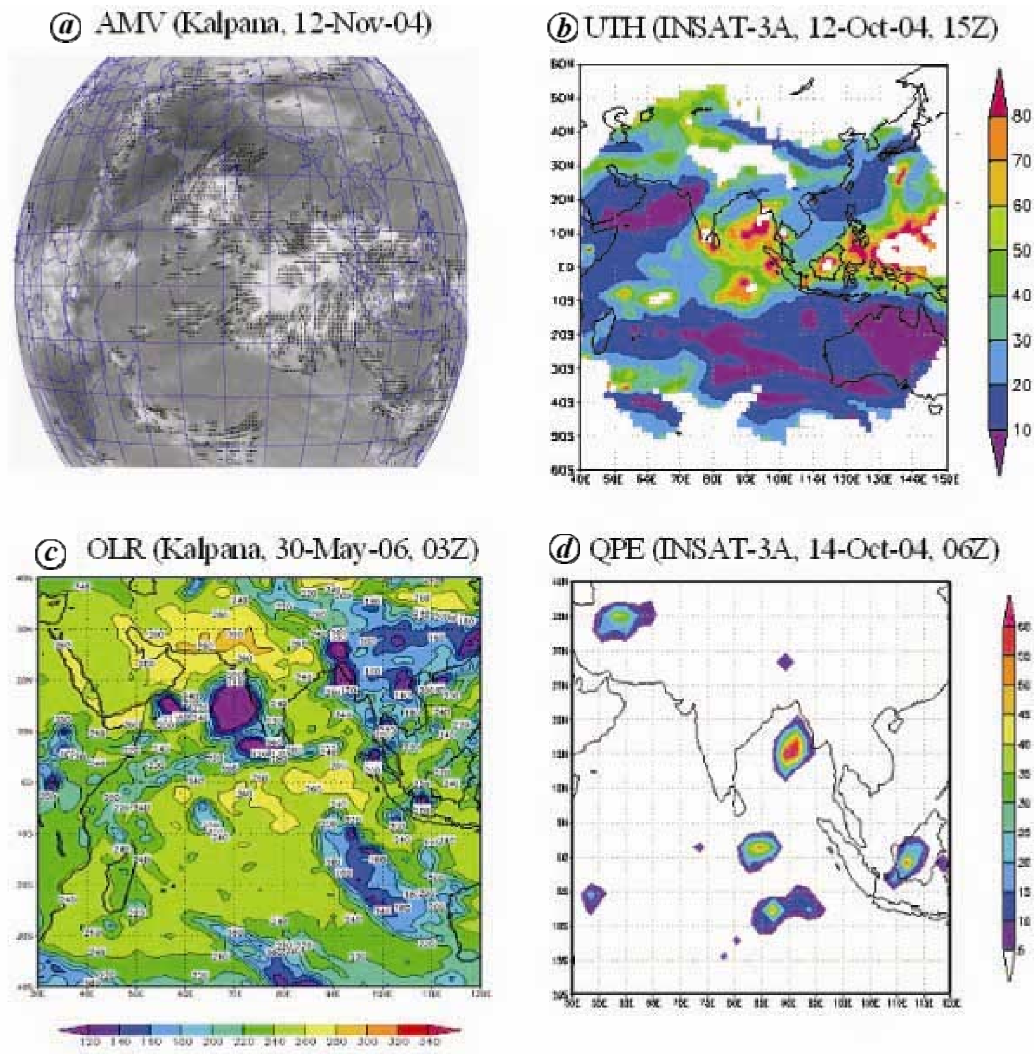

Figure 6. Sample of meteorological products derived from INSAT-3A (Kalpana): ***a***, Atmospheric motion vector (m/s); ***b***, Upper tropospheric humidity (%); ***c***, Outgoing longwave radiation; ***d***, Quantitative precipitation index (mm).

broadband infrared flux, using an empirical relationship (Figure 6 *c*). OLR estimates are useful for earth radiation budget estimation and also for model diagnostics. Quantitative Precipitation Estimation (QPE) is made from 3-hourly cloud top temperature information inferred from thermal IR channel of VHRR accumulated over 2.5° × 2.5° latitude/longitude grids and correlated to rainfall (Figure 6 *d*). The QPE over the oceans fills an important gap in rainfall measurements and is a key input to numerical weather models.

Polar orbiting satellites with meteorological applications

Indian remote sensing satellites (IRS) series was primarily designed for land and coastal resource surveys while some of the payloads have potential applications to meteorology. IRS-P3 and IRS-4 (also known as Oceansat-1) had sensors useful for meteorological applications. IRS-P3 launched on 21 March 1996, was an experimental satellite for the remote sensing of the earth. It carried Wide Field Scanner (WiFS) for land observation at three spectral bands, viz. 0.62–0.68, 0.77–0.86 and 1.55–1.75 μm, a Modular Optoelectronic Scanner (MOS, provided by DLR, Germany) with 4 channels in MOS-A (0.755–0.768 μm), 13 channels in MOS-B (0.408–1.01 μm) and one channel in MOS-C (1.6 μm), and an X-ray sensor for astronomical observations. The IRS P4 (Oceansat-1) launched in 1999 carried a Multi-frequency Scanning Microwave Radiometer (MSMR) and Ocean Colour Monitor (OCM). MSMR Operated at 6.6, 10.6, 18 and 21 GHz in both vertical and horizontal polarization. MSMR observations were used to retrieve the atmospheric parameters such as cloud liquid

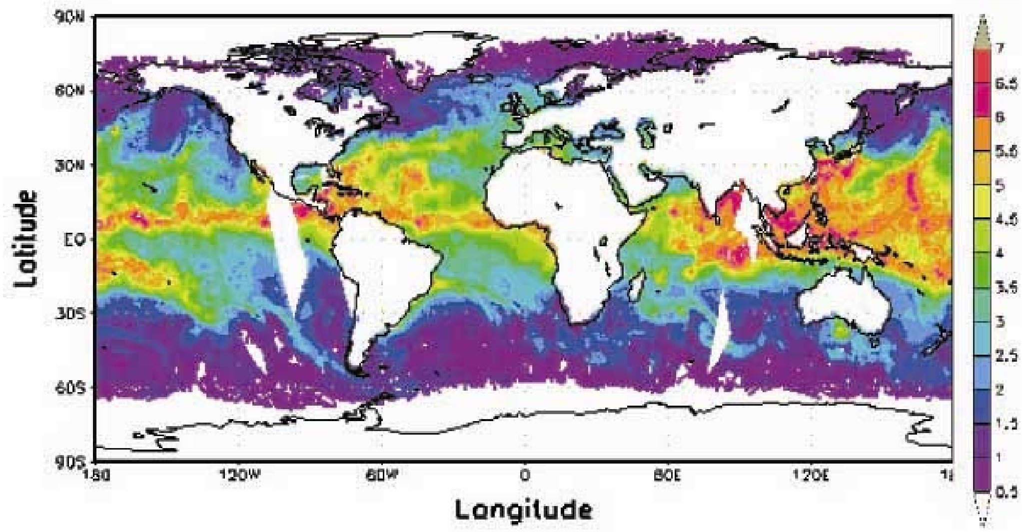

Figure 7. MSMR derived water vapour content (g/cm^2) for 29–30 September 2001.

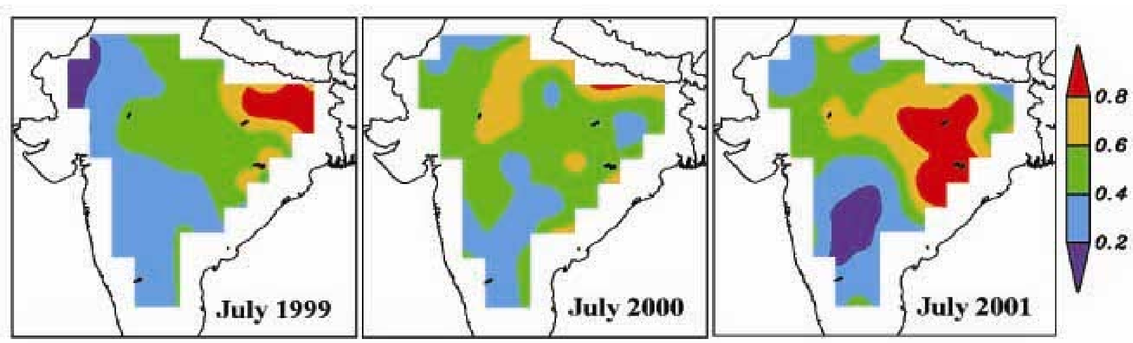

Figure 8. MSMR derived mean soil wetness index maps.

water content, total water vapour, besides sea surface temperature and winds. Figure 7 shows an example of MSMR retrieved water vapour during July 2001. Geophysical parameters obtained from MSMR measurements have been used to study various atmospheric and oceanic processes[38,39]. OCM is a linear array CCD based solid state camera operating in eight narrow spectral bands in the VIS–NIR wavelength range of 0.4–0.885 µm. This is the first 'pushbroom technique' based sensor for ocean colour studies. OCM provides measurements on the biological properties, like chlorophyll concentration, with a ground resolution of 360 m over a swath of 1420 km. MSMR data has also been used to determine a few value-added products like soil moisture, and oceanic heat fluxes. Microwave observations show very high sensitivity to the soil moisture due to the high contrast in emissivity between water and dry soil. Previous studies have demonstrated the application of lower frequencies (6.6 GHz in Nimbus-SMMR) to the soil moisture estimation. Spatial resolution at lower frequencies is coarse, ~100 km, which is however suitable for use in numerical modelling. MSMR data have also been utilized to retrieve soil wetness index[40] over Indian region during June–July for three years 1999–2001. Figure 8 shows the monthly average soil moisture for July 1999–2001. MSMR observations are also used to retrieve near-surface specific humidity and surface latent heat fluxes using a multivariate regression technique[41].

Future satellite missions

India is planning to launch advanced meteorological satellites to meet the requirements of the meteorology community, e.g. INSAT-3D, Oceansat-2 and Megha-Tropiques. A brief description of these satellites is given in Table 1.

Applications in meteorological studies

Most important of the applications of the satellite data is in the field of monsoon circulation. The finer details of the cloud structure in the visible, infrared and the water

Table 1. Payload characteristics and applications of future Indian satellites for meteorological studies

Satellite	Payload	Bands/Resolution	Resolution	Applications
INSAT-3D	6 Channel IMAGER	Spectral bands (μm)	1 km	
		Visible: 0.55–0.75	1 km	
		Short wave IR: 1.55–1.70	4 km	Cloud characterization
		Mid-wave IR: 3.70–3.95	4 km	
		Thermal IR-1: 6.50–0.10	4 km	Mesoscale processes
		Thermal IR-2: 10.30–11.30	8 km	
		Water vapour: 11.30–2.50		
	19 Channel sounder	Short wave infra red: Six	10 km	Atmospheric water vapour/temperature profiles
		Mid-wave infra red: Five		
		Long wave infra red: Seven		
		Visible: One		
Megha-Tropiques	SAPHIR	Six bands around 183 GHz	10 km	Water vapour profile
				Six atmospheric layers up to 12 km height
	SCARAB	Radiation instrument in short and long wave	40 km	Radiation budget
	MADRAS	89 and 157 GHz radiometer	10 km	Ice particles in cloud tops
		10, 18 and 37 GHz radiometer		cloud liquid water and precipitation; sea surface wind speed
				23 GHz: Integrated water vapour
Oceansat-2	Scatterometer	Ku-band	25 km	Ocean winds, ocean state forecast, tropical
	OCM	Vis-NIR bands	360 m	cyclone, monsoon ocean colour, aerosol

vapour channel are useful in monitoring heavy rainfall events. The water vapour and the surface wind data over the Indian Ocean have led to many predictors for the onset of the monsoon. The intraseasonal oscillations in all the satellite-derived parameters have brought out new features of these oscillations, which in turn are useful for assessing the active break monsoon cycle[35,36,38,42–45]. INSAT is routinely used for monitoring the genesis, intensification and movement of tropical cyclones in Indian seas, with the availability of VHRR onboard these satellites. The water vapour imagery gives an indication of the steering motion in the atmosphere. A combination of microwave and optical data has led to many intensity-prediction studies. A combination of future Oceansat-2 scatterometer and Megha-Tropiques with INSAT VHRR and sounder data holds significant promise for tropical cyclone studies[46].

Satellite data has also been used for many process studies, like cloud–radiation interactions, and aerosol characterization[39,47]. The most important contribution has been in the inputs to numerical models. Inclusion of atmospheric humidity in the initial field has been found to simulate the monsoon depressions well[48,49]. The radiometer data onboard MSMR gave information about Antarctic sea ice and its dynamics and has linkage to global climate change[50].

Carbon fixation/exchange studies in the oceans using satellite data

Primary production in the sunlit zone (photic zone, the top ~100 m) of the oceans is responsible for the fixing of atmospheric carbon by biota through photosynthesis. This is the chief mechanism responsible for removing excess anthropogenic carbon from the atmosphere to the deep ocean, also known as the biological pump. Satellites can monitor spatial and temporal variations in the ocean biota by sensing the light reflected by the Chlorophyll-*a* pigments in them. The Ocean Colour Monitor (OCM) in the Indian satellite IRS-P4 has been very useful in giving ocean colour data from the Arabian Sea and the Bay of Bengal. Primary production is characterized by new and regenerated productions. New production is defined as the part of primary production, supported by external nitrogenous inputs of upwelled, riverine or eolian origin introduced in the photic zone, whereas regenerated production is defined as that part of the primary production which sustains on recycled nutrients like ammonia and urea, within the photic zone[51]. The organic carbon exported to the deep ocean from the photic zone is known as the export production. This is equal to new production under steady state[52]. However, on longer time scales, new production is known to be coupled to export production, even under non-steady state[53] and is referred to interchangeably as new production[54]. Therefore, the proper understanding of the role of new production and nutrient regime of an oceanic region in the global carbon cycle is important as it helps to estimate the magnitude and efficiency of the biological pump[55]. The ratio of new to total production is called the f-ratio and represents the probability that a nitrogen atom is assimilated by phytoplankton due to new production; likewise (1–f) is the probability of assimilation by regenerated production[52] (nitrogen is always assimilated in regions where it is the limiting

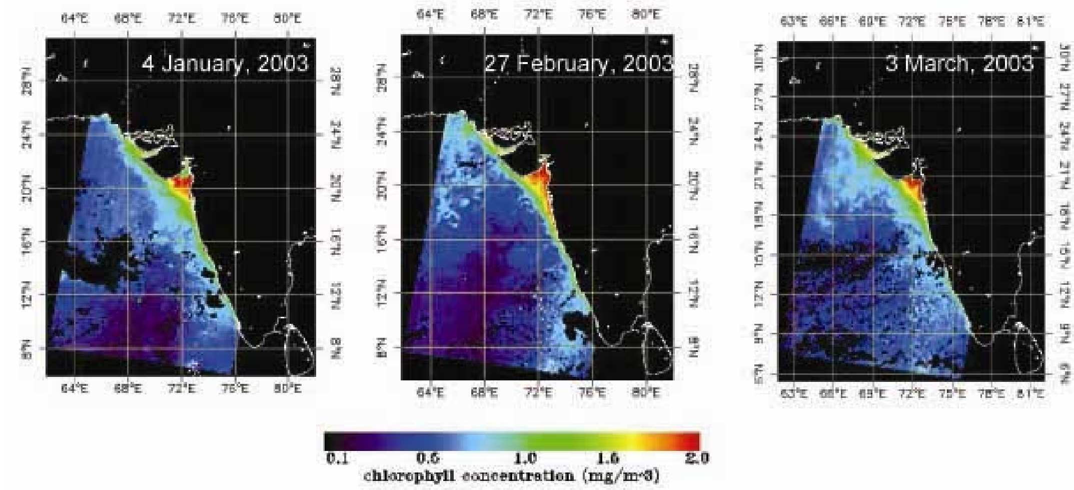

Figure 9. Chlorophyll images generated from Oceansat-I/OCM data.

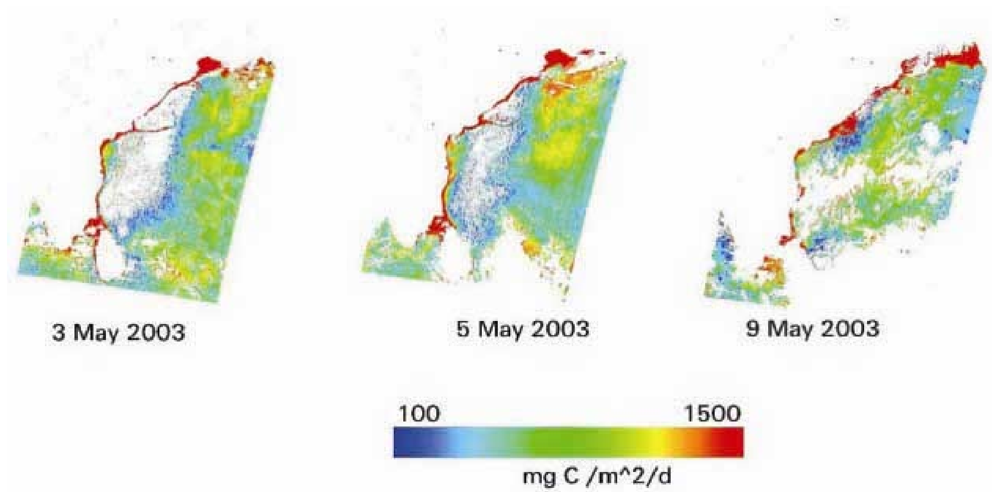

Figure 10. Primary productivity map of the Bay of Bengal.

nutrient). Both the new and total productions in the Bay of Bengal and the Arabian Sea have been measured[56–58].

Here the empirical algorithm proposed by O'Reilly *et al.*[59], known as Ocean Chlorophyll 2 or OC2, for processing SeaWiFS ocean colour data has been used. OC2 captures the inherent sigmoidal relationship between $R_{rs}490/R_{rs}555$ band ratio and the chlorophyll concentrations, where R_{rs} is remote sensing reflectance. The simple and reversible functional form used by OC2 as well as its statistical and graphical results are superior to other formulations evaluated. Methods for estimating primary productivity range from relatively simpler (empirical) to complex (spectral) models. During the present study non-spectral irradiance model proposed by Platt and Sathyendranath[60] has been used with the following assumptions: (a) Biomass is uniform throughout the upper mixed layer depth, (b) Negligible spectral structure of irradiance, and (c) Sinusoidal variation of surface irradiance. This model takes the mathematical form, where water column primary production is proportional to the biomass, assimilation number and Day length and inversely proportional to attenuation coefficient and also depends on function of normalized irradiance.

Figure 9 shows chlorophyll images generated from Oceansat I/OCM data for three different dates corresponding to ship measurements (4 January, 27 February and 3 March 2003). Chlorophyll image of 4th January shows a slight increase in chlorophyll from south to north. This spatial variability can be seen distinctly in 27 February and 3 March images with 18°N latitude as a clear demarcation line. Chlorophyll pattern with higher concentration in the Northern Arabian Sea in these two images is due to additional cooling of surface waters by northeasterly trade winds and the resulting convection. Temporal variability of chlorophyll pattern in the Northern Arabian Sea can also be seen from the figure. Relatively less chlorophyll concentration in the 4th January image corresponds to the initial phase of winter bloom in this area, whereas, when the bloom becomes intense during February–March, patches of higher chlorophyll concentration can be seen in lighter blue colour.

Primary productivity maps have been generated for the Bay of Bengal during September–October 2002 and April–May 2003. Sample maps obtained for the relatively cloudfree days are shown in Figure 10. In general, the

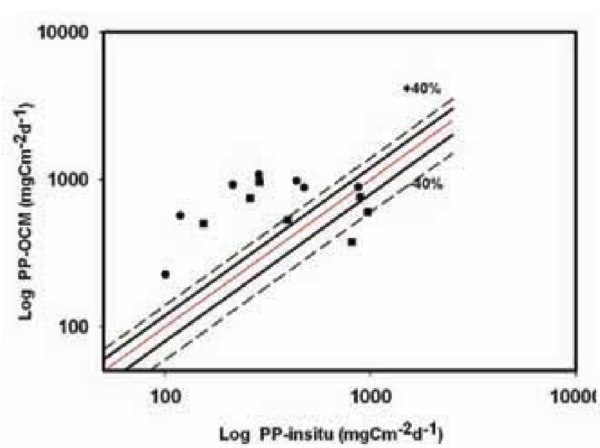

Figure 11. The log–log plot of euphotic zone integrated *in situ* primary productivity estimated by ^{15}N technique and corresponding climatological mixed layer integrated OCM derived values.

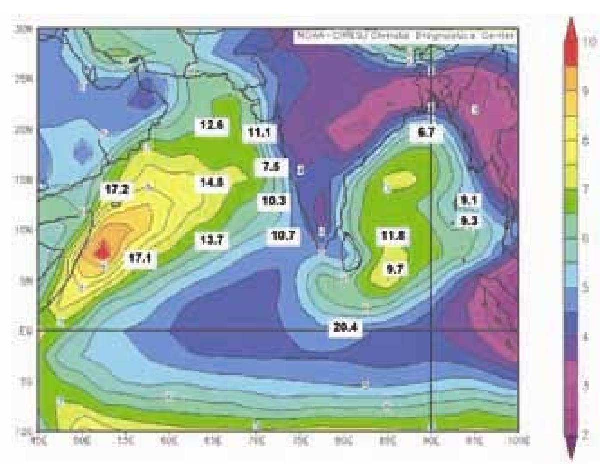

Figure 12. Comparison of satellite-derived scatterometer winds with the air–sea CO_2 exchange rate. In general, higher wind speeds enhance the rate of exchange (source: Dutta[64]). Contours of long-term mean scalar wind speed (labelled in m s^{-1}) at the surface over the northern Indian Ocean region and bomb-^{14}C based air–sea CO_2 exchange rates (numbers in units of mol.m^{-2} yr^{-1}).

total productivity varied from 100 to 1500 mg C m^{-2} d^{-1}. The upper limit of productivity was mainly seen in the coastal waters (red colours). It has been shown[61] that the OC2 algorithm when applied on OCM data works quite well for open ocean (r^2 = 0.85; rms value = 0.175 mg m^{-3}), whereas, it was not found satisfactory in the sediment laden case–2 waters (coastal waters). This adds to a high level of uncertainty in the primary productivity estimation of coastal waters. However, in general the error in chlorophyll determination by OCM data[61] has been around 35% in the range 0.01–10 mg m^{-3} and hence, the minimum error in productivity values, also. The productivity maps during September–October show the cloud cover over the Bay in the September that diminishes at the beginning of October. The cloud cover over the Bay seems to be a permanent feature that is evident during April–May 2003, particularly in the coastal region. Pixel-wise examination of the productivity values suggests in general overestimation of productivity by remote sensing data compared to *in situ* values, measured using the ^{15}N technique[56]. The overestimation is more during September–October than April–May, where *in situ* values are relatively higher. Figure 11 shows the log–log plot of measured and OCM generated productivity values. When OCM data of same day as experiment is not available, due to difference in the times of experiment and satellite pass, the value of the previous or next satellite pass has been taken. The same exercise has been done for cloudy pixels. The OCM productivity to represent the *in situ* measurement location has been estimated by taking the average of 3 × 3 pixels around the exact location. Figure 11 indicates the overestimation of primary productivity by more than 40% at most of the locations by OCM, particularly during September–October. The observed overestimation in productivity is due to the sum of errors involved in estimation of bio-optical and assumed *P–I* parameters. The *P–I* parameter values taken for calculation seem to be higher for the Bay of Bengal leading to an overestimation of the productivity. The value taken is actually of summer period for the Arabian Sea and is known to overestimate productivity in the intermonsoon. Changes in *P–I* parameters ($\alpha^B = 0.06$ mg C (mg Chl)$^{-1}$ h^{-1} (Wm^{-2})$^{-1}$) leads to a significant decrease in the estimated productivity indicating the assumed high *P-I* parameters as one of the reasons for overestimation. The *in situ* determination of *P–I* parameters would greatly enhance the accuracy of productivity estimation by OCM data; however, *P–I* parameters are still scarce in the Arabian Sea and the Bay of Bengal, leading to significant error in productivity estimation by OCM data. Inversion algorthims[62] are likely to perform better in the satellite retrieval of chlorophyll-*a*. The advantage of this algorithm is that it does not need precise knowledge of the scattering phase function of the medium and the results are better even in the presence of a reflecting bottom that significantly influences the upwelling light field.

Satellites can be useful in quantifying the air–sea exchange of CO_2, an important parameter for climate models. First, using satellite-borne scatterometer sea surface winds can be measured. Sea truth measurement of the air–sea exchange rate is possible by the measurement the bomb-produced radiocarbon (an isotope of carbon with mass number 14, decays with a half life of ~5760 years) activity in the atmosphere and the oceans simultaneously. Assuming that the atmosphere and the ocean are in equilibrium, it is possible to calculate[63,64] the carbon exchange rates. This exchange rate, however, depends on the wind speed over the oceans[65]. Figure 12 shows an example of air–sea exchange rates, measured in the northern Indian Ocean using radiocarbon. It is clear that the values are high, where the scatterometer-derived winds are high. This calibration, if confirmed by more measurements of sea truth, can be useful in estimating air–sea exchange over large spatial and temporal scales.

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