Seasonal and annual variation of AIRS retrieved CO₂ over India during 2003–2011

ANJU GUPTA¹, S K DHAKA^{1,*} , Y MATSUMI², R IMASU³, S HAYASHIDA⁴ and VIR SINGH⁵

¹Radio and Atmospheric Lab, Department of Physics, Rajdhani College, University of Delhi, New Delhi 110 015, India.

²ISEE, Nagoya University, Nagoya, Japan.

³Atmosphere and Ocean Research Institute, The University of Tokyo, Chiba, Japan.

⁴Nara Women's University, Nara, Japan.

⁵Guru Nanak Institute of Technology, Kolkata, India.

*Corresponding author. e-mail: skdhaka@rajdhani.du.ac.in skdhaka@gmail.com

MS received 6 October 2017; revised 10 July 2018; accepted 3 September 2018; published online 28 March 2019

The present study shows spatio-temporal variability in carbon dioxide (CO₂) in the mid-tropospheric region over India (0–32°N, 60–100°E) during 2003–2011. The CO₂ data used in the study is retrieved from Atmospheric Infra-Red Sounder (AIRS). Analysis of 9 yrs of data shows that the CO₂ exhibits a linear increasing trend of 2.01 ppm/year. Besides displaying the linear increasing trend, data show strong seasonal and annual variability. Concentration of CO₂ is observed to be highest around April–May (summer months), which decreases by 4–5 ppm during the monsoon months. Seasonal decrease in CO₂ concentration appeared to be influenced by the monsoonal activity. Low OLR (proxy of convection) associated with high rainfall during summer monsoon via increasing vegetation index (NDVI) appears to be the primary cause for the seasonal decrease in CO₂ through photosynthesis. Correlation coefficient between CO₂ and NDVI is of the order of –0.90 suggesting vegetation as a seasonal sink of CO₂. Decrease in CO₂ concentration takes place at a delay of 2–3 months of rainfall. However, convection seems to be another component, which causes uplifting of CO₂ during dry summer (April and May) making high concentration in the mid-troposphere as shown by increase in the planetary boundary layer (PBL) height in this period. Eastward propagating intra-seasonal oscillations with period 30–40 days in OLR anomalies are found to modulate (with a fluctuation of 1–2 ppm) mid-tropospheric CO₂. Analysis of seasonal anomalies in CO₂ over four different regions (northern, southern, western and eastern) of India is also being investigated. The regional variability of CO₂ in northern region show marginal larger values suggesting more anthropogenic activities especially during late winter.

Keywords. Carbon dioxide; seasonal variability; monsoonal activity; intra-seasonal oscillations.

1. Introduction

Indian summer monsoon rainfall between June and September contributes to about 80–90% of the annual rainfall over the Indian subcontinent

(Parthasarth 1984; Mooley and Shukla 1987). It is known that Indian summer monsoon is significantly influenced by 30–60 days intra-seasonal oscillations and these intra-seasonal oscillations are known to be closely associated with the active

and break monsoon conditions over India (Krishnamurti and Bhalme 1976; Yasanuri 1979; Krishnamurti and Subrahmanyam 1982). Low values of OLR (proxy of convection) are known to show intra-seasonal variability over Indian region associated with monsoonal rainfall (Kiladis and Weickmann 1992; Fukutomi and Yasanuri 1999). The intra-seasonal variability with 30–60 days timescale exhibits an eastward propagation in wind, convection, cloud system and temperature (Yasanuri 1979; Sikka and Gadgil 1980).

Carbon dioxide (CO₂) is a major greenhouse gas in the atmosphere, which plays a significant role in warming the earth by radiative forcing through entrapment of outgoing long-wave radiations from earth to space. Atmospheric CO₂ has become the largest contributor, among all anthropogenic greenhouse gases, towards warming of the global climate (IPCC 2002, 2007). Therefore, regional and global study of CO₂ in different years and seasons has become important. Recently the CO₂ mixing ratios in the middle troposphere (~ 5 – 10 km) have been retrieved from the Atmosphere Infrared Sounder aboard National Aeronautics and Space Administration (NASA's) Aqua satellite (Chahine *et al.* 2005, 2006, 2008). Global daily CO₂ dataset has shown rich variability with time scales from semi-annual to inter-annual (Chahine *et al.* 2008; Jiang *et al.* 2010). AIRS mid-tropospheric CO₂ product is retrieved using as input, the AIRS temperature, water vapour, and ozone geophysical products and selected channels of cloud-cleared radiances within the CO₂ absorption bands, i.e., 704 – 721 cm⁻¹ (Chahine *et al.* 2005, 2006, 2008). The spatial resolution at nadir is 90×90 km, and the product is a column weighted average of the CO₂ volume mixing ratio profile. Validation by comparison to *in-situ* aircraft and ground based measurements demonstrates that individual retrievals of AIRS CO₂ are accurate to 1–2 ppm between latitudes 30°S and 85°N (Chahine *et al.* 2008). This unprecedented AIRS mid-tropospheric CO₂ dataset provides great opportunity for climate studies and unique constraints for climatic models. Various studies (Tiwari *et al.* 2006; Chahine *et al.* 2008; Engelen *et al.* 2009) recently have discussed about CO₂ data retrieved from AIRS and its spatial variability all over the globe. Tiwari *et al.* (2011, 2013) have shown CO₂ variability during 1992–2003 at a single station located in the southern Indian region. They have shown a clear annual variation and a seasonal sink in CO₂,

which is explained on the basis of the vegetation index.

In order to address regional differences in CO₂ concentration and its temporal variation over Indian peninsula, retrievals of CO₂ from AIRS is a very useful dataset. We have focussed the study over the Indian landmass, the Indian Ocean and the Bay of Bengal region. Large geographical region with a different topography will provide opportunity to understand regional characteristics of CO₂. Role of convection and vegetation is examined to present a broad view in terms of intra-seasonal and annual variation as well as averaged features of 9 yrs data.

In a recent study by Jiang *et al.* (2008) it has been shown that convection in some of the chemistry climate models has to be strengthened in order to reproduce observed CO₂ latitudinal gradient. Also the impact of changes in the Walker circulation over the central and western Pacific Ocean as a result of ENSO (El-Nino Southern Oscillations) have been detected in the AIRS mid-tropospheric data. So we can expect that convection and large scale vertical motion may also regulate CO₂ on the intra-seasonal scale and thus AIRS mid-tropospheric CO₂ data may be able to reveal this variability. Therefore, an effort is made to investigate this intra-seasonal variability in CO₂, in association with convection. The region of study is chosen over India since until now CO₂ observations and studies over India are very sparse and limited (Nayak *et al.* 2011; Preethi *et al.* 2011; Tiwari *et al.* 2011, 2013).

In our previous study (Gupta *et al.* 2013a), we have presented a detailed study of latitudinal variation of temperature at different longitudes over Indian region at 100 hPa using 9 yrs of AIRS temperature and OLR data. We have also examined the long term variability in temperature in the UTLS (Upper Troposphere Lower Stratosphere) region and investigated the role of ozone in influencing this variability using AIRS total column ozone and temperature data (Gupta *et al.* 2013b).

In the present work, 9 yrs data from 2003 to 2011 (retrievals of AIRS mid-troposphere CO₂) were analysed to examine intra-seasonal, spatio-temporal and regional variability over India. Outgoing long wave radiation (OLR) is used from AIRS for the parallel period. Precipitation data from Tropical Rainfall Measuring Mission (TRMM) is also used in the present analysis.

2. Data

The AIRS/AMSU sounding system (Aumann *et al.* 2003; Chahine *et al.* 2006) on the NASA Aqua platform has been operational since 1 September 2002. The AIRS and AMSU instruments are each cross track scanning nadir sounders that are co-aligned and have a swath roughly 1650 km wide. The AIRS instrument is a 2378-channel grating spectrometer measuring infrared radiance at wavelengths in the range 3.7–15.4 μm with a horizontal resolution of about 13.5 km at nadir (Aumann *et al.* 2003). The AMSU instrument is a 15-channel microwave radiometer with a horizontal resolution of about 45 km at nadir (Lambrigtsen *et al.* 2003).

For the present study we have used 9 yrs (2003–2011) of AIRS gridded mid-tropospheric CO_2 data (<http://disc.sci.gsfc.nasa.gov/AIRS>).

The mid-tropospheric CO_2 data are retrieved using the Vanish Partial Derivative Method (Chahine *et al.* 2005, 2008). AIRS mid-tropospheric CO_2 data retrieved globally in the middle troposphere day and night and under clear and cloudy condition. Validation by comparison to *in-situ* aircraft measurements and retrievals by land-based upward looking Fourier Transform interferometers demonstrates that AIRS CO_2 is accurate to 1–2 ppm between latitudes 30°S and 85°N (Chahine *et al.* 2005, 2008).

To study the variability of atmospheric CO_2 associated with intra-seasonal oscillations (ISO) in OLR we have used AIRS (AIRX3STM) version 5 level 3 monthly gridded OLR data (Divakarla *et al.* 2001; Lambrigtsen 2003; Fetzner 2006; Gao *et al.* 2006). Precipitation data from Tropical Rainfall Measuring Mission (TRMM) is used in the present study to show rainfall variation. Precipitation data were used to calculate the Indian monsoon rainfall (area mean of rainfall in 0–32°N, 60–100°E) (Meehl and Arblaster 2002). TRMM precipitation data are available at $0.25^\circ \times 0.25^\circ$ (latitude by longitude) from 50°S to 50°N covering from 180°W to 180°E.

3. Results and discussion

3.1 Spatio-temporal variability of CO_2

Figure 1(a) shows the temporal variations of AIRS mid-tropospheric CO_2 concentrations (ppm) with time from 2003 to 2011 over India. Data is averaged over 0–32°N and 60–100°E to represent Indian longitude and latitudes section for analysis. Analysis exhibits a linear increasing trend of 2.01 ppm/year with distinct annual cycles. To examine the seasonal and annual variability of CO_2 we have de-trended the data (i.e., by subtracting linear increasing trend using least square fit) as shown in figure 1(b). De-trended data thus obtained

Figure 1. (a) Trends of time series of CO_2 (ppm) over Indian subcontinent (0–32°N, 60–100°E) and (b) de-trended time series of CO_2 (ppm) for 9 yrs (2003–2011).

show strong annual cycles with seasonal kinks. Concentration of CO_2 is seen to be the highest around April–May (summer months) and thereafter it starts decreasing turning minimum around October–November. There is clear year to year variation in the annual cycle. Seasonal decrease in CO_2 apparently seems due to increase in summer monsoon rainfall and followed by increase in vegetation index (NDVI) over the region. Figure 2(a) shows time series of de-trended OLR (top panel), de-trended Indian monsoon rainfall (obtained from TRMM) (middle panel) and de-trended CO_2 (bottom panel) over the Indian region for 9 yrs. The low concentration of CO_2 during July–August–September (JAS) is found to be coinciding with high monsoon seasonal values of NDVI (figure 2b). However, there is a time delay of about 2–3 months after rainfall to maximize vegetation index and which eventually act as a sink for CO_2 concentration through increased photosynthesis over a large region (see figure 2c, there is time delay of ~ 2 months in NDVI following rainfall). Correlation coefficient between CO_2 and NDVI is computed, which is of the order of -0.89 using 9 yrs monthly averaged data; annual cycles in NDVI suggest increased vegetation during summer monsoon period, which is acting as a sink for CO_2 by about 3 ppm, thus reducing its concentration hence association of CO_2 and NDVI is reverse during June/July. After October, concentration of CO_2 again increases gradually and peaking till April in the following year due to decrease in vegetation. During winter (peaking in December and January), decreased vegetation (autumn period and later) allows CO_2 to rise gradually with time until summer months. Thus after June/July and January, the association of CO_2 and NDVI are getting reverse as increase in one parameter is acting to counterbalance the other.

Climatological features of CO_2 of the entire Indian region over nine years are shown in figure 3. A clear picture emerged of strong anti-correlation (-0.90) between CO_2 and NDVI, the reduction of CO_2 concentration takes place after May when there is a sign of increasing NDVI. Lowering of CO_2 concentration continues till November and then rising of CO_2 starts gradually.

Indian region is vast and the topography and vegetation scenario is different, hence it is expected the seasonal variation in CO_2 will be different in northern, southern, and eastern and western regions. We have investigated this aspect and shown in figure 4.

Figure 4 shows the regional climatological characteristics of CO_2 and NDVI. High anti-correlations (-0.90) persists in all regions besides southern, where the anti-correlation coefficient (~ -0.59) is less comparatively. In southern region, there are apparently two broad peaks of NDVI, one is during February and the second is during August and September. NDVI stays stronger till October in eastern region, which is examined from lat-log sections of 9 yrs averaged data (not shown here). Seasonal cycle in vegetation index (peak) due to monsoon rain in June and July is causing the reverse association with CO_2 , which further reverses during December and January when there is a lack of vegetation and thus reduction in photosynthesis takes place causing rise in CO_2 . These seasonal features make reverse association of CO_2 and NDVI.

Annual variability and strong relationship between NDVI and CO_2 is seen in four different regions are shown in figure 5. In northern and eastern regions, there is a clear broad single peak appearance of NDVI variation. However, in southern and western regions twin peaks behaviour is more common though the peak in NDVI during summer is more prominent. The lowering of CO_2 in southern region is delayed by 2 months. These are some clear differences in four regions of Indian peninsula. Distribution and rain pattern during early winter and summer is attributed for this kind of difference in the southern region. Though there is no clear distinction between annual amplitude variations in CO_2 in all four regions.

Arrival and withdrawal timings of monsoon along with distribution of rain pattern during summer and early winter in several part of Indian southern peninsula is different in comparison to the northern region. For instance, there is a large area in south region, which receives good rain during October and is bit different than several parts of the north India. This feature particularly of twin peak behaviour of NDVI is responsible of lowering correlation coefficient in the southern region.

Spatial distribution of CO_2 in different months (covering summer, rainy, and winter seasons) averaged over 9 yrs is shown in figure 6. Striking differences in CO_2 concentrations over land and ocean is noted, for instance, during April to June vast region pertaining to Indian Ocean near equator and Arabian Sea show less concentration while during July to November Indian Ocean side is more rich in CO_2 concentration. The difference is of the order of 3–5 ppm. One more prominent

Figure 2. (a) Top, middle and bottom panels show the de-trended plot of OLR (black), rainfall (red) and CO₂ (blue) over India, arrows indicate timings of occurrence of connected peaks, (b) annual cycle of CO₂ and NDVI are shown over 2003–2011. Blue colour denotes CO₂ and green the NDVI, and (c) climatological features (averaged over 2003–2011) of NDVI (green) and rainfall (blue). NDVI follows rainfall pattern with a delay of ~2 months.

Figure 3. Climatological features (averaged over 2003–2011) of CO₂ (blue) and NDVI (green).

Figure 4. Climatological features (averaged over 2003–2011) of CO₂ (blue) and NDVI (green) in four different regions. Top to down panels denote northern, southern, western, and eastern regions, respectively.

feature noted is that gradual increase in CO₂ concentration takes place from northern region to southeast direction during March to May a period of peak summer. A stretch of Arabian Sea side to the landmass remains in most of the months at a low concentration (a few ppm) in comparison to other region except during summer. As discussed above that NDVI enhances during August–October after rainfall over most of the part of Indian landmass acting as a sink for the CO₂. However, NDVI

increases late in southern region and hence making low concentration in December and January. The results in southern region matched with [Tiwari et al. \(2013\)](#) as they have used only a single station.

Increase of CO₂ during summer (April and May) in northern region partly can be understood on the basis of convection. Planetary boundary layer lifts due to convection as vertical motions get stronger with a possibility of pumping lower troposphere CO₂ concentration into middle troposphere (see

Figure 5. Annual cycle of CO₂ (blue) and NDVI (green) in four different regions (a) northern, (b) southern, (c) western, and (d) eastern regions.

Figure 6. Climatological features (averaged over 2003–2011) showing the spatio-temporal variation of carbon dioxide over land and ocean.

Dhaka *et al.* 2001, 2002, 2003a, b, 2005, 2006) for strong vertical motions using radar during summer. Satellite observations (COSMIC data by radio-occultation) by Ratnam and Basha (2010) have shown recently the increased planetary boundary layer in the tropical landmass during summer. Figure 7 depicts the planetary boundary layer

(PBL) height, using NCEP data in 2009, spatial structure during summer and winter seasons. During March–May, there is strong qualitative agreement in the spatial distribution of PBL and CO₂ concentration. The contrast PBL structure over land and ocean suggests that advection (wind flow and direction) is not a predominant factor.

3.2 Intra-seasonal oscillations in OLR, rainfall, and CO₂

Mainly climatological features are shown in the previous section 3.1. Time delay was noted in some physical processes to take place such as rainfall and vegetation. In this section, we focus on wave fluctuation in CO₂ concentration on intra-seasonal basis. Convective activity (represented by low OLR values) is known to show intra-seasonal oscillations during June–September; mostly these are eastward propagating wave modes embedded with large scale and meso-scale convective systems. Intra-seasonal oscillation (ISO) in OLR and other parameters are discussed earlier by several researchers (Shibagaki *et al.* 2006; Jain *et al.* 2011; Panwar *et al.* 2012) in their study over Indian and Indonesian region. It may be noted that the intra-seasonal oscillations in OLR could induce similar wave modulation in mid-tropospheric CO₂. Therefore, an attempt is made to delineate the intra-seasonal oscillations

in CO₂ and to demonstrate the association of the same with the observed oscillations in OLR and rainfall. For investigation, daily mean of precipitation, OLR and CO₂ data for the period 1st May to 30th September 2007 (153 days) over Indian region are analysed. Summer monsoon period is favourable for the formation of eastward moving convective system (e.g., Madden and Julian 1994). Precipitation data is obtained from TRMM, while OLR and CO₂ data are obtained from AIRS. To examine the nature of oscillations, time series of anomalies in different parameters (OLR, rainfall and CO₂) are smoothed by taking the running average over 13 days so as to remove the short-period oscillations of period <13 days (Jain *et al.* 2011) as shown in figure 8. Top, middle and bottom panel denotes 13-day averaged plot for OLR, rainfall and CO₂, respectively. Figure 8 shows the presence of intra-seasonal oscillations in all the parameters. To further examine the nature and direction of propagation of the oscillations, averaged time series

Figure 7. Latitude–longitude sections of planetary boundary layer (PBL) height in 2009 using NCEP data (similar features are seen for other years, for the sake of brevity we are showing only one year).

Figure 8. 13 days averaged time series plots for OLR (top panel), rainfall (middle panel) and CO₂ (bottom panel) over May–September 2007.

Figure 9. 13 days averaged OLR anomalies (May–September 2007) is shown over different parts; ASIWC (black), ILM (red), and BOB (blue).

Figure 10. 13 days averaged CO₂ anomalies (May–September 2007) over different parts ASIWC (red), ILM (blue), and BOB (black) is shown using different colour.

of anomaly in OLR (ΔOLR) and CO₂ (ΔCO_2) are plotted over three regions, i.e., the Arabian Sea and Indian west coast (ASIWC) (10–20°N, 70–75°E), the Indian land Mass (ILM) (10–20°N, 72.5–82.5°E) and the Bay of Bengal (BOB) (10–20°N, 85–90°E) as shown in figures 9 and 10. It can be noticed from figure 9 that the anomaly in OLR over the ILM region attains maximum at Julian day numbers 132, 180–185 and 220–225. Similar periodicity can also be noted in the ΔCO_2 time series (figure 10) with maxima at

Julian day numbers 140, 190–220 and 240–258. Figures 9 and 10 show that intra-seasonal oscillation in OLR modulates CO₂ over the three regions. The oscillation can be seen moving eastward as the signatures appears first over the ASIWC and then over BOB. Figures 9 and 10 thus show two prominent features: period of intra-seasonal oscillation varied from 30 to 40 days as the monsoon had progressed and intra-seasonal oscillation in

Figure 11. FFT spectrum applied in CO₂ data showing peak at 0.03 (day⁻¹) corresponding to 33 days.

Figure 12. Band pass filter (15–60 days) of CO₂ (red) and OLR (black), showing OLR is leading in comparison to CO₂.

OLR have modulated CO₂. Fast Fourier Transform (FFT) show a peak around 0.033 (~33 days) exhibiting the presence of intra-seasonal oscillations (see figures 10 and 11). The cycle of the oscillation varied and remained close to 30–40 days.

In order to understand the co-variability (lead and lag behaviour) of the ISO in CO₂ and OLR, band-pass filter of 15–40 days is applied as shown in figure 12 (to fit the OLR data, scale is divided by a factor of 10). Figure 12 shows OLR is leading CO₂. Therefore, formation of convective systems in terms of ISO during monsoon period plays a very significant role in inducing wave fluctuation in several parameters including CO₂.

4. Summary and concluding remarks

In this paper, spatio-temporal, inter-annual and intra-seasonal variability in mid-tropospheric CO₂ retrievals from AIRS over Indian region for the

period of 9 yrs (2003–2011) are shown. We have also examined the variability in CO₂ over different Indian regions (northern, southern, western and eastern regions) along with NDVI and rainfall parameters. Following are the highlights:

1. Data exhibit a strong seasonal and annual variability in CO₂ over India with a linear increasing trend of 2.01 ppm/yr.
2. Climatological features presented in the form of spatio-temporal sections show clear differences in distribution of CO₂ concentration over land-mass and ocean region. During summer period in northern Indian region CO₂ enhances primarily due to the lack of vegetation and strong convection. During monsoon period (June to September), NDVI enhances and photosynthesis in plants acts as a sink for CO₂ in most of the parts of Indian landmass except southern region. There is a strong anti-correlation (−0.90) between CO₂ and NDVI. On the other hand, Indian Ocean region show larger CO₂ concentration during monsoon period, when landmass experiences low concentration. However, low concentration is seen over Arabian side during winter season.
3. CO₂ concentration is studied in consonance with NDVI in four different Indian regions, which is divided as northern, southern, eastern and western regions. Northern and southern regions show some striking differences, there is twin peaks behaviour in NDVI and CO₂ in southern side. During late winter season larger variation in CO₂ concentration is seen in the northern region suggesting larger anthropogenic activities during this period, probably burning in agriculture waste in country side is adding to such a scenario.
4. Intra-seasonal oscillations (~1–2 ppm) are quite dominant during summer monsoon period. These oscillations are usually formed as a consequence of convective system, which move eastward slowly. These quasi-periodic oscillations are seen in other atmospheric parameters such as OLR, rainfall and CO₂. Therefore, it may be concluded that ~30 days oscillations are induced in CO₂ concentration in the mid-troposphere due to organized and moving convective system, OLR is used as a proxy for convection.
5. Thus the seasonal decline in the CO₂ concentration during and after monsoon period is due to increased vegetation as shown, and wave

perturbations in CO₂ are caused by large and meso-scale convective system.

Acknowledgements

Satellite data are obtained from <http://airs.jpl.nasa.gov/>. Present work is supported by ISRO/DOS, Government of India, through a research project under CAWSES-II India Program. Planetary boundary layer (PBL) height is taken from <https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html>. Authors are thankful to Dr Vinay Kumar for his help in coding for NDVI and other parameters.

References

- Aumann H H, Chahine M T, Gautier C, Goldberg M D, Kalnay E, McMillin L M, Revercomb H, Rosenkranz P W, Smith W L and Staelin D H 2003 AIRS/AMSU/HSB on the aqua mission: Design, science objectives, data products, and processing systems; *IEEE Trans. Geosci. Remote Sens.* **41**(2) 253–264, <https://doi.org/10.1109/tgrs.2002.808356>.
- Chahine M, Barnett C, Olsen E T, Chen L and Maddy E 2005 On the determination of atmospheric minor gases by the method of vanishing partial derivatives with application to CO₂; *Geophys. Res. Lett.* **32** L22803, <https://doi.org/10.1029/2005GL024165>.
- Chahine Moustafa T and co-authors 2006 AIRS: Improving weather forecasting and providing new data on greenhouse gases; *Bull. Am. Meteorol. Soc.* **87** 911–926.
- Chahine M T, Chen L, Dimotakis P, Jiang X, Li Q, Olsen E T, Pagano T, Randerson J and Yung Y L 2008 Satellite remote sounding of mid-tropospheric CO₂; *Geophys. Res. Lett.* **35** L17807, <https://doi.org/10.1029/2008GL035022>.
- Dhaka S K, Preveen K, Devrajan K, Choudhary R K, Shibagaki Y and Fukao S 2001 Indian MST radar observations of gravity waves activity associated with tropical convection; *J. Atmos. Sol. Terr. Phys.* **63** 1631–1642.
- Dhaka S K, Choudhary R K, Malik S, Shibagaki Y and Fukao S 2002 Observable signature of convectively generated wave field over tropics using Indian MST radar at Gadanki (13.5°N, 79°E); *Geophys. Res. Lett.* **29** 1872–1875.
- Dhaka S K, Takahashi M, Kawatani Y, Shibagaki Y and Fukao S 2003a Observations of deep convective updrafts in tropical convection and their role in the generation of gravity waves; *J. Meteorol. Soc. Jpn.* **81**(5) 1185–1199.
- Dhaka S K, Takahashi M, Shibagaki Y, Yamanaka M D and Fukao S 2003b Gravity wave generation in the lower stratosphere due to passage of the typhoon 9426 (Orchid) observed by the MU radar at Shigaraki (35°N, 136°E); *J. Geophys. Res. (Atmos.)* **108**(D19) 4995.
- Dhaka S K, Yamamoto M K, Shibagaki Y, Hashiguchi H, Yamamoto M and Fukao S 2005 Convection induced gravity wave characteristics by the equatorial atmosphere radar (0.20°S, 100.32°E) in Indonesia; *Geophys. Res. Lett.* **32** L14820, <https://doi.org/10.1029/2005GL022907>.
- Dhaka S K, Yamamoto M K, Shibagaki Y, Hashiguchi H, Fukao S and Chun H Y 2006 Equatorial atmosphere radar observations of short vertical wavelength gravity waves in the upper troposphere and lower stratosphere region induced by localized convection; *Geophys. Res. Lett.* **33** L19805, <https://doi.org/10.1029/2006GL027026>.
- Divakarla M G, Barnett C D, Goldberg M D, McMillin L M, Maddy E, Wolf W, Zhou L and Liu X 2006 Validation of atmospheric infrared sounder temperature and water vapor retrievals with matched radiosonde measurements and forecasts; *J. Geophys. Res.* **111** D09S15, <https://doi.org/10.1029/2005JD006116>.
- Engelen R J, Serrar S and Chevallier F 2009 Four dimensional data assimilation of atmospheric CO₂ using AIRS observations; *J. Geophys. Res.* **114** D03303, <https://doi.org/10.1029/2008JD010739>.
- Fetzer E J 2006 Preface to special section: validation of atmospheric infrared sounder observations; *J. Geophys. Res.* **111** D09S01, <https://doi.org/10.1029/2005JD007020>.
- Fukutomi Y and Yasanuri T 1999 10–25 days intraseasonal variations of convection and circulation over East Asia and western North Pacific during early summer; *J. Meteorol. Soc. Jpn.* **77** 753–769.
- Gao W, Zhao F and Gai C 2006 Validation of AIRS retrieval temperature and moisture products and their application in numerical models; *Acta Meteorol. Sin.* **64** 271–280.
- Gupta A, Dhaka S K, Panwar V, Bhatnagar R, Kumar V and Dash S K 2013a AIRS satellite observations of seasonal variability in meridional temperature gradient over Indian region at 100 hPa; *J. Earth Syst. Sci.* **122**(1) 201–213.
- Gupta A, Dhaka S K, Panwar V, Bhatnagar R and Kumar V 2013b Long term temperature variability in the upper troposphere and lower stratosphere over Indian and Indonesian region using AIRS observations; *Indian J. Radio Space Phys.* **42** 298–308.
- IPCC 2002 *Climate change 2001: Synthesis report*; Cambridge University Press, New York.
- IPCC 2007 *Climate change 2007: Synthesis report. Contribution of working groups I, II and III to the fourth assessment report of the Intergovernmental Panel on Climate Change*; IPCC, Geneva.
- Jain A R, Panwar V, Johnny C J, Mandal T K, Rao V R, Gautam R and Dhaka S K 2011 Occurrence of extreme low cold point tropopause temperature during summer monsoon season: ARMEX campaign and CHAMP and COSMIC satellite observations; *J. Geophys. Res.* **116** D03102, <https://doi.org/10.1029/2010JD014340>.
- Jiang J H, Wang B, Goya K, Hocke K, Eckermann S D, Ma J, Wu D L and Read W G 2008 Geographical distribution and inter-seasonal variability of tropical deep convection: UARS MLS observations and analyses; *J. Geophys. Res.* **109** D03111, <https://doi.org/10.1029/2003JD003756>.
- Jiang X, Chahine M T, Olsen E T, Chen L L and Yung Y L 2010 Inter-annual variability of mid-tropospheric CO₂ from atmosphere infrared sounder; *Geophys. Res. Lett.* **37** L13801, <https://doi.org/10.1029/2010GL042823>.
- Krishnamurti T N and Bhalme H N 1976 Oscillations of a monsoon system. Part I. Observational aspects; *J. Atmos. Sci.* **33** 1937–1954, 10.1175/15200469(1976)033<1937:OOAMSP>2.0.CO;2.

- Krishnamurti T N and Subrahmanyam D 1982 The 30–50 days mode at 850 mb during MONEX; *J. Clim.* **14** 780–793.
- Kiladis G N and Weickmann K M 1992 Circulation anomalies associated with tropical convection during northern winter; *Mon. Weather Rev.* **120** 1900–1923, [https://doi.org/10.1175/1520-0493\(1992\)120<1900:CAAWTC>2.0.CO2](https://doi.org/10.1175/1520-0493(1992)120<1900:CAAWTC>2.0.CO2).
- Lambrigtsen B H 2003 Calibration of the AIRS microwave instruments; *IEEE Trans Geosci. Remote Sens.* **41**(2) 369–378, <https://doi.org/10.1109/tgrs.2002.808247>.
- Madden R A and Julian P R 1994 Observations of 40–50 day tropical oscillation: A review; *Mon. Weather Rev.* **122** 814–837.
- Meehl G A and Arblaster J M 2002 The tropospheric biennial oscillation and Asian Australian monsoon rainfall; *J. Clim.* **15** 722–744, [https://doi.org/10.1175/15200442\(2002\)015<0722:TTBOAA>2.0.CO2](https://doi.org/10.1175/15200442(2002)015<0722:TTBOAA>2.0.CO2).
- Mooley D and Shukla J 1987 *Variability and forecasting of the summer monsoon rainfall over India*; Oxford University Press, Oxford.
- Nayak R K, Dadhwal V K, Majumdar A, Patel N R and Dutt C B S 2011 Variability of atmospheric CO₂ over India and surrounding oceans and control by surface fluxes; *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*.
- Panwar V, Jain A R, Goel A, Mandal T K, Rao V R and Dhaka S K 2012 Some features of water vapour mixing ratio in tropical upper troposphere and lower stratosphere: Role of convection; *Atmos. Res.* **108** 86–103.
- Parthasarath B 1984 Inter-annual and long-term variability of Indian summer monsoon rainfall; *Proc. Indian Acad. Sci. (Earth Planet. Sci.)* **93** 371–385.
- Preethi B, Revadekar J V and Kriplani R H 2011 Anomalous behaviour of the Indian summer monsoon 2009; *J. Earth Syst. Sci.* **5** 783–794.
- Ratnam M V and Basha S G 2010 A robust method to determine global distribution of atmospheric boundary layer top from COSMIC GPS RO measurements; *Atmos. Sci. Lett.* **11** 216–222.
- Sikka D R and Gadgil S 1980 Maximum cloud zone and the ITCZ over India longitude during the southwest monsoon; *Mon. Weather Rev.* **108** 1840–1853.
- Shibagaki Y, Kozu T, Shimomai T, Mori S, Murata F, Hashiguchi H and Fukao S 2006 Evolution of a super cloud cluster and the associated wind fields observed over the Indonesian maritime continent during the first phase of CPEA campaign; *J. Meteorol. Soc. Jpn.* **84A** 19–31.
- Tiwari Y K, Gloor M, Engelen R J, Chevallier F, Roedenbeck C, Koerner S, Peylin P, Braswell B H and Heimann H 2006 Comparing CO₂ retrieved from atmospheric infrared sounder with model predictions: Implications for constraining surface fluxes and lower to upper troposphere transport; *J. Geophys. Res.* **111** D17106, <https://doi.org/10.1029/2005JD0066881>.
- Tiwari Y K, Patra P K, Chevallier F, Francey R J, Krummel P B, Allison C E, Revadekar J V, Chakraborty S, Langenfelds R L, Bhattacharya S K, Borole D V, Ravi Kumar K and Steele L P 2011 Carbon dioxide observations at Cape Rama India for the period of 1993–2002: Implications for constraining Indian emissions; *Curr. Sci.* **101** 1562–1568.
- Tiwari Y K, Revadekar J V and Ravi Kumar K 2013 Variations in atmospheric carbon dioxide and its association with rainfall and vegetation over India; *Atmos. Environ.* **68** 45–51.
- Yasanuri T 1979 Cloudiness fluctuations associated with the northern hemisphere summer monsoon; *J. Meteorol. Soc.* **57** 227–242.

Corresponding editor: A K SAHAI