Long-term trends of different stability indices of Earth's atmosphere measured using the COSMIC radio occultation technique

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ABSTRACT

GPS radio occultation (GPS RO) technique, performed on the COSMIC micro-satellites, is capable of providing plausible answers to several unraveled issues of both lower and upper atmosphere regions of the Earth, primarily due to its ability to provide very accurate, all-weather, round-the clock and global coverage of the atmosphere and ionosphere constituents with unprecedented resolutions. By exploiting the extreme prowess of COSMIC RO satellites, we present, in this study the long-term trends of the Earth's atmosphere stability indices, including CAPE and CIN for more than six continuous years (2007-2012). It is found that the wavelike nature consistently in CAPE seasonal and diurnal trends between June solstice- September equinox and December solstice- March equinox seasons by confining to northern and southern hemispheres and solar activity dependencies, are observed. The wavelike nature in CAPE trends seems to follow the inter tropical convergence zone (ITCZ) movement, which is again confirmed by analyzing outgoing long-wave radiation (OLR) database, thereby indicating that these CAPE trends may be useful to ascertain the ITCZ movements during different years. As the diurnal trends of CAPE are concerned, maximum (minimum) values are noticed during daytime (nighttime) hours consistent with earlier studies. CAPE magnitudes are showing solar activity dependencies by showing maximum (minimum) values during 2007 (2013), implying that CAPE magnitudes are showing a decreasing trend with the progress of time. Further, monthly CAPE variations near Delhi and near Kolkata, which are located in northern and eastern parts of India, are showing higher values during July-September and June-August respectively during the majority of the years. These trends also have great coincidence with onset times of monsoon periods in northern and eastern parts of India.

1.INTRODUCTION

Determination of atmospheric indices is imperative to assess the instability nature of earth's weather, which are often useful in the forecasting and nowcasting of intense convective and severe weather (thunderstorms and lighting). Although several new atmospheric indices are being continually introduced and evaluated [*Blanchard, 1998*], one can find a list of indices in the literature, including Showalter index [SI, *Showalter, 1953*], lifted index [LI, *Galway 1956*], convective available potential energy [CAPE, *Moncrieff and Miller 1976*], convective inhibition [CIN, *Romero et al., 2007*] and etc.

Prior to model-based studies, ground-based remote sensing instruments were used widely to compute instability indices of the atmosphere around the world. In general, atmospheric instability indices determined from the thermodynamic profiles of the atmosphere with the aid of a typical balloon- borne radiosonde instrument and a typical ground-based microwave radiometers. Nevertheless, most of the radiosonde instruments are confined to land areas only and, hence, over the oceans coverage is inadequate. In such circumstances, it is feasible to use the information derived from satellite sounding techniques such as a GPS based radio occultation (GPS RO) technique as it can provide very accurate and high resolution vertical profiles of temperature, humidity and pressure over a larger spatial and temporal scales. The main advantages of GPS RO products are unprecedented vertical resolution, global coverage and all weather capability and high accuracy.

COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate) GPS RO [*Anthes et al., 2008*] technique is capable of providing global trends of atmospheric indices with relatively higher resolutions. Added to this, recently launched six COSMIC satellites are able to provide an order of magnitude increase in the number of GPS RO profiles. According to the studies of *Brahmanandam et al. [2010] and Anthes [2011]*, COSMIC satellites provide approximately ~12 times higher database than the earlier RO missions and, on average, ~1500-2000 profiles will be available during a day around the globe.

2. FEW VALIDATION STUDIES AND ANALYSIS PROCEDURE OF ATMOSPHERIC INDICES

Figure 1 shows the number of occultations made by COSMIC RO satellites globally during January 2008, which are 51044 (on average, around 1650 profiles in a day globally). One can understand from this Figure that the number of occultations is extremely high for the latitude sector 80^0S- 80^0N, which is due to the high inclination of COSMIC micro-satellites (78^0), while the coverage in the equatorial region is relatively lesser. Another important observation is that near- Polar regions (~ 80^0-90^0) are marked with very low coverage. Bottom panels of Figure 1 left (right) one depicts temperature (pressure) profile measured using nearby radiosonde, RO technique and provided by NCEP reanalysis data, respectively. In general, comparisons of temperature and pressure profiles among these independent observations reveal a good correspondence [*Anisetty et al., 2014; Brahmanandam et al., 2010*] however with few following exceptions. For example, left (right) panel in Figure 1 shows temperature (pressure) profiles measured by COSMIC micro-satellite number 06, co-located radiosonde and NCEP reanalysis data at geographic latitude 0.070 S, geographic longitude 180.00 E on 1 March 2007 between 0 and 30 km. Here, geographic latitude and longitude represents a COSMIC satellite occultation location, whereas radiosonde measurements were taken 141 km and 01:45 hours away from the COSMIC satellite location. It is obvious that there is a slight difference in temperatures measured by these three independent observations from 0 to ~8 km altitude range, which is due to interference from water vapor existence at those altitudes. Good agreement was found between the COSMIC and various reanalysis outputs, with mean global differences and differences in the height range from 8 to 30 km being less than 1 K. Largest deviations were observed spatially over polar latitudes and altitude wise at the tropical tropopause with differences being 2–4 K. On the other hand, a cent percent consistency in magnitudes of pressure is found. It is, therefore, clear that temperature and pressure profiles show nearly good agreement between these three measurements, thereby providing confidence in using COSMIC RO retrieved temperatures.

To compute CAPE, we have used wet temperature profiles (wetPrf) provided by RO technique performed on COSMIC satellites from the following website (http).//www.cosmic.ucar.edu). According to the American Meteorological Society (AMS), mathematically CAPE can be expressed as

$$\text{CAPE}= \int_{R_{LFC}}^{P_{El}} (\alpha_p - \alpha_e) dp \ldots (1)$$

where α_p is the specific volume of the air parcel, and α_e is the environmental specific volume, P_{LFC} is the pressure where the level of free convection occurs, and P_{EL} is the pressure at which the parcel becomes neutrally buoyant. Nevertheless, for real-time measurements of the atmosphere's profile, eq. 1 must be expressed as a finite number of pressure levels

$$\text{CAPE}=\left(\sum_{P_{LFC}}^{P_{EL}}(\alpha_p-\alpha_e)\right)\Delta p\ldots(2)$$

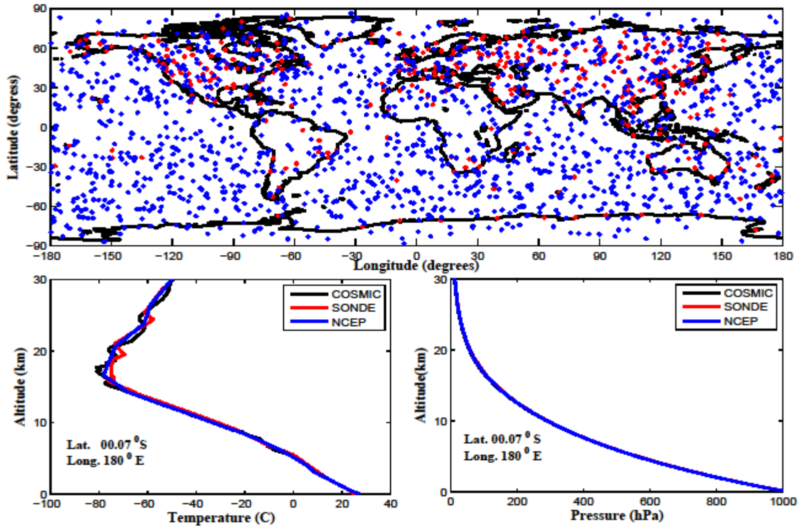

Figure 1. Top panel shows global occultations (1465 in number) made by the COSMIC satellites (blue circles) and number of radiosonde locations (667 in number) (red circles) on 01 March 2007 and bottom left (right) panel shows vertical temperature (pressure) profile measured by COSMIC, nearby radiosonde and provided by NCAR-NCEP reanalysis data on 01 March 2007.

3. GLOBAL TRENDS

Figure 2 shows the longitude vs. latitude structures of CAPE (measured in J/kg) during four seasons (left to right) during 2007 and 2012 (from top to bottom panels) at the tropical region. It is obvious from Figure 2 that over land area larger CAPE values are observed during most of the seasons between 2007-2012, consistent with general tendencies of them as well as with earlier studies [*Narendra Babu et al., 2009*]. Nevertheless, some of oceanic areas are also associated with large values when compared with land areas. For instance, western Pacific Ocean regions are associated with higher values during all MAM seasons consistently during 2007-2012, while eastern Pacific Ocean regions are associated with higher values during all JJA seasons consistently during 2007-2012. Most important observation from this Figure is that most of the larger CAPE values are following a wave-like pattern between JJA and SON and DJF MAM seasons during 2007-2012. More clearly, higher (lower) values are found to be located in northern (southern) hemisphere during JJA and SON (DJF and MAM) seasons, which directly implying that the CAPE trends are following inter-tropical convergence zone (ITCZ) where large moisture values often present. ITCZ, which appear as a band of clouds with thunderstorms, is the area encircling the earth near the equator and its location varies over time [*Das, 1991; Asnani, 1993*]. It has, therefore, been revealed, for the first time, that it is possible to track the evolution of ITCZ indirectly (by calculating CAPE values) during different seasons.

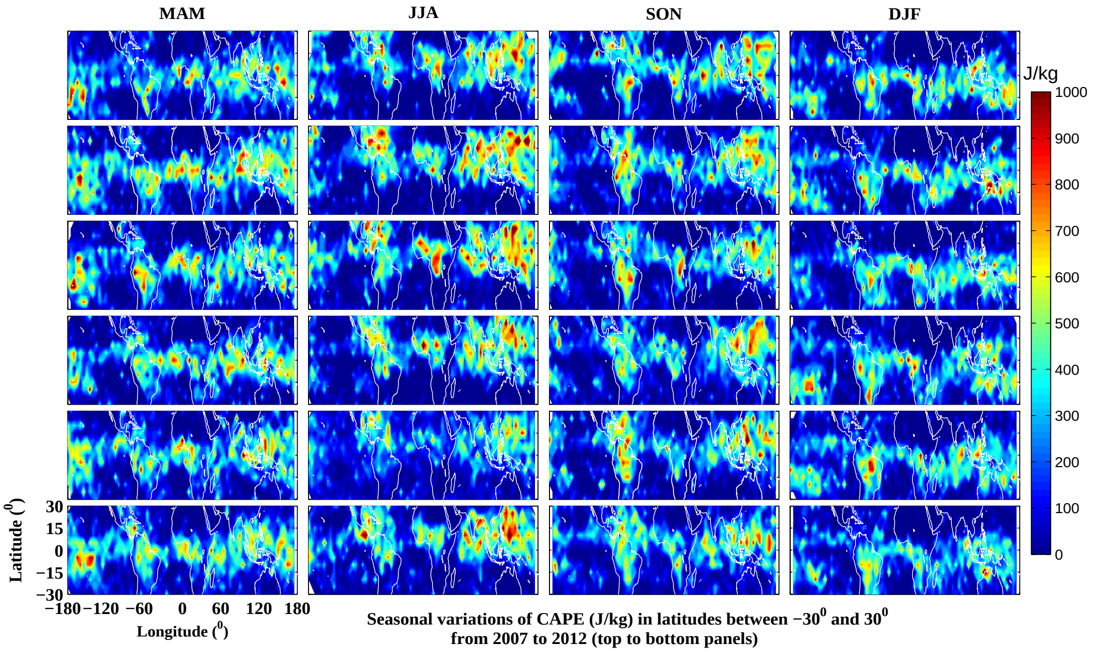

Figure 2. Seasonal variation of CAPE (March, April and May (MAM), June, July and August (JJA), September, October, November (SON), and December, January and February (DJF)) during 2007-2012 (from top to bottom panels) in latitudes between -30^0 and $+30^0$

3. CAPE MAGNITUDES

In order to know the maximum value that a CAPE value could attain during this long observation period at tropics, we have made a statistical survey and presented them in the following lines. Figure 3 shows a three-dimensional bar graph of CAPE magnitudes during four seasons and total CAPE values are divided into four different categories of magnitudes that fall between 0 and 1000, 1000 and 2500, 2500 and 5000, and 5000-10000. It is found from this Figure that category one cases (those are having magnitudes between 0-1000) during MAM, JJA, SON and DJF are 235609, 241536, 220598 and 238961, category two (those are having magnitudes between 1000-2500) are 17413, 20590, 16618 and 14421, category three (those are having magnitudes between 2500-5000) are 1760, 2715, 1884 and 1437 and category four (those are having magnitudes between 5000-10000) are 290, 437, 307 and 252, respectively. It is clear that majority (94%) of CAPE values belong to category one only, followed by two, three and fourth category.

4. DIURNAL VARIATIONS

In this study, it is also verified diurnal variations of CAPE trends during different seasons. Figure 4 shows local time vs. latitudinal variations of CAPEs during MAM, JJA, SON and DJF seasons (left to right panels) between 2007 and 2012 (top to bottom panels). It is interesting to note that a wave-like pattern in CAPE trends is observed, more clearly, CAPE trends are located in northern (southern) hemisphere during JJA and SON (DJF and MAM) seasons. This wave-like pattern is also observed in CAPE trends over tropics that shown in Figure 2, which indicates the confidence in this present analysis. As per as the diurnal variations of CAPE are concerned, maximum values are found during daytime hours, particularly around between 0600 and 0900 LT and around between 1300 and 1500 LT, and minimum values are found during nighttime hours (around between 2100 and 0400 LT) in different seasons. Additionally, though solar activity dependencies are not seen significantly in seasonal trends of CAPEs presented in Figure 2, such signatures are pretty evident in diurnal variations of CAPEs as shown in Figure 4. More elaborately, with the progress of time the magnitudes associated with CAPEs are decreasing from 2007 and 2012. Though it is known that global increases in temperatures lead to a general decreases of the frequency of occurrence of deep convective activities, with this mere study it may not be possible to dig-out a link between both of them and that important aspect come out of the scope of this research.

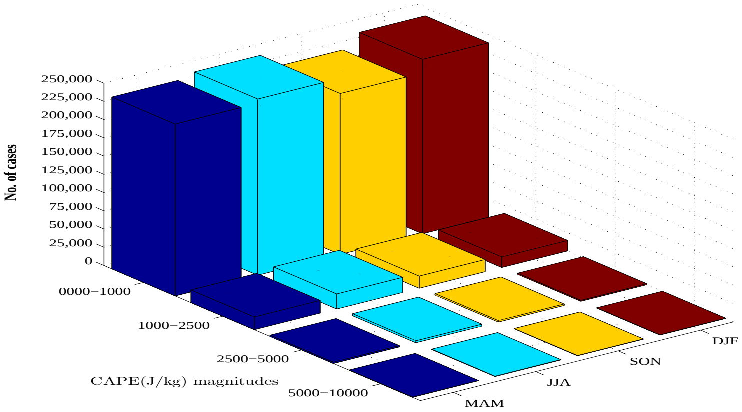

Figure 3. Three-dimensional bar graph is showing magnitudes of CAPE (J/kg) during different seasons between 2007 -2012. It is clear that majority (94%) of CAPE values during different seasons are lie between 0 and 1000 range.

5. CIN GLOBAL TRENDS

While CAPE describes the potential buoyancy available to idealized rising air parcels, convective inhibition (CIN) describes a stable surface layer, which rising air parcels need to overcome to reach the instable layer.

CIN can be defined as

CIN = GRAVTY * SUMN (DELZ * (TP - TE)/TE)….(3)

where SUMN = sum over sounding layers from top of the mixed layer to LFCT for which (TP - TE) is less than zero, DELZ =incremental depth; TP=temperature of a parcel from the lowest 500 m of the atmosphere, raised dry adiabatically to the LCL and moist adiabatically thereafter; TE= temperature of the environment.

Seasonally averaged CIN during 2007 are presented in Figure 5. Though seasonally averaged CIN are not as pronounced as in CAPE, a few important features are found. One can clearly observe from this Figure that a near bimodal distribution in CIN trends, with minimum values at around the geographic equator and maximum values at around 10^0 -15^0 latitudes on both sides of the equator. Bimodal distribution during different seasons in CIN trends was also found by *Reimann-Campe et al. [2009]* in the ERA-40 reanalysis model data, however, with maximum values at around 30^0 latitudes on both sides of the equator and minimum values at the equator. As the air transports to poleward and descends along the 30th latitude, wherein CIN (CAPE) associated with higher (lower) values according to the theory put forth by Reimann-Campe et al. (2009). Nevertheless, though CIN trends in our study also show a bimodal modal distribution in the same lines with the Reimann-Campe study, the exact physics behind this large latitudinal difference observed in our study needs to be understood.

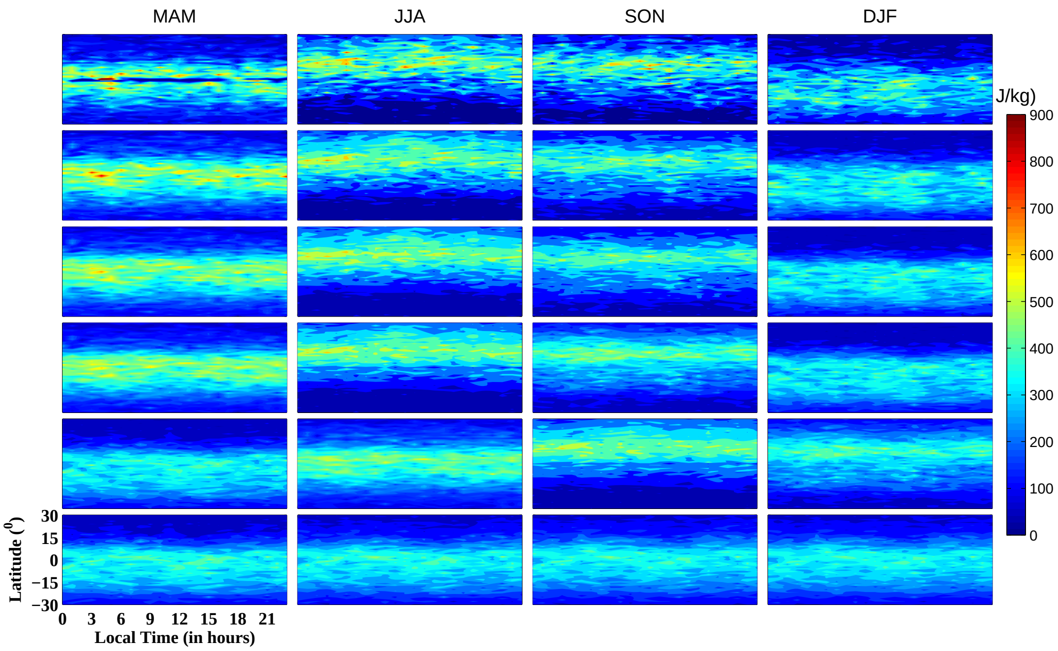

Figure 4. Local time vs. latitude variations of CAPE during March, April and May (MAM), June, July and August (JJA), September, October, November (SON), and December, January and February (DJF) seasons during 2007-2013 (top to bottom panels).

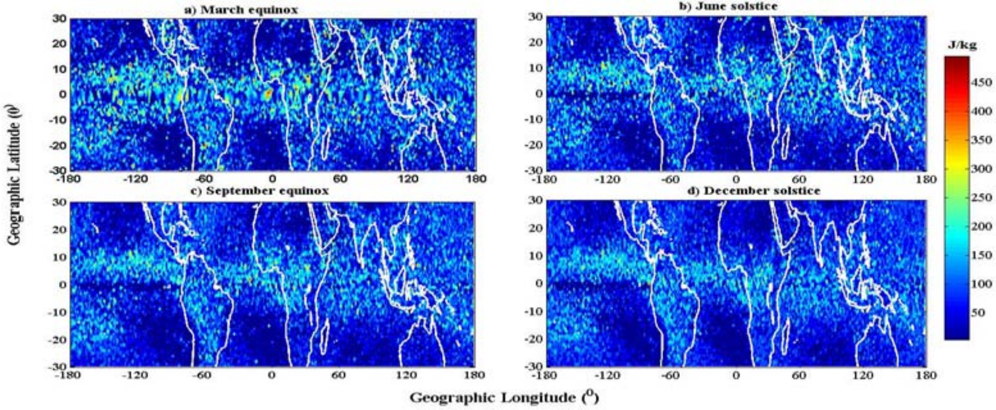

Figure 5. CIN seasonal trends at tropics for different seasons, including a) March equinox b) June solstice c) September equinox, and d) December solstice in 2007.

6. Monthly variations of CAPE trends at individual locations in India

Figure 6 shows monthly variations of CAPE near Delhi (28.3^0 N, 77.1^0 E) during 2007- 2013. It is to be noted that a five-point running mean has been applied on monthly variations of CAPE values in order to avoid some unnecessary spurious values. It can be seen from this Figure that higher CAPE values are observed around July-September period during majority of years consistently, a time at which the monsoon is active in northern India [*Dhaka et al., 2007*]. Though there are few differences noticed between peak values observed by us and Dhaka et al. [2010] near Delhi, almost similar CAPE trends are noticed by both these studies. The magnitude differences could be attributed to the different observational techniques used for calculating CAPE. Figure 7 shows monthly variations of CAPE near Kolkata (22.3^{0}N, 88.2^{0}E) during 2007-2013. It can be seen that these monthly trends have a great similarities with those observed near Delhi and the peak values near Kolkata are found during June-August during most of the years.

The earlier CAPE peak values near Kolkata can be justified based on the fact that the onset time of monsoon in eastern part of India is earlier than northern part, which indicating that these CAPE trends are having similarities with earlier results [*Dhaka et al., 2010*].

N. Conclusion

The salient results of the present study are summarized hereunder

a) A wave-like feature in CAPE seasonal and diurnal trends is noticed consistently, by confining to the northern (southern) hemisphere during June solstice and September equinox (December solstice and March equinox) seasons

b) CAPE trends seem to be following ITCZ movements, which are again confirmed by analyzing OLR database during different seasons

c) Maximum CAPE values are observed during daytime, while minimum are seen during nighttime consistent with earlier studies.

d) Solar activity dependency is clearly witnessed, with highest CAPE values in 2007 and minimum values during 2012, strongly implying that those are showing decreasing trend with the progress of time

e) Monthly trends near Delhi and Kolkata, two typical northern and southern locations in India, are showing highest values during July- September and June-August months during majority of years, and

f) The CAPE monthly trends at individual locations are not only consistent with earlier observational results, though few differences in their magnitudes are noticed, and also occurred during the onset time of monsoon at Indian region.

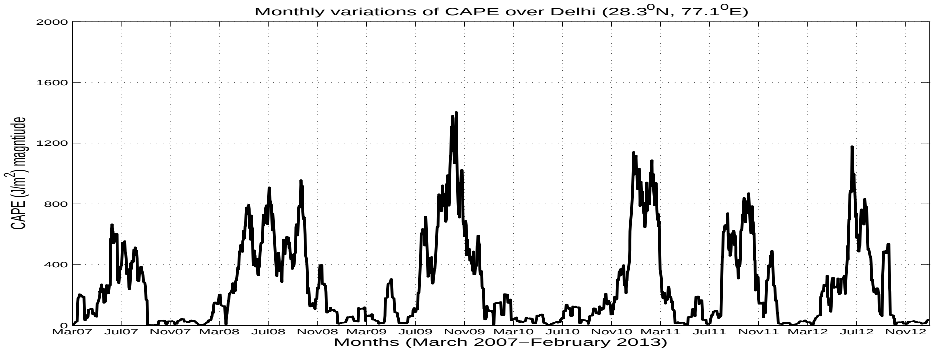

Figure 6. Shows monthly variations of CAPE near Delhi (28.3^0 N, 77.1^0 E), a typical northern location in India, during 2007- 2013.

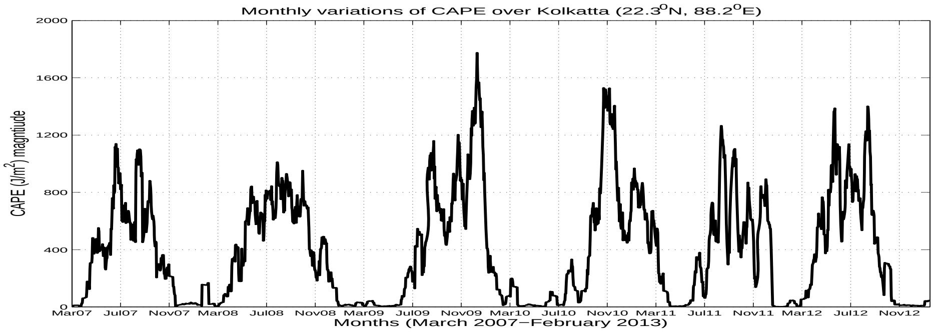

Figure 7. Shows monthly variations of CAPE near Kolkata (22.3^0N, 88. 2^0E), a typical eastern location in India, during 2007- 2013.

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