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Studies of Two Important Stability Indices of Earth's Atmosphere Determined by using the COSMIC GPS Radio Occultation Technique

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Abstract

Objectives: To study the seasonal variations of two important atmosphere stability indices, i.e. Convective Available Potential Energy (CAPE) and Convective Inhibition (CIN) for the selected years, i.e. from 2007 to 2012 using the COSMIC (Constellation Observing System for Meteorology, Ionosphere, and Climate) Radio occultation (RO) technique. **Methods/Analysis:** We used the COSMIC RO technique as we consider that it provides more accurate, all-weather, round-the-clock and global coverage of the lower atmosphere and ionosphere constituents with unprecedented resolutions. Further, we used the lower atmosphere database provided by the COSMIC RO technique in order to study the above two parameters (CAPE & CIN). **Findings:** It was found that, for the very first time, the consistency of wavy nature in CAPE seasonal trends which are confined to northern and southern hemispheres alternatively. The wavelike nature in CAPE trends seems to be following Inter- Tropical Convergence Zone (ITCZ) movement and, in such case, the CAPE trends may be useful to ascertain the ITCZ movements during different seasons of a year and the CAPE magnitude shows higher values over land than oceanic regions, which confirms the consistency of their calculations. In this regard, the trends of both CAPE and CIN have shown a close bimodal distribution. **Applications/Improvement:** As a result, we find better correlations of both CAPE and CIN computed through the atmospheric data measured with the COSMIC RO and collocated Radiosonde technique when the profile data are reaching to the near- surface of the Earth.

Keywords: Convective Available Potential Energy (CAPE), Convective Inhibition (CIN), GPS RO Technique, ITCZ

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[1], one can find a list of indices in the literature, including Showalter Index[2] (SI), Lifted Index[3] (LI), Convective Available Potential Energy[4] (CAPE), Convective Inhibition[5] (CIN).

It is true that each index has its own significance in evaluating the character of the state of the atmosphere. To be more specific, vertically integrated indices, including CAPE, CIN are being widely used by the community when compared with single-level stability indices including, SI and others. In order to carry out analysis and forecasting of severe weather associated with convective precipitation, both CAPE and CIN indices are often used. Global climatologies of CAPE have been derived from seven years NCAR/NCEP reanalyses (National Centers for Atmospheric Research/ National Centers for

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Environmental Prediction[6,7]) and regional climatologies of both CAPE and CIN have been computed using the ERA-40-European Center for Medium-Range Weather Forecast[8] (ECMWF). By using 44 years (1958-2001) ERA-40 reanalysis data, it was presented the global climatologies of CAPE and CIN in terms of seasonal means, variances, and trends[9]. Nevertheless, a tenacious problem for numerical and weather forecast models is that their inability to capture convective phenomena properly. As the accurate representation of convection is particularly important in the tropics, the so-called models often fail to represent the true convective scenario.

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. It was reported that studies on global long-term trends of CAPE were scarce[10], possibly due to the unavailability of database particularly over oceanic regions. On the other hand, several research groups have reported on CAPE trends at individual locations. For instance, researchers have used long and stable records of radiosonde measured temperature profiles[11-15] and other few meteorological instruments, including balloon-borne packets, microwave radiometers (MWR) and dropsondes[15-18,] to measure CAPE and other atmospheric indices at various locations. Possibly because of their availability of records for the last several decades at numerous tropical locations and as they provides in-situ, high-resolution temporal and spatial sampling of the vertical temperature and moisture structures, multi-decadal trends of CAPE have been reported in the literature with the help of radiosonde measured temperatures[19-21]. Nevertheless, most of the radiosonde instruments are confined to terrain localities only and, the ocean coverage is very less. In that situations, it is sensible to use the information derived from satellite sounding techniques such as a Global Positioning System (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.

It has also been verified that the mutual effects of the positive temperature and moisture trends in the change of convective activity by computing CAPE trends at 15 tropical sounding stations[10]. The research conducted by[22] had revealed a low correlation between CAPE and rainfall comparisons and monthly CAPE anomalies were generally positively correlated with sounding derived precipitable water (PW) and lapse rate. It was found that an increasing trend in CAPE associated with decreases in temperature at the 100-hPa pressure level on all time scales while digging out the relationship between seasonal, annual and large-scale variations in CAPE and the temperature at 100-hPa pressure level using radiosonde measurements during 1980-2006 over different locations in northern, eastern and southern parts of India[13]. It is now confirmed that the scientific community could not understand how large-scale structures of temperature and moisture of the tropical troposphere were manifested in convective activity globally, primarily due to the unavailability of global databases. In this context, COSMIC GPS RO technique assumes great significance as it enables one to study global trends of them with relatively higher resolutions[23]. Added to this, recently launched six COSMIC satellites can give an order of magnitude augment in the amount of GPS RO profiles. It was reported COSMIC micro satellites provide twelve times higher occultations when compared to the earlier RO missions[24,25].

This article is organized as follows. Section 2 includes validation studies of temperature, pressure, and specific humidity profiles. Analysis procedure and seasonal trends of both CAPE and CIN are presented in the section 3, which also has a dialogue about the inference of the results presented in this research. Section 4 provides conclusions.

2. Observational Results and Discussion

2.1 Validation Studies of Temperature, Pressure, and Specific Humidity

In order to show how many occultation events will be possible with the COSMIC RO during a day and how temperature, pressure, relative humidity profiles vary in comparison with radiosonde and model-based studies, a few validation case studies are carried out. Figure 1 shows the accusations made by COSMIC and redesigned, which were 1465 and 667 on 01 March 2007. On the other hand, the bottom left (right) panel of the Figure 1 shows temperature (pressure) profiles measured using nearby radiosonde, COSMIC RO technique and provided by NCEP reanalysis data, respectively. It was reported that comparison of both temperature and pressure profiles between these independent observations divulge a superior correspondence[24,26]. The geographic latitude and longitude represents the COSMIC satellite occultation locations. It can be seen that, a minor difference in temperatures measured by these three independent observations from 0 to 8 km altitude range, possibly due to the intrusion of water vapor. For instance, [27]carried out a study, based on the operational stratospheric analyses, including NCEP, the Japanese 25- year Reanalysis (JRA-25) and the United Kingdom Met Office (UKMO) data sets. Largest deviations were observed spatially over polar latitudes and altitude wise at the tropical tropopause with differences being 2–4 K. It was studied the relationship between temperature variations and increasing trend of atmospheric carbon dioxide in Fars Province, Iran[28].

Humidity profiles from GPS RO are retrieved using 1D-var technique[29-31], which is an efficient technique to unite information provided by the GPS RO and a given priori atmospheric state in a statistically optimal way. Figure 2 presents the vertical specific humidity profiles measured by the COSMIC RO technique, nearby radiosonde and provided by NCAR/NCEP reanalysis data on 01 March 2007 at 01:20 Universal Time Coordinated (UTC) (left panel) and 1259 UTC (right panel) between 0 and 10 km altitude range.

The specific humidity is derived from the water vapor and pressure using the method given by[32]. It is obvious from the Figure 2 that a good correlation between the three independent techniques, both in the trend and magnitude, is found except below 2 km. It is also true from both the figures that the COSMIC specific humidity profile is showing its trend only from near to 1 km altitude range, which indicates the majority of COSMIC profiles are not reaching to the surface of the Earth and we suspect this could be one of the reasons for the mismatch of trends and magnitudes of specific humidity profiles below the 2 km altitude range.

From the above comparisons as temperature, pressure, and specific humidity profiles demonstrate good quality agreement, it may conclude that the COSMIC retrieved temperature and pressure profiles are reliable and accurate.

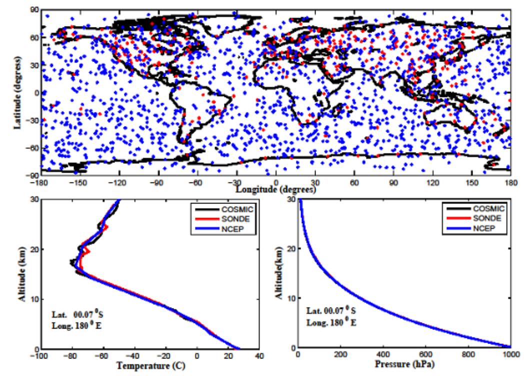

Figure 1. Top panel shows global occultations (1465 in number) made by COSMIC satellites (blue circles) and number of radiosonde locations (667 in number) (red circles) on 01 March 2007 and bottom left (right) panel shows vertical temperature (pressure) profile measured by COSMIC, nearby radiosonde and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

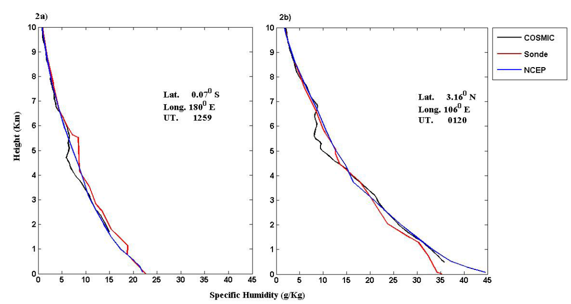

Figure 2. Vertical specific humidity profiles measured by COSMIC, nearby radiosonde and provided by NCAR/NCEP reanalysis data on 01 March 2007 at 0120 UTC (left panel, Figure 2a) and 1259 UTC (right panel, Figure 2b).

3. Computation Procedure of Important Indices and its Variations

3.1 CAPE

We have considered post-processed COSMIC RO atmosphere data for this study. The minimum altitude level of temperature (wetPrf) used to calculate CAPE is 600 meters since the majority of radiosonde data were available reliably from this altitude range only. It may be worth mentioning here that by virtue of Open-Loop (OL) tracking approach which is implemented on the COSMIC RO mission, more than 90% of the profiles penetrate below 1 km[33], which means that majority of profiles were utilized to compute these atmospheric indices. On the other hand, a few researchers have adopted various methods to enhance the GPS Receiver Tracking Loop Performance in Multipath Environment Using an Adaptive Filter Algorithm[34].

According to the American Meteorological Society (AMS), mathematically CAPE can be expressed as

$$\text{CAPE}= \int_{R_{LEF}}^{P_{EL}} (a_p - a_e)dp \qquad (1)$$

Where α_p is the specific volume of the saturated air parcel, and α_e is the environmental specific volume, $P_{LFC/}R_{LFC}$ 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, equation (1) must be expressed as a finite number of pressure levels

$$\text{CAPE}= \left(\sum_{P_{LEF}}^{P_{El}} (a_p - a_e)\right)\Delta p \qquad (2)$$

Once the computation procedure of CAPE is completed over the tropics, data gridding allowed us to show them onto 5º X 5º resolutions and those trends are further grouped as March equinox (March, April and May (MAM)), the June Solstice (June, July, and August (JJA)), September equinox (September, October, and November (SON), and December solstice (December, January, and February (DJF)).

Note that since calculated CAPE values have been averaged over a large spatial region and during different local times of the day during a season, CAPE values are associated with smaller values. Figure 3 (a-d) depicts the CAPE seasonal trends in March equinox, the June solstice, September equinox, and the December solstice of 2007. It is clear from these figures that CAPE values are found to be higher over land compared to oceanic regions during different seasons. This observational evidence is confirming the consistency of CAPE calculations. The research study conducted by using COSMIC observations over tropics has also shown large CAPE magnitudes at land regions than over oceanic regions in the similar lines with our study[35].

Another important observation is that the CAPE trend seems to follow a wavelike pattern by confining to the northern hemisphere during the June solstice and September equinox seasons and to the southern hemisphere during the December solstice and March equinox seasons, respectively. In order to know whether the so-called wavelike nature is also appearing during the entire observation period (2007-2012), CAPE global trends are presented in the following lines. Figure 4 shows the longitude vs. latitude structures of CAPE during four seasons (left to right) during 2007 and 2012 (from top to bottom panels). It is noticeable from Figure 4 that land areas have observed larger CAPE values during four seasons of the entire observation period. More clearly, higher (lower) values are found to be located in northern (southern) hemisphere during JJA and SON (DJF and MAM) seasons, which implying that the CAPE trends are following the ITCZ movements where large moisture values often present. However, a plethora of databases needs to be analyzed to verify whether the same wavelike nature does really exist or not. 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[36,37].

Therefore, it may be possible to track the evolution of the ITCZ indirectly (by calculating CAPE values from RO based data) during different seasons of a year. To the best of the authors' knowledge, wavelike features in CAPE trends for more than six continuous years have not yet been reported any research workers, by using either COSMIC RO or any other model-based data. Although the exact plausible mechanisms responsible for this wavelike nature have not understood with this research, it cannot be ruled out that the migration of CAPE back and forth from south to north may be articulated to the seasonal migration of solar radiation. However, it has been revealed by the scientific fraternity that the exact associations between CAPE and its attachment with temperature in the upper troposphere are not understandable[38] [10]studied trends in CAPE, mainly in the Western Pacific region, and highlighted that most of the increment in CAPE can be linked with increment in temperature and/or moisture at 990 hPa. However, they observed a decreasing trend in CAPE at a few locations in their study, which still means there are uncertainties prevailing in their relations. Due to the unavailability of the global database, till now no effort has been made to assess the bond between CAPE variability and the response of the temperature field in the upper troposphere. As such, the exact relation between CAPE seasonal trends and its association with temperatures may be ruled out for the time being.

A strong relationship between convection and vertically propagating atmospheric wave motions in the upper troposphere and lower stratosphere on a wide temporal and spatial spectrum has been established by several research studies[39-41]. In general, it is known that strong vertical coupling is the result of large CAPE (i.e., large convective activity), which favors strong vertical coupling. Since this atmospheric index, CAPE, is basically an integrated atmospheric index, the dominance of vertical wave motion in the CAPE's seasonal trends cannot also be ruled out. Nevertheless, since we have observed a wavelike nature in CAPE's seasonal trends in the east-west direction, it is not possible, at this juncture, to know the dominance of wave activities, if they really exist, in the east-west direction as we do not have any direct observational facility to measure this wavelike nature.

Therefore, this intriguing wavelike nature will be left as an unexplained phenomenon at this moment. However, as a large number of GPS RO database become available in the coming years with the commissioning of COSMIC-2 RO mission, it may be possible to unravel the exact physics, if it really does exist behind this wavelike nature in the seasonal trends of CAPE in the near future.

The quantification of CAPE is also very much essential, particularly in the aviation field. Unexpected convection over oceans can adversely affect airplane travel and the Federal Aviation Agency (FAA) of the USA is on their continuous effort to build up a method that notify the approaching convection[42]. The FAA has decided to use CAPE as a potential useful meteorological index since the earlier algorithms that often provide false alarms about hazardous convective cells over the oceanic regions for more than 40% of the time[42]. Further, atmospheric indices are highly applicable to meteorologists that specialize in the forecast of thunderstorms and other types of moist convection, which, in general, are readily computed from sounding data[43].

In order to know the maximum value that a CAPE value could attain during this long observation period at the tropics, a statistical survey is made by us, which is presented in the following lines. Figure 5 shows a bar graph of CAPE magnitudes during four seasons and total CAPE values are divided into four different categories of magnitudes that fall between 0 to 1000, 1000 to 2500, 2500 to 5000, and 5000 to 10000. It is found from this figure that category-I cases (those which are having magnitudes between 0 to 1000) during MAM, JJA, SON and DJF are 235609, 241536, 220598 and 238961, category-II (those are having magnitudes between 1000 and 2500) are 17413, 20590, 16618 and 14421, category-III (those which are having magnitudes between 2500 to 5000) are 1760, 2715, 1884 and 1437 and category-IV (those are having magnitudes between 5000 to 10000) are 290, 437, 307 and 252, respectively. It is clear that the majority (94%) of CAPE values belong to only category-I, and it is followed by II, III and IV. Table 1 shows the stability of air parcel in related with the various CAPE values.

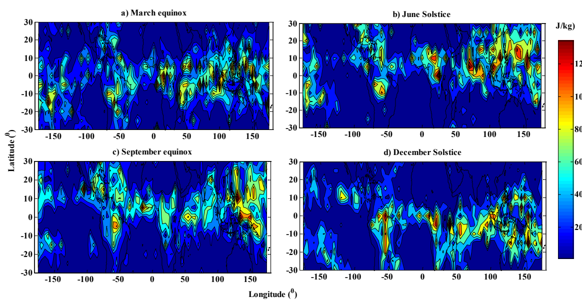

Figure 3. CAPE seasonal trends at tropics for different seasons, including a) March equinox b) June solstice c) September equinox, and d) December solstice in 2007.

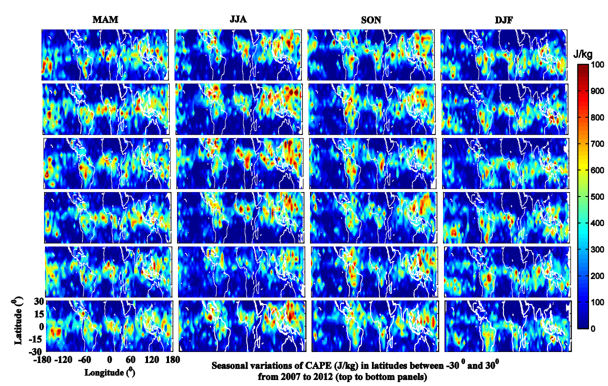

Figure 4. CAPE seasonal trends at tropics for different seasons including, March equinox, the June solstice, September equinox and December solstice (left to right panels) during 2007-2012 (top to bottom panels).

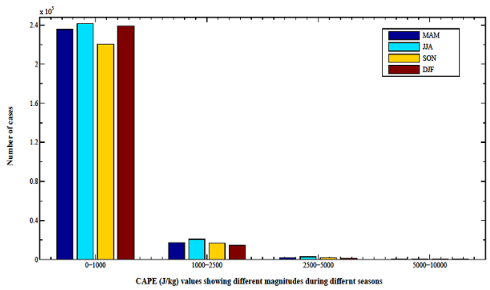

Figure 5. Bar graph shows the magnitudes of CAPE (J/kg) during different seasons between 2007 -2012. It is clear that the majority (94%) of CAPE values during different seasons are lying between 0 and 1000 range.

Table 1. Shows how various CAPE values correlate to air parcel stability

S. No.	CAPE value range	Convective potential Category
1.	0	Stable
2.	0-1000	Marginally Unstable
3.	1000-2500	Moderately Unstable
4.	2500-3500	Very Unstable
5.	3500+	Extremely Unstable

3.2 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 = GRAVITY * 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, and the TE= temperature of the environment.

Seasonally averaged CIN during the year 2007 are presented in Figure 6. Though seasonally averaged CIN trends are not as pronounced as of CAPE, a few important features have been observed. 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^{o} -15^{o} latitudes on both sides of the equator. Bimodal distribution during different seasons in CIN trends was also noticed by[9] in the ERA-40 reanalysis model data, however, with maximum values at around 30^{o} latitudes on both sides of the equator and minimum values at the equator. As the air transports to poleward and descends along the 30^{th} latitude, wherein CIN (CAPE) associated with higher (lower) values according to the theory put forth by[9]. The CIN trends in our study also show a bimodal modal distribution in the same lines with the Reimann-Campe study, besides a significant latitudinal difference that needs to be understood.

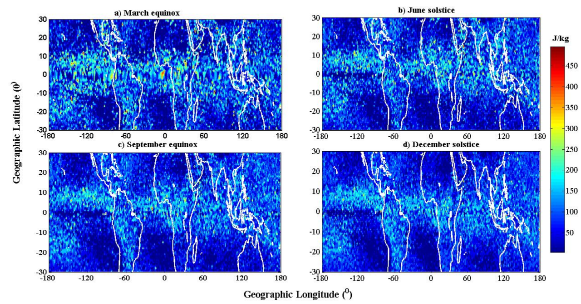

Figure 6. CIN seasonal trends at tropics for different seasons, including a) March equinox b) June solstice c) September equinox, and d) December solstice in 2007.

3.3 Correlation Studies of CAPE and CIN Measured with COSMIC RO and Collocated Radiosonde Techniques

Comparison of convective indices calculated by the GPS RO and collocated radiosonde techniques during June 2007 are presented in the following scatter plots. Figure 7 shows comparisons of CAPE, while Figure 8 shows comparisons of CIN. Note that the steepness of the slopes and r^2 values for each plot and also the correlations between COSMIC RO soundings which are ~200 km and ±2 hours apart from radiosonde data are plotted.

From Figures 7 and 8, it is obvious that relatively better correlations for CAPE and CIN measured with the COSMIC RO and collocated radiosonde techniques. More specifically, it is obvious from Figure 7 that the value of r^2 is 0.6724, which means that the regression line formula can be able to explain the 67% of the variability between these two independent techniques. On the other hand, although a one-to- one correspondence is found for CIN measured with the COSMIC RO and collocated radiosonde techniques, the r^2 is showing only 0.5206 (see Figure 8). The above statistics indicate that, still further refinements in the current determination methods/approaches of these important atmospheric indices are needed as to improve the correlation statistics of the COSMIC RO technique with ground-based remote sensing technique[44].

Further, through this study, it can be said that a great care has been taken while selecting appropriate temperature and pressure profiles that are used to measure these important atmospheric indices. We reiterate here that one has not to consider the profile data that did not reach the surface of the Earth while computing these important atmospheric indices. It was found by us a mere 22.9% (21%) correlation existed for CAPE (CIN) computed using the COSMIC RO retrieved and nearby radiosonde measured atmosphere data when we had considered profiles reaching 1 km altitude range (not shown here). It was also noticed by [15]that the percentage of error, particularly with CAPE, has shown an increasing trend (51%, 69 %, 82 %, and 96 %) when they considered altitude levels at 1 km, 1.5 km, 2 km, and 3 km, respectively.

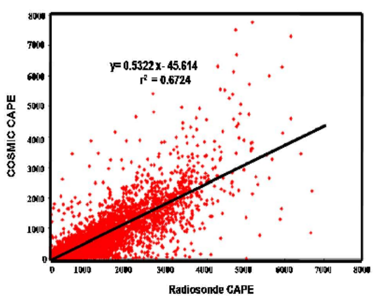

Figure 7. Figure illustrates the regression line, correlations, and the r^2 values between COSMIC and collocated radiosonde measured CAPE for June 2007.

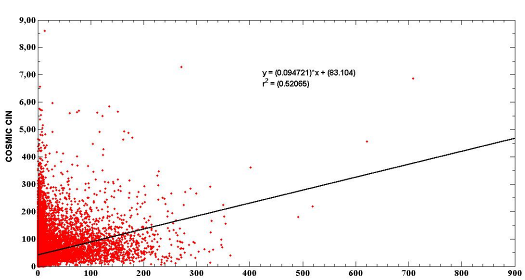

Figure 8. This figure illustrates the regression line, correlations, and the r^2 values between COSMIC and collocated radiosonde measured CIN for June 2007.

4. Conclusion

With this extensive research, it can be observed that the convection activities not only play an important role in Earth's atmosphere but also it often responsible for adverse weather conditions. Here, both CAPE and CIN are considered as efficient parameters for forecasting moist convection. As it is mentioned earlier, CAPE is nothing but the energy available for moist convection in an air column once a parcel is lifted to the level of free convention where it becomes buoyant with respect to its environment. In general, CAPE is used in association with CIN which describes the energy that a parcel needs to overcome the capping inversion during ascent and become buoyant[45,46].

However, the detailed global and seasonal variations of CAPE and CIN are not yet properly understood, particularly due to the paucity of the global database. GPS RO measurements performed on COSMIC satellites have provided a great opportunity for us to get this information for more than six continuous years i.e. from 2007 to 2012. A serious attempt is made in this research to study CAPE and CIN seasonal trends for more than seven continuous years using the COSMIC GPS RO technique. The CAPE seasonal variations in different seasons from 2007 to 2012 exposed a few significant features. Initially, a wavelike trend in CAPE is noticed consistently by confining to the northern hemisphere during the June solstice and September equinox seasons and to the southern hemisphere during the December solstice and March equinox seasons alternatively. CAPE trends seem to be following ITCZ, where the convective activity is predominant. As expected, land regions have associated with higher CAPE values compared to oceanic regions. Simultaneously, a bimodal distribution is seen in CIN trends, in the similar lines with earlier studies. A better correlation has found for CAPE and CIN measured with COSMIC RO and collocated radiosonde measurements.

5. Acknowledgements

Atmosphere database used in this research obtained from the COSMIC Data Analysis and Archive Centre (CDAAC). Radiosonde data are obtained from the

University of Wyoming, USA website (http://weather.uwyo.edu/upperair/sounding.html).

6. References

1. Blanchard DO. Assessing the Vertical Distribution of Convective Available Potential Energy. Weather Forecast. 1988; 13:870–77.
2. Showalter AK. A stability index for thunderstorm forecasting. Bulletin of American Meteorological Society. 1953; 34(3):250–52.
3. Galway JG. The lifted index as a predictor of latent instability. Bulletin of American Meterological Society. 1956; 37:528–29.
4. Moncrieff MW, Miller MJ. The dynamics and simulation of tropical cumulonimbus and squall lines. Quarterly Journal of Royal Meteorological Society. 1976; 102(432):373–94.
5. Romero R, Gaya M, Doswell tCA. European climatology of severe convective storm environmental parameters: a test for significant tornado events. Atmospheric Research. 2007; 83(2-4):389–404.
6. Brooks HE, Lee JW, Craven JP. The spatial distribution of severe thunderstorm and tornado environments from global reanalysis data. Atmospheric Research. 2003; 67–68:73–94.
7. Brooks HE, Anderson AR, Riemann K, Ebbers I, Flachs H. Climatological aspects of convective parameters from the NCAR/NCEP reanalysis. Atmospheric Research. 2007; 83(2-4):294–305.
8. Romero R, Gaya M, Doswell CA. European climatology of severe convective storm environmental parameters, a test for significant tornado events. Atmospheric Research. 2007; 83(2-4):389–404.
9. Riemann K, Fraedrich K, Lunkeit F. Global climatology of Convective Available Potential Energy (CAPE) and Convective Inhibition (CIN) in ERA-40 reanalysis. Atmospheric Research. 2009; 93(1-3):534–45.
10. Gettelman A. Multidecadal trends in tropical convective available potential energy. Journal of Geophysical Research. 2002; 107(21):1–8.
11. Williams E, Renno N. An analysis of the conditional instability of the tropical atmosphere. Monthly Weather Review. 1993; 121:21–36.
12. DeMott CA, Randall DA. Observed variations of tropical convective available potential energy. Journal of Geophysical Research. 2004; 109(2):1–11.
13. Dhaka SK, Panwar V, Sapra R, Bhatnagar R. Large scale variation in observed convective available potential energy (CAPE) over Chennai, Kolkata, and Delhi using radiosonde. In Proceedings of the Eleventh International Workshop on Technical and Scientific Aspects of MST Radar. 2007; 720–23.
14. Dhaka SK, Sapra R, Panwar V, Goel A, Bhatnagar R, Kaur M, Mandal TK, Jain AR, Chun HY. Influence of large-scale variations in convective available potential energy (CAPE) and solar cycle over temperature in the tropopause region at Delhi (28.3∘N, 77.1∘E), Kolkata (22.3∘N, 88.2∘E), Cochin (10∘N, 77∘E), and Trivandrum (8.5∘N, 77.0∘E) using radiosonde during 1980–2005. Earth Planets Space. 2010; 62:319–31.
15. Ratnam M V, Durga Santhi Y, Rajeevan M, Rao SVB. Diurnal variability of stability indices observed using radiosonde observations over a tropical station: Comparison with microwave radiometer measurements.Atmospheric Research. 2013; 124:21–33.
16. Chan PW. Performance and application of a multi wavelength, ground-based microwave radiometer in intense convective weather. Meteorology Zeitschrift. 2009; 18(3):253–65.
17. Cimini D, Campos E, Ware R, Albers S, Giuliani G, Oreamuno, Paul JJ, Steve E K, Stewart C, Westwater Ed. Thermodynamic Atmospheric Profiling During the Winter Olympics using Ground-Based Microwave Radiometry. IEEE transactions on Geoscience and Remote Sensing. 2011; 49(12):4959–69.
18. Cimini D, Pierdicca N, Pichelli E, Ferretti R, Mattioli V, Bonafoni S, Montopoli M, Perissin D. On the accuracy of integrated water vapor observations and the potential for mitigating electromagnetic path delay error in In SAR. Atmos Meas Tech Discuss. 2012; 5:1015–30.
19. Gutzler DS. Climatic variability of temperature and humidity over the tropical western Pacific. Geophysical Research Letters. 1992; 19(15):1595–8.
20. Gutzler DS. Low-frequency ocean-atmosphere variability across the tropical western Pacific. Journal of Atmosheric Sciences. 1996; 53(19):2773–85.
21. Gaffen DJ, Santer BD, Boyle JS, Christy JR, Graham N, Ross R. Multidecadal changes in the vertical temperature structure of the tropical atmosphere. Science. 2000; 287(5456):1242–45.
22. De Mott CA, Randall DA. Observed variations of tropical convective available potential energy. J Geophysical Research. 2004; 109(2):1–14.
23. Anthes RA, Bernhardt PA, Chen Y, Cucurull L, Dymond KF, Ector D, Healy SB, Ho SP, Hunt DC, Kuo YH, Liu H, Manning K, Mccormick C, Meehan TK, Randel WJ, Rocken C, Schreiner WS, Sokolovskiy SV, Syndergaard S, Thompson DC, Trenberth KE, Wee TK, Yen NL, Zeng Z. The COSMIC/FORMOSAT-3 Mission: Early Results. Bulletin of American Meteorological Society. 2008; 89:313–33.
24. Brahmanandam PS, Chu YH, Liu J. Observations of equatorial Kelvin wave modes in FORMOSAT-3/COSMIC GPS RO temperature profiles. Terrestial, Atmospheric and Ocean Science. 2010 ;(5):817–27.
25. Anthes RA. Exploring Earth's atmosphere with radio occultation: contributions to weather, climate and space weather. Atmospheric Measurement Techniques. 2011; 4:1077–103.
26. Prasad Rao Anisetty SKAV, Brahmanandam PS, Uma G, Babu NA, Huang CY, Kumar AG, Ram TS, Wang HL, Chu YH. Planetray-scale wave structures in Earth's atmosphere using COSMIC observations. Journal of Meteorological Research. 2014; 28(22):281–95.

27. Kishore P, Namboothiri SP, Jiang JH. Global temperature estimates in the troposphere and stratosphere: A validation study of COSMIC/FORMOSAT-3 measurements. Atmospheric Chemistry and Physics. 2009; 9(3):897–908.
28. Sabzevari AA, Miri GR. Studying Temperature Component Variations in Relation with the Increase of the Atmosphere Carbon Dioxide in Fars Province, Iran. Indian Journal of Science and Technology. 2012 Sep; 5(9):3281–87.
29. Healy S, Eyre J. Retrieving temperature, water vapor and surface pressure information from refractive-index profiles derived by radio occultation: A simulation study. Journal of Royal Meteorlogical Society. 2000; 126(566):1661–83.
30. Healy SB, Eyre JR. Retrieving temperature, water vapor and surface pressure information from refractive-index profiles derived by radio occultation, A simulation study. Journal of Royal Meteorlogical Society. 2000; 126(566):1661–83.
31. Gurbanov G, Kornblueh L. Principles of variational assimilation of GNSS radio occultation data. Max Planck Institute for Meteorology: Germany, 2003.
32. Ross RJ, Elliott WP. Tropopsheric water vapour climatology and trends over North America. Journal of Climate. 1994; 9(3):3561–74.
33. Ao CO, Hajj GA, Meehan TK, Dong D, Iijima BA, Mannucci AJ, Kursinski ER. Rising and setting GPS occultations by use of open-loop tracking. Journal of Geophysical Research. 2009; 114 pp.
34. Mariappan S, Sasibhusana Rao G, Ravindra Babu S. Enhancing GPS Receiver Tracking Loop Performance in Multipath Environment using an Adaptive Filter Algorithm. Indian Journal of Science and Technology. 2014 Nov; 7(S7):156–64.
35. Babu NA, Nee JB, Kumar KK. Seasonal and diurnal variation of convective available potential energy (CAPE) using COSMIC/FORMOSAT-3 observations over the tropics. Journal of Geophysical Research. 2010; 115(4):1–8
36. Das PK. The Monsoons, National Book Trust: New Delhi. 1991; 254 pp.
37. Asnani GC. Tropical Meteorology. Indian Institute of Tropical Meteorology. 1993; 1(1):1202.
38. Emanuel KA, Neelin J, Bretherton C. On large scale circulations in convecting atmospheres Q. Journal of Royal Meteorological Society. 1994; 120(519):1111–43.
39. Dhaka SK, Takahashi M, Kawatani Y, Shibagaki Y, Fukao S. Observations of deep convective updrafts in tropical convection and their role in the generation of gravity waves. Journal of Meteorological Society of Japan. 2003; 81(5):1185–99.
40. Dhaka SK, Yamamoto MK, Shibagaki Y, Hashiguchi H, Yamamoto M, Fukao S. Convection-induced gravity waves observed by the Equatorial Atmosphere Radar (0.2°S, 100.32°E) in Indonesia. Geophysical Research Letters. 2005; 32(9):14–820.
41. Dhaka SK, Yamamoto MK, Shibagaki Y, Hashiguchi H, Fukao S, Chun HY. Equatorial Atmosphere Radar observations of short vertical wavelength gravity waves in the upper troposphere and lower stratosphere region induced by localized convection. Geophysical Research Letters. 2006; 33(19):1–7.
42. Donovan MF. The Identification and Verification of Hazardous Convective Cells over Oceans using Visible and Infrared Satellite Observations. Journal of Applied Meteorology Climatology. 2007; 47:164–84.
43. Glickman TS. Glossary of Meteorology. Second Edition. American Meteorological Society: Boston, MA. 2000; 855 pp.
44. Hernandez MK, Kuo Y-H, Douglas CH, Rachel H. Utilizing radio occultation soundings to estimate convective potentials over ocean.12th Conference on IOAS-AOLS. 2007; 1–16.
45. Doswell CA, Rasmussen E. The effect of neglecting the virtual temperature correction on CAPE calculations. Weather and Forecasting. 1994; 9:625–29.
46. Blanchard DO. Assessing the Vertical Distribution of Convective Available Potential Energy. Weather Forecasting. 1988; 13:870–77.