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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

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We have shown the relationship between seasonal, annual, and large-scale variations in convective available potential energy (CAPE) and the solar cycle in terms of temperature at the 100-hPa pressure level using daily radiosonde data for the period 1980–2006 over Delhi (28.3°N, 77.1°E) and Kolkata (22.3°N, 88.2°E) and for the period 1989–2005 over Cochin (10°N, 77°E) and Trivandrum (8.5°N, 77.0°E), India. In general, there was a tendency for increases in CAPE to be associated with decreases in temperature at the 100-hPa pressure level on all time scales. Decreasing linear trends in temperature were found at Delhi and Kolkata over the period 1990–2006. Our analysis suggests that the trend towards increasing convective activity in the troposphere leads—at least partly—to the trend towards cooling in the tropopause region. High CAPEs are, in general, associated with high rainfall. The minimum annual temperatures were observed almost simultaneously with enhanced annual CAPE during the northern summer, with a larger anti-correlation (-0.62) over Delhi than at other stations. The influence of the solar cycle on the control of temperature was significant (~4–5°C) only around 8–10°N. Temperature variations in the upper troposphere are viewed as being jointly controlled by CAPE and the solar cycle, with the respective contribution of each being location-dependent.

Key words: Solar cycle, tropopause, convective available potential energy (CAPE), rainfall.

1. Introduction

A long-term change in convective available potential energy (CAPE) is associated with changes in convective activity and atmospheric stability in a particular region. CAPE therefore can act as a potential indicator of climate change, essentially providing an indication of the potential energy available for moist convection. Relationships between CAPE and convective triggering frequency and CAPE's association with temperature in the upper troposphere are not clear (Emanuel *et al.*, 1994; Gettelman *et al.*, 2002). Gettelman *et al.* (2002) studied trends in CAPE, mainly in the Western Pacific region, and emphasized that most of the CAPE increases can be associated with increases in temperature and/or moisture at 990 hPa. However, at a few locations in their study, they also observed a decreasing trend in CAPE. To date, no effort has been made to evaluate the relationship between CAPE variability and response of the temperature field in the upper troposphere. Given the correlation between large CAPE and precipitable water, as discussed by Gaffen *et al.* (1991), one can expect a dynamical link between lower troposphere convective activities and variations in the temperature field in the troposphere. Seidel and Randel (2006) found variability and trends in the global tropopause estimated from radiosonde data and showed that the temperature of the tropopause decreases on the order of 0.41±0.09 K/decade, indicating a lapse rate tropopause. These tropopause trends are accompanied by significant stratospheric cooling and smaller tropospheric warming. In the study reported here, our aim is to whether the CAPE directly causes variability in the temperature field, on a small to larger scale, around the 100-hPa level over the Indian region.

Numerous studies have established 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 (Dhaka *et al.*, 1995, 2003, 2005, 2006). Large CAPE (i.e., large convective activity) favors strong vertical coupling. In a preliminary study, Dhaka *et al.* (2007) showed seasonal and annual variability in CAPE over three Indian stations separated latitudinally. The seasonal variability showed a dependency upon the presence of the monsoon, with peaks in the CAPE appearing first in southern India, then gradually shifting with time in step with the march of the monsoon to northern India. However, the association of CAPE with the temperature field in the upper troposphere and lower stratosphere was not investigated in that study. In the present

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study, we have made an effort to investigate how the temperature is controlled via dynamics on a seasonal, annual, and large scale. Atmospheric stability and available moisture content have seasonal and annual variations that can certainly affect the upper tropospheric system.

Long-term data of temperature, rainfall, and CAPE at four stations, namely, 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), were in our study. These stations are latitudinally separated over the Indian region, representing the northern, eastern, and southern parts, respectively. We also examined the presence and latitudinal variation in the solar cycle signal in terms of temperature at the 100-hPa level. In addition to seasonal and annual variability in temperature control from below, the possibility of seasonal and annual variability in temperature from topside due to solar variation is also a key component contributing to the overall variability on a large time scale. As mentioned above, the stations are separated latitudinally: Delhi is an inland station located away from the tropics, while Kolkata is a coastal station facing the Bay of Bengal, which is a highly convective region. Cochin and Trivandrum are also costal stations, but facing the Arabian Sea. Some differences in the relationship under study may be due to of the specific locations of these stations.

To examine the strong seasonal dependency, we have shown daily variations in CAPE and temperature at the 100-hPa level, especially during summer months (May–August) when moisture content is enhanced. The relation between CAPE and rainfall is also investigated to determine whether there is an association between rainfall and atmospheric convective systems. This article is organized into sections, with the data and method of analysis described in Section 2, the results and discussion presented in Section 3, and the summary given in Section 4.

2. Data Used and Method of Analysis

In this study, we have utilized 27 years of daily radiosonde data collected at the Delhi and Kolkata stations from 1980 to 2006 and 17 years of radiosonde data collected at the Cochin and Trivandrum stations between 1989 and 2005, all collected at 1200 hours GMT. These data were used to compute CAPE and to show temperature variations at the 100-hPa level. This level is representative of the tropopause height region and is a standard meteorological level for atmospheric parameters. Routine radiosonde temperature data were acquired from the India Meteorological Department (IMD). The error in the basic temperature measurements, due to the temperature sensor as given by IMD, is expected to be ∼1 K. The radiosonde data were collected using a thermistor for the temperature measurements. These thermistors have semi-conducting properties and are composed of inorganic oxides and ceramic materials; they are coated with a white pigment that has a reflectivity ∼0.89 and a consequent absorbance of radiation of ∼0.11. Details on the sensors and their comparison with U.S. sensors are reported by Jain *et al.* (2006) and Schmidlin (1988). Radiosonde data were used to compute CAPE. There are a number of methods to compute CAPE from radiosonde data, including those suggested and discussed by William and Renno (1993), Mc Bridge and Frank (1999), Gettelman *et al.* (2002) and, recently, Roy Bhowmik *et al.* (2008). The estimates of CAPE in these studies are somewhat different, primarily due to the assumption made in the computation. In our study, the following criterion is used to compute CAPE

$$\mathrm{CAPE} = g\int_{z=\mathrm{LFCT}}^{z=\mathrm{LNB}} ((T_\mathrm{p} - T_\mathrm{e})/T_\mathrm{e})dz$$

where, T_p is the temperature of a parcel from the lowest 500 m of the atmosphere raised dry adiabatically to the lifted condensation level (LCL) and moist adiabatically thereafter, and T_e is the temperature of the environment. This expression is integrated over the sounding layers from the level of free convection (LFCT) to the level of neutral buoyancy (LNB) for which $(T_\mathrm{p} - T_\mathrm{e})$ is greater than zero. The LNB denotes a level at which a parcel from the lowest 500 m of the atmosphere is raised dry adiabatically to the LCL and moist adiabatically to a level above which the temperature of the parcel is the same as the environment. If more than one equilibrium level exists, the highest one is chosen. If more than one LFCT exists, the lowest level is chosen.

Monthly mean time series were constructed for the CAPE and temperature at the 100-hPa level using daily values at 1200 hours GMT for revealing large-scale variability. There were a very few gaps in data that were filled by averaging adjacent months. The short-scale variations are studied by using daily values of CAPE and temperature at the 100-hPa pressure level in the summer months (May–August). We have made use of sunspot numbers to construct a 11-year solar cycle. Monthly averaged sunspot number data were obtained from the NASA website (http://www.nasa.gov), and monthly mean rainfall data for 26 years (1980–2005) obtained from the IMD for the Delhi, Kolkata, and Trivandrum stations were used. Rain data for the Cochin station were not be available for the parallel period.

3. Results and Discussion

3.1 Large-scale variations in CAPE and temperature

3.1.1 (a) Large-scale variations in CAPE and temperature over Delhi We analyzed 27 years of CAPE and temperature (at 100-hPa pressure level) data for the period spanning 1980–2006 at Delhi for studying the annual and large-scale variations in CAPE and to evaluate the influence of CAPE on the temperature field in the upper troposphere.

Composites of temporal variations in the monthly mean temperature at the 100-hPa pressure level and CAPE at Delhi are shown in Fig. 1. The top panel shows the annual temperature variation of between −65°C and −78°C, with an average variability of ∼12°C. The lowest annual temperature was recorded during the summer seasons at 100 hPa. A year-to-year variability in temperature is clearly seen, with the amount of change in year-to-year annual temperatures being of the order of 3–5°C on both the low and high sides of the range over a period of 27 years. Change in temperature over the period seems to be part of a large-scale variability that seems to be associated with climate variability. This large-scale variation appears to have a period greater than 11 years (solar forcing). In order to dis-

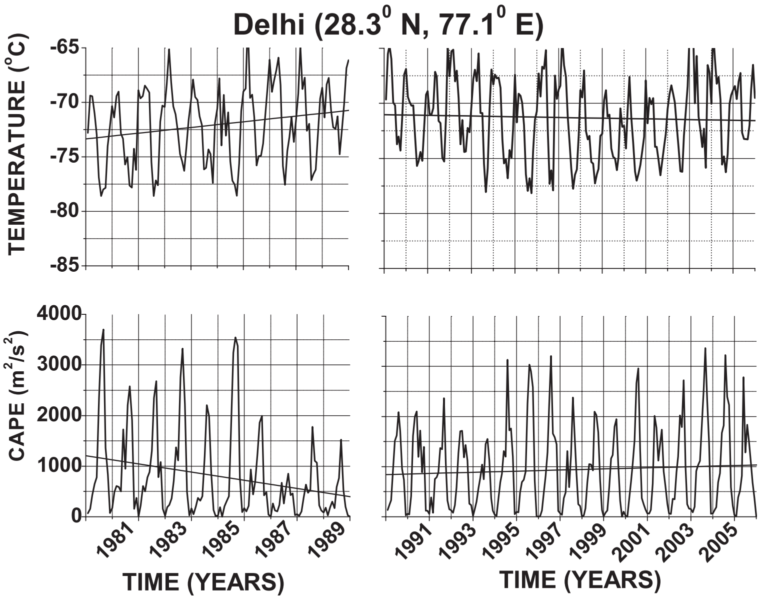


Fig. 1. Monthly mean temperature (top panels) at the 100-hPa level (∼16 km height) and monthly mean CAPE (bottom panels) are plotted for 1980–1989 and 1990–2006, respectively, at Delhi. A linear trend (solid straight line), at the 95% confidence level is shown in both parameters. Linear trends are quite significant over the period 1980–1989 and are insignificant during 1990–2006 but are retained for comparison.

cern the trends accurately, we used linear trends at the 95% confidence level. The linear trend in the data appears to be biased depending upon the time selection of the linear fitting. For instance, there is a clear increasing linear trend in temperature for the period 1980–1989, while between 1990 and 2006, there is a decreasing tendency. It is apparent that our 27-year data set covers about two and half solar cycles. Solar forcing may also contribute significantly to the temperature variation at 100-hPa level (see Section 3.3). However, in this section we focus mainly on the influence of CAPE on temperature in the tropopause region. Therefore, we only show the analysis of CAPE to determine the control of temperature over a wider temporal scale.

The lower panel of Fig. 1 shows a single broad peak in CAPE around July–August, a time at which the monsoon is active in northern India. The annual peak in CAPE in 1980, 1983, 1985, 1995–1997, and 2004–2005 was enhanced up to 3000 m^2/s^2 in comparison to the rest of the study period when peak values remained around 2000 m^2/s^2. In most of the years when was CAPE enhanced, rainfall also reached a peak value, as shown in Fig. 11. Similar to the top panel of Fig. 1, the linear trend is shown in CAPE. Annual variability is quite clear in CAPE, with large values occurring during the summer (June–July) that correspond to the active monsoon season in northern India.

Year-to-year variation in CAPE is also quite significant. From 1980 to 1986, CAPE consistently showed annual larger values in comparison to the period 1987–1995. It is quite noteworthy that the annual peak in CAPE occurs simultaneously with the peak in annual low temperature, thereby supporting the theory of a strong relationship. The linear trend in CAPE is also shown in the two time segments (during 1980–1989 and 1990–2006), as for the temperature data. The linear trends in CAPE are opposite to those seen in temperature. In general, prominent trends in the time segments of the 27-year period are such that an increase in temperature and a decrease in CAPE are common. For instance, for the period of 1990–1998, the rise in CAPE is associated with a tendency for temperature to decrease, indicating that there is a strong coupling of these parameters and, consequently, that large convective activity (CAPE) supports a decrease in temperature at the 100-hPa level.

The correlation coefficient between CAPE and temperature is computed using monthly data, which is of the order of −0.62 (at the 1% significance level; see Table 1, column 2 for other stations). Student's t-test is used to show the significance level, i.e., to check if the computed correlation coefficients are statistically significant or not at a particular confidence level. This is a fairly large value, suggesting that both the annual peak in CAPE and the large-scale variability are strongly linked to decreases in the temperature at the 100-hPa level at Delhi. One should note that Delhi is an inland station, and we can assume it representative of characteristics of the northern Indian region.

The mechanism of the decrease in temperature in the upper troposphere could be understood on the basis of those vertical motions usually becoming enhanced during the summer in comparison to other seasons. Evidence based on the observations using Indian MST radar located at Gadanki (13.5°N, 77.0°E) during May–June and Equatorial Atmosphere Radar (EAR) at Kota Tabang (0.2 S, 100.32 E) shows that vertical winds become enhanced when associated with convective activity (Dhaka *et al.*, 2001, 2002, 2006; Yamamoto *et al.*, 2007). As a result, adiabatic expansion of air mass at higher levels can lead to cooling. Outgoing long-wave radiation (OLR) data from the National center for environmental prediction (NCEP) confirms that northern India is under highly convective clouds during the summer monsoon season (not shown here), while after September the low OLR spread is replaced by high OLR.

The seasonal variation of tropical tropopause tempera-

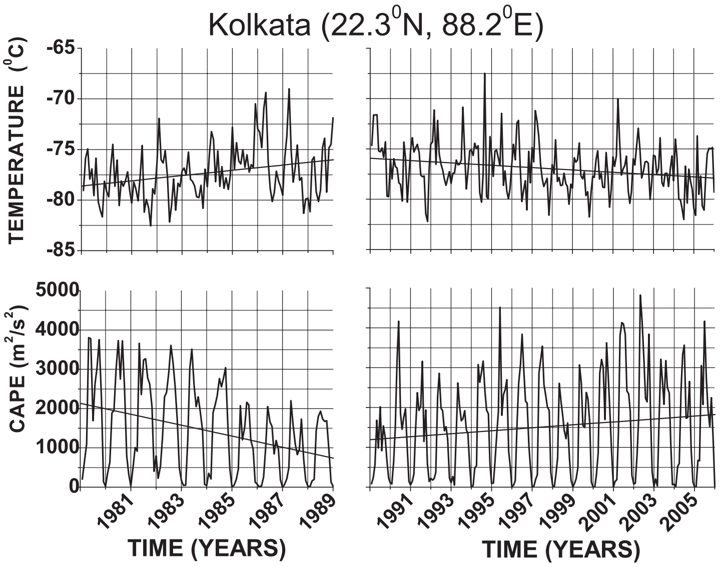


Fig. 2. Monthly mean temperature (top panels) at the 100-hPa level (~16 km height) and monthly mean CAPE (bottom panels) are plotted for 1980–1989 and 1990–2006, respectively, at Kolkata. Linear trends are shown in both parameters (solid straight line). Over a period 1980–1989 and 1990–2006 linear trends are quite significant at the 95% significance level.

ture is also partially controlled by another phenomenon, the Brewer-Dobson (BD) circulation. The BD circulation, also known as the stratospheric meridional residual circulation, is driven by extratropical wave forcing in the middle atmosphere (Yulaeva *et al.*, 1994; Holton *et al.*, 1995). It consists of an upward motion across the tropopause in the tropics and downward return flows in the extratropics in each hemisphere, leading to an enhanced meridional temperature gradient in the upper troposphere and lower stratosphere (UTLS). In addition, wave driving is stronger in the Northern Hemisphere (NH) winter than in the Southern Hemisphere (SH) winter, with the tropical tropopause temperature lower in the NH winter than in the SH winter.

3.1.2 (b) Large-scale variations in CAPE and the temperature over Kolkata In this section, we show data over Kolkata station. Figure 2 shows the relationship between monthly mean CAPE and temperature data. Presentation of the data is similar to the data shown in Fig. 1. In this case also, analysis is performed to observe annual variation and year-to-year variability. We also examine the relationship between CAPE and temperature at a small scale (seasonal) (shown in Section 3.2) to reveal the control of temperature in the upper troposphere ranging over a wide temporal scale. Annual temperature variation is seen between −68°C and −82°C with clear year-to-year changes. The peaks of the annual lowest and highest temperatures are shown in the form of primary and secondary maxima, unlike the single peak manifestation observed over Delhi.

Annual peaks in CAPE are bimodal in nature in some years at Kolkata; however, the primary peak occurs during the pre-monsoon (April–May) and monsoon (June–September) period. Peaks in the pre-monsoon/monsoon period are stronger than those in October. The annual peak in CAPE also appears earlier than that at Delhi because the monsoon arrives earlier at this location. Some of the features of CAPE related with seasonal dependency are discussed by Dhaka *et al.* (2007). Large CAPE is also seen during the 1980–1986 period, similar to that seen at the Delhi station, thereby confirming the general high reliability of the data presentation. A comparatively weaker CAPE is also observed from 1986 to 1995, with an exception of around 1992 (strong ENSO year). In general, CAPE is larger at Kolkata than at Delhi.

Annual peaks in temperature are not as distinct as those observed over Delhi and are rather fluctuating. This indistinctness seems partly to be due to a bimodal peak in CAPE and temperature and because convection stays longer at Kolkata than at Delhi. Kolkata, being located facing Bay of Bengal, shows different characteristics. In addition, the winter returning monsoon also causes rain in this area. An intriguing feature is that the lowest temperature annual peaks correspond to secondary peaks of CAPE during October. This is seen in most of the years studied, but more clearly for the period of 1996–2006. Roy Bhowmik *et al.* (2008) demonstrated that the belt of maximum CAPE shifts to the southern peninsula during the post-monsoon and winter season. We found a secondary peak in CAPE during October over Kolkata that seems to be more effective in controlling the temperature at the upper troposphere.

Latitudinal variability can be seen in the temperature data set at 100 hPa. The temperature at Kolkata is lower than that at the Delhi station by about ~5°C. This is due to a transitional change in temperature moving towards the equator from 28.3°N to 22.3°N. This range of latitude lies at the boundary of the equatorial region and extra-tropical region; consequently, the temperature near 100 hPa show changes in magnitude partly due to the tropopause level being a lower height in the extra-tropical region than in the equatorial region. This result is in accordance with the global tropopause variability with latitude shown by Seidel and Randel (2006).

The entire data set is divided into two time segments, i.e., 1980–1989 and 1990–2006 to discern the linear trends. The decreasing trend in temperature over Kolkata after 1990 is quite significant in that is similar to the results discussed by Seidel and Randel (2006) and, more recently, by Randel *et al.* (2009). The linear trend in the data seems to be biased depending upon the time selection of linear fitting. For example, for the period 1980–1989, there is a clear increasing linear trend in temperature, while CAPE shows a decreasing trend. We have also examined the effect of the rising trend in CAPE and decreasing trend on temperature with the corresponding rainfall record. The rising trend tendency in CAPE after 1990 could not be confirmed with similar trends in rainfall data. However, the R_{xy} computed between CAPE and rainfall is 0.46 when the entire data set is taken into account (details are shown in Section 3.4). Similarly, over Delhi station, R_{xy} computed between CAPE and rainfall is 0.59. Therefore, almost simultaneously, CAPE and rainfall annual temporal variation shows a strong relationship. Roy Bhowmik *et al.* (2008) reported that during the pre-monsoon period, CAPE enhances earlier than rainfall based on 1 year of model data. However, we could not find any convincing trend in rainfall that resembled that found in CAPE.

The correlation coefficient between CAPE and temperature was computed and found to be -0.21 (at the 1% significance level). The value of R_{xy} is less than that of the Delhi station. As seen from Fig. 2, peaks in CAPE as well as temperature gradually changed in shape from a broad peak (Delhi) to bi-modal peaks (Kolkata).

3.1.3 (c) Large-scale variations in CAPE and temperature over Cochin Figure 3 shows the variability in temperature and CAPE for the period 1991–2005 over Cochin. This station is located 10°N, in the equatorial region, and facing the Arabian Sea. It's location is quite different from hose of the two stations discussed in the previous sections.

Temperature variations at the 100 hPa pressure level are shown in the upper panel. The mean temperature at 100 hPa is $\sim -76°$C, which is about 1°C higher than that at Kolkata and about 4°C lower than that at Delhi. The annual fluctuation from mean temperature is of the order (~8–10°C), which is similar to that of the Delhi and Kolkata stations. For this station also, there is a significant year-to-year variation in the data. No linear trend in temperature at the 100-hPa pressure level is found at the Cochin station using monthly mean data. When we screened monthly mean data at Delhi and Kolkata for the period following 1990, we found a signature of decreasing temperature. Thus, at all three stations discussed up to this point, we found characteristics of decreasing (Delhi and Kolkata) or constant (Cochin) temperature from 1990 onwards.

The lower panel of Fig. 3 shows the temporal variation in CAPE parallel to the temperature data shown in the upper panel. In general, twin peaks are noted: one around April–May and the second near the October-post-monsoon period. Peaks during the pre-monsoon and monsoon are stronger than those during October. However, the occurrences of lowest annual temperature peaks are not very clear if they are associated with primary or secondary peaks in CAPE. Both primary and secondary peaks in CAPE show a close association with dips in temperature at the 100-hPa level. The association of CAPE with temperature over Delhi was seen to be quite significant, as a single peak emerged in both parameters. This feature is partly related with atmospheric stability over the Indian region. Over Delhi, the increase in the moisture during rainfall has an advective origin and appears predominantly during the summer, whereas the other regions (Kolkata, Cochin, and Trivandrum) show an *in situ* presence of moisture (Roy Bhomik *et al.*, 2008).

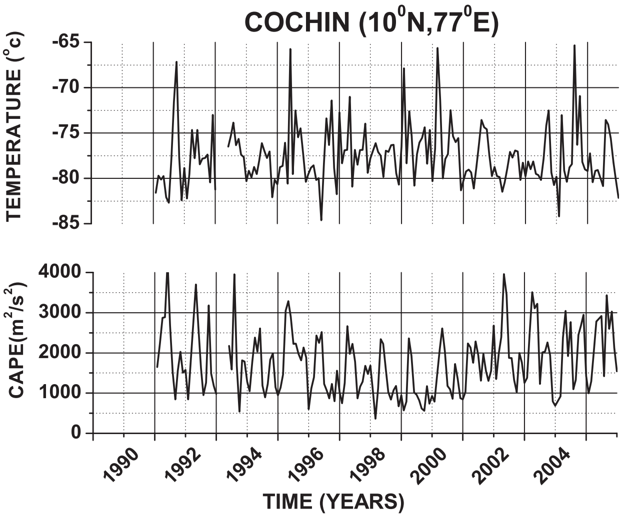


Fig. 3. Monthly mean temperature (top panel) at the 100-hPa level (~16 km height) and monthly mean CAPE (bottom panel) is plotted over the period 1991–2005 at Cochin.

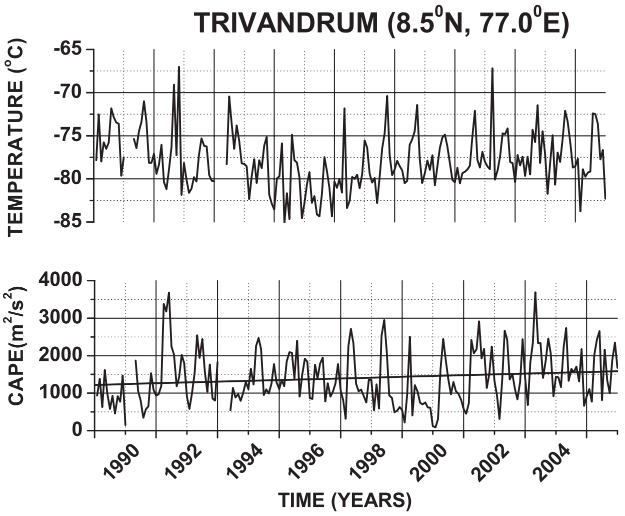


Fig. 4. Monthly mean temperature (top panel) at the 100-hPa level (~16 km height) and monthly mean CAPE (bottom panel) is plotted for the period 1989–2005 at Trivandrum. Linear trend (solid straight line) shown in CAPE (bottom panel) is significant at the 95% significance level.

As there was a large gap in the data near 1990, we have discarded those data for 2 years. The tendency of the linear trend during 1991–2005 is similar to that found at the other two stations. This tendency again confirms that CAPE increase leads to a temperature decrease in the upper troposphere. Low values of CAPE during 1996–2001 were accompanied by larger values for temperature in the corresponding period.

The correlation coefficient between CAPE and temperature using monthly means over a period of 15 years has been computed (~ −0.1), but R_{xy} is not significant at Cochin. Note that R_{xy} decreased from Delhi (−0.62) to Kolkata (−0.21) and then to Cochin (−0.10). We tried to examine the influence of the solar cycle, which can be a significant factor in weaking the CAPE and temperature relationship when the location shifts from 28°N (Delhi) to 8.5°N (Trivandrum). Temperature depends on two important factors, i.e., solar energy and CAPE. Depending on the latitude, the relative contribution of these factors changes.

3.1.4 (d) Large scale variations in CAPE and temperature over Trivandrum Figure 4 shows the temporal variation of CAPE (lower panel) and temperature (upper panel) at the 100-hPa pressure level from 1989 to 2005 at Trivandrum. A mean temperature of about −77.5°C is seen at 100 hPa, with much colder annual peaks during the 1995–1998 period in comparison to other stations. Other factors, such as year-to-year variability, is also similar, as seen at the above stations. Bi-modal behavior in CAPE peaks is noticed in most of the years, with primary peaks occurring during the pre-monsoon period followed by secondary peaks during the post-monsoon period around October. Close inspection shows that both the primary peak of CAPE (during April–May) and a dip in temperature occur frequently. There are a few cases when two dips in temperature are also noted annually, and these correspond to both peaks of CAPE in different seasons. The correlation coefficient between CAPE and temperature is computed and noted as −0.12 (at the 5% significance level). The value of R_{xy} is similar to that seen at Cochin.

Linear trend in CAPE is drawn showing a slight increase in CAPE like at other stations but with no clear trend in temperature (not shown), which apparently modulated by solar cycle signal, which is reflected very well around 1994–1999 (shown in Section 3.3). Trivandrum station is located at 8.5°N, which is near to Arabian Sea, therefore similar to Kolkata and Cochin stations *in-situ* moisture have an impact on formation of local convective systems and their subsequent role in controlling the temperature.

3.1.5 (e) Inter-annual variations in CAPE and temperature over all stations To analyze the inter-annual variations in CAPE and temperature, we have examined the relationship between yearly averaged data of CAPE and temperature at the 100-hPa level at all stations. The temporal variation in annually averaged CAPE and temperature data from 1980 to 2006 at Delhi and Kolkata, from period 1991 to 2005 at Cochin, and from 1989 to 2005 at Trivandrum is shown in Fig. 5.

R_{xy} between the yearly averaged CAPE and temperature at the 100-hPa level is computed at all stations and shown in Table 1 (last column). The R_{xy} values shown at Kolkata and Cochin are significant at the 5% significance level using Student's t-test, whereas R_{xy} is insignificant at Delhi and Trivandrum. However, an anti-correlation between CAPE and temperature is observed at all stations. Our observations of temporal variations in annual CAPE and temperature data revealed that CAPE and temperature are positively correlated at Delhi and Kolkata over a certain period of time, especially in the years after 1998–1999. This variation in the CAPE and temperature relationship is attributed partly to the climatic changes at specific locations of the stations, especially those located away from the equator and from 1998–1999 onwards.

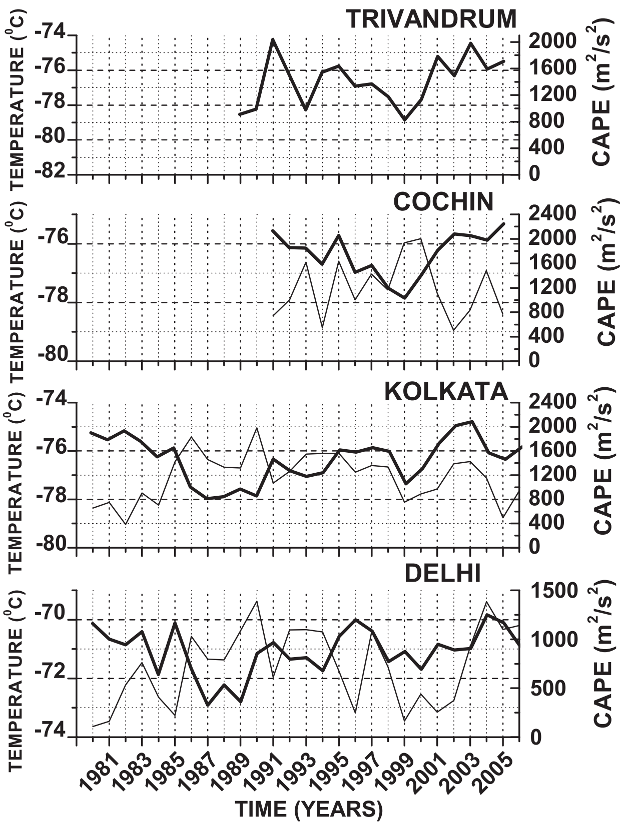


Fig. 5. Temporal variation of yearly averaged temperature at the 100-hPa level with CAPE (over a period the 1980–2006 at Delhi and Kolkata stations, 1991–2005 at Cochin and 1989–2005 at Trivandrum). Thick solid lines denote CAPE, while thin line denote temperature.

3.2 Small-scale (seasonal) variations

3.2.1 (a) Small-scale variation at Delhi In Section 3.1, our results from four stations confirmed a relation in which increases in CAPE favor a decrease in temperature in the upper troposphere with varying negative R_{xy}. In this section, we examine the relation between CAPE and temperature on a small scale, especially during the summer season. This analysis is aimed at providing evidence supporting the view that such mechanisms and processes can operate at almost all time scales. We have used daily values of both parameters for the summer months (May–August). Correlation coefficients between CAPE and temperature at the 100-hPa level are computed for all stations. However, we were unable to present the data for the same years at all four stations. Therefore, we have carefully selected those years which have maximum available daily values for the respective stations.

Composites of temporal variation in CAPE and temperature at the 100-hPa level in 1998 and 2001 at Delhi are shown in Fig. 6(a) and (b), respectively. Linear trends with a 95% confidence level are also shown in both panels.

It is noted that while CAPE increased from May to August, the temperature decreased during 1998 and 2001. The slope of the trends are different in different years depending upon the intensity of the monsoon and prevail-

Table 1. Correlation coefficients between monthly and annually averaged CAPE and temperature at the 100-hPa level over the Delhi, Kolkata, Cochin, and Trivandrum stations. Using the monthly averaged data, R_{xy} is statistically significant (using Student's t-test) at the 1% significance level at Delhi and Kolkata and significant at the 5% significance level at Trivandrum. However, it is insignificant at Cochin station. In contrast, using the annually averaged data, R_{xy} is statistically significant at the 5% significance level at the Kolkata and Cochin stations and insignificant at the Delhi and Trivandrum stations.

Stations	Correlation coefficient between monthly averaged CAPE and temperature at the 100-hPa pressure level	Correlation coefficient between annually averaged CAPE and temperature at the 100-hPa pressure level
Delhi	−0.62	−0.19
Kolkata	−0.21	−0.43
Cochin	−0.10	−0.48
Trivandrum	−0.12	−0.25

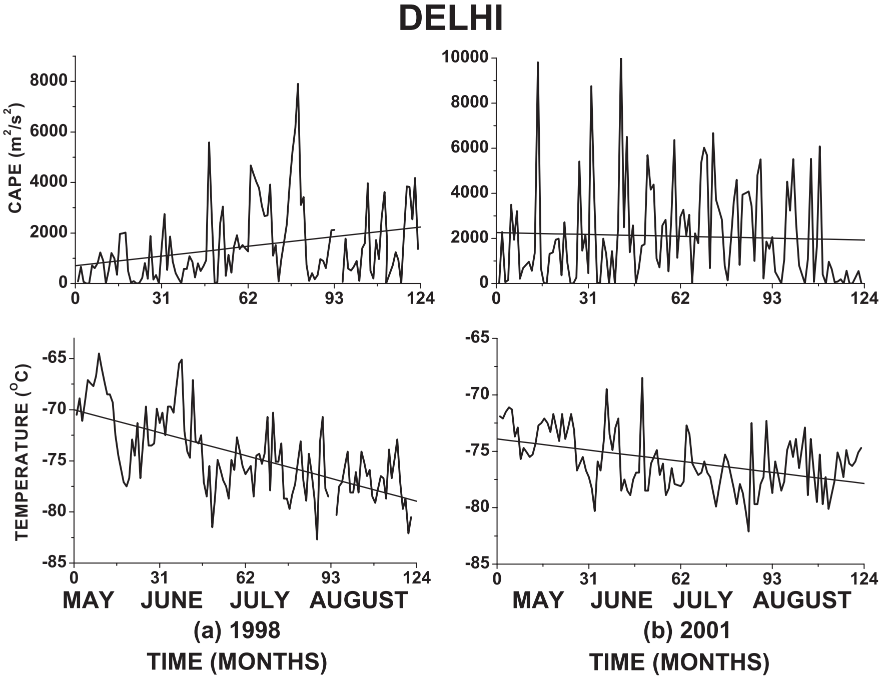


Fig. 6. Temporal variation of CAPE (upper panel) and temperature at the 100-hPa level (lower panel) during May–August in (a) 1998 and (b) 2001 at Delhi. Linear trends (at 95% confidence level) are shown (with solid straight line) in all panels. With the exception of the top panel (2001), all linear trends are significant.

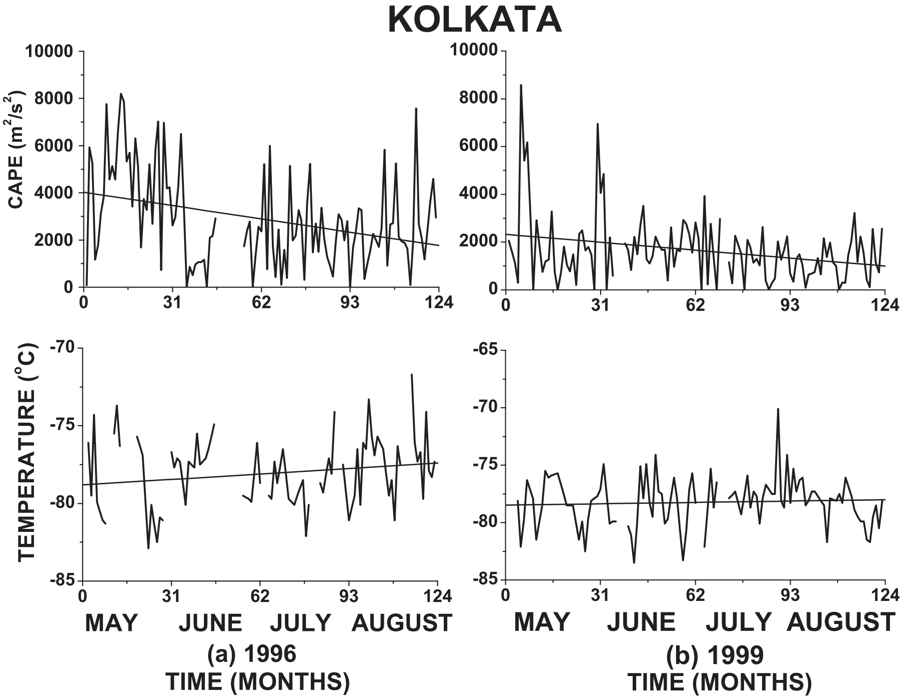
ing atmospheric conditions. The correlation coefficient between CAPE and temperature is found to be −0.34 and −0.23 in 1998 and 2001, respectively. (Note that the correlation coefficients shown in this section are, in most cases, at the 1% significance level using Student's t-test. However, in a few cases, correlations are near to the 5% significance level.) It is indicative that CAPE and temperature variations at 100 hPa are anti-correlated. Wave fluctuations with dominant periodicity of a few days are seen in the temperature data.

Similarly, Fig. 7(a) and (b) show the temporal variation in CAPE and temperature in 1996 and 1999, respectively, at Kolkata. A decreasing linear trend in CAPE is seen to have a close association with a consistent increase in the temperature over a period of 4 months in 1996 and 1999. Temperature data at the 100-hPa level are missing for several days in 1996. The correlation coefficient between CAPE and temperature is found to be −0.18 and −0.38 in 1996 and 1999, respectively. Anti-correlation persists between CAPE and temperature at the 100-hPa pressure level although trends changed over Kolkata in comparison to Delhi during the summer season. CAPE shows large values during May (pre-monsoon period) that subsequently decrease towards August. On the other hand, temperature rises from May to August as upward motions tend to decrease in the region due to less CAPE.

We extended this analysis of short-scale variation on the Arabian side using the Cochin and Trivandrum stations.

Temporal variation of CAPE and temperature at the 100-hPa pressure level in 1997 and 2001 is shown in Fig. 8(a) and (b), respectively, for the Cochin station. The linear trends in CAPE and temperature are quite significant, but the gap in the data for 2001 is large. Wave fluctuations and trends are similar, as noted at the Kolkata station, but the decrease in the CAPE trend and increase in temperature trend are stronger than those found for the Kolkata station. The correlation coefficient (R_{xy}) between CAPE and temperature at the 100-hPa pressure level is −0.34 and −0.053 in 1997 and 2001, but that for 2001 is not statistically significant.

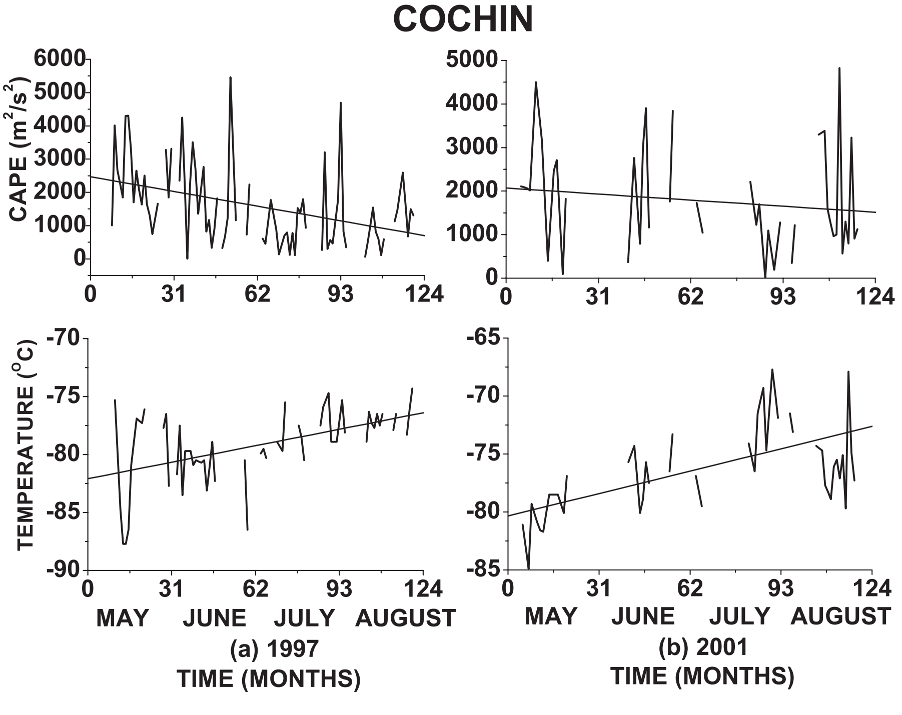
Figure 9(a) and (b) shows the temporal variation in CAPE and temperature at 100 hPa in the summer months (May–



(a) 1996
TIME (MONTHS)

(b) 1999
TIME (MONTHS)

Fig. 7. Same as Fig. 6, but at Kolkata during (a) 1996 and (b) 1999. Gaps denote no data. Except for (b; bottom panel), all linear trends are significant at the 95% significance level (data for (b) are retained for comparison).



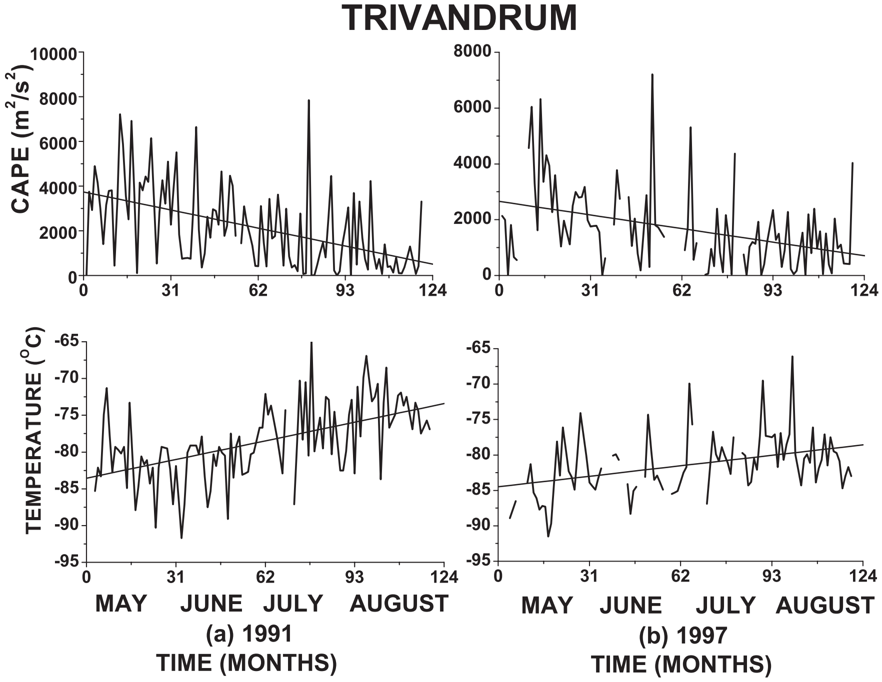
(a) 1997
TIME (MONTHS)

(b) 2001
TIME (MONTHS)

Fig. 8. Same as Fig. 6, but at Cochin during (a) 1997 and (b) 2001. Gaps show no data. Except for (b; top panel), all linear trends are significant at the 95% significance level (data for (b)) are retained for comparison.

August) in 1991 and 1997, respectively, at Trivandrum. At this station, linear trends in CAPE and temperature are very clear and similar to those of the Kolkata and Cochin stations, although they are steeper. An increase in temperature of about 7–8°C is noted from May to August. The R_{xy} between CAPE and temperature at the 100-hPa pressure level is -0.48 and -0.13 in 1991 and 1997, respectively. However, the R_{xy} in 1997 is not significant. A large CAPE is seen during April, a pre-monsoon period, at almost all stations, with the exception of Delhi, which includes an enhancement of CAPE during June–July. The quasi-periodic behavior of CAPE peaks and response in temperature perturbations are also seen at the Trivandrum station.

An anti-correlation between CAPE and temperature at the 100-hPa pressure level with varying values of R_{xy} exists at all stations. During the summer season, the increase



(a) 1991
TIME (MONTHS)

(b) 1997
TIME (MONTHS)

Fig. 9. Same as Fig. 6, but at Trivandrum during (a) 1991 and (b) 1997. Linear trends shown in all panels are significant at the 95% significance level.

(decrease) in the CAPE linear trend favors a decrease (increase) in the temperature trend with year-to-year variability in R_{xy}.

3.3 Relation between temperature at the 100-hPa pressure level and solar cycle

In the above sections, we have shown an association between CAPE and temperature on both small and large scales. The possible modulating role of the 11-year solar cycle on temperature in the upper troposphere is examined in this section. To analyze the relation between solar activity and temperature, we have examined the variations in yearly averaged temperature at the 100-hPa pressure level against the solar cycle at all stations. Sun spot numbers are used to construct the solar cycle.

The temporal variations in the annually averaged temperature at the 100-hPa pressure level with solar cycle from 1980 to 2006 at Delhi and Kolkata and from 1989 to 2005 over Cochin and Trivandrum stations are shown in Fig. 10. The latitudinal variability in temperature in relation to the solar cycle is seen clearly from Trivandrum to Delhi. At Trivandrum and Cochin, which are located at 8.5°N and 10°N, solar modulation on temperature is quite significant. Except at one point during 1991–1992 (which corresponds to a strong ENSO event), almost all annually averaged temperature points closely follow the solar cycle. In a recent study, Randel *et al.* (2009) mention that the Mt. Pinatubo eruption had caused a rise in temperature after 1991 at 100 hPa and above, but that the rise in temperature is much more evident at 30–70 hPa. For pressure levels below 100 hPa, tropical temperature anomalies are dominated by ENSO variability. Similar behavior (rise in temperature after 1991) is noted at Cochin station. Solar modulation of temperature at Trivandrum and Cochin is approximately 4°C.

The R_{xy} between yearly averaged temperature at the 100-

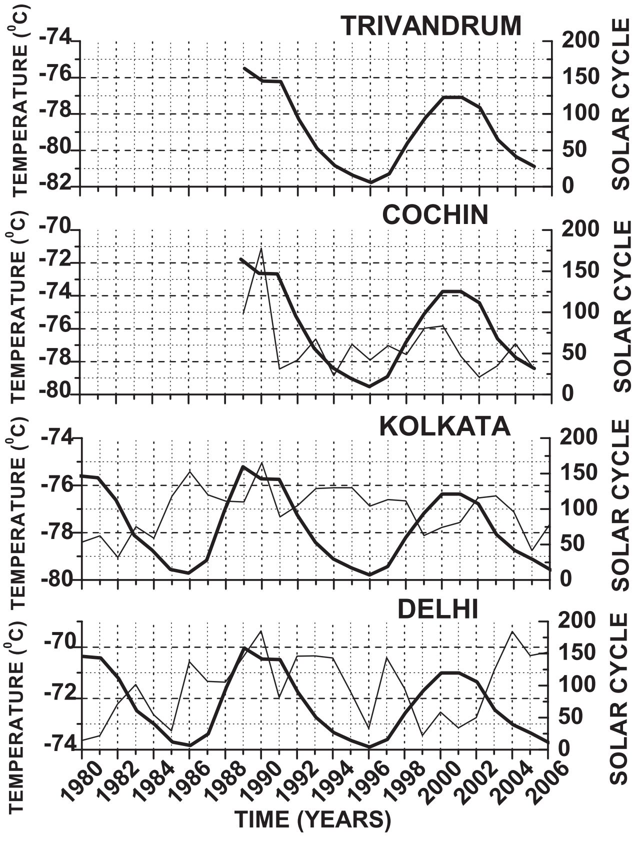


Fig. 10. Temporal variation of yearly averaged temperature at the 100-hPa pressure level with the solar cycle (from 1980–2006 at Delhi and Kolkata station, and from 1989 to 2005 at Cochin and Trivandrum). Thick solid lines denote sun spot numbers, while thin line denote temperature.

Table 2. Correlation coefficients (using Student's t-test) between yearly averaged temperature at the 100-hPa level and sunspot number over the Delhi, Kolkata, Cochin, and Trivandrum stations. R_{xy} is statistically significant at the 5% significance level at Cochin and at the 1% significance level at Trivandrum; R_{xy} is not statistically significant at Delhi and Kolkata.

Stations	Correlation coefficient between yearly averaged temperature at 100 hPa and the solar cycle
Trivandrum	0.68
Cochin	0.44
Kolkata	−0.25
Delhi	−0.25

hPa level and the solar cycle is computed at all stations and shown in Table 2. R_{xy} values shown at Cochin and Trivandrum are significant using Student's t-test, whereas they are not significant at Delhi and Kolkata. There is a good positive correlation in the equatorial region maximizing around 8–10°N. This result compares well with the analysis of Chun *et al.* (2007) showing that the convective heating variation maximizes around 8–10°N and 8–10°S using global data of brightness temperature (see their Fig. 2). Solar cycle modulation over Delhi and Kolkata are not seen; rather, there is an insignificant negative correlation. Delhi is located some distance from the equator, and we have seen some seasonal differences in CAPE and temperature that differ from those seen at the other stations, such as the CAPE at Delhi shows a rising trend in summer months, while a decreasing trend is favored at other stations. The correlation coefficient between yearly averaged temperature at the 100-hPa level and solar cycle is also negative and insignificant at Kolkata, despite the fact that it shows similar trends and features as those noted at Trivandrum and Cochin. However, a deep convective activity and large CAPE with bimodal characteristics is distinctive for Kolkata, possibly due to the presence of a local intense convection system (in both seasons, summer and winter) that could offset the influence of solar cycle.

Indian MST radar observations (Dhaka *et al.*, 2002, 2003) have shown the existence of large vertical motions (∼10 m/s) during convection. Although the radar is located at 13.5°N and Kolkata is at 22.3°N, the similar convective system is similar as it originates in the Bay of Bengal and sometimes moves over the radar region. We have not investigated the effects of other factors on temperature, such as ENSO, among others, in this region and therefore, cannot completely rule out these other factors. Despite all these factors, one common feature is apparent from the annual temperature plots in Fig. 10, (thin solid lines): a decreasing tendency from 1990 onwards (except Delhi). Note that CAPE trends at all stations show a slight increase from 1990 onwards.

Thus, we conclude that the solar effect on the temperature at the 100-hPa pressure level is more dominating at stations located around 8°N–10°N than at those further away from the tropical latitudes.

We compared the R_{xy} obtained from Table 1 (between monthly averaged CAPE and temperature and between yearly averaged CAPE and temperature at the 100-hPa level, respectively) with that of Table 2 (between yearly averaged temperature at 100 hPa and the solar cycle). The data on between-monthly averaged CAPE and temperature in these tables on Delhi to Trivandrum shows that the magnitude of R_{xy} decreases and is significant at Delhi, Kolkata, and Trivandrum, whereas at Cochin, the correlation is not significant. On the other hand, R_{xy} between yearly averaged temperature at 100 hPa and solar cycle, enhanced gradually from Delhi to Trivandrum, shows that solar forcing offset the CAPE and temperature association on a large scale and that R_{xy} is significant at Cochin and Trivandrum while it is insignificant at Delhi and Kolkata. However, on a seasonal scale (Figs. 8, 9), the relationship between CAPE and temperature dominates.

In comparison, in the case of the yearly averaged CAPE and temperature, the magnitude of the anti-correlation increases from Delhi to Kolkata; as it is highly convective, the temperature at 100 hPa is mainly controlled by CAPE. In addition, R_{xy} is significant at Kolkata and insignificant at Delhi. The magnitude of the anti-correlation decreases still further from Cochin to Trivandrum. Note that the significant R_{xy} at Cochin becomes insignificant while moving to Trivandrum. In the case of the yearly averaged temperature and solar cycle, the positive correlation increases from Cochin to Trivandrum (while R_{xy} between yearly averaged CAPE and temperature showed the opposite trend) and is found to be a maximum at Trivandrum, suggesting that at around 10°N the temperature at 100 hPa is modulated by solar cycle.

Thus, the solar cycle signal becomes stronger as we move from Delhi to Trivandrum (i.e., move towards equator) and modulates the temperature field on a 11-year time-scale most effectively in the 8–10°N latitude range. Chun *et al.* (2007) have shown variability in deep convective heating at varying latitudes in both hemispheres using satellite data. They found that maximum heating takes place near 10°N–10°S, which then decreases on both sides of the equator. Other geophysical phenomena, such as the influence of ENSO on temperature and CAPE, and a mechanism of complex response of CAPE on the upper troposphere in the presence of varying atmospheric stability conditions in the equatorial region are some of the other key factors that cannot be ruled out. However, these aspects are beyond the scope of the present study.

3.4 CAPE and rainfall correlation

We have shown a relationship between CAPE and temperature from the long term down to the small scale as well as solar cycle modulation of temperature at the 100-hPa pressure level. Gaffen *et al.* (1991) discussed that the step-like increases in CAPE are also consistent with step-like increases in precipitable water in the Pacific region. However, large CAPE formation may appear prior to the monsoon (Roy Bhowmik *et al.*, 2008) over the Indian region. In this section, we investigate whether there is any significant relationship between annual and large-scale variation in CAPE and rainfall at these stations using monthly mean data.

The monthly rain data of 26 years (1980–2005) obtained at three stations (we had no rain data for the Cochin station) were used to analyze rainfall variations with CAPE data.

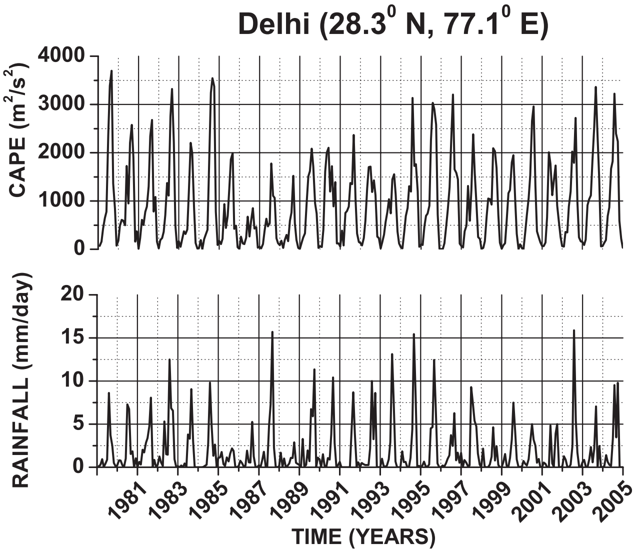


Fig. 11. Temporal variation of CAPE (upper panel) and rainfall (lower panel) during 1980–2005 at Delhi.

Table 3. Correlation coefficients (R_{xy}) at the 1% significance level (using Student's t-test) between CAPE and rainfall data at the Delhi, Kolkata, and Trivandrum stations.

Stations	Correlation coefficient between CAPE and rainfall data
Delhi (1980–July 2005)	0.59
Kolkata (1980–August 2005)	0.42
Trivandrum (1989–April 2005)	0.24

The temporal variation in CAPE and rainfall during 1980–2005 at the Delhi station is shown in Fig. 11.

A single broad peak around June–July is noted for rainfall in most years and bimodal peaks around June–July and November–December are found in some of the years. The frequency of rainfall is found to increase from April–May attaining a peak frequency in June–July. Rainfall over Delhi in the winter season is characterized by western disturbances (WD) over northwest India (Rao and Srinivasan, 1969). An intense WD is occasionally seen as lower tropospheric-induced cyclonic, which causes good rainfall activity over northern India during the passage of this system. Although no linear trend is observed in the rainfall data, the R_{xy} between CAPE and rainfall is positive (0.59).

R_{xy} is computed for all stations at the 1% significance level using Student's t-test; the results are shown in Table 3. As mentioned above, we utilized the monthly means data; therefore, we could not examine the characteristics of CAPE vis-á-vis rainfall at a fine time scale (less than a month). Using monthly data, we found a good correlation between CAPE and rainfall; however, we could not ascertain the trend.

The temporal variation of CAPE and rainfall during 1980–2005 at Kolkata is shown in Fig. 12. A single broad peak is found in the rainfall data (bottom panel) in each year. Maximum rainfall (∼35 mm) occurred in 1984, and the mean rainfall is 5 mm.

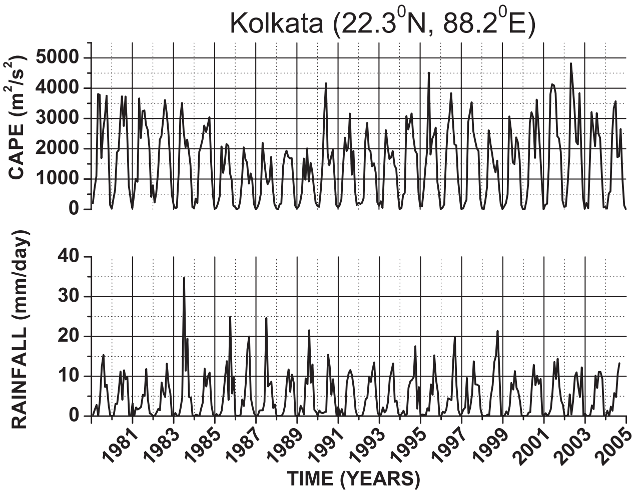


Fig. 12. Same as Fig. 11, but for the Kolkata station.

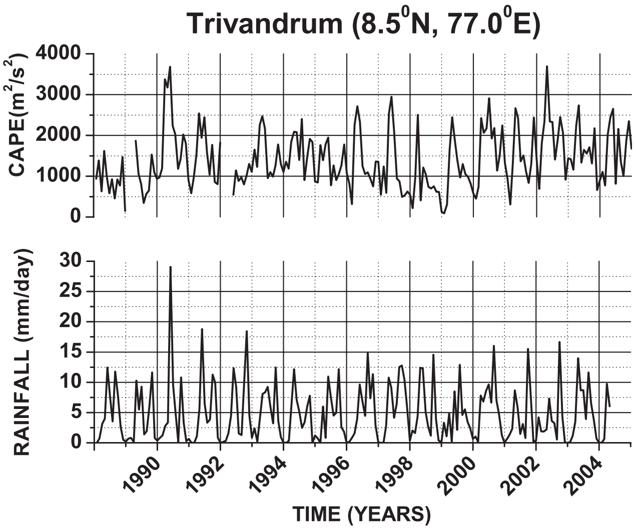


Fig. 13. Same as Fig. 11, but for the Trivandrum station.

The maximum rainfall and high CAPE values at Kolkata are high relative to the other stations; however no trend is observed in rainfall data.

It is interesting to note that in about 50% of cases, maximum rainfall occurs during the winter rather than summer. This is due to the active north-east monsoon. The CAPE had a bimodal character with the secondary peak corresponding to the active northeastern monsoon period which occurs during the winter season. We noticed that in most years the lowest annual temperature at the 100-hPa level appeared during the winter rather than the summer, corresponding to the secondary peak of CAPE. Roy Bhowmik *et al.* (2008) reported that CAPE is large during the pre-monsoon period but that the role of convective inhibition energy (CINE) is also important for the rainfall, if it has a large negative value, which is an unfavorable condition for rainfall. The magnitude of CINE is nearly zero during the monsoon season and CAPE also tends to fall. Their results show that the presence of a strong thermodynamic environment is not sufficient for the occurrence of deep convection. Factors such as proper dynamic conditions also play a very important role in controlling the occurrence of deep convection. We have not computed CINE in our case but, based on their analysis, it is most likely an important factor when attempting to understand the occurrence of the lowest annual temperature during the winter over Kolkata (as mentioned in Section 3.1).

Figure 13 shows the temporal variation in CAPE and rainfall during 1989–2005 at the Trivandrum station. Here, a bimodal peak is noted in rainfall data in most years. Maximum rainfall (∼30 mm) is found in 1991, and the mean value of rainfall is 5 mm, which is similar to that found at the Kolkata station. No linear trend is discerned in the rain data, such as at the Delhi and Kolkata stations. The correlation coefficient (R_{xy}) between CAPE and rainfall data is positive (0.24), which is less in comparison to that at other stations (see Table 3). At the Trivandrum station, rainfall also shows a bimodal character. Interestingly, peak rainfall occurred during the winter, especially from 1993 onwards corresponding to a secondary CAPE peak. The bimodal behavior of CAPE and rainfall is well reflected on temperature at the 100-hPa level: a single strong peak in lowest annual temperature (as seen at Delhi) was not observed; instead, two weak peaks appeared during the pre-monsoon and post-monsoon season. Results at Trivandrum matches with those at the Kolkata station, as both the stations are affected by large CAPE during the winter followed by significant rainfall; this ultimately influences temperature in the upper troposphere.

We could not find any linear trends in rainfall at any of the stations studied; however, a positive correlation coefficient is noted between CAPE and rain, showing maxima at Delhi and decreasing towards Trivandrum.

4. Summary and Concluding Remarks

The results presented here reveal temperature variability in the upper troposphere at the 100-hPa pressure level at four stations (Delhi, an inland station; Kolkata, Cochin, and Trivandrum, costal stations) representing Indian northern, eastern coastal, and southern regions, respectively. Distinct dominant features emerged at each station, with the signatures of solar control on the temperature field vis-á-vis CAPE from Delhi (28.3°N) to Trivandrum (8.5°N) showing contrary effects. The influence of the solar cycle on temperature is clearly reflected at Cochin and Trivandrum (8.5°N–10°N), while CAPE control was found to be weaker on a large scale (more than annual). However, the increasing trend in CAPE and the decreasing trend in temperature are quite significant on seasonal basis (summer months). On the other hand, at Delhi and Kolkata, which are located at 22.3°N and 28.3°N, respectively, the effects of the solar cycle control are rather negative. Year-to-year variation in CAPE and temperature is well correlated at the Delhi station, with a strong anti-correlation coefficient (−0.62) showing a robust single peak in both parameters. At the Kolkata station, the anti-correlation coefficient (−0.22) decreased with changing single peak behavior to a bimodal character in CAPE and temperature. This change is due to the presence of the pre-monsoon and post-monsoon rise in CAPE and rainfall. In some cases, peaks in rainfall are also observed during the winter, unlike Delhi. In addition, the lowest annual temperature was observed that corresponds to winter peaks (secondary peaks) in CAPE. These factors offset the magnitude of the correlation coefficients in comparison to the Delhi station. The seasonal behavior of the decrease in CAPE tends to increase temperature in the upper troposphere with a show of anti-correlation.

The similarity of the twin peaks in CAPE and lowest annual temperature is commonly seen over Kolkata, Cochin, and Trivandrum. Rainfall peaks are also commonly seen during the winter to coincide with the lowest annual temperature at 100 hPa level. Roy Bhowmik *et al.* (2008) discussed the fact that CAPE shifts towards the southern Indian region during the winter and is responsible for the winter rain. Corresponding to winter CAPE and rainfall, we observed a dip in temperature at 100 hPa, which was not seen at Delhi. This further strengthens the view of CAPE and temperature having a strong relationship. On the other hand, the influence of the solar cycle is robust on temperature, modulating the latter in the order of ∼4°C over Cochin and Trivandrum. Therefore, the annual cycle behavior of temperature and CAPE, which we observed at Delhi, is not as evident at these stations. These are the intriguing features observed over Indian latitudes.

Rainfall and CAPE showed a positive correlation over Delhi, Kolkata, and Trivandrum, with the maximum value at Delhi, decreasing toward Trivandrum. No linear trend was observed in rainfall although there was a slightly increasing trend in CAPE at all stations. The enhanced CAPE associated with rainfall peaks over the Indian region is similar to that reported by Gaffen *et al.* (1991) in the Pacific region.

As mentioned above, the Kolkata region is highly dominated by convective activity due to its close vicinity to the Bay of Bengal. A comparison revealed that CAPE is larger on the Bay of Bengal side than on the Arabian side. An increase in convective activity is found to be consistent with the decrease in temperature at the 100-hPa pressure level. The daily variations of CAPE and temperature at 100 hPa confirmed that CAPE and temperature follow opposite trends. There were especially large CAPE values with increasing linear trend over Kolkata (Fig. 2), and these were associated with a decreasing trend in temperature after 1990. These results show that there is a close relation between convection in the lower atmosphere and temperature in the upper atmosphere irrespective of solar cycle influence. Figure 10 shows that annual temperature tends to decrease at all stations except Delhi (over Kolkata, after 1990, the signature is quite clear). This matches with the findings of Seidel and Randel (2006) and Randel *et al.* (2009)—at least in terms of decreasing tropopause temperature. Nevertheless, temperature is more controlled by the solar cycle at low latitudes. Upward motion due to deep convection in the troposphere is believed to cool the upper troposphere via the adiabatic expansion. The cooling trend at Kolkata is indicative of such processes, which can operate at seasonal, annual, and large-scale time scales.

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