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Supplement of

Long-term trends of instability and associated parameters over the Indian region obtained using a radiosonde network

Rohit Chakraborty et al.

Correspondence to: Madineni Venkat Ratnam (vratnam@narl.gov.in)

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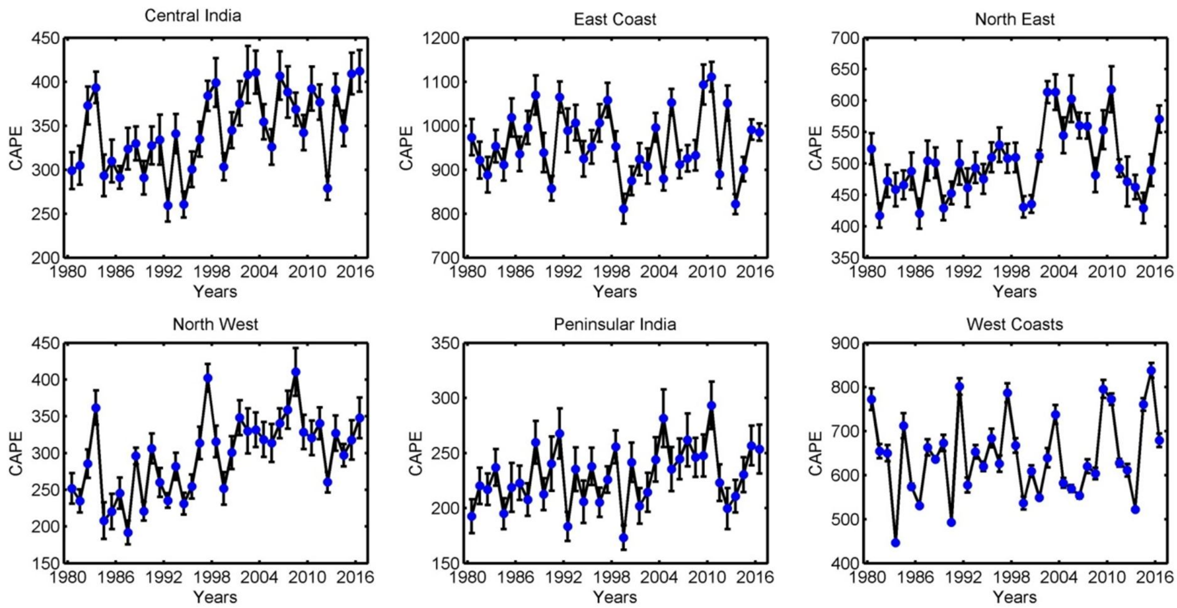

Figure S1: Climatic trends of CAPE for all six Indian Regions using ERA Interim monthly average datasets

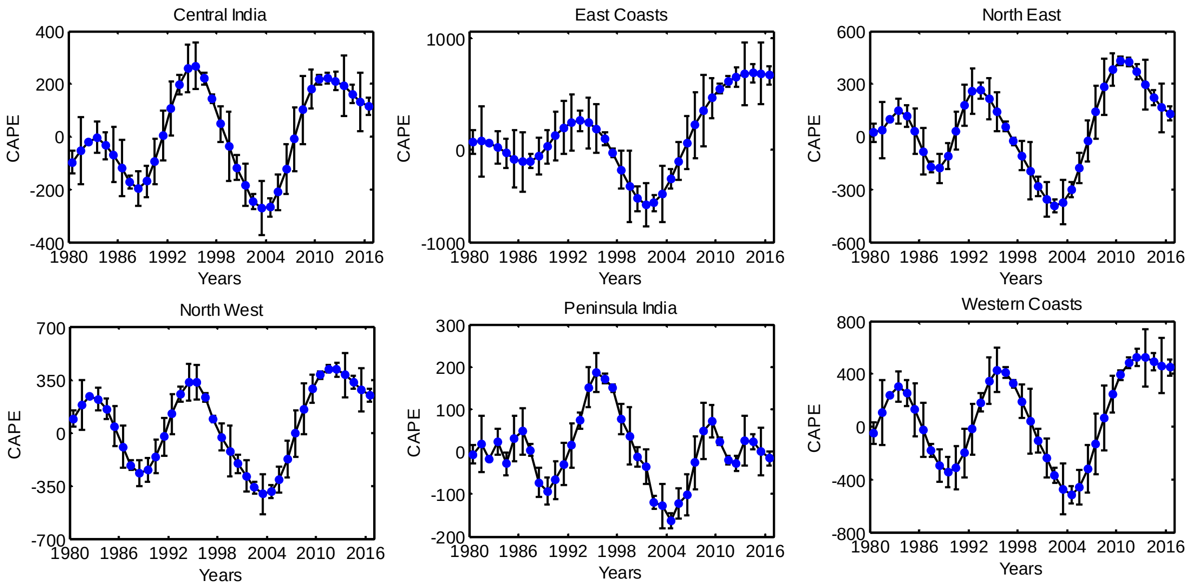

Figure S2: MCO periodicities of CAPE for all Indian regions.

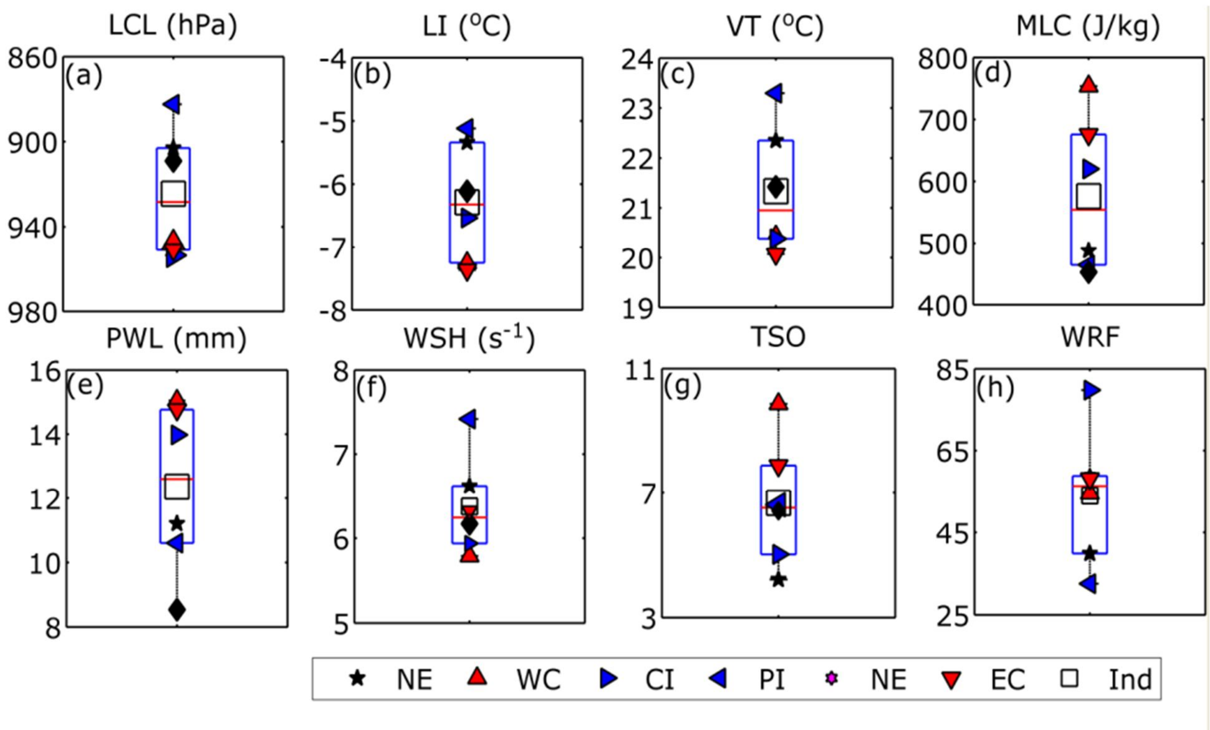

Figure S3: Climatological mean values of (a) LCL, (b) LI, (c) VT, (d) MLC, (e) PWL, (f) WSH, (g) TSO and (h) WRF over the six sub-divisions of India. Coastal Regions are represented by red cones, the north eastern and western regions are denoted by black stars and diamonds while the blue cones represent the inland regions. Here the box limits refer to the upper and lower quartiles (25% and 75%) while the whiskers refer to the outlier limit of the data (5% and 95% limit of the population)

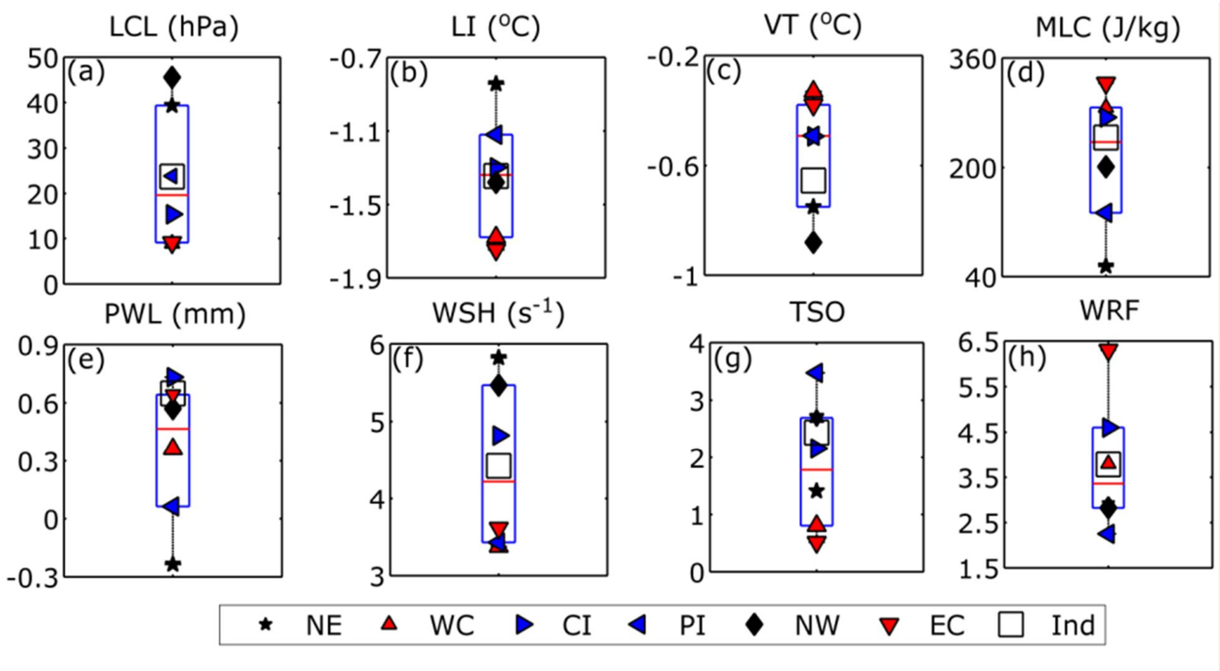

Figure S4: Long-term variation of (a) LCL, (b) LI, (c) VT, (d) MLC, (e) PWL, (f) WSH, (g) TSO and (h) WRF over the six sub-divisions of India during the period 1980-2016. Legends are same as in Figure S3.

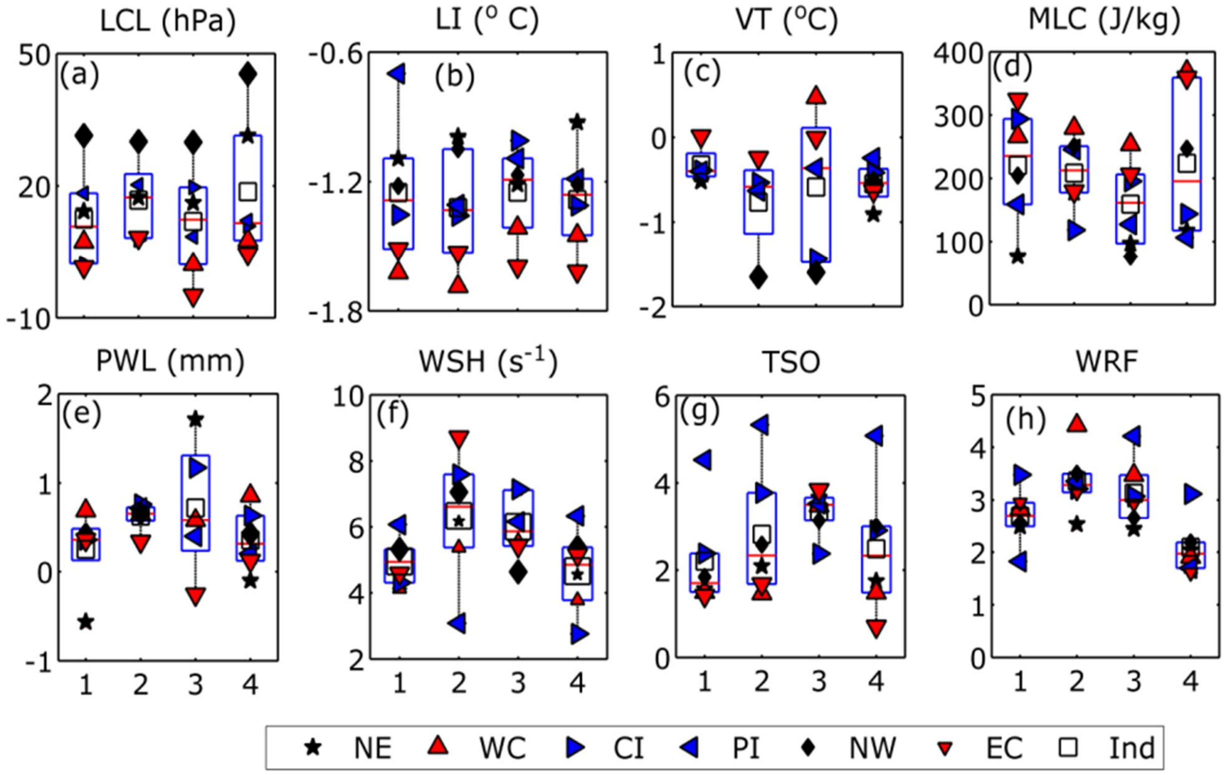

Figure S5: Seasonal trend of long-term variation for (a) LCL, (b) LI, (c) VT, (d) MLC, (e) PWL, (f) WSH, (g) TSO and (h) WRF over India during all seasons. Here 1 refers to pre-monsoon (March-May), 2 refers to Monsoon (June-September), 3 for Post-monsoon (October-November) and 4 for Winter (December-February). Legends are same as in Figure S3.

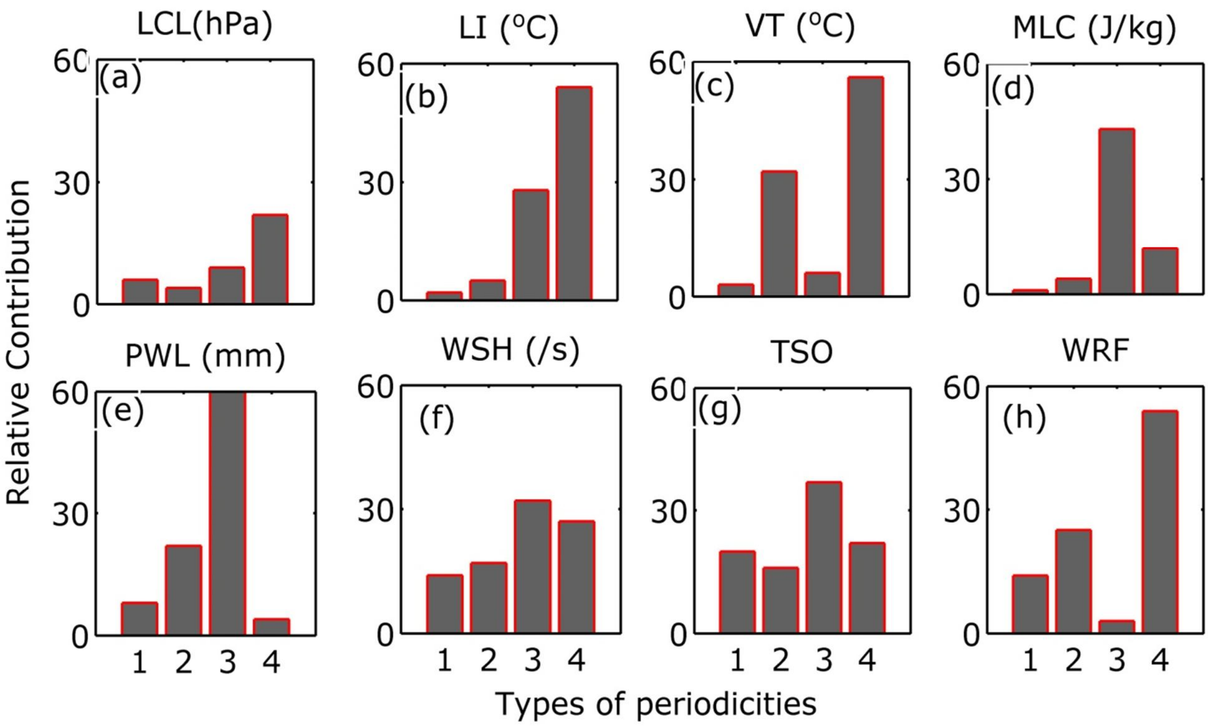

Figure S6: Percentage contribution of various periodicities on long-term trend of all instability parameters over India namely: 1.5 -2.5 years periodicity denoted as 1, 4 -6 years periodicity denoted as 2, 10-12 years periodicity displayed as 3 and 16-20 years periodicity represented as 4.

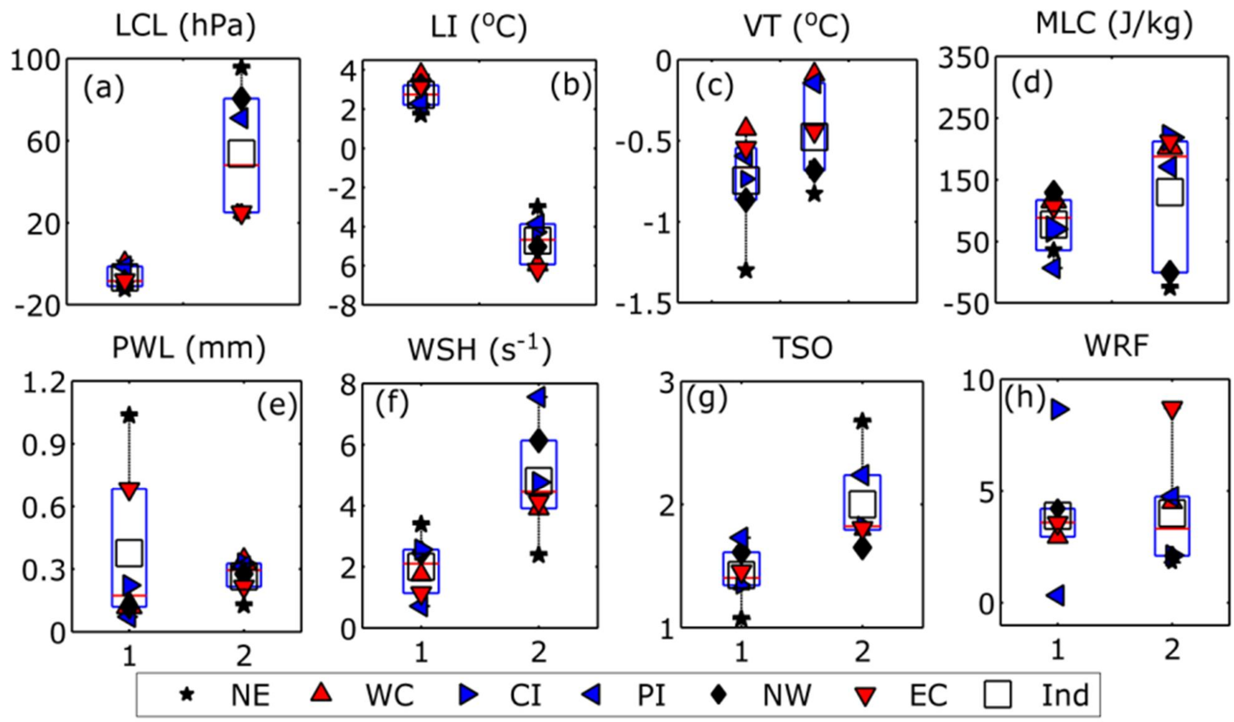

Figure S7: Comparison of average values for two time periods indicating the trend of various instability parameter over the six sub-divisions of India in two half periods of 18 years each (the numbers 1 and 2 represent the first and second period, C1 and C2, during 1980-1997 and 1999-2016, respectively) during 1999-2016. Legends are same as in Figure S3.

Text S1: Breif Description of the parcel and instability parameters used

(a) Lifted Condensation level (LCL): It is the height at which an air parcel would attain condensation if it is raised dry adiabatically from the surface. This is because at that height, the air parcel mixing ratio becomes equal to saturation mixing ratio. Lower values of it indicate presence of tall clouds reaching the surface during convective events. The height of LCL can be reliably calculated from surface meteorological data using a complex formulation technique as shown in Romps (2017).

(b) Level of Free Convection (LFC): It is defined as that level of atmosphere above the LCL where the parcel of air lifted moist adiabatically would for the first time be warmer than its surrounding. Lower heights of LFC indicate more probability of moist air parcels to be lifted upwards leading to more convective strength in the system. The height of LFC is determined by calculating the parcel temperature profiles from pseudo adiabatic lapse rate equation (Hess 1979).

(c) Equilibrium Level (EL): It is the level of atmosphere where a parcel would attain same temperature as of surroundings and would cease its upward motion. However, due to excess momentum sometimes, the parcel can also flow past the EL. Higher the EL, more the energy contained within the convective system.

(d) Lifted Index (LI): It is the difference between the temperature of the environment with that of an air parcel lifted adiabatically to 500 mbar pressure (Galway 1956). Negative or near negative value of LI reflects condensation of saturated vapour parcel to liquid indicating instability and severe weather conditions. LI generally indicate the intensity of the convective activities like CAPE and is calculated as:

$$LI = T_{500} - Tp_{500}$$

(e) Vertical Totals Index (VT): It represents the instability component of TTI. It is calculated as the temperature gradient between 850 and 500 hPa pressure levels (Miller 1967). This parameter is a sensitive measure of atmospheric instability.

$$VT = T_{850} - T_{500}$$

(f) Convective Available Potential Energy (CAPE): CAPE indicates the buoyant energy available to accelerate an air parcel vertically and is calculated using the summation of positive buoyant energy from LFC to EL(Emmanuel 1994). Higher CAPE provides more energy for convective growth thereby leading to more intense thunderstorms; hence CAPE should be high in convective conditions and less in normal conditions. According to standard research attempts, the values of CAPE > 1500 J kg−1 are essential for super cell formation (Rasmussen and Wihemson, 1983). CAPE is normally calculated from this equation.

$$\text{CAPE} = \int_{LFC}^{EL} g \, \frac{T_{vparcel-T_{venv}}}{T_{venv}} \, dz$$

(g) Mixed Layer CAPE (MLC): This parameter is similar to CAPE, but this one is mostly used to assess the atmospheric instability during well mixed conditions in a better way than surface based CAPE. The main difference between CAPE and MLCAPE is that, this parameter constitutes the total positive energy attained by the parcel when it is lifted from the LFC to 100 mb pressure level in the troposphere. However, it may be noted that in this paper, the effect of UTLS on CAPE and thunderstorm severity has been shown in a focussed way. Also in clear weather conditions, EL mostly resides along ~300 hPa over all Indian regions. Hence to separate the effect of UTLS near 100 hPa during intense convection, here the summation is taken only up to 300 hPa levels.

(h) Convective Inhibition Energy (CINE): This is the summation of negative buoyant energy from surface level to LFC. Being the opposite of CAPE, higher values of CINE produce strong hindrance to convective genesis.

$$\text{CINE} = \int_{SFC}^{LFC} g\, \frac{T_{vparcel-T_{venv}}}{T_{venv}} dz$$

(i) Precipitable Water Vapor (PWV): This is the total column water vapour present per unit area. High values indicate higher moisture favouring convective processes.

(j) Precipitable Water Vapour at Lower troposphere (PWL): Lower level moisture contents particularly upto the boundary layer height (maximum 700 hPa) are also useful for controlling all rainfall occurrences and hence they are taken additionally. Again, if both PWL and PWV are taken, then the contribution of the middle and upper troposphere can be clearly understood for all Indian regions.

(k) Horizontal Wind Shear (WSH): This is a common parameter which is calculated as the gradient of horizontal winds between the surface and the 6 km height level. Large values of this prevent convective updrafts and hence it reduces thunderstorm severity.

(l) Temperature at 100 hPa Pressure levels (T100): This represents the atmospheric temperatures present at the 100 hPa pressure level and it is recorded from the radiosonde profiles. This parameter is taken to investigate whether at all there are any reliable relationships between UTLS cooling and CAPE as already hinted earlier in previous research attempts over India.

(m) Ordinary Thunderstorm Frequency (TSO): This parameter is calculated for each station as the number of radiosonde launches per year at 00Z where the colocated surface wind speed values as obtained from base radionde data (obtained by Woyming Portal is between 31-62 km/hr as already cited out by IMD reports and Saha et al. (2018).

(n) Severe Thunderstorm Frequency (TSS): This is similar to TSO, only here the number of radiosonde launches at 00Z are counted for which the surface wind speed is above 62 km/hr as again cited out by IMD reports and Saha et al. 2018.

(o) Weak Rainfall Frequency (WRF): This parameter is calculated for each station as the number of radiosonde launches or days per year at 00Z when the obtained one day rainfall accumulation is very low (below 7.5 mm) as specified by IMD reports.

(p) Severe Rainfall Frequency (SRF): This parameter is similar to WRF; the only difference is that this parameter is calculated for each station as the number of radiosonde launches or days per year at 00Z when the obtained one day rainfall accumulation is very high (above 124.5 mm) as again cited by the IMD reports.

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