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# Climatology of thunderstorm activity over the Indian region : A study of east -west contrast

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**सार** – भारत के 276 स्थानों के केन्द्रों के गर्ज भरे तूफान के दिनों (टी.एच.एन.) के मासिक नंबर और अधिकतम धरातलीय वायु औसत तापमान (टी मैक्स) के नवीनतम आँकड़ों (भारत मौसम विज्ञान विभाग 1999) के आधार पर इस अध्ययन में भारत के गर्ज भरे तूफान की घटना की बारंबारता में पूर्व–पश्चिम विषमता के विचाराधीन विषय का समाधान वास्तविक विस्तार के साथ किया गया है। स्थान के संजाल के प्रिमाइज पर और आई.टी.सी.जेड. के स्थान पर भारत को दो प्रदेशों में बाँटा गया है ; भारत के अक्षांशीय रेखा 79° पूर्व पर पूर्वी प्रदेश और पश्चिमी प्रदेश पर गर्ज भरे तूफान वाले दिनों की वैषम्यपूर्ण विशेषताओं के परिणामों को यहाँ प्रस्तुत किया गया है। हमारे विश्लेषण से यह पता चला है कि वार्षिक गर्ज भरे तूफानों की संख्या पूर्वी प्रदेश में 4763 है और पश्चिमी प्रदेश में इनकी संख्या 3194 है और गर्ज भरे तूफान वाले दिनों के मुख्य अंतर का, पूर्वी प्रदेश और पश्चिमी प्रदेश की मानसून वर्षा ऋतु के महीनों के साथ संबंद्ध होना है। गर्ज भरे तुफान वाले दिनों की घटना के तापमान की संवेदनशीलता से यह पता चलता है कि गर्ज भरे तूफान वाले दिन, दोनों क्षेत्रों में किंतु पूर्वी प्रदेश पर उनकी संवेदनशीलता में स्पष्ट विषमता के साथ अर्द्धवार्षिक और वार्षिक समय श्रृंखलाओं पर अधिकतम धरातलीय वायु तापमान में साधारण वृद्धि घातांकी रूप में देती है। यह परिणाम अनेक अध्ययनों में बताए गए परिणामों से अच्छा मेल खाते हैं, जहाँ भूमंडलीय उष्णकटिबंधीय धरातलीय वायु तापमान और जी.ई.सी. प्राचलों के मध्य संबंध की जाँच की गई है। हमारे विश्लेषण से यह बात स्पष्ट होती है कि पूर्वी प्रदेश के आई.टी.सी..जेड. के गर्म और आर्द्र व्यापक भूप्रदेश अधिक उपयुक्त है और गर्ज भरे तुफान के विकसित होने के लिए उत्तरदायी है। आगे, परिणामों से यह पता चलता है कि सी.पी.ए.ई. के उच्चतर मान और पूर्वी प्रदेश के नमी वाले क्षेत्रों की चर्चा यह समझने के लिए की गई है कि ये पूर्व और पश्चिम के गर्ज भरे तूफानों की सक्रियता में विषमता दिखाते हैं। यह माना जाता है कि इस अध्ययन में बताए गए परिणाम उपयोगी सिद्ध होंगें।

**ABSTRACT.** Based on the latest data (I. M. D., 1999) of monthly number of station thunderstorm days (Thn) and mean maximum surface air temperatures ($T_{max}$) of 276 Indian stations, an important and a long pending issue of east- west contrast in the frequencies of occurrence of thunderstorms over India is resolved in substantial details in this study. On the premise of nearly equal land areas, and density of the station network, and location of ITCZ; India is divided in two regions: Eastern Region (ER) and Western Region (WR) across the 79° E longitude line over India. Results pertaining to the contrasting features of Thn over ER and WR are presented. Our analysis showed that the annual total Thn over the ER are 4763, and over the WR are 3194 and the prominent difference in Thn is associated with monsoon season months over the ER and WR. The temperature sensitivity of occurrence of Thn showed that thunderstorms respond exponentially to modest increment in $T_{max}$ on the semi-annual and annual time-scales in both the regions but with clear contrast in their sensitivity over ER. This result is in good agreement with the results cited in many studies, where relationship between global tropical surface air temperatures and GEC parameters are investigated. Our analysis suggests that the hot and humid extensive land region of the ITCZ of the ER is more suitable and responsible for the development of thunderstorms. Further, results showing higher values of CAPE and moisture field over the ER are discussed to explain the E-W pronounced contrast in the thunderstorm activity. It is believed that the results presented in this study will be useful.

**Key words** – Thunderstorm, Climatology, CAPE.

## 1. Introduction

The tropical land region of the Earth is well understood as a central player in the convective overturn of the atmosphere (Riehl and Malkus, 1958) and as a result is acknowledged also for the preponderance of the world's majority of the thunderstorm activity (Williams, 2001). Thunderstorms being one of the main agencies of energy exchange in the atmosphere, and also being the potential source of precipitation on the surface of the earth, an understanding of their frequencies of occurrence over a region is useful in many studies like Global Electric Circuit (GEC), global energetics etc. The juxtaposition of the land and seas to the south of India and the expanse of the hot and humid land surface to the north, are well suited for the large-scale development of thunderstorms over India. These circumstances produce a valuable data base to scientific community to carryout studies of frequencies of thunderstorms at regular intervals over India. However, a review of the literature (Kendrew, 1949; Rao *et al*., 1971; and Manohar *et al*., 1999) on the thunderstorm studies over India indicates that scientific community have shown infrequent concern with long periods of waiting involved. Some significant remarks concerning the activity of thunderstorms over India from the above mentioned literature are noteworthy and are furnished below.

Kendrew, 1949 - "The world community has perceived a tendency to underestimate the frequencies of occurrence of thunderstorms over India and especially so in the summer monsoon season". Further in this report it is stated that "For a humid tropical land, India is remarkably free from thunder. In monsoonal climates the tendency is to a pronounced maximum in the transitional months at the beginning and end of the summer monsoon and little during the height of the monsoon; this is strongly marked in India".

Rao *et al*., 1971 - "Thunderstorm frequencies on an average over most parts of the eastern India are higher than those over the western parts of India such that there exists a steep gradient of thunderstorms from west to east".

Manohar *et al*., (1999) - in their recent study on thunderstorm activity over India and the Indian southwest monsoon, have addressed some issues pointed out in the above literature; and have shown the convincing evidence to describe the importance of thunderstorms in relation to the monsoon phenomena and global electrical circuit. Earlier studies correlating the seasonal rainfall with frequencies of thunderstorms were by Landsberge (1971) and Freier (1978). Their results showed that, in general, the low-precipitation regimes matched with lower frequencies of thunderstorms or were due to lack of thunderstorms-producing weather conditions. Markson, 1986, have discussed association of tropical convection with ionospheric potentials and global circuit variation. Further, Rutledge *et al*. (1992) and Williams *et al*. (1992) in discussions of electrification and precipitation development of the monsoonal and continental thunderstorms over Australia have expressed a need for procurement of similar information also from the Indian region. Global or regional lightning activity is a highly variable parameter on many time-scales. This variability is usually attributable to changes in the flash rate per thunderstorm, and to the number of thunderstorms themselves. It is reported that among the above two factors the contribution of number of thunderstorms is 2-3 times greater than the change in lightning flash frequency of an individual thunderstorm (Williams *et al*., 2000). Identification and proper documentation of such regions of contrasting frequencies of thunderstorms over the tropics therefore becomes an important topic of study. Manohar *et al*. 1999 in their study of the southwest monsoon over India have showed that the monsoon trough region is a vulnerable zone for the development of thunderstorms. The important summary of the foresaid studies suggests that thunderstorm activity, precipitation and many other issues related with thunderstorms over a region are strongly linked with each other. A climatological study of thunderstorm activity over India is therefore most essential.

In the present work attention is focused on conducting a comprehensive study of frequencies of occurrences of thunderstorms over India with a special reference to quantify their east-west contrast in substantial details. The latest available data of monthly normals of number of thunderstorm days and mean maximum surface air temperatures for 276 Indian stations are used in this study. It is expected that this study will be helpful in the understanding of the problems related with the Indian southwest monsoon.

## 2. Data and method of analysis

The India Meteorological Department (IMD) has recently (1999) brought out a voluminous but very useful publication entitled "Climatological Normals 1951-80". Normals provided in the publication are in the form of tables of mean monthly values of surface data of meteorological parameters for a large number of Indian Observatories. For the present study we have selected monthly data of number of thunderstorm days (Thn) and monthly mean of daily maximum surface air temperatures ($T_{max}$) for 276 stations having standing for a minimum of 25 years except for the station Agatti having data for 15 years. Table 1 gives the details of the stations and Fig. 1 shows the network of the stations used in this study.

It is noted from this figure that the stations are well spread and also are uniformly distributed over the extent of the country .The distance between the nearest two stations is 20 km or more. This would therefore effectively reduce the chance of a single storm being reported simultaneously by the two stations.

**TABLE 1**

**Details of station network**

| Station (1) | Lat. (2) | Long. (3) | Height above msl (4) |
|---|---|---|---|
| Abu | 24.6 | 72.72 | 1195 |
| Agartala | 23.88 | 91.25 | 16 |
| Agatti | 10.85 | 72.47 | 4 |
| Agra | 27.17 | 78.03 | 169 |
| Ahmedabad | 23.07 | 72.63 | *55* |
| Ahmednagar | 19.08 | 74.8 | 657 |
| Ajmer | 26.45 | 74.62 | 486 |
| Akola | 20.7 | 77.03 | 282 |
| Alappuzha | 9.55 | 76.42 | 4 |
| Alibag | 18.63 | 72.87 | 7 |
| Aligarh | 27.88 | 78,07 | 187 |
| Alirajpur | 22.28 | 74.4 | 293 |
| Allahabad | 25.45 | 81.73 | 98 |
| Ambala | 30.38 | 76.77 | 272 |
| Ambikapur | 23.17 | 83.25 | 611 |
| Amraoti | 20.93 | 77.78 | 370 |
| Amritsar | 31.63 | 74.87 | 234 |
| Anantpur | 14.68 | 77.62 | 350 |
| Angul | 20.83 | 85.1 | 139 |
| Arogyavaram | 13.53 | 78.05 | 701 |
| Aurangabad | 19.88 | 75.33 | 581 |
| Azamgarh | 26.05 | 83.22 | 78 |
| Baghdogra (A) | 26.63 | 88.32 | 131 |
| Bagratawa | 22.63 | 77.98 | 331 |
| Bahraich | 27.57 | 81.6 | 124 |
| Balasore | 21.52 | 86.97 | 20 |
| Balehonnur | 13.37 | 75.45 | 885 |
| Ballia | 25.75 | 84.17 | 64 |
| Banda | 25.47 | 80.37 | 121 |
| Bangalore | 12.97 | 77.58 | 921 |
| Baramati | 18.15 | 74.58 | 551 |
| Bareilly | 28.37 | 79.4 | 173 |
| Baripada | 21.93 | 86.77 | 54 |
| Barmer | *25.75* | 71.38 | 194 |
| Baroda | 22.3 | 73,25 | 34 |
| Beed | 19 | 75.72 | 519 |
| Belgaum | 15.85 | 74.53 | 753 |
| Bellary | 15.15 | 76.85 | 747 |
| Berhampore | 24.13 | 88.43 | 19 |
| Betul | 21.87 | 77,93 | 653 |
| Bhagalpur | 25.23 | 86,95 | 49 |
| Bhavnagar | 21.75 | 72.18 | 11 |
| Bhawani Patna | 19.92 | 83.18 | 261 |
| Bhopal | 23.28 | 77.35 | 523 |
| Bhubaneshwar | 20.25 | 85,83 | 46 |
| Bhuj | 23.25 | 69.67 | 80 |
| Bidar | 17.92 | 77.53 | 664 |
| Bijapur | 16.82 | 75.72 | 594 |
| Bikaner | 28 | 73.3 | 224 |
| Bokaro | 23.67 | 85.88 | 242 |
| Bombay | 18.9 | 72.82 | 11 |
| Brahmapuri | 20.6 | 79.85 | 229 |
| Buldana | 20.53 | 76.23 | 650 |
| Burdwan | 23.23 | 87.85 | 32 |
| Calcutta | 22.53 | 88.33 | 6 |
| Car-Nikobar | 9.17 | 92.83 | 10 |
| Chaibasa | 22.55 | 85.82 | 226 |
| Chambal | 24.92 | 75.58 | 351 |
| Champa | 22.03 | 82.7 | 245 |
| Chandbali | 20.78 | 86.73 | 6 |
| Chandrapur | 19.97 | 79.3 | 193 |
| Cherrapunji | 25.25 | 91.73 | 1313 |
| Chhindwara | 22.1 | 79 | 685 |
| Chitradurga | 14.23 | 76.43 | 733 |
| Churu | 28.25 | 74.92 | 291 |
| Coimbatore | 11 | 76.97 | 409 |
| Contai | 21.78 | 87.75 | 11 |
| Cooch Behar | 26.33 | 89.47 | 43 |
| Cuddalore | 11.77 | 79.77 | 12 |
| Cuddapah | 14.48 | 78.83 | 130 |
| Cuttack | 20.I7 | 85.93 | 27 |
| Dahanu | 19.97 | 72.72 | 5 |
| Dalhousie | 32.53 | 75.97 | 1959 |
| Daltonganj | 24.05 | 84.07 | 221 |
| Darbhanga | 26.17 | 85.9 | 49 |
| Darjeeling | 27.05 | 88.27 | 2127 |
| Deesa | 24.2 | 72.2 | 136 |
| Dehra Dun | 30.32 | 78.03 | 682 |
| Dehri | 24.92 | 84.18 | 107 |
| Devgad | 16.38 | 73.35 | 36 |
| Dhanbad | 23.78 | 86.43 | 257 |
| Dharmsala | 32.27 | 76.38 | 1211 |
| Dholpur | 26.67 | 77.83 | 176 |
| Dhubri | 26.02 | 89.98 | 35 |
| Dibrugarh | 27.48 | 95.02 | 111 |
| Dohad | 22.83 | 74.27 | 333 |
| Dumka | 24.27 | 87.25 | 149 |
| Fatehpur | 28.93 | 80.83 | 114 |
| Ferozpore | 30.92 | 74.67 | 200 |
| Forbesganj | 26.3 | 87.27 | 61 |
| Fort Cochin | 9.97 | 76.23 | 3 |
| Gadag | 15.42 | 75.63 | 650 |
| Gangtok | 27.33 | 88.62 | 1812 |
| Gannavaram | 16.53 | 80.8 | 24 |
| Gaya | 24.75 | 84.95 | 116 |
| Goalpara | 26.18 | 90.63 | 38 |
| Gonda | 27.13 | 81.97 | 110 |
| Gondia | 21.47 | 80.2 | 313 |
| Gopalpur | 19.27 | 84.88 | 17 |
| Gorakhpur | 26.75 | 83.37 | 78 |
| Gulberga | 17.35 | 76.85 | 458 |
| Gulmarg | 34.05 | 74,4 | 2655 |
| Guna | 24.65 | 77.32 | 478 |
| Guwahati | 26.1 | 91.58 | 54 |
| Gwalior | 26.23 | 78.25 | 207 |
| Halflong | 25.17 | 93.02 | 682 |
| Hanamkonda | 18.02 | 79.57 | 269 |
| Hardoi | 27.38 | 80.17 | 142 |
| Harnai | 17.82 | 73.1 | 20 |
| Hassan | 13 | 76.15 | 960 |
| Hazaribagh | 23.98 | 85.37 | 611 |
| Hissar | 29.17 | 75.73 | 221 |
| Honavar | 14.28 | 74.45 | 26 |
| Hoshongabad | 22.77 | 77.77 | 302 |
| Hydrabad (A) | 17.45 | 78.47 | 545 |
| Imphal | 24.77 | 93.9 | 781 |
| Indore | 22.72 | 75.8 | 567 |
| Jabalpur | 23.2 | 79.95 | 393 |
| Jagdalpur | 1908 | 82.03 | 553 |
| Jaipur | 26.82 | 75.8 | 390 |
| Jaisalmer | 26.9 | 70.92 | 242 |
| Jalgaon | 21.05 | 75.57 | 201 |
| Jalpaiguri | 26.53 | 88.72 | 83 |
| Jammu | 32.67 | 74.83 | 367 |
| Jamnagar | 22.47 | 70.02 | 20 |
| Jamshedpur | 22.82 | 86.18 | 129 |
| Jamui | 24.93 | 86.3 | 82 |
| Jawai Bandh | 25.08 | 73.08 | 295 |
| Jeur | 18.2 | 75.2 | 521 |
| Jhansi | 25.45 | 78.58 | 251 |
| Jharsuguda | 21.92 | 84.08 | 230 |
| Kakinada | 16.83 | 82.23 | 8 |
| Kalimpong | 27.07 | 88.47 | 1209 |
| Kalingpatnam | 18.33 | 84.13 | 6 |
| Kallakkurichchi | 11.73 | 78.97 | 127 |
| Kanker | 20.27 | 81.48 | 402 |
| Kanpur(A) | 26.43 | 80.37 | 126 |
| Karnal | 29.7 | 77.03 | 249 |

**TABLE 1 (*Contd.*)**

| Station (1) | Lat. (2) | Long. (3) | Height above msl (4) |
|---|---|---|---|
| Karwar | 14.78 | 74.13 | 4 |
| Keonjhargarh | 21.62 | 85.58 | 463 |
| Khammam | 17.25 | 80.15 | 112 |
| Khandwa | 21.83 | 76.37 | 318 |
| Kheri-Lahimpur | 27.9 | 80.8 | 147 |
| Kochi | 9.95 | 76.27 | 3 |
| Kodaikanal | 10.23 | 77.47 | 2343 |
| Kolhapur | 16. 7 | 74.23 | 570 |
| Kondul | 7.22 | 93.73 | 8 |
| Koraput | 18.82 | 82.72 | 913 |
| Kota | 25.18 | 75.85 | 257 |
| Kothagudem | 17.55 | 80.63 | 111 |
| Kozikode | 11.25 | 75.78 | 5 |
| Krishnanagar | 23.4 | 88.52 | 15 |
| Kurnool | 15.83 | 78.07 | 281 |
| Leh | 34,15 | 77.57 | 3514 |
| Long Island | 12.42 | 92.93 | 25 |
| Lucknow (Amausi) | 26.75 | 80.88 | 128 |
| Ludhiana | 30.93 | 75.87 | 247 |
| Lumding | 25.75 | 93.18 | 149 |
| Madras | 13 | 80.18 | 16 |
| Mahabaleshwar | 17.93 | 73.67 | 1382 |
| Mahbubnagar | 16.75 | 78 | 505 |
| Mahuva | 21.08 | 71.78 | 9 |
| Mainpuri | 27.23 | 79.05 | 157 |
| Majbat | 26.75 | 92.35 | 120 |
| Malda | 25.03 | 88.13 | 31 |
| Malegaon | 20.55 | 74.53 | 437 |
| Manali | 32.27 | 77.17 | 2039 |
| Mandi | 31.72 | 76.97 | 761 |
| Mandla | 22.58 | 80.37 | 443 |
| Mangalore | 12.87 | 74.85 | 22 |
| Marmugao | 15.42 | 73.78 | 62 |
| Masulipatanam | 16.18 | 81.13 | 3 |
| Mayabandar | 12.92 | 92.92 | 28 |
| Medikeri | 12.42 | 75,73 | 1152 |
| Meerut | 29.02 | 77.63 | 222 |
| Midnapore | 22.42 | 87.32 | 45 |
| Minicoy | 8.3 | 73 | 2 |
| Minicoy | 8.3 | 73 | 2 |
| Miraj | 16.82 | 74.68 | 554 |
| Motihari | 26.67 | 84.92 | 66 |
| Mukhim | 30.58 | 78.48 | 1981 |
| Mukteswar | 29.47 | 79.65 | 2311 |
| Mussoorie | 30.45 | 78.08 | 2042 |
| Mysore | 12.3 | 76.7 | 767 |
| N. Lakhimpur | 27.23 | 94.12 | 102 |
| Nagapattinam | 10.77 | 79.85 | 9 |
| Nagpur | 21.1 | 79.05 | 310 |
| Nainital | 29.4 | 79.47 | 1953 |
| Najibabad | 29.62 | 78.38 | 270 |
| Nancowry | 7.98 | 93.53 | 26 |
| Nanded | 19.08 | 77.33 | 358 |
| Nandurbar | 21.33 | 74.25 | 206 |
| Nasik | 20 | 73.78 | 598 |
| Nellore | 14.45 | 79.98 | 20 |
| New Delhi | 28.58 | 77,2 | 216 |
| New Kandla | 23 | 70.22 | 14 |
| Nidadavolu | 16.92 | 81.67 | 13 |
| Nimach | 24.47 | 74.9 | 496 |
| Nizamabad | 18.67 | 78.1 | 381 |
| Nowgong | 25.07 | 79.45 | 229 |
| Ongal | 15.57 | 80.05 | 12 |
| Orai | 25. 98 | 79.5 | 141 |
| Pachmarhi | 22.47 | 78.43 | 1075 |
| Palayamkottai | 8.73 | 77.75 | 51 |
| Palghat | 10.77 | 76.65 | 97 |
| Pamban | 9.27 | 79.3 | 11 |
| Panchet Hills | 23.62 | 86.78 | 119 |
| Panjim | 15.48 | 73.82 | 60 |
| Parbhani | 19.27 | 76.83 | 423 |
| Pasighat | 28.1 | 95.38 | 157 |
| Pathankot | 32.23 | 75.63 | 312 |
| Patiala | 30.33 | 76.47 | 251 |
| Patna (A) | 25.6 | 85.1 | 60 |
| Pendra | 22.77 | 81.9 | 625 |
| Phalodi | 27.13 | 72.37 | 234 |
| Phulbani | 20.48 | 84.27 | 489 |
| Port Blair | 11.67 | 92.72 | 79 |
| Punalur | 9 | 76.92 | 34 |
| Punasa | 22.23 | 76.4 | 267 |
| Pune | 18.53 | 73.85 | 559 |
| Puri | 19.8 | 85.82 | 6 |
| Purnea | 25.77 | 87.47 | 38 |
| Purulia | 23.33 | 86.42 | 255 |
| Radhanpur | 23.83 | 71.6 | 30 |
| Raichur | 16.2 | 77.35 | 400 |
| Raigarh | 21.88 | 83.38 | 220 |
| Raipur | 21.23 | 81.65 | 298 |
| Rajgarh | 24 | 76.72 | 382 |
| Rajkot (A) | 22.3 | 70,78 | 138 |
| Ramgarh | 23.63 | 85.5 | 335 |
| Ranchi (A) | 23.32 | 85.32 | 652 |
| Ratlam | 23.32 | 75.05 | 486 |
| Ratnagari | 16.98 | 73.33 | 67 |
| Rentachintala | 16.55 | 79.55 | 106 |
| Roorkee | 29.85 | 77.88 | 274 |
| Sabaur | 25.23 | 87.07 | 37 |
| Sagar | 23.85 | 78.75 | 551 |
| Sagar Island | 21.75 | 88.05 | 3 |
| Salem | 11.65 | 78,17 | 278 |
| Sambalpur | 21.47 | 83.97 | 148 |
| Sandheads | 20. 85 | 88.25 | 10 |
| Satna | 24.57 | 80.83 | 317 |
| Seoni | 22. 1 | 79.55 | 619 |
| Sheopur | 25.67 | 76.68 | 235 |
| Shimoga | 13.93 | 75.63 | 571 |
| Sibsagar | 26.98 | 94.63 | 97 |
| Sidhi | 24.42 | 81.87 | 272 |
| Sikar | 27.62 | 75.13 | 432 |
| Silchar | 24.82 | 92.8 | 29 |
| Simla | 31.1 | 77.17 | 2202 |
| Sironcha | 18.85 | 79.97 | 123 |
| Solapur | 17.67 | 75.9 | 479 |
| Sri Niketan | 23.65 | 87.7 | 59 |
| Sriganganagar | 29.92 | 73.88 | 177 |
| Srinagar | 34.08 | 74.83 | 1587 |
| Sultanpur | 26.25 | 82 | 97 |
| Surat | 21.2 | 72. 83 | 12 |
| Suri | 23.88 | 87.53 | 77 |
| Tahri | 30.4 | 78.48 | 770 |
| Tangla | 26.65 | 91.92 | 78 |
| Tezpur | 26.62 | 92.78 | 79 |
| Thikri | 22.07 | 75.4 | 172 |
| Thriuvananthapuram | 8.48 | 76.85 | 64 |
| Tiructichinappallai | 10.77 | 78.72 | 88 |
| Titalgarh | 20.3 | 83.3 | 211 |
| Tura | 25.52 | 90.23 | 370 |
| Tuticorin | 8.8 | 78.15 | 4 |
| Udaipur | 24.58 | 73.7 | 582 |
| Umaria | 23.53 | 80.88 | 459 |
| Uthagamandalam | 1 1.4 | 76.73 | 2249 |
| Varanasi | 25.45 | 82.87 | 76 |
| Vellore | 12.92 | 79.15 | 214 |
| Vengurla | 15.87 | 73.63 | 9 |
| Verval | 20.9 | 70.37 | 8 |
| Vishakhapatnam | 17.72 | 83.23 | 3 |
| Yeotmal | 20.4 | 78.15 | 451 |

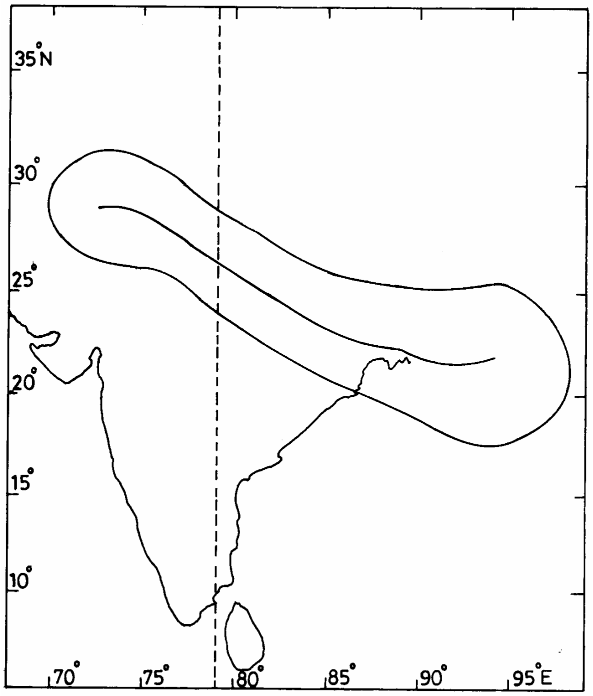



**Fig. 1.** Map of India showing station network of 276 stations used in this study. Map also shows mean position of monsoon trough and envelop around is showing one standard deviation of variation in monsoon trough

The east-west expanse of the mean position of the monsoon trough over the Indian region was studied by Paul and Sikka (1976); and Rajkumar and Narsimha (1996). Their study indicated that the portion of the monsoon trough line east of 79° E longitude is contained almost within the tropics (+25° N, Williams, 1994), and the portion of the trough line west of 79° E longitude lies north of 25° N latitude. We therefore see that the 79° E longitude line demarcates the trough line into two regions: eastern region and western region, each of which lies distinctly within and outside of the tropics. Thus it is felt that the two sections of the trough line, eastern and western, on the premise of tropics and subtropics provide a logistic support in the examination of the east-west contrast in thunderstorm activity over India. Therefore, for an examination of the east-west contrast, we have divided India in two regions: Eastern Region (ER) and Western Region (WR), on either side of the 79° E longitude line across the country (Fig. 1). It is noted from this figure that the land areas of the eastern and western regions are nearly the same or well comparable for the purpose of the present study. The numbers of stations contained in the eastern and western regions are 132 and 144 respectively which shows nearly equal and uniform distribution of stations over the two regions. It is noted that both the regions appear to be balanced with respect to each other. Monthly data of Thn and $T_{max}$ for the stations contained in the ER and WR are used to obtain the seasonal (monthly) means of Thn and $T_{max}$ over the two regions.

## 3. Results and discussion

### 3.1. *Observations of east -west contrast*

Figs. 2 (a&b) shows the seasonal variation of Thn and $T_{max}$ respectively for the two regions under study. It is noted from Fig. 2(a) that in the ER and WR the semi-annual oscillation of the seasonal variation in Thn is clearly seen. In the ER, the first maximum is seen to occur in the month of June while in the WR the first maximum is seen to spread over in the months of May and June. It is also noted that in the ER and WR the amplitudes of the second maximum which occur in the months of August and September respectively, are reduced by 15 % and 40 %. A careful examination of the two curves of Thn in Fig. 2(a) indicates that in 10 out of the 12 months the curve for the ER lays well over the curve for the WR. This feature is valid right from the month of January and continues up to the month of October. During these 10 months, the curve for the ER is seen to show consistently higher amplitudes of Thn as compared to that for the WR. The prominence in the difference in their monthly amplitude is alarmingly high in the five months period from May-September which covers the last month of the pre-monsoon season and whole of the monsoon season. During these five months, Thn over the ER are in excess in the range 36 % to 139 % of the WR. Some additional quantitative information of contrasting thunderstorm activity over the ER and WR are: Annual total number of thunderstorm days over the ER and WR are 4763 / 3194 and monthly mean Thn per station are 3.0 / 1.8 respectively. Comparison between the seasonal variations of Thn and $T_{max}$ over the two regions enables us to obtain quantitative estimates of sensitivity to temperature changes of thunderstorm occurrence. Our records show that over both the regions, the increase in Thn during pre-monsoon season was in the range 33-36 % per 1° C rise in the $T_{max}$. The corresponding increase in Thn on semi-annual time-scale in the tropical land regions, obtained by Williams (1994), was in the range 30-40 %. We note the consistency in these results. Correlation coefficients over the annual period of 12 months between $T_{max}$ and Thn over the ER and WR work out to be 0.74 and 0.84, while these correlations for the monsoon season months work out to be 0.95 and 0.98 respectively. These correlation coefficients are significant at 0.01, 0.001, 0.05 and 0.02% level of significance respectively. The seasonal percentage distribution of the annual thunderstorm activity revealed that 60 % (49 %), 28 % (32 %), 7 % (13 %) and 5 % (6 %) thunderstorms occur during the monsoon, pre-monsoon, post-monsoon (O-N) and winter season (D-J-F) months respectively over the ER (WR). One month shift between the first maximum in Thn and $T_{max}$ in both the regions is witnessed. We compare our results with the results of Williams 1994. Our results clearly corroborate the nearly one month time lag in heating of the land surface following the maximum in insolation. For the results presented so far we refer to studies of Williams (1994, 1997) where relationship between the tropical surface air temperature for the globe and many other parameters of GEC, including thunderstorm days, has been examined. These studies revealed a good phase agreement between surface air temperature and GEC parameters and an apparent sensitivity of global circuit response to temperature in the range of 10-100% per 1° C. These results are attributed to the influence of temperature on convective activity. It is seen here that, thunderstorm activity responds to surface air temperature on both the time-scales, semi-annual and annual over the two regions but with clear contrast in their sensitivity of occurrence.

### 3.2. *Topographical influence*

The present study has produced valid evidences to show that the ER dominates over the WR in terms of their thunderstorm frequencies. Our findings now clearly corroborate the early results of Rao *et al*. 1971. This validation of the results requires some explanations and results supported by other parameters. To our understanding, explanation for these results can be sought on the basis of the contrasts in the properties of surface meteorological parameters and some situations prevalent over these regions. It is well known that the elevation of land surface above the mean sea level is an important property in deciding the surface heating of a region. This situation is some what similar and hence comparable to one where surface heating is dominated by the relative prevalence of land and water (Williams, 2002). In either case the lower land areas are known to be systematically hotter than the far elevated ones and the ones dominated by the surrounding extensive presence of waters. The average altitude above mean sea level of the ER works out to be 3 meter, while that of the WR works out to be 580 meters. This more than two orders of lower elevation of the ER is an important factor in maintaining a $T_{max}$ contrast in influencing the development of strong convection and development of thunderstorms.

This contrast in the average elevation of these regions makes the ER systematically hotter, over major parts of the annual period than over the WR. Fig. 2(b) shows a plot of $T_{max}$ over the two regions. It is noted that during the pre-monsoon and monsoon season months the $T_{max}$ over the ER are hotter in the range 0.15 to 1.3° C than over the WR. We note that this period of seven months is larger than the remaining five months period

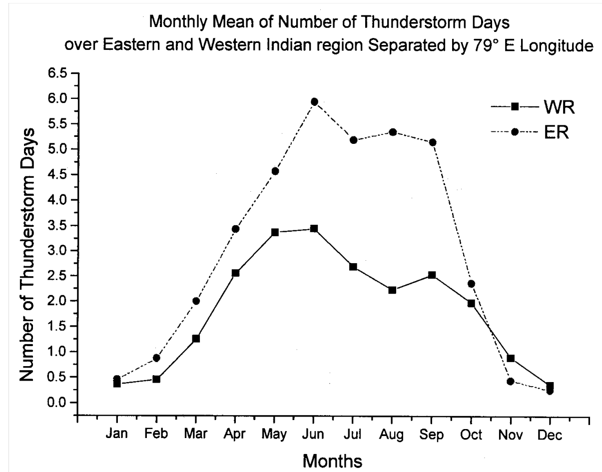



**Fig. 2(a).** Monthly mean number of thunderstorm days over the ER and WR of India separated by 79° E longitudes

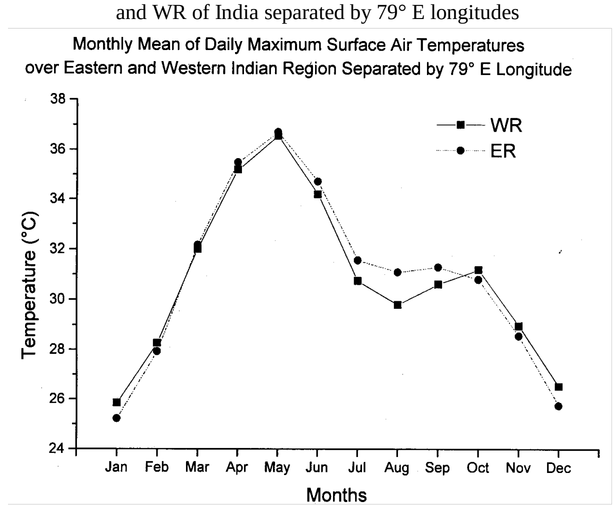



**Fig. 2(b).** Monthly mean maximum surface air temperatures over the ER and WR of India separated by 79° E longitudes

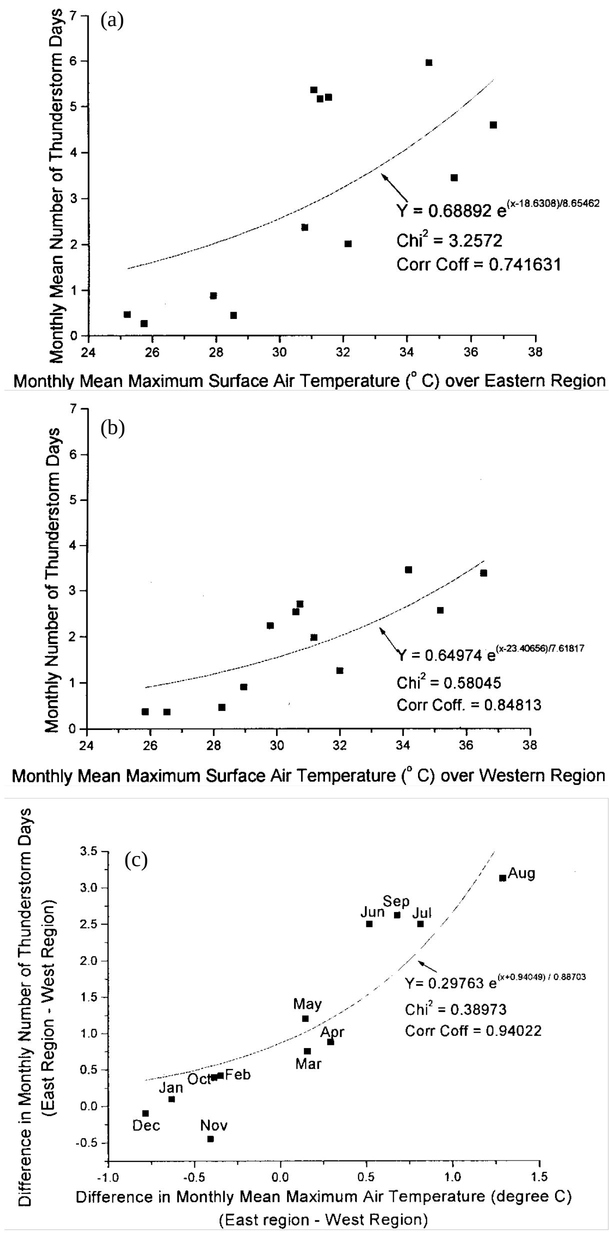
when western region temperatures are just marginally in excess of the eastern region. Evidences for a primary role of dry bulb temperature in influencing deep convection, development of thunderstorms, and lightning on regional and global scales can be found in some of the recent studies (Williams, 1992, 1994, 1999; Price, 1993). The important conclusion of their studies is that the extensive hot land regions of the tropics are more suitable and responsible for the development of deep convection and occurrences of thunderstorms. The present study therefore stresses the importance of subtle higher values of $T_{max}$ in their effect on parcel buoyancy in the dry phase that substantially impacts the moist stage.

### 3.3. *Sensitivity and prediction equation between Thn and* $T_{max}$

We propose to obtain suitable prediction equations of the Thn in relation to $T_{max}$ over the ER and WR. These equations are used for studying the difference in the sensitivity of occurrences of Thn with changes in $T_{max}$ over the two regions. Figs. 3(a&b) shows the scatter diagram of x-y plot of $T_{max}$ *versus* Thn. Further, exponentially growing best fit curves have been fitted to the scatter points in each figure. The best fit statistics for these figures are also presented in each diagram.

From the exponential nature of the curves and from their prediction equations following inferences are drawn. We note that, the sensitivity of occurrences of Thn with subtle changes in $T_{max}$ is higher over the ER than that over the WR. For example, at 34° C of $T_{max}$, Thn over the ER is 4.0 and over the WR it is 2.6. At 36° C of $T_{max}$ the Thn over ER and WR are 5.1 and 3.3 respectively. From the analysis it is inferred that for $T_{max}$ in the range 34-36° C, the amplitudes of occurrences of Thn over the ER are nearly 54 % larger than that over WR. This result is in agreement with the findings that the aggregate number of Thn over the ER (~4800) is found to be nearly 50% larger than that of the aggregate number (~3600) over the WR. Further, from the Figs. 3(a&b) we also note that, over the ER the gradient of Thn per 1° C change in $T_{max}$ in the range 32-34° C is 0.55 and for the temperature in the range 34-36 ° C the gradient is 0.65. The corresponding values over the WR are 0.25 and 0.45. Thus, we note that the gradient of sensitivity of occurrences of Thn over the ER is distinctly higher than that over WR.

Fig. 3(c), shows a scatter diagram of x-y plots of the monthly differences in $T_{max}$ between the ER and WR versus the similar monthly differences in Thn. An exponentially growing best fit curve, statistics of best fit and the month corresponding to each scatter point is presented in this figure. We note that, the best fit curve not only corroborates the results discussed in the previous paragraph but also reveals seasonal features of the thunderstorm activity associated with changes in $T_{max}$ over the two regions. It is noted from the labels of the months that the cluster of the months exhibits a systematic pattern of seasonality evolving during the course of the annual period. It is observed that the scatter points present at the lower end of the curve are associated with the post-monsoon and winter season months. Points near the central portion of the curve are of the pre-monsoon season months and the points along the upper reaches of the exponentially growing curve are associated with the monsoon season months. We thus note the systematic pattern of evolution of higher values of Thn associated with the seasons. We also note that the major difference in the Thn activity over the ER is linked in a strong manner with the higher temperatures (0.15 - 0.55° C) in the pre-monsoon and more so (0.55 - 1.3° C) in the monsoon season months. In the monsoon season difference in Thn over the ER enhances from about two thunderstorms per




**Figs. 3(a-c).** Scatter plot of (a) $T_{max}$ *vs*. Thn over ER, (b) $T_{max}$ *vs*. Thn over WR and (c) Difference in $T_{max}$ (ER - WR) *vs*. Thn (ER - WR)

station per month for difference in temperature of about 0.75° C; and attains a peak value of 3.6 thunderstorms corresponding to temperature difference of about 1.25° C. It may be summarized that the sensitivity of the occurrences of the thunderstorms is clearly associated with the subtle changes in the temperature and moisture conditions of the atmosphere which are prevalent during the pre-monsoon and monsoon seasons. The results showing the higher values of wet-bulb potential

**TABLE 2**

**Monthly mean maximum wet-bulb potential temperature ($T_{\theta w}$ °C) during the monsoon season months of the years 1972 and 1975 over the ER and WR**

| Months | 1972 | | | | 1975 | | | |
|---|---|---|---|---|---|---|---|---|
| | WR (results based on data of 40 stations) | | ER (results based on data of 38 stations | | WR (results based on data of 40 stations) | | ER (results based on data of 38 stations | |
| | $T_{\theta w}$ °C | CAPE (J/kg) | $T_{\theta w}$ °C | CAPE (J/kg) | $T_{\theta w}$ °C | CAPE (J/kg) | $T_{\theta w}$ °C | CAPE (J/kg) |
| June | 24.9 | 1950 | 26.2 | 3300 | 24.6 | 1750 | 26.1 | 3200 |
| July | 24.8 | 1800 | 26.3 | 3500 | 24.8 | 1800 | 26.0 | 3150 |
| August | 24.2 | 1150 | 25.9 | 3000 | 24.9 | 1950 | 26.3 | 3500 |
| September | 23.5 | 500 | 25.5 | 2800 | 24.5 | 1600 | 25.9 | 300 |

temperatures, and CAPE, over the eastern region during the monsoon season are briefly presented below.

Previous studies by Williams *et al*. (1992), Williams (1992 and 1994) and Jayaratne (1993) have used the monthly mean maximum wet-bulb temperature to compare its association with deep convection in the tropics (Williams, 1997). The use of surface wet-bulb temperature was common and consistent in these studies because the wet-bulb temperature records simultaneously the effect of temperature and moisture, both of which are important for the thermodynamics of moist convection. Also, in a recent study Manohar *et al*. (1999) have used the monthly mean maximum values of surface wet-bulb temperatures to understand the association between wet-bulb temperature and thunderstorms days over the Indian region. Their studies have shown that a modest increase in the wet-bulb temperature is associated with an exponential increase in the occurrences of thunderstorms. To complement our results of contrasting number of thunderstorm days described above, we present in brief the surface temperature conditions in terms of $T_{\theta w}$ °C; (monthly mean maximum surface wet-bulb potential temperature), and the values of (CAPE,J/kg) in the monsoon environment over the two regions. For this purpose $T_{\theta w}$ data for the 78 Indian stations are taken from the studies of Manohar *et al*. (1999), since these data are unfortunately not available in the IMD normals. Table 2 presents regional average picture of $T_{\theta w}$ and that of the CAPE representing the two regions. CAPE values are retrieved from the relation between $T_{\theta w}$ and CAPE from the studies of Williams *et al*., 1992.

We note that the $T_{\theta w}$ values and the CAPE over the ER are consistently higher than those over the WR. The $T_{\theta w}$ values are larger in the range 1.2° C - 2.1° C over the ER and the CAPE values are as much higher as the CAPE values themselves over the WR. This result therefore shows that the eastern tropical land region is more conditionally unstable and the larger CAPE values favour the deep and frequent convection that produces thunderstorms. Thermodynamic structure of the atmosphere over India during southwest monsoon season was also studied by Srinivasan and Sadasivan (1975). The analysis of their relative humidity data of six representative stations over both the regions have showed that the percentage increase in the average relative humidity over the ER was in the range 1-32 % in the vertical column of the atmosphere ranging from 1000 hPa - 300 hPa.

3.4. *Influence of TCZ*

From Fig. 2 (a) and Fig. 3(c) it is seen that in the monsoon season the mean Thn over the ER and WR are 5.3 and 2.7 respectively while in the pre-monsoon season these means are 3.3 and 2.3 respectively. These figures indicate that thunderstorm activity during the monsoon season over the ER is enhanced by 60% with respect to the pre-monsoon season, while the similar enhancement over the WR is only 17%. The important point of information of this analysis is that the seasonal enhancement in the thunderstorm activity is a common feature of both the regions. But activity-wise the ER is clearly seen to dominate over the WR. Similar enhancement in the thunderstorm activity over the Indian region was also pointed out in a recent study by Manohar *et al*. 1999. Their results which were based on analysis of 11 years (1970-80) monthly data of thunderstorm days for 78 Indian stations showed an average enhancement of 56 % in the monsoonal thunderstorm days with a standard deviation of 23 over the 11 year period of study. All this information clearly shows that, the seasonal enhancement in Thn is a consistent and regular feature. Therefore, the east-west (E-W) disparity in their activity needs some explanation.

The east-west disparity in the enhancement in the Thn, witnessed above may be attributed to a large extent to the seasonal expanse of the mean location of tropical convergence zone (TCZ) across the 79° E longitude over the Indian region. TCZ is a dominant upwelling zone which favors the monsoonal convection and the development of thunderstorm (Rutledge *et al*. 1992, Williams *et al*. 1992, and Manohar *et al*. 1999). The character of the TCZ is that it produces monsoonal convection mainly as a result of synoptic-scale convergent air motion. These air motions are themselves driven by horizontal pressure gradients that are set up by latitudinal gradients in surface temperatures. Although these monsoonal thunderstorms are in excess in number than the pre-monsoon seasons ones, the above mentioned studies have clearly shown that these thunderstorms are weakly electrified and their per-thunderstorm contribution to rainfall is much larger than those of the pre-monsoon season. Fig. 1 shows the normal position and the areal coverage of TCZ over the Indian region. It is evident that the areal coverage and horizontal extent of the TCZ east of 79 ° E is much larger than that over the region west of 79° E longitude. Thus it appears that the dominance of thunderstorms activity and steep gradient from west to east is mainly attributed to the lateral extent and expanse of the TCZ over the two regions.

## 4. Conclusions

The climatological data sets of Thn were used to determine their mean seasonal variation over ER and WR. It was noted that over both the regions Thn showed clear signals of the semi-annual oscillations of the seasonal variation. But the first maximum of this signal over the ER occurred in the month of May, while over the WR it occurred in the months of May and June. It was noted that the amplitude of the first maximum over the ER was higher by about 72 % than over WR. The second maximum of the seasonal variation over ER and WR occurred in the months of August and September respectively. It is noted that in both the regions the amplitude of the maximum dominated significantly over the second maximum. The monthly mean amplitudes of the seasonal variation of Thn over the ER exceeded those over the WR during most parts of the annual period. This feature was witnessed particularly in the five months period from May to September. The annual total number of thunderstorm days over ER was noted to be 4763 and over the WR were 3194. This analysis showed that thunderstorm activity over ER is nearly twice higher than that over WR. The computation of correlation coefficients between monthly values of Thn and $T_{max}$ showed that Thn and $T_{max}$ were highly correlated. This result indicates that there exists a good phase agreement between $T_{max}$ and the occurrence of thunderstorm over the two regions. The analysis pertaining to temperature sensitivity of occurrence of Thn for 1° C increment in $T_{max}$ showed that thunderstorm respond exponentially to modest increase in $T_{max}$ on the semi annual and annual time-scales in both the regions. But the response over ER was nearly twice higher than that over WR. Our analysis suggested that the more hot and humid extensive plain land region of the TCZ of the ER is more suitable and responsible for the higher development of thunderstorm. Results showing higher values of moisture and CAPE and surface wet-bulb potential temperature over ER explain the east-west contrast in thunderstorm activity over India.

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