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# A synoptic and thermodynamic analysis for forecasting of squalls at Agartala

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**सार** – प्री-मानसून सीजन में अगरतला और उसके आस-पास के इलाकों में आंधी-तूफान के साथ आंधी-तूफान भारी तबाही मचाता है। इस पेपर में, 2011 - 2020 के दौरान अगरतला (23.90°N, 93.25°E) में तूफानों से जुड़ी समसामयिक स्थितियों, स्थिरता सूचकांकों और निचले स्तर के पवन पैटर्न का विश्लेषण किया गया है ताकि घटनाओं के घटित होने में उनके प्रतिशत योगदान और महत्वपूर्ण मूल्यों को प्राप्त किया जा सके। अलग-अलग प्रतिशत के साथ, घटनाओं में योगदान देने वाली पांच प्रमुख पर्यायवाची स्थितियां पाई जाती हैं। कम से कम 80% घटनाओं के लिए उनके योगदान के आधार पर शोलेटर इंडेक्स, लिफ्टेड इंडेक्स, के-इंडेक्स, स्वेट इंडेक्स, टोटल टोटल इंडेक्स के महत्वपूर्ण मूल्य प्राप्त किए जाते हैं। 925 hPa और 850 hPa पर हवा की दिशा दक्षिणी घटक के साथ आंधी की घटना के लिए एक और महत्वपूर्ण अग्रदूत पाया गया है।

**ABSTRACT.** Thunderstorms accompanied with squalls cause a serious damage in Agartala and its neighbouring areas in the pre-monsoon season. In this paper, the synoptic conditions, stability indices and lower level wind pattern associated with squalls at Agartala (23.90° N, 93.25° E) during 2011 - 2020 are analysed to obtain their percentage contributions and critical values in occurrence of the events. Five major synoptic conditions are found to have contribution to the events, with varying percentages. The critical values of Showalter Index, Lifted Index, K-Index, SWEAT Index, Total Totals Index are obtained based on their contribution for at least 80% of the events. Wind direction at 925 hPa and 850 hPa with southerly component is found to be another important precursor for occurrence of the squalls.

**Key words** – Thunderstorm, Squall, Synoptic conditions, Stability indices.

## 1. Introduction

Thunderstorms are considered as one of the most hazardous natural phenomena all across the globe. There are a number of other severe weather phenomena associated with thunderstorms, for example, lightning, gusty wind/squall, hailstorm, heavy rainfall which proves to belife-threatening for the living beings. There is a large temporal and spatial variation of thunderstorms across the world. In India, the pre-monsoon season (March to May) is the peak season for occurrence of thunderstorms. However, the characteristics of those thunderstorms are different in different regions of the country. Dust-storms/sand-storms are common features in north India in this season, while Norwesters or 'Kalbaisakhis' causes severe squalls in east and north-east India. The eastern and northeastern regions of the country are considered as one of the most prone areas for thunderstorms (Tyagi, 2007). In this region, thunderstorms generally start in the month of March and continue till May, with its peak during April and May. The mean number of thunderstorm days is more than 30 in some places of northeast India during April and May (Singh *et al*., 2011). Sometimes, violent squalls with wind speed exceeding 50 knots are also accompanied with them. However, in June, the southwest monsoon advances into the region and severity of the thunderstorms decreases with that.

Every year, thousands of casualties are reported in India due to phenomena associated with thunderstorms, like lightning strikes, squalls and hails etc. The associated squally winds cause damage to the properties like Kachcha houses, thatched huts and asbestos houses, telephone and electric poles and other structures amounting to crores of rupees every year. Apart from standing crops which get severely damaged, it also affects transport sector like highways, railways and aviation resulting in human and revenue losses. In view of the large-scale damage caused by thunderstorms, it is of great need to forecast them effectively for strengthening the disaster preparedness. In recent years, there have been great improvements in the daily operational weather

**TABLE 1**

**Definition and description of Stability Indices**

| Index with equation | Description | |
|---|---|---|
| Showalter Index (SHOW) $= T_{500} - T_{parcel}$ | $T_{500}$ | = Temperature at 500 hPa |
| | $T_{parcel}$ | = Temperature at 500 hPa of a parcel of air lifted from 850 hPa |
| Lifted Index (LI) $= T_{500} - T_{parcel}$ | $T_{500}$ | = Temperature at 500 hPa |
| | $T_{parcel}$ | = Temperature at 500 hPa of a parcel of air lifted from near the surface |
| Total Totals Index (TTI) $= (T_{850} - T_{500}) + (TD_{850} - T_{500})$ | $T_{850}$ | = Temperature at 850 hPa |
| | $TD_{850}$ | = Dewpoint temperature at 850 hPa |
| | $T_{500}$ | = Temperature at 500 hPa |
| K-Index (KINX) $= (T_{850} - T_{500}) + TD_{850} - (T_{700} - TD_{700})$ | $T_{850}$ | = Temperature at 850 hPa |
| | $T_{500}$ | = Temperature at 500 hPa |
| | $TD_{850}$ | = Dewpoint temperature at 850 hPa |
| | $T_{700}$ | = Temperature at 700 hPa |
| | $TD_{700}$ | = Dewpoint temperature at 700 hPa |
| Severe Weather Threat Index (SWEAT) $= 12\times TD_{850}+20\times TERM2+2\times SKT_{850}+SKT_{500} + SHEAR$ | $TD_{850}$ | = Dewpoint temperature at 850 hPa |
| | TERM2 | = MAX (TTI - 49, 0) |
| | TTI | = Total Totals Index |
| | $SKT_{850}$ | = wind speed in knots at 850 hPa |
| | $SKT_{500}$ | = wind speed in knots at 500 hPa |
| | SHEAR | = 125 × [SIN (DIR500 - DIR850) + .2] |
| | $DIR_{500}$ | = wind direction at 500 hPa |
| | $DIR_{850}$ | = wind direction at 850 hPa |
| Convective Available Potential Energy (CAPE) $= g\int_{z^{LFC}}^{z^{LNB}} \frac{Tve - Tvp}{Tve} dz$ | $g$ | = acceleration by gravity |
| | $z$ | = height |
| | $T$ve | = virtual temperature of the environment |
| | $T$vp | = virtual temperature of the air parcel and |
| | $Z^{LNB}$ | = Height at Level of neutral buoyancy |
| | $Z^{LFC}$ | = Height at Level of Free Convection |

forecasts of India Meteorological Department (IMD). The increase in the resolutions of Numerical Weather Prediction (NWP) models, faster reception of satellite products of India as well as from other countries, strengthening of Doppler Weather Radar (DWR) network across the country have played a major role in the improvement of IMD's forecasting system. IMD, IITM (Indian Institute of Tropical Meteorological) and NCMRWF (National Centre for Medium Range Weather Forecasting) have come up with mesoscale model derived short range forecast products for thunderstorms and related hazards such as lightning, wind gust, hail probability etc. Apart from the national centres, some global centres have also come up with location specific products for the Indian region. The Ensemble meteograms developed by ECMWF also provide guidance about location specific forecasts. The nowcasting software like WDSSII and SWIRLS have also been installed along with DWRs to get a track of possible movements of thunderstorms during subsequent two hours. All these have greatly aided the thunderstorm prediction system of IMD. Apart from the numerical weather prediction models in short range forecasting and the aid of satellite and DWRs in nowcasting, the traditional method of forecasting location specific occurrence of thunderstorms with the help of thermodynamic indices derived from upper air observations shows a great result in forecasting of thunderstorms. These indices mainly give a quantitative idea about the instability in the atmosphere, which is likely to lead to the occurrence of thunderstorm over a region. The NWP models in conjunction with the thermodynamic indices is expected to give further improved short range forecasting at specific locations.

The essential criteria for occurrence of thunderstorms are, (*i*) feeding of moisture at the lower levels of the atmosphere, (*ii*) instability in the atmosphere and (*iii*) vertical lifting of air in the atmosphere

(Khole and Biswas, 2007). Although the essential requirements are same for all thunderstorms, but different places, based on their geographic locations, have their own favourable synoptic conditions that trigger the occurrence of thunderstorms. The instability requirement also varies from place to place. The instability of the atmosphere can be estimated based on certain stability indices, which are calculated based on the data ofupper air observations from Radiosonde/Radio wind (RS/RW) ascents. The threshold values of the indices for occurrence of thunderstorms are also different for different places. Even the values of the same index are different for different intensities of thunderstorms.

In the present study, an attempt has been made to find out the synoptic conditions and instability indices favourable for occurrence of squalls at Agartala (23. 90° N, 93.25° E) during the period 2011-2020. A total of 90 squalls have been recorded at Agartala Airport during this period. Agartala is the capital of the state Tripura and an important city in northeast India. It is also an airport and shares international boundary with Bangladesh. The meteorological observatory of IMD located here, has recorded an annual mean of 81 thunderstorm days, with 28 thunderstorm days during April and May (based on 1981-2010 climatology). Some of these thunderstorms cause severe damage in the region. The annual mean number of thunderstorm related deaths in the whole state of Tripura is 6 and that of injuries is 13 (*Source* : Revenue Department, Government of Tripura). The squalls associated with those thunderstorms also cause damage to houses, communication, electricity, agriculture, etc. The flight operations at Agartala airport are also hampered by those severe squalls. In view of the damage associated with the devastating squalls, it is necessary to understand the favourable conditions for occurrence of such squalls, so that early warning can be disseminated for preparedness to the public and disaster managers.

## 2. Data and methodology

The Aerodrome Meteorological Office (AMO) of India Meteorological Department at Agartala has instruments (Distance Indicating Wind Equipment) for continuous observation of wind at the Airport. These instruments give the wind direction and speed at every instant of time. The wind data along with their time of occurrence recorded during the squalls are used in this study. Radiosonde/Radio wind (RS/RW) observations are also taken at Meteorological Centre, Agartala daily at 0000 UTC and the data are transmitted worldwide. Various stability indices can be derived from the data, which indicates whether the atmosphere is favourable for occurrence of thunderstorms and related phenomena. The calculated stability indices are also available in the website of University of Wyoming. In this study, the indices for the period 2011-2020 are taken from their website (http://www.uwyo.edu/). The indices considered for this study have been described in Table 1. The synoptic conditions associated with the squalls have been obtained from the all India weather inference prepared by the National Weather Forecasting Centre (NWFC), IMD, New Delhi and from the analysed weather charts obtained from Weather Section, IMD, Pune.

A higher negative value of Showalter Index (SHOW) and Lifted Index (LI) indicates more instability in the atmosphere. Showalter (1953) found that thunderstorms have increasing probability as the value of his index falls from +1 °C to -2 °C and a value of -3 °C or less is indicative of severe thunderstorms. Mukhopadhyay *et al*. (2003) investigated the values of certain parameters for thundery/non-thundery days over three northeastern stations, namely, Agartala, Guwahati and Dibrugarh and the value of Lifted Index less than -0.2 °C was found to have more potential for thunderstorm development. Singh *et al*. (2014) considered the values of less than 2 °C and less than 0°C respectively for the two indices, as threshold for occurrence thunderstorm over Agartala. Higher values of K-Index (KINX) and Total Totals Index (TTI) are more favourable for development of thunderstorms. Tyagi *et al*. (2011) found the values of KINX and TTI to be ≥ 24 °C and ≥46 °C respectively for higher possibility of thunderstorm development in Kolkata. Singh *et al*. (2014) used the thresholds of 24 °C and 45.5 °C respectively for favourability of thunderstorm over Agartala. Severe Weather Threat Index (SWEAT) considersthe low-level moisture availability at 850 hPa level, instability in terms of Total Totals Index, wind direction and speed at lower and middle-levels of 850 and 500 hPa. The Convective Available Potential Energy (CAPE) physically means the vertically integrated positive buoyancy of an adiabatically rising parcel. Singh *et al*. (2014) considered the values of SWEAT>100 and CAPE>1200 Joules/Kg as thresholds for thunderstorm over Agartala. Stensrud *et al*. (1997) considered the range of CAPE 1000 - 2500 Joules/Kg as moderate instability and 2500 - 4000 Joules/Kg as strong and >4000 Joules/Kg as extreme instability.

## 3. Results and discussion

### 3.1. *Climatological aspects of squalls at Agartala*

Fig. 1. suggests that frequency of squalls at Agartala is highest in April (4.1), followed by May (3.6), as observed during 2011-2020. There are also a few events observed during March and June with annual frequencies of 0.9 and 0.4 respectively. No squall has been reported in other months of the year during the study period. The annual frequency of squalls during this period is found to

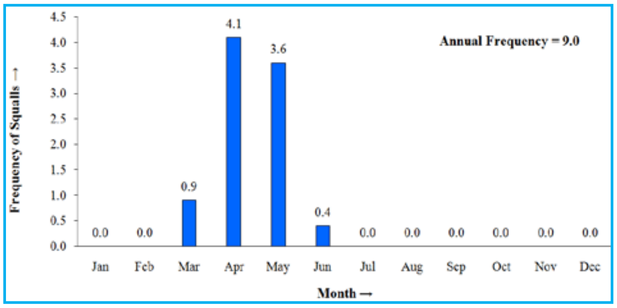



**Fig. 1.** Frequency of occurrence of squalls in different months (2011-2020)

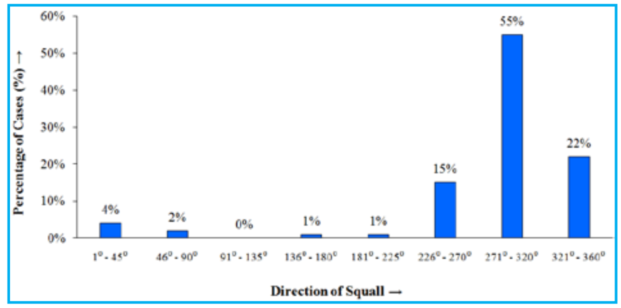



**Fig. 3.** Percentage of cases with wind direction associated with the squall in different ranges (2011-2020)

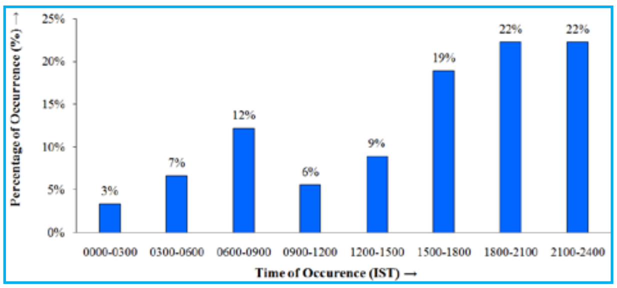



**Fig. 2.** Percentage of occurrence of squalls at every three hours interval (2011-2020)

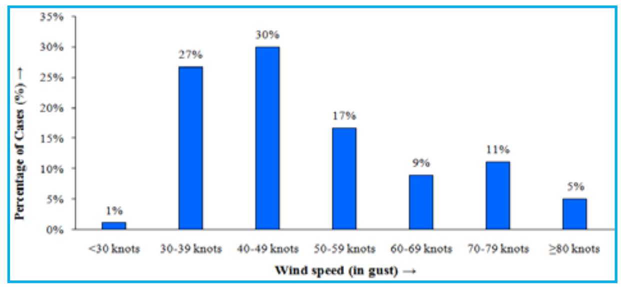



**Fig. 4.** Percentage of squalls with maximum wind speed (in gust) reaching up to different ranges (2011-2020)

be 9.0, which is higher than the long period average of 1981-2010 (8.1 per year). Fig. 2. shows that the diurnal variation of the squalls at Agartala based on its time of occurrence. It indicates that the number of squalls is highest during 1800 - 2100 IST and 2100 - 2400 IST, with 22% of those occurring in both the periods. The period of the day during 1500 - 1800 IST has also recorded 19% of the events. 12% of the events have also been observed during morning hours between 0600 - 0900 IST. Biswas and Biswas (1975) also found the high percentage of occurrence of squalls during evening at Agartala, with about 35% of those occurring during 1600 - 1900 IST. Percentages of events during remaining period of the days are comparatively less. The least numbers of squalls are observed during 0000 - 0300 IST, with only 3% of the total cases. In view of the peaks during 1800 - 2100 IST and 2100 - 2400 IST, the analysis has been separately done for squalls during these two periods also.

Fig. 3. shows that 54% of the squalls during this period have associated wind direction from westerly to north-westerly (271° - 320°) direction and 22% of them have from north-westerly to northerly (321° - 360°) direction. On 14% of the cases, associated wind direction is from south-westerly to westerly (226° - 270°) direction. There are very few cases where wind direction during the squalls is from other directions. Similar feature of squalls was found for another city, Guwahati over the northeast India by Kumar & Mohapatra (2006), with most of the squalls from north-westerly (60%) direction followed by westerly (15%) and south-westerly (11%) directions. The high-speed winds associated with the squalls are a matter of serious concern, as it causes serious damage to life and property. Fig. 4. shows the various ranges of wind speed associated during the squalls. 99% of the squalls observed during the period have wind speed reaching 30 knots or more. The highest percentage of cases (30%) were observed with maximum gusty wind reaching up to 40-49 knots. But there are also some events (5%) of wind speed reaching as high as ≥80 knots.

### 3.2. *Favourable synoptic conditions for occurrence of squalls at Agartala*

The development of thunderstorms is greatly governed by the overall synoptic scale disturbances. It isthe synoptic scale disturbances which create the conditions favourable for the out-break of thunderstorms (Srinivasan *et al.*, 1973). They found that, a low pressure area / a trough of low pressure or a cyclonic circulation in the lower levels over Bihar, West Bengal and Bangladesh is a favourable synoptic situation for occurrence of thunderstorms over northeast India. A well-marked east-west oriented discontinuity between easterlies over Sub-Himalayan West Bengal and Assam and southerlies or southwesterlies to the south, low level jet over Gangetic

**TABLE 2**

**Number of events (squalls) associated with five different synoptic conditions**

| Synoptic condition | Percentage of squalls associated during the synoptic conditions, occurred during | | |
|---|---|---|---|
| | Whole 24 hours of the day | 1800 - 2100 IST | 2100 - 2400 IST |
| (i) | 64% | 70% | 60% |
| (ii) | 43% | 15% | 30% |
| (iii) | 36% | 30% | 40% |
| (iv) | 32% | 20% | 50% |
| (v) | 11% | 20% | 10% |

**TABLE 3 (a)**

**Mean, Median and Standard Deviation of the indices associated with squalls at Agartala**

| | SHOW (°C) | LI (°C) | SWEAT | KINX (°C) | TTI (°C) | CAPE (J/kg) |
|---|---|---|---|---|---|---|
| Mean | -0.92 | -2.61 | 280.42 | 32.32 | 47.26 | 965.57 |
| Median | -0.95 | -2.65 | 259.40 | 33.24 | 46.70 | 828.15 |
| Standard Deviation | 2.95 | 4.03 | 106.95 | 5.86 | 4.33 | 984.33 |

**TABLE 3 (b)**

**Mean, Median and Standard Deviation of the indices associated with squalls occurring during 1800-2100 IST at Agartala**

| | SHOW (°C) | LI (°C) | SWEAT | KINX (°C) | TTI (°C) | CAPE (J/kg) |
|---|---|---|---|---|---|---|
| Mean | -1.07 | -4.40 | 283.66 | 32.54 | 48.22 | 1294.32 |
| Median | -1.29 | -4.61 | 255.40 | 33.90 | 48.40 | 1389.00 |
| Standard Deviation | 2.67 | 4.34 | 111.19 | 5.36 | 4.52 | 1008.40 |

**TABLE 3 (c)**

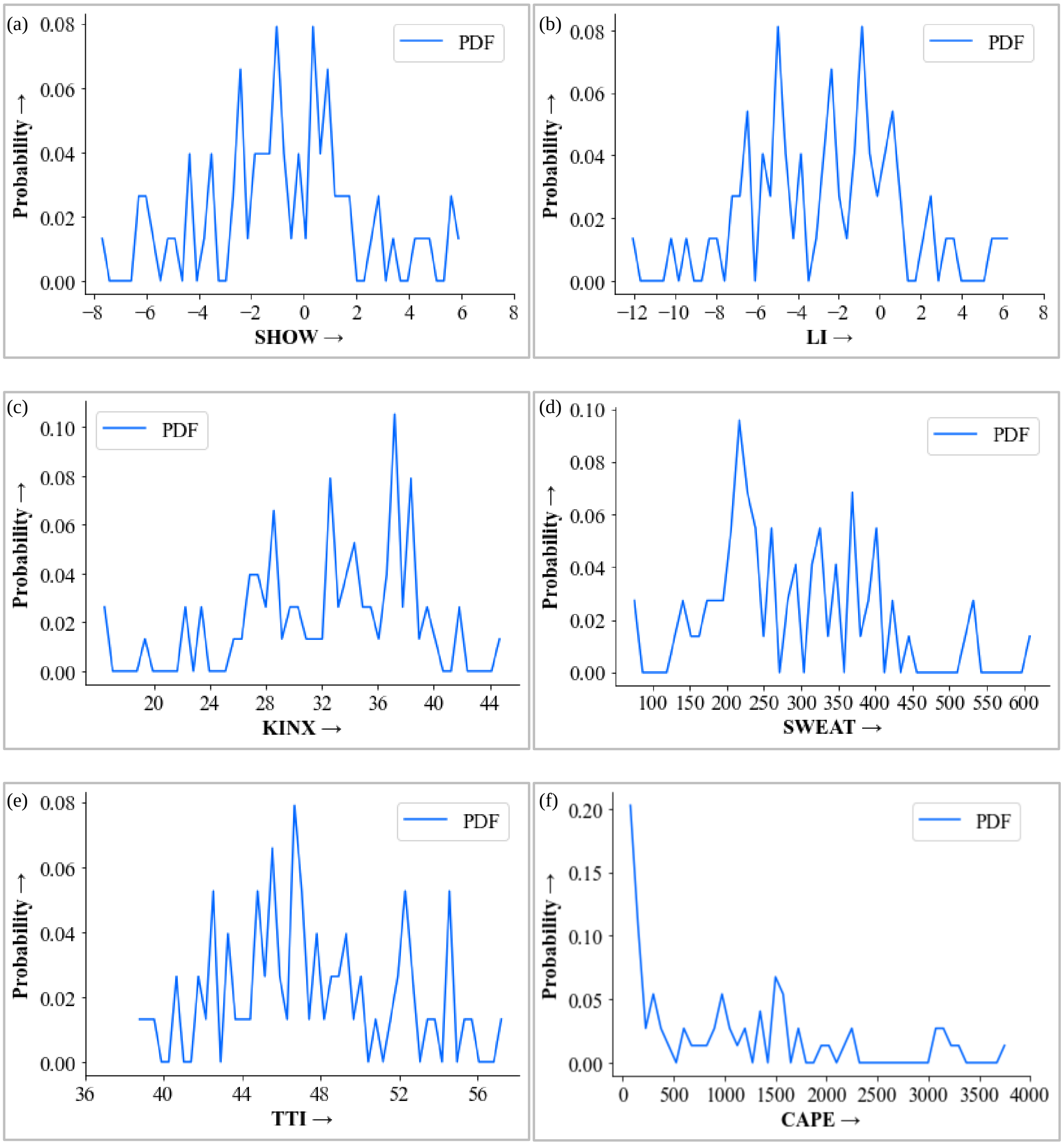
**Mean, Median and Standard Deviation of the indices associated with squalls occurring during 2100-2400 IST at Agartala**

| | SHOW (°C) | LI (°C) | SWEAT | KINX (°C) | TTI (°C) | CAPE (J/kg) |
|---|---|---|---|---|---|---|
| Mean | -0.88 | -2.80 | 274.31 | 33.56 | 46.98 | 888.31 |
| Median | -0.78 | -2.32 | 241.00 | 32.90 | 46.80 | 623.40 |
| Standard Deviation | 1.58 | 2.13 | 68.82 | 4.15 | 2.72 | 866.09 |

West Bengal and Bangladesh and an eastward moving trough in the westerly flow over the middle latitudes are also found to be favourable for thunderstorms over the region.

The synoptic conditions associated with squalls at Agartala during 2011-2020 have been analysed in the present study. It has been found that there are five primary synoptic conditions associated with the squalls.

(*i*) A cyclonic circulation at lower tropospheric levels over Bihar/Jharkhand/East Uttar Pradesh/Sub-Himalayan West Bengal/Gangetic West Bengal or Bangladesh.




**Figs. 5(a-f).** Probability distribution of (a) SHOW (b) LI (c) KINX (d) SWEAT (e) TTI and (f) CAPE during the days of occurrence of squall

(*ii*) A north-south oriented trough (sometimes northeast-southwest or northwest-southeast oriented) at lower tropospheric levels over east India.

(*iii*) An upper air cyclonic circulation at lower tropospheric levels over Assam-Meghalaya or Nagaland-Manipur-Mizoram-Tripura (NMMT).

(*iv*) An east-west oriented trough extending upto northeast India or Sub-Himalayan/Gangetic West Bengal at surface or at lower tropospheric level.

(*v*) A north-south oriented trough at mid tropospheric level over east or northeast India, moving eastwards.

Table 2 suggests that the highest number of squalls at Agartala (64% of the cases) are associated with a cyclonic circulation at lower tropospheric levels over Bihar/Jharkhand/East Uttar Pradesh/Sub-Himalayan West Bengal/Gangetic West Bengal or Bangladesh. The association of this synoptic situation is higher with the events occurred during 1800 - 2100 IST (70% of the cases). Other important synoptic conditions include a

**TABLE 4(a)**

**Frequencies of different ranges of Showalter Index (SHOW) associated with the squalls**

| Range of SHOW Index | Percentage of total events occurred during | | |
|---|---|---|---|
| | Whole 24 hours | 1800-2100 IST | 2100-2400 IST |
| >4 | 9% | 6% | 0% |
| 2 to 4 | 5% | 0% | 0% |
| 0 to 2 | 26% | 29% | 40% |
| -2 to 0 | 29% | 29% | 40% |
| -4 to -2 | 17% | 29% | 13% |
| <-4 | 14% | 6% | 7% |

**TABLE 4(b)**

**Frequencies of different ranges of Lifted Index (LI) associated with the squalls**

| Range of SHOW Index | Percentage of total events occurred during | | |
|---|---|---|---|
| | Whole 24 hours | 1800-2100 IST | 2100-2400 IST |
| >4 | 5% | 6% | 0% |
| 2 to 4 | 5% | 0% | 0% |
| 0 to 2 | 9% | 0% | 0% |
| -2 to 0 | 23% | 25% | 43% |
| -4 to -2 | 17% | 6% | 36% |
| <-4 | 39% | 63% | 21% |

**TABLE 4(c)**

**Frequencies of different ranges of K Index (KINX) associated with the squalls**

| Range of (KINX) Index | Percentage of total events occurred during | | |
|---|---|---|---|
| | Whole 24 hours | 1800-2100 IST | 2100-2400 IST |
| <20 | 5% | 6% | 0% |
| 20-24 | 5% | 0% | 0% |
| 24-28 | 15% | 18% | 7% |
| 28-32 | 15% | 12% | 20% |
| 32-36 | 26% | 29% | 40% |
| 36-40 | 30% | 35% | 27% |
| >40 | 4% | 0% | 7% |

**TABLE 4(d)**

**Frequencies of different ranges of SWEAT Index associated with the squalls**

| Range of SWEAT Index | Percentage of total events occurred during | | |
|---|---|---|---|
| | Whole 24 hours | 1800-2100 IST | 2100-2400 IST |
| <150 | 9% | 7% | 0% |
| 150-200 | 9% | 13% | 7% |
| 200-250 | 28% | 27% | 47% |
| 250-300 | 12% | 13% | 7% |
| 300-350 | 15% | 7% | 20% |
| 350-400 | 16% | 27% | 20% |
| >400 | 9% | 7% | 0% |

**TABLE 4(e)**

**Frequencies of different ranges of Total Totals Index (TTI) associated with the squalls**

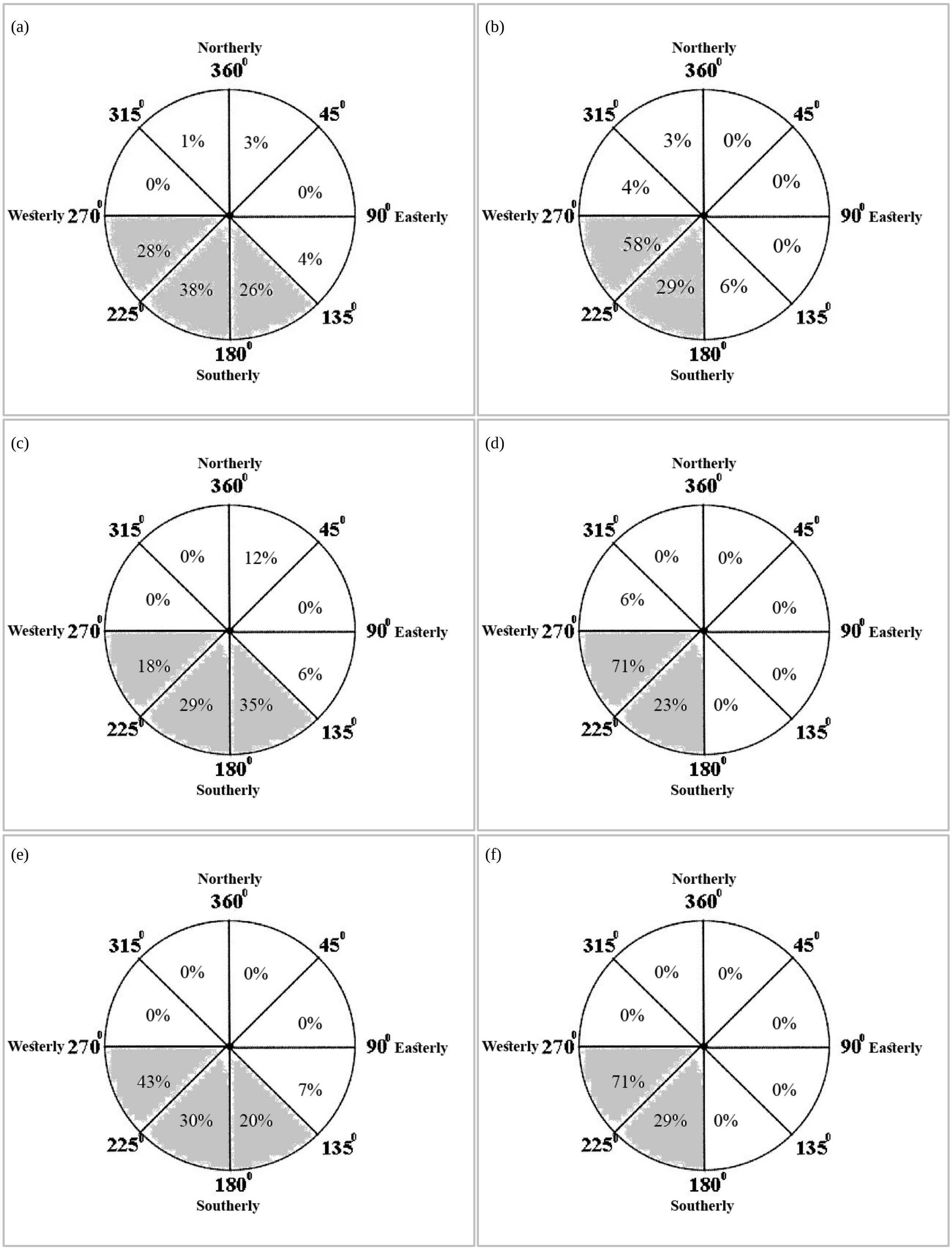
| Range of TTI Index | Percentage of total events occurred during | | |
|---|---|---|---|
| | Whole 24 hours | 1800-2100 IST | 2100-2400 IST |
| <40 | 5% | 6% | 0% |
| 40-44 | 15% | 6% | 13% |
| 44-48 | 40% | 35% | 53% |
| 48-52 | 21% | 29% | 20% |
| 52-56 | 18% | 24% | 13% |
| >56 | 1% | 0% | 0% |

**TABLE 4(f)**

**Frequencies of different ranges of CAPE associated with the squalls**

| Range of CAPE | Percentage of total events occurred during | | |
|---|---|---|---|
| | Whole 24 hours | 1800-2100 IST | 2100-2400 IST |
| <500 | 44% | 31% | 40% |
| 500-1000 | 15% | 0% | 33% |
| 1000-1500 | 17% | 25% | 13% |
| 1500-2000 | 11% | 31% | 0% |
| 2000-2500 | 4% | 0% | 7% |
| 2500-3000 | 0% | 0% | 0% |
| >3000 | 9% | 13% | 7% |

north-south oriented trough at lower tropospheric levels over east India and upper air cyclonic circulation at lower tropospheric levels over Assam-Meghalaya or Nagaland-Manipur-Mizoram-Tripura (NMMT), which accounts for 43% and 36% of the total cases respectively. However, the association of the north-south oriented trough at lower tropospheric levels is found to be comparatively lower with the events during 1800-2100 IST. An east-west




**Figs. 6(a-f).** Direction of wind (a) at 925 hPa (b) at 850 hPa during the days of squalls (c) at 925 hPa (d) at 850 hPa on the days when squall occurred during 1800-2100 IST (e) at 925 hPa and (f) at 850 hPa on the days when squall occurred during 2100-2400 IST at Agartala

**TABLE 5**

**Critical values obtained for different indices and wind direction**

| Index/Parameter | Threshold | Percentage of total cases | | |
|---|---|---|---|---|
| | | Whole 24 hours | 1800-2100 IST | 2100-2400 IST |
| Showalter Index | ≤ 2°C | 86% | 94% | 100% |
| Lifted Index | ≤ 0°C | 81% | 94% | 100% |
| K Index | ≥ 24°C | 90% | 94% | 100% |
| SWEAT Index | ≥ 200 | 82% | 80% | 93% |
| Total Totals Index | ≥ 44°C | 80% | 88% | 87% |
| Wind Direction at 925 hPa | 135° - 270° | 92% | 82% | 93% |
| Wind Direction at 850 hPa | 180° - 270° | 87% | 94% | 100% |

oriented trough extending upto northeast India or Sub-Himalayan/Gangetic West Bengal at surface or at lower tropospheric level is also associated with 32% of the events during the period. This synoptic situation has been found to be associated with 50% of the squalls occurred during 2100 - 2400 IST. A north-south oriented trough at mid tropospheric level over east or northeast India is also a favourable synoptic condition for the occurrence of squall sat Agartala (11% of the events). There are cases when more than one synoptic condition was present simultaneously during the day of occurrence of the squall. It is found that in 38% of the cases only one out of the five favourable synoptic conditions was present, whereas in 43%, 13% and 6% of the cases two, three and four favourable conditions co-existed during the event.

### 3.3. *Important atmospheric indices associated with squalls at Agartala*

The stability indices derived from the 0000 UTC RS/RW ascent at Agartala have been studied for the days of occurrence of squalls. The mean, median and standard deviation of the indices are shown in Tables 3(a-c). The mean and median values are close to the values proposed for occurrence of thunderstorms in earlier studies.

The probability distribution of the indices during the days when one or more squalls have been observed at Agartala are shown in Figs. 5(a-f). Tables 4(a-f) show the percentage of squalls observed at Agartala during 2011-2020 associated with different ranges of Showalter Index (SHOW), Lifted Index (LI), K Index (KINX), Severe Weather Threat Index (SWEAT), Total Totals Index (TTI) and Convective Available Potential Energy (CAPE). Table 4(a) suggests that 86% of the events during the period of study have occurred when the value of Showalter Index is ≤ 2 °C. After that, there is a sharp decline in percentage of cases in the next range (from 26% in range 2-4 °C to 5% in range 0 to 2 °C). For the events occurred during 1800 - 2100 and 2100 - 2400 IST, it is found that 94% and 100% of the events were associated with the same range of Showalter Index. Similarly, Lifted Index value of ≤ 0 °C is associated with 81% of the events (94% of the events during 1800 - 2100 IST and 100% of the events during 2100 - 2400 IST) [Table 4(b)]. The values of K Index, SWEAT Index and Total Totals Index of ≥ 24 °C, ≥200 and ≥44 are associated with 90%, 82% and 80% of the squalls over Agartala respectively [Tables 4(c-e)]. Theoretically, a higher value of CAPE is more favourable for occurrence of thunderstorms (also squalls). However, in this study it is seen that CAPE values of lower than 1500 J/Kg are associated with 76% of the squalls at Agartala, with highest number of events in the range < 500 J/Kg (44%). Hence, CAPE is not found to be a suitable indicator for occurrence of squalls at Agartala during the period of study. Only for the squalls that occurred during 1800 - 2100 IST CAPE > 1000 J/Kg is found be associated with 69% of the cases.

### 3.4. *Importance of lower level winds for occurrence of squalls*

The lower level winds play an important role in occurrence of thunderstorms and related phenomena, as it works as a moisture feeder for those events. The Bay of Bengal located towards the south of Agartala acts as a huge source of moisture for the region. Hence, southerly winds at lower levels over the region works significantly as moisture feeding agent for occurrence of thunderstorm events, including squalls. Pradhan *et al*. (2012) also found that, if the wind direction at lower levels (up to 0.9 km) is either Southerly or South-Easterly then moisture incursion takes place over the eastern Indian region from Bay of Bengal and the chances of formation of thunderstorm are

**TABLE 6**

**Number of squalls in 2009 and 2010 associated with five different synoptic conditions (*numbers as defined in section 3.2*)**

| Synoptic condition | Number of squalls associated | Percentage of total |
|---|---|---|
| (i) | 8 | 89% |
| (ii) | 2 | 22% |
| (iii) | 3 | 33% |
| (iv) | 1 | 11% |
| (v) | 2 | 22% |

**TABLE7**

**Ranges of different indices and wind direction for the squalls during 2009 and 2010**

| Index/Parameter | Ranges | Percentage of cases in range defined in Table 5 |
|---|---|---|
| Showalter Index (°C) | -8.0 to 0.7 | 100% |
| Lifted Index (°C) | -11.2 to -1.4 | 100% |
| K Index (°C) | 28.2 to 43.0 | 100% |
| SWEAT Index | 220 to 590 | 100% |
| Total Totals Index (°C) | 41.5 to 59.6 | 89% |
| Wind Direction at 925 hPa | 135° - 250° | 100% |
| Wind Direction at 850 hPa | 015° - 270° | 89% |

very high. Fig. 6. shows percentage of days with wind direction at (a) 925 hPa and (b) 850 hPa obtained from 0000 UTC RS/RW accents at Agartala on the days of occurrence of the squalls in eight-point compass. Figs. 6(c-f) shows their respective values for the days when squalls have occurred during 1800 - 2100 and 2100 - 2400 IST. Fig. 6(a) indicates that 92% of the total cases have wind direction in the range 135° - 270° (southeasterly to westerly) at 925 hPa level. Similarly, 87% of the total cases have wind direction in the range $180^0$ - 270° (southerly to westerly) at 850 hPa level as seen in Fig. 6(b). Similarly, for the squalls occurred during 1800 - 2100 IST, wind directions at 925 hPa and 850 hPa in the same ranges are found to be associated with 82% and 94% of the cases [Figs. 6(c&d)]. There corresponding values for the squalls during 2100 - 2400 IST are found to be 93% and 100% respectively [Figs. 6(e&f)]. The higher percentage of winds from 225° - 270° and very few cases in 135° - 180° at 850 hPa level, as compared to 925 hPa level also indicates veering of winds with height, which is another favourable situation for occurrence of thunderstorms. In 67% of the cases, clockwise turning of winds with height, *i.e*., veering has been observed in this study.

Hence, if we define the critical values of the indices, based onat least 80% of the total number of cases with a decrease of at least 10% in the next range as shown in Tables 4(a-f) and at least 80% of the total number of cases for wind direction we obtain the values as given in Table 5. It has been observed that the squalls during 2100 - 2400 IST has higher association in terms of SHOW, LI, KINX and SWEAT in the defined ranges than those during 1800 - 2100 IST.

3.5. *Validation of predictions*

In order to validate the association of synoptic conditions and the obtained thresholds for an independent data set, the squalls observed at Agartala during the years 2009 and 2010 have been considered (nine squalls). The synoptic conditions and the stability indices associated with those squalls have been studied. The number and percentage of squalls in the two years associated with different synoptic conditions have been shown in Table 6. As seen in Table 2, a cyclonic circulation at lower tropospheric levels over Bihar/Jharkhand/East Uttar Pradesh/Sub-Himalayan West Bengal/Gangetic West Bengal or Bangladesh is the most favourable synoptic condition for occurrence of squalls at Agartala. The same has been observed for the squalls in 2009 and 2010 also, with this system being favourable to eight out of those nine events (89% of the cases). The contributions of other synoptic conditions defined in section 3.2, have also been found with the systems in those two years. The systems include, an upper air cyclonic circulation at lower tropospheric levels over Assam-Meghalaya or NMMT (three events); north-south oriented trough lower tropospheric levels over east India and a north-south oriented trough at mid tropospheric level over east or northeast India (in two events each); an east-west oriented trough extending upto northeast India or Sub-Himalayan/Gangetic West Bengal at surface or at lower tropospheric level (in one event). The ranges of various indices and wind direction associated with the events have been shown in Table 7. It has been observed that most of the indices satisfy the defined range of threshold for the squalls observed in the two years. In only one out of the nine events, the Total Totals Index and the Wind Direction at 850 hPa do not fall in the defined range, however all other parameters are within the defined range. Hence, it indicates that even if some indices or parameters do not satisfy the values in the critical range, still there are chances of squalls when the synoptic conditions are favourable and most of the other indices satisfy the criteria.

## 4. Conclusions

Thunderstorms and its associated weather phenomena cause a lot of casualties all across the world. The north-eastern region of India is one of the most prone areas for occurrence of thunderstorms. Some of those thunderstorms are accompanied with devastating squalls. The high-speed wind associated with the squalls often causes serious damage in the region. Falling of branches of trees, or sometimes the whole tree, electric poles etc. causes threat to life, damages houses, blocks roads, disrupts electricity and communication. Agartala, the capital of the state Tripura, also records quite a good number of squalls every year. They generally start in March and most of them occur in April and May. But some events are also observed during June. Considering the damage caused by the squalls in the region, an early warning of such events is very important. In the present study, a synoptic and thermodynamic analysis of the squalls occurring in Agartala during the ten years period of 2011-2020 has been done. The following conclusions can be drawn from this study:

(*i*) The annual mean number of squalls during this period (9.0) is found to be higher than the climatological mean of 1981-2010. 63% of the total squalls occurred during afternoon, evening and late night (1500 - 2400 IST). The associated wind direction in the squall is westerly to north-westerly in 55% of the total events. In most of the cases, the wind speed in the squall is in the range 40-49 knots, but there are events with wind speed as high as ≥80 knots also. In view of the two peaks during 1800 - 2100 IST and 2100 - 2400 IST, all the analysis have been performed separately for the events occurring in those two time periods of the day.

(*ii*) The synoptic analysis suggests that a cyclonic circulation at lower tropospheric levels over Bihar/Jharkhand/East Uttar Pradesh/Sub-Himalayan West Bengal/Gangetic West Bengal or Bangladesh is the most favourable synoptic condition for occurrence of squall over Agartala, which is associated with 64% of the total squalls during the period. Other important synoptic conditions include a north-south oriented trough at lower tropospheric levels over east India, an upper air cyclonic circulation at lower tropospheric levels over Assam-Meghalaya or Nagaland-Manipur-Mizoram-Tripura, an east-west oriented trough extending upto northeast India or Sub-Himalayan/Gangetic West Bengal at surface or at lower tropospheric level and a north-south oriented trough at mid tropospheric level over east or northeast India.

(*iii*) The stability indices derived from 0000 UTC RS/RW ascents have been analysed and their critical values have been obtained based on their association with at least 80% of the cases. The critical values for Showalter Index (SHOW) ≤ 2 °C, Lifted Index (LI) ≤ 0 °C, K Index (KINX) ≥ 24°C, SWEAT Index ≥ 200 and Total Totals Index ≥ 44°C have been found suitable.

(*iv*) The lower level winds act as moisture feeding winds for the region, which incurs moisture from the Bay of Bengal located to its south. The winds at 925 hPa and 850 hPa have been analysed and found that in 92% of the cases the wind direction at 925 hPa is 135° - 270° and in 87% cases the wind direction at 850 hPa is 180° - 270°. This indicates that low level winds with southerly component has an important role in occurrence of squalls at Agartala.

These results may be helpful in forecasting the squalls over Agartala and dissemination of early warning to the public and disaster managers.

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