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Cumulonimbus cloud with anvil over India : Synoptic cloud type observations 1970-2000

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सार – इस शोध–पत्र में भारत में निहाई वाले कपासी वर्षी मेघों की घटना की आवृत्तियों के प्रेक्षणात्मक पहलुओं के लक्षणों को प्रस्तुत किया गया है। इस कार्य के लिए भारत मौसम विज्ञान विभाग की समान रूप से वितरित 101 श्रेणी–I सतही वेधशालाओं से 1970–2000 तक की अवधि के मानसून पूर्व महीनों के सिनॉप्टिक मेघ प्रकार के प्रेक्षणों को लिया गया है।

इनसे प्राप्त हुए परिणामों से निहाई वाले कपासीवर्षी मेघों की संरचना में प्रतिदिन मेघ के क्षेत्रों में बढ़ोतरी की प्रवृति और सुबह तड़के के समय उनमें भारी कमी का पता चलता है। निहाई वाले कपासीवर्षी मेघों के स्थानिक विकास से 0900 यू. टी. सी. से 2100 यू. टी. सी. तक की अवधि के दौरान संवहनीय मेघ गतिविधि की चरम सीमा 1200 यू. टी. सी. पर होती है। इस अध्ययन से गर्ज के साथ तूफान आने के चरम मई के महीने में कालिक और स्थानिक लक्षण वाले कपासवर्षी मेघों की पाँच पट्टियों का पता चला है। पहली पट्टी भारत के पश्चिमी तट के साथ दक्षिण प्रायद्वीप के क्षेत्रों केरल, तमिलनाडु और पुद्दुचेरी, दक्षिणी अंदरूनी कर्नाटक, तटीय कर्नाटक, उत्तरी अंदरूनी कर्नाटक के भागों कोंकण और गोवा, मध्य महाराष्ट्र तथा पश्चिम मध्य प्रदेश (3–10 दिन) तक फैली है। दक्षिणी अंदरूनी कर्नाटक और समीपवर्ती केरल तथा तमिलनाडु में निहाई वाले कपासीवर्षी मेघ लगभग 10 दिनों तक रिपोर्ट किए गए। दूसरी पट्टी में हिमाचल प्रदेश और समीपवर्ती जम्मू और कश्मीर, उत्तराखंड और समीपवर्ती पश्चिम उत्तर प्रदेश आते है। तीसरी पट्टी में छत्तीसगढ़ और समीपवर्ती विदर्भ, ओड़ीशा, गांगेय पश्चिमी बंगाल और झारखंड और बिहार के समीपवर्ती क्षेत्र आते हैं। चौथी पट्टी में उपहिमालयी पश्चिम बंगाल, असम और मेघालय, गुवाहाटी और शिलांग आते हैं। पांचवी पट्टी में त्रिपुरा और समीपवर्ती मिजोरम के क्षेत्र आते हैं। शेष उत्तरपूर्वी भारत में 1–3 दिनों तक की औसत से निहाई वाले कपासीवर्षी मेघों का पता चला है। दक्षिण बिहार और समीपवर्ती झारखंड़ तथा गांगेय पश्चिम बंगाल के क्षेत्र में 5 से 7 दिनों की औसत से निहाई वाले कपासीवर्षी मेघों का पता चला है।

ABSTRACT. The features of observational aspects of frequencies of occurrence of Cb clouds with anvil over India have been presented. Synoptic cloud type observations for 101 uniformly distributed Class I surface observatories of India Meteorological Department for pre-monsoon months for period 1970-2000 is taken.

The results reveal that the formation of Cb clouds with anvil exhibit the diurnal tendency of growth of cloud areas and show drastic decrease in the early morning hours. The temporal evolution of Cb clouds with anvil show that during the period from 0900 UTC to 2100 UTC, the maximum peak of convective cloud activity occur at 1200 UTC. This study has brought forth five prominent belts of Cb clouds prevalence showing both temporal and spatial characteristics during the month of May which is the month of peak thunderstorm activity. The first belt extends from South peninsula along West Coast of India covering regions of Kerala, Tamil Nadu and Puducherry, South Interior Karnataka, Coastal Karnataka, parts of North Interior Karnataka, Konkan and Goa, Madhya Maharashtra and West Madhya Pradesh (3 to 10 days). The region South Interior Karnataka and adjoining Kerala and Tamil Nadu has reported Cb clouds with anvil to be about 10 days. The second belt comprises Himachal Pradesh and adjoining Jammu & Kashmir, Uttarakhand and adjoining West UP. The third belt covers spatial areas of Chhattisgarh and adjoining Vidharbha, Orissa, Gangetic West Bengal and adjoining areas of Jharkhand and Bihar. The fourth belt is SHWB, Assam and Meghalaya covering Guwahati and Shillong. The fifth belt comprises regions of Tripura and adjoining Mizoram. The rest of Northeast India report Cb clouds with anvil on the average of 1 to 3 days. The region South Bihar and adjoining Jharkhand and Gangetic West Bengal report Cb clouds with anvil on the average of 5 to 7 days.

Key words – Cumulonimbus (Cb), Anvil, Convective clouds.

1. Introduction

Cloud is an aggregate of very small water droplets, ice crystals or a mixture of both, with its base above the earth's surface (McIntosh, 1975). Cloud genera is classified into ten basic characteristic forms or types comprising Cirrus (Ci), Cirrocumulus (Cc), Cirrostratus (Cs), Altocumulus (Ac), Altostratus (As), Nimbostratus (Ns), Stratocumulus (Sc), Stratus (St), Cumulus (Cu) and Cumulonimbus (Cb). Clouds affect solar radiation, terrestrial radiation and precipitation. Hence, clouds are considered very important component in the Earth's Climate System. A Cumulonimbus cloud is generally thick (many kilometres), with a base near earth's surface and a top frequently reaching an altitude of 10 km (33,000 feet) and sometimes much higher. Generally, due to high and cold cloud tops of Cb, the energy radiated to outer space is lower than it would be without the cloud (the cloud greenhouse forcing is very large). But as they are also thick, they reflect much of the solar energy back to space (their cloud albedo forcing is also large). As a consequence, overall, the cloud greenhouse and albedo forcings almost balance and the overall effect of Cumulonimbus clouds is neutral - neither warming nor cooling. But this observation is not correct for Asian Monsoon region. Rajeevan and Srinivasan (1999) have shown that the net cloud radiative forcing over the Asian monsoon region is large and negative by using the ERBE data for the period June-September during 1985- 88. They have concluded that the cloud-radiation feedback is negative in the deep convective regions of Asia during June-September. Their results also show that the cloud type 9 (Cirrostratus and Cumulonimbus, with mean optical depth 10, cloud albedo 0.6 and IR transmission 0.4%) makes the largest single contribution to the net cloud forcing. At large optical depths, the effect of cloud albedo exceeds the cloud greenhouse effect and hence these clouds cause large negative net cloud forcing. Deshpande (1975) has highlighted the data sparse status of Cb clouds in a tropical country like India. With little available data of height of Cb cloud tops, he studied characteristics of Cb clouds over the Bay of Bengal and found that the mean height of Cb tops is 38,300 feet in the pre-monsoon season. It is well known that the convective activity is more during the pre-monsoon season in India. The Deccan Plateau and adjoining plains of Andhra Pradesh and east Maharashtra have reported high frequency of height of Cb cloud tops (12 to 14 km and 15 km) during May due to seasonal low and wind discontinuity in radar study of Cb cloud (Thomas, 1973). Cb clouds produce most of the rainfall in the tropics during the summer months of March, April and May. It constitutes main components of thunderstorms, hailstorms, tornadoes and hurricanes (Houze, 1993). Norris (1998) reported the highest frequency of occurrence for Cb with anvil in the tropical regions with maximum surface convergence.

Rajeevan *et al*., (2001) studied the seasonal and annual cloud climatology of the Indian Ocean based on ship observations for summer monsoon and found that total cloud cover and low cloud cover over the Arabian Sea and the equatorial Indian Ocean are observed to decrease during El-Nino and Southern Oscillations (ENSO) events and cloud cover over Bay of Bengal is not modulated by the ENSO events. Warren and Eastman (2007) have done a comprehensive study of cloud cover and cloud types over land from surface observations. They examined trends and linked some trends to ENSO variations. Deep convective clouds in the atmosphere exist in a wide spectrum of time scales. Typical life cycle of Cb cloud is about half an hour to one hour and that of a thunderstorm is a few hours and average life cycle of larger Mesoscale convective systems (MCSs) is about 10 hours (Ludlam, 1980; Houze, 1993).

Weather observers generally report cloud observations which include form (type) of cloud and amount in okta. In addition they report height of base of lowest cloud and direction of movement for low, medium and high clouds. National Data Centre (NDC) of India Meteorological Department (IMD), Pune has been archiving the synoptic surface cloud type observations in 80 bytes IMD format (Daily surface TB3 format) and data is available from 1969 onwards. Synoptic surface cloud type observations are particulary useful for studying low cloudiness because human observers identify clouds by morphological type, which is qualtitatively related to the dynamical and thermodynamical environment in which the clouds occur (Houze 1993). Surface observers sometimes have difficulty in identifying clouds in dark nights (Hahn *et al*., 1995). This problem may occur for the detection of middle and high clouds but it may also effect the identification of low cloud type (Rozendaal *et al*., 1995). During night time, the Cumulonimbus clouds can be identified with the help of lightning seen in the sky. However, it is difficult for the observer to classify Cb clouds with anvil from Cumulonimbus clouds sometimes. According to World Meteorological Organisation (WMO) low cloud classification, Low cloud type 9 is Cumulonimbus, the upper part of which is clearly fibrous (cirriform), often in the form of anvil, either accompanied or not by Cumulonimbus without anvil or fibrous upper part, by Cumulus, Stratocumulus, Stratus or pannus. If enough atmospheric instability, moisture and lift are present, then strong updrafts can develop in the Cumulus cloud leading to a mature, deep Cumulonimbus cloud, *i.e.*, thunderstorm producing heavy rain. In addition, cloud electrification occurs within Cumulonimbus clouds due to many collisions between charged water droplet, graupel (ice-water mix), and ice crystal particles. This in turn results in lightning and thunder.

The authors are aware that though more literature is available on the convective activity during pre-monsoon season in India only few cases studies have been dealt with Cumulonimbus clouds separately (*e.g.*, Mathew & Kaimal 2001; Cornford, 1975; Puniah, 1973; Mukherjee and Chaudhary 1971; Mukherjee *et al*., 1972; Ray, 1971; Mazumdar, 1965; Kulshrestha, 1962 etc.). But study of occurrence of Cb clouds with anvil reported by weather observers over the surface observatories of IMD has not been studied. The Cb clouds with anvil produce thunderstorms, hailstorms, tornadoes and heavy precipitation during pre-monsoon season in India. Most of the rainfall we get in pre-monsoon season is through convective clouds namely Cumulonimbus. Intense thunderstorms are produced from Cb clouds with anvil and so they are very important for tropical country, like India. Cb clouds with or without anvil is source of convective rains during pre-monsoon season and are hazardous to aviation sector. Cumulonimbus with anvil clouds generally has cloud tops above 0 °C level. The precipitation formation processes will involve ice phase in addition to warm rain processes. The downdrafts can be initiated by water loading and cooling due to evaporation of cloud liquid or rain water and melting of the ice particles. Convective clouds are formed in vertical motions that result from the causative factors namely heating at the bottom of an air layer, cooling at the top of the air layer, lifting or saturation of a potentially unstable layer and a combination of all the above. Formation of convective clouds begins early if instability and relative humidity is large enough. Generally after reaching a maximum in the afternoon the cumulus activity decreases and finally the clouds dissolve in the late afternoon or early evening.

With this in mind, this paper highlights the features of climatological occurrence of Cb clouds with anvil over India. Such knowledge is important for planning and harvesting water resources, town planning, agriculture sector and aviation sector. In this study frequency of observations of Cb clouds with anvil reported at 8 synoptic hours for summer months of March, April and May for period 1970-2000 is taken. A total of 101 uniformly distributed class I surface observatories of IMD are selected. Cb clouds with reported amount of 1 okta over these observatories are also analyzed. The frequencies are investigated for finding out synoptic scale observational aspects of Cb clouds with anvil over India.

2. Data and methodology

The synoptic cloud type observations of Low cloud type 9 (Cb with anvil) with amount in oktas from daily surface synoptic hour data archived at NDC, Pune were used in the study of Cb clouds. The data retrieved is for 101 class I surface observatories selected for the present study for pre-monsoon months for the period 1970-2000. The frequencies of occurrence of Cb clouds with anvil over the stations during March to May at 8 synoptic hours (0000 UTC to 2100 UTC) were computed. With the purpose to study potential areas of commencement of development of Cb clouds a threshold value of cloud amount of 1 okta was selected and their frequencies over stations were also computed separately. We have adopted Cressman interpolation technique as suggested by Cressman (1959).

The technique interpolates station data to a user-defined latitude-longitude grid. Multiple passes are made through the grid at consecutively smaller radii of influence to increase precision. The radius of influence is defined as the maximum radius from a grid point to a station by which the observed station value may be weighted to estimate the value at the grid point. Stations beyond the radius of influence have no bearing on a grid point value. At each pass, a new value is calculated for each grid point based on its correction factor. This correction factor is determined by analyzing each station within the radius of influence. For each such station, an error is defined as the difference between the station value and a value arrived by interpolation from the grid to that station. A distance-weighted formula (shown below) is then applied to all such errors within the radius of influence of the grid point to arrive at a correction value for that grid point. The correction factors are applied to all grid points before the next pass is made. Observations nearest the grid point carry the most weight. As the distance increases, the observations carry less weight. The cressman function calculates the weights as follows:

$$W = (R^2 - r^2)/(R^2 + r^2)$$

Where,

R = influence radius and r = distance between the station and the grid point.

As the radius of influence is tightened, results become more representative of the observed data. The analysis value at each grid point is calculated as the analysis value from the previous pass added to the sum of the products of the calculated weights and the difference between the actual station value and the interpolated background value at the station, divided by the sum of the weights.

Here the indirect observation is number of occurrence of Cb clouds with anvil (*i.e.*, days with low

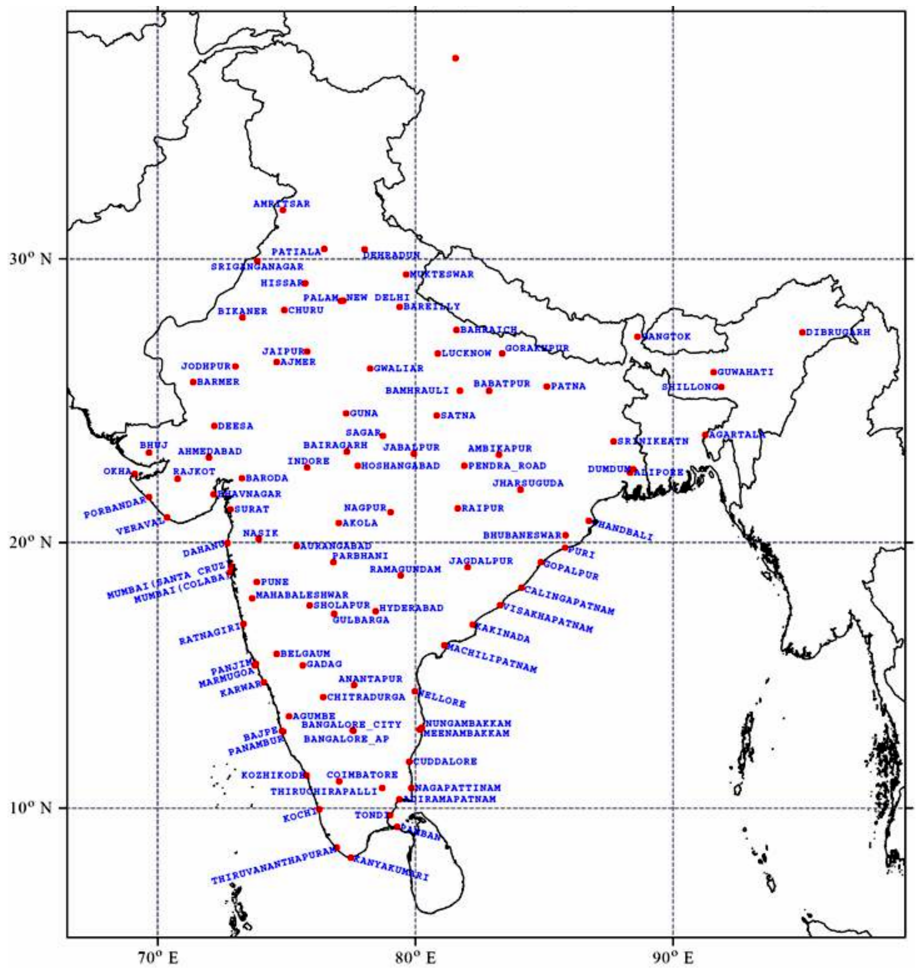


Fig. 1. List of class I observatories selected for study

cloud type 9) reported during the period 1970-2000. In the analysis, first guess is set in by Oacres in-built function in Grads. Oacres function sets the initial value of the analysis grid to the arithmetic average of the observation in the area. The Cress man interpolation technique explained above is referred from the Website http://ingrid.Ideo.columbia.edu/dochelp/StatTutorial/Interpolation/.

Two special cases of Cb cloud with anvil climatological data (during March to May) are considered:

(*i*) Day reporting Cb with anvil at synoptic observations with 1-8 okta cloud amount.

(*ii*) Day reporting Cb with anvil at synoptic observations with a threshold of 1 okta cloud amount.

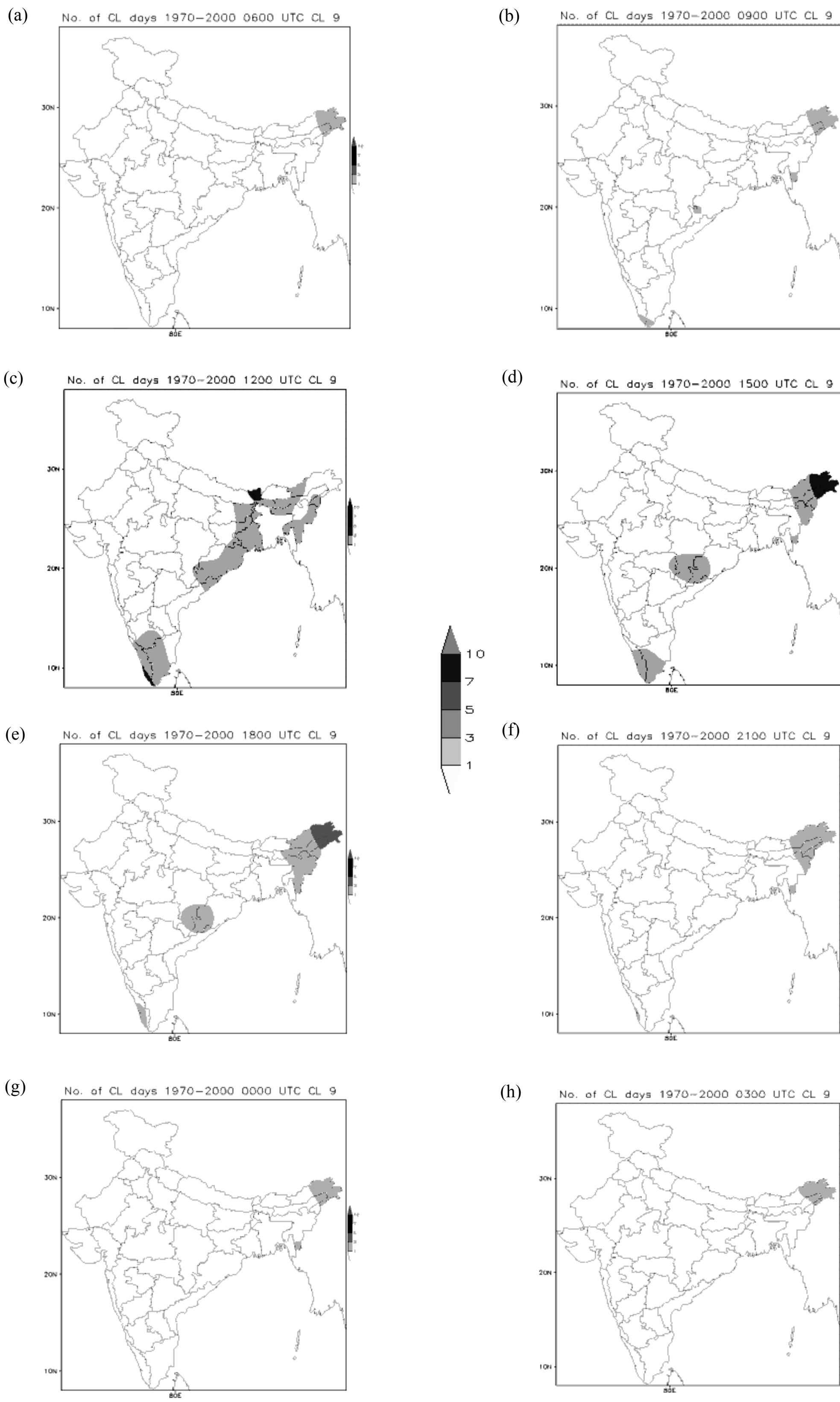
The threshold of 1 okta cloud amount is selected to capture the observational features of Cb cloud development in different areas over India. The features of observational aspects of Cb cloud with anvil investigated in case (*i*) are also presented. Fig. 1 depict the selected stations used for study of Cb clouds.

The plots of Average Number of CL day reporting CL = 9 (Cb cloud with anvil) with all 1-8 okta and of Number of CL day reporting CL = 9 (Cb with anvil) with 1 okta separately at 8 synoptic hours are generated and analysed.

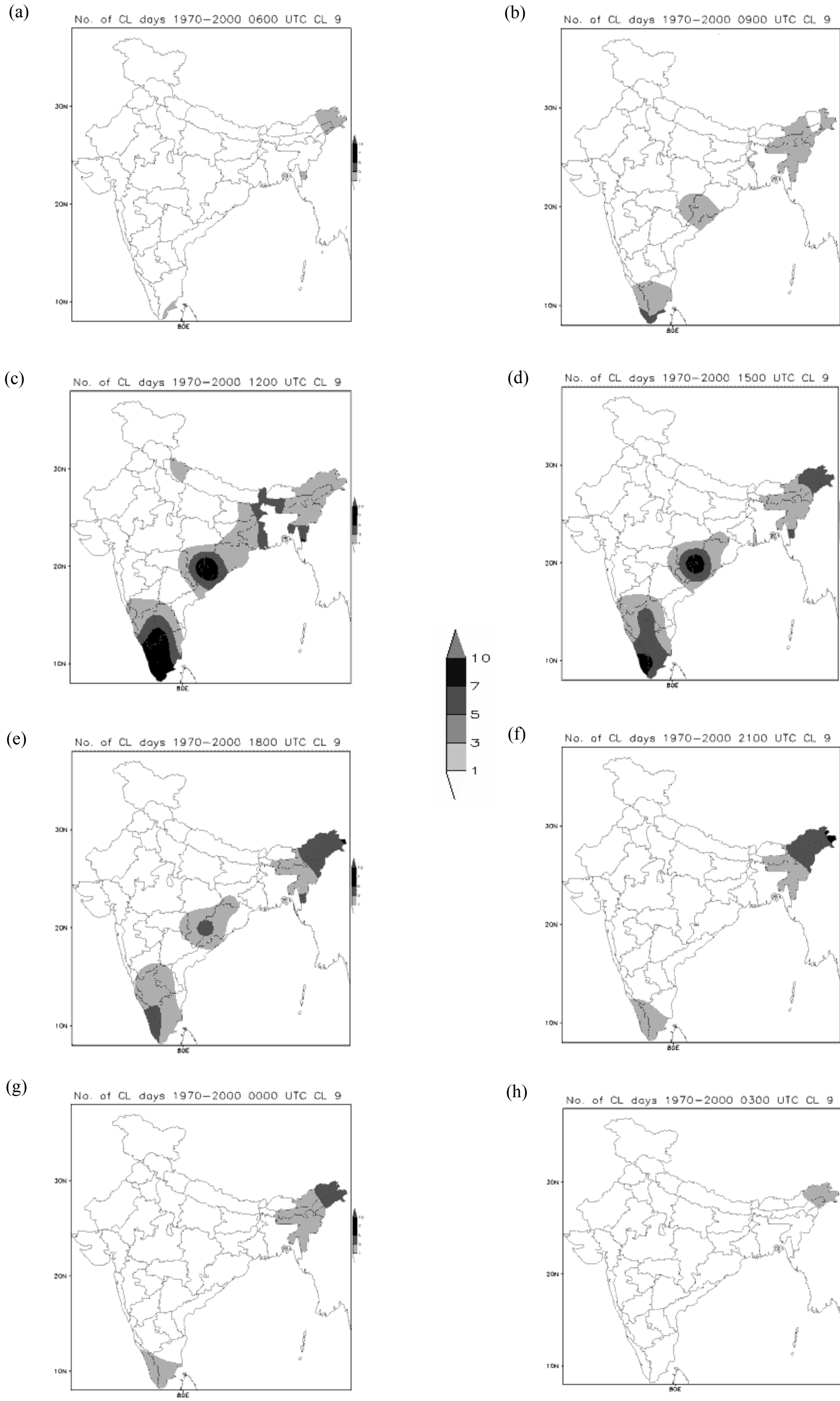
3. Results and discussion

3.1. Case (*i*) : *Cb with anvil with 1-8 okta cloud amount*

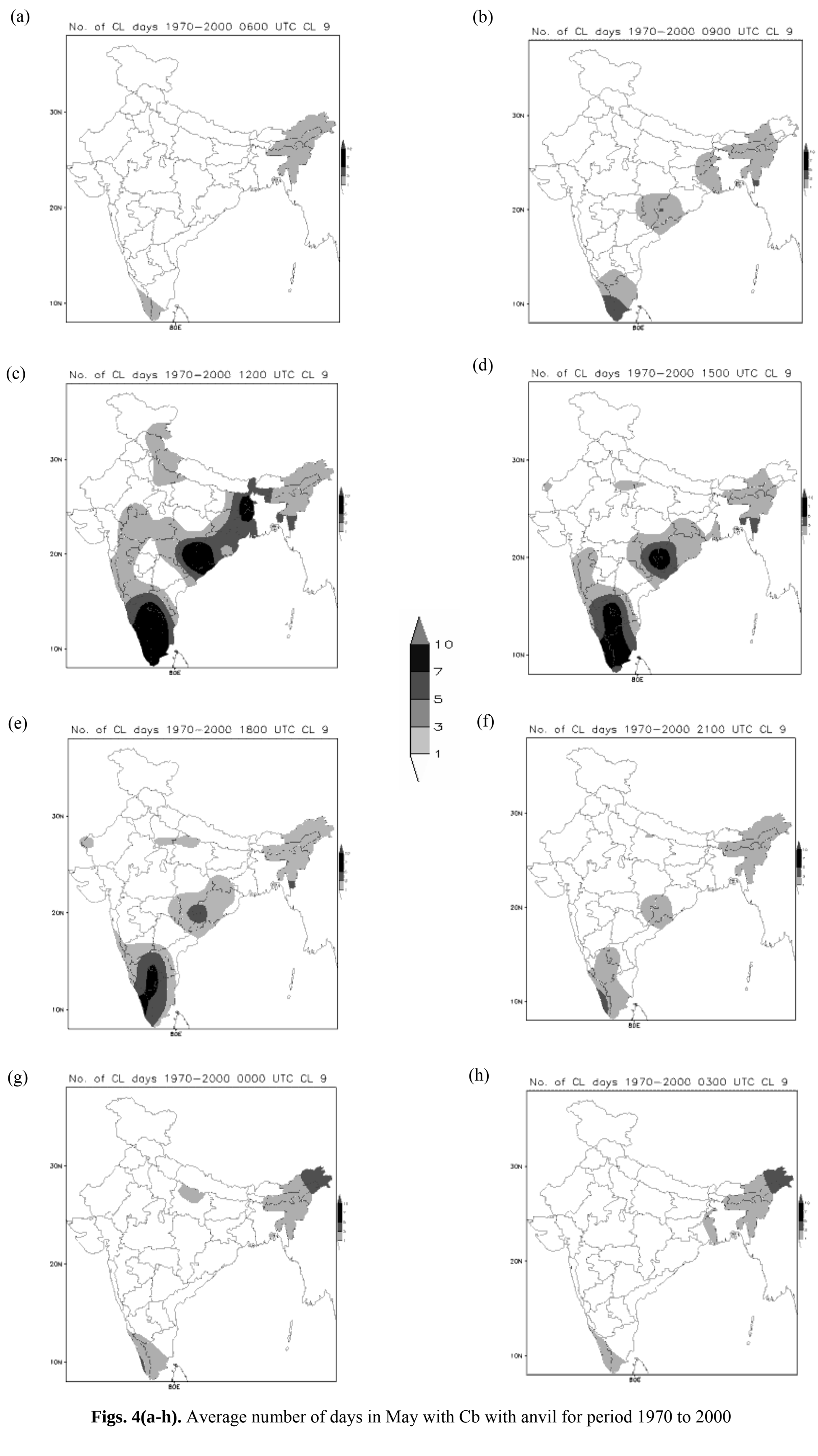
March to May monthly climatology of Cb cloud with anvil is presented in the following sections. For the representation of monthly climatology we have taken Average Number of CL days reporting CL = 9.



Figs. 2(a-h). Average number of days in March with Cb with anvil for period 1970 to 2000



Figs. 3(a-h). Average number of days in April with Cb with anvil for period 1970 to 2000



Figs. 4(a-h). Average number of days in May with Cb with anvil for period 1970 to 2000

3.1.1. *March*

Average Number of CL days reporting CL = 9 in March is shown in Figs. 2 (a-h). Fig. 2(a) shows the spatial coverage of occurrence of Cb clouds with anvil at 0600 UTC over the area of North Upper Assam and adjoining Arunachal Pradesh in the range of 3 to 5 days. Fig. 2(b) isolates extreme tip of Indian peninsula, namely, south Kerala and adjoining Tamil Nadu and Puducherry with Cb clouds with anvil prevalence in the range of 3 to 5 days at 0900 UTC. Also South Mizoram shows Cb clouds with anvil prevalence during this synoptic hour. Fig. 2(c) depicts the maximum peak of convective cloud activity at 1200 UTC. It represents frequent occurrence of Cb clouds over four areas of India. The first area is the belt comprising Southern Peninsula covering South Interior Karnataka and adjoining Rayalaseema, Kerala and Tamil Nadu and Puducherry (3 to 7 days), second - North Coastal Andhra Pradesh, Orissa, Gangetic West Bengal, Jharkhand and adjoining Bihar (3 to 5 days), third - areas of Northeast India particularly SHWB, Meghalaya, Lower Assam and adjoining Arunachal Pradesh (3 to 7 days), fourth - belt covering Tripura, Mizoram, Nagaland and Manipur (3 to 5 days). At 1500 UTC, in Fig. 2(d), the areas which have reported Cb clouds with anvil are Chhattisgarh and Orissa, Kerala and adjoining Tamil Nadu and Puducherry and Upper Assam and adjoining Arunachal Pradesh and Manipur, Mizoram of Northeast India. Northeast India has reported average number of Cb clouds with anvil in the range 3 to 7 days. Fig. 2(e) shows that the region of Kerala, Chhattisgarh and Orissa and Northeast India report Cb clouds with anvil at 1800 UTC. At 2100 UTC, we notice Cb cloud with anvil over Upper Assam and adjoining Arunachal Pradesh of Northeast India [Fig. 2(f)]. No significant changes are seen at 0000 UTC [Fig. 2(g)]. Only Northeast India (Upper Assam and Arunachal Pradesh) have reported Cb clouds with anvil in the range of 1 to 3 days [Fig. 2(h)].

3.1.2. *April*

During April, at 0900 UTC, the prominent areas where Cb clouds with anvil are reported are Southwest peninsula (Kerala and neighbourhood) (on average 3 to 7 days), region from Coastal Andhra Pradesh and adjoining Chhattisgarh (3 to 5 days), Northeast India (1 to 5 days) [Fig. 3(b)]. Fig. 3(c) shows that at 1200 UTC areas of Uttarakhand, Kerala (10 days), area from North Coastal Andhra Pradesh, Chhattisgarh and Orissa to SHWB (2 to 7 days), Northeast India (1 to 7 days), South Konkan and Goa (1 to 3 days) have reported occurrence of Cb with Anvil. Figs. 3(d-f) exhibit the spatial features of Cb Clouds with anvil as seen in Fig. 3(c). It is observed that there are three belts showing Cb clouds with anvil. The first belt extends from Southern tip of peninsula covering Konkan and Goa. The second belt comprises areas covering Chhattisgarh, Orissa. The third belt comprises SHWB and Northeast India. Figs. 3(g-h) only isolate the areas of South peninsula and Northeast India.

3.1.3. *May*

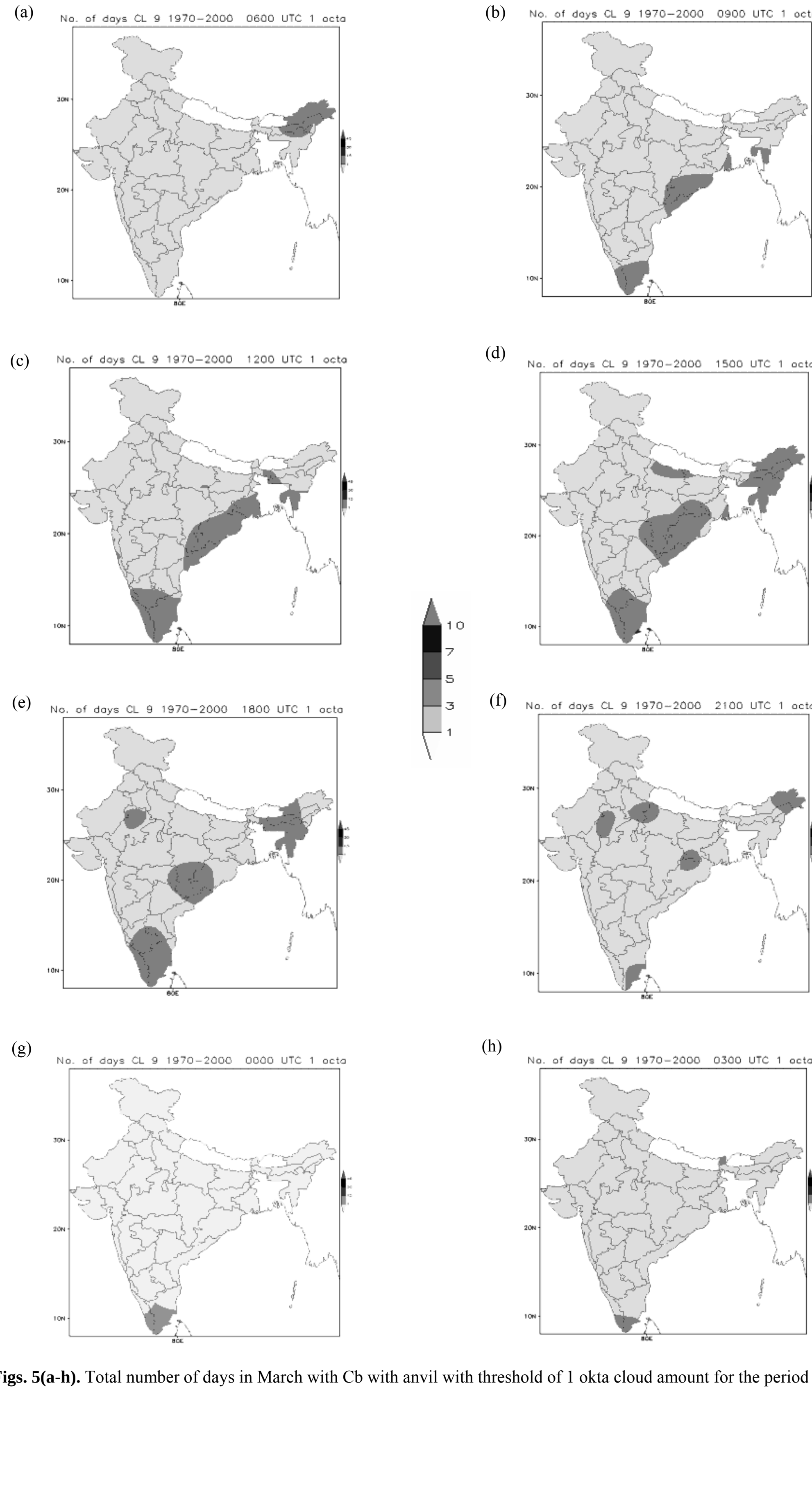
Average numbers of days with Cb clouds with anvil in May are shown in Figs. 4(a-h). Figs. 4(a&b) show the dominant areas of Cb clouds with anvil occurrence to be Kerala, Northeast India (Agartala and Mizoram, Assam and Meghalaya), area comprising Orissa and Chhattisgarh and Gangetic West Bengal and adjoining Jharkhand and South Bihar. Day temperatures are highest in May over most parts of India. It is observed from Fig. 4(c) that at 1200 UTC there are five distinct belts where Cb clouds with anvil occur frequently. The first belt extends from South peninsula along West Coast of India covering regions of Kerala, Tamil Nadu and Puducherry, South Interior Karnataka, Coastal Karnataka, parts of North Interior Karnataka, Konkan & Goa, Madhya Maharashtra and West Madhya Pradesh (3 to 10 days). The region South Interior Karnataka and adjoining Kerala and Tamil Nadu has reported Cb clouds with anvil to be about 10 days. The second belt comprises Himachal Pradesh and adjoining Jammu and Kashmir, Uttarakhand and adjoining West UP. The third belt covers spatial areas of Chhattisgarh and adjoining Vidharbha, Orissa, Gangetic West Bengal and adjoining areas of Jharkhand and Bihar. The fourth belt is SHWB, Assam and Meghalaya covering Guwahati and Shillong. The fifth belt comprises regions of Tripura and adjoining Mizoram. The rest of Northeast India report Cb clouds with anvil on the average of 1 to 3 days. The region South Bihar and adjoining Jharkhand and Gangetic West Bengal report Cb clouds with anvil on the average of 5 to 7 days. Figs. 4(d-f) show the frequent occurrence of Cb clouds with anvil is 3 to 7 days over India. Figs. 4(d-f) clearly show prevalence of Cb cloud with anvil over region of South Interior Karnataka and adjoining area of Rayalaseema. The Cb Cloud with anvil dissipates at 0000 UTC over this area and there is no occurrence of Cb cloud with anvil at 0300 UTC.

3.2. Case (*ii*) : *Cb clouds with anvil with threshold of 1 okta cloud amount*

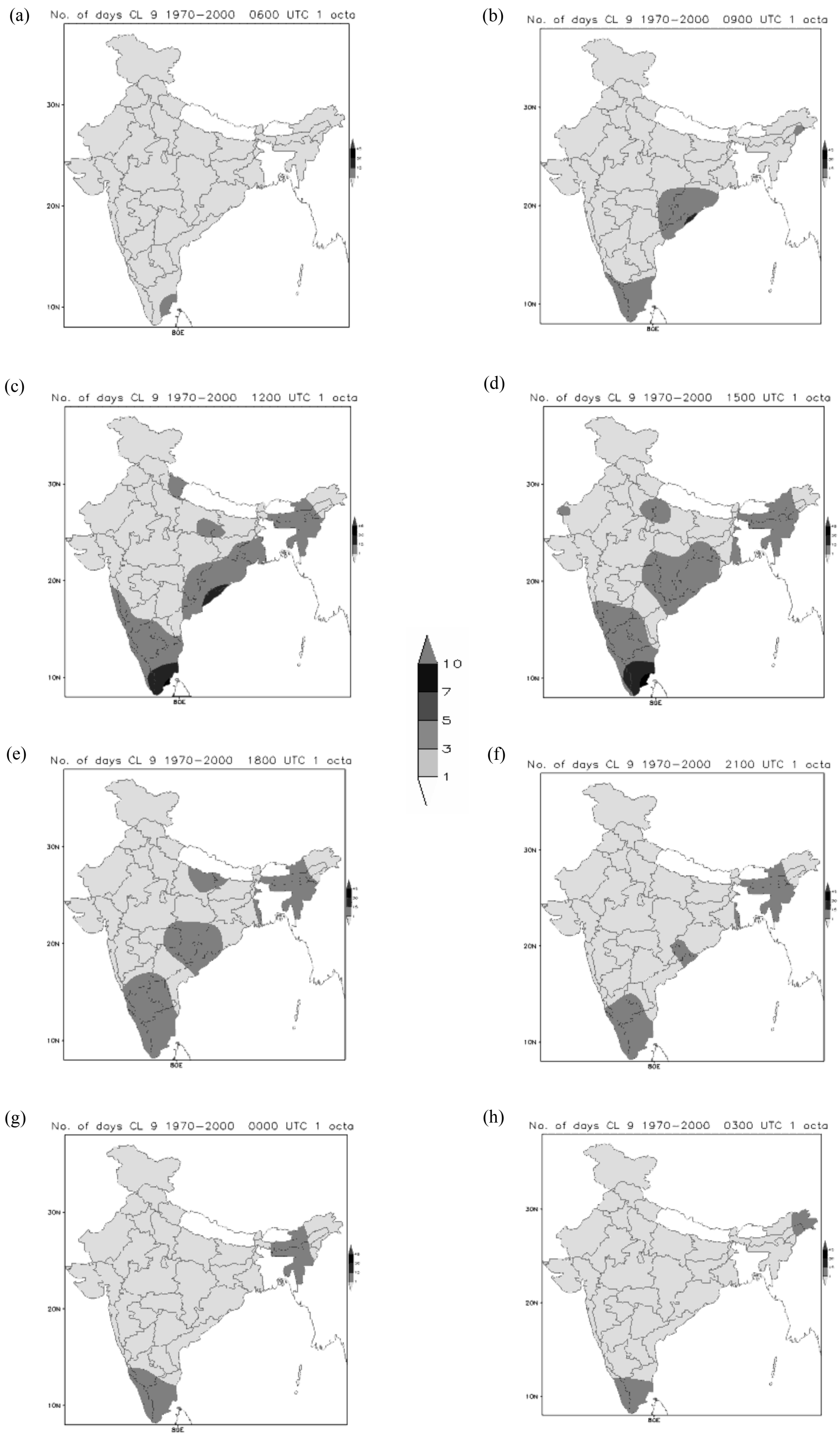
Monthly evolution of Cb clouds with anvil with threshold of 1 okta cloud amount is presented in following sections.

3.2.1. *March*

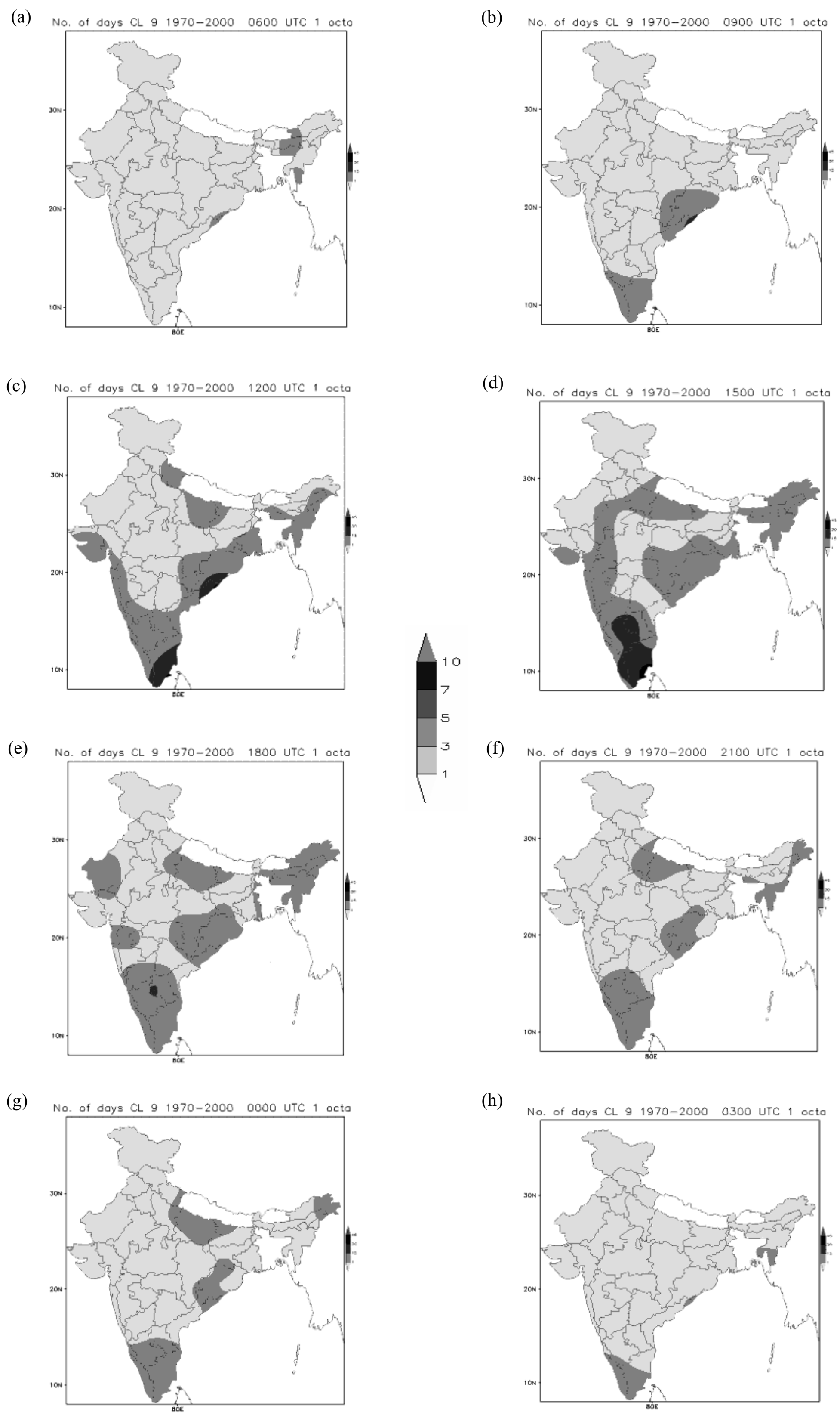
Total numbers of days with Cb clouds with anvil reporting 1 okta cloud amount in March are shown in



Figs. 5(a-h). Total number of days in March with Cb with anvil with threshold of 1 okta cloud amount for the period 1970 to 2000



Figs. 6(a-h). Total number of days in April with Cb with anvil with threshold of 1 okta cloud amount for the period 1970 to 2000



Figs. 7(a-h). Total number of days in May with Cb with anvil with threshold of 1 okta cloud amount for the period 1970 to 2000

Figs. 5(a-h). Cb clouds with anvil of amount 1 okta are noticed over regions, namely, Northeast India (Upper Assam and Arunachal Pradesh) at 0600 UTC [Fig. 5(a)]. However, Development of Cb with anvil occurs over South Kerala and adjoining Tamil Nadu and Puducherry, North Coastal Andhra Pradesh and Orissa, Tripura and adjoining Mizoram and East Gangetic West Bengal at 0900 UTC [Fig. 5(b)]. At 1200 UTC, significant development of Cb clouds with anvil over North coastal Andhra Pradesh to Gangetic West Bengal, Southern peninsula (Kerala, Tamil Nadu and Puducherry and South Interior Karnataka), Lower Assam and Meghalaya and Tripura and adjoining Mizoram are noticed [Fig. 5(c)]. Around 1800 UTC and 2100 UTC Cb clouds with anvil of 1 okta cloud amount are reported over East Rajasthan, Assam and Meghalaya, Tripura, Mizoram and West Aruchachal Pradesh, East Vidharbha, South Chattisgarh and adjoining Orissa and Coastal Andhra Pradesh [Figs. 5(e&f)]. Cb clouds with anvil with threshold of 1 okta have reported in the range 1-15 days over India at 0000 UTC and 0300 UTC in 31 years as depicted in the Figs. 5(g&h).

3.2.2. *April*

During April, high frequency of Cb clouds with anvil is observed at 1200 UTC over the belt from Konkan & Goa to Southern peninsula (South Interior Karnataka, Kerala, Tamil Nadu and Puducherry), North coastal Andhra Pradesh, South Chattisgarh, Orissa to Gangetic West Bengal, SHWB and Northeast India, Uttarakhand and East UP and adjoining Bihar [Fig. 6(c)]. Figs. 6(d-f) show the areas of reported Cb clouds with anvil to be same as depicted in Fig. 6(c). But areas of East Gangetic West Bengal have reported Cb clouds with anvil at 1500 UTC [Fig. 6(d)]. However, the spatial coverage of Cb clouds with anvil is decreasing temporally as seen from the Figs. 6(d-f). The frequency of Cb clouds with anvil has decreased as seen in Figs. 6(g&h) indicating dissipation of these clouds.

3.2.3. *May*

During May, the pattern of Cb cloud with anvil is same as for April however frequency is more as compared to April. Cb cloud with anvil frequently develops around 0900 UTC over Tamil Nadu and Puducherry and over Coastal Andhra Pradesh [Figs. 7(a&b)]. Fig. 7(c) shows the areas of frequent development of Cb clouds with anvil to be Saurashtra, Kutch and Diu, Konkan and Goa, South peninsula (Kerala, Tamil Nadu and Puducherry, South Interior Karnataka, Coastal Karnataka), North Coastal Andhra Pradesh, Orissa to Gangetic West Bengal, East UP and adjoining Bihar, East SHWB, Meghalaya, Tripura, Mizoram, Nagaland, Manipur and Upper Assam at 1200 UTC. Convective clouds develop over South Interior Karnataka and East Rayalseema areas around 1500 UTC to 1800 UTC [Figs. 7(d&e)].

4. Results and discussion

Rao and Ramamurti (1968) have noted slightly higher pressures over the Arabian Sea and the Bay of Bengal in March. Around 1200 UTC there is a weak low pressure cell noticed over Bihar and East Uttar Pradesh. Cb clouds noted over southeast Bihar plains from Fig. 2(c) are in agreement with Mukhopadhyay *et al*., (2005). Their study indicates development of Nor'westers over Bihar and Jharkhand regions around 1100 UTC and well developed systems reaching Gangetic West Bengal by around 2230 hrs local time (1700 UTC) fading away to leave little cloud or precipitation soon afterwards. However it is not reflected in Fig. 2(e). Fig. 2(d) suggests prominent pattern of Cb clouds (with anvil) occurrence over Chhattisgarh and Orissa. Our results agree with Galvin (2009) which highlights peak development of large MCSs over Eastern Ghats between Visakhapatnam and Kolkata around 2100 hrs local time (1530 UTC). The convergence with south-westerly flow in land allows rapid development and peaking over this region. Coastal Upwelling results in rather low temperatures (mean daily Maximum) along the coast between Visakhapatnam and Puri as noted by Rao and Ramamurti (1968).

Further prominent areas where Cb cloud with anvil reported are seen in Figs. 3(a-h). These are area from North Coastal Andhra Pradesh, Chhattisgarh and Orissa to SHWB, Southern Indian Peninsula (Kerala and neighbourhood) and Northeast India. This is in agreement with Rao and Ramamurti (1968). In the month of April a trough runs southwards from low over Uttar Pradesh, East Madhya Pradesh and Bihar and over the Peninsula a trough forms with its axis along longitude 78° E. Figs. 3(b-g) show presence of Cb clouds with anvil over Northeast India (Lower Assam and adjoining Meghalaya). [Kumar and Mohapatra (2006)] have studied some climatological aspects of thunderstorms and squalls over Guwahati Airport and found most of pre-monsoon thunderstorms commenced during mid-night to early morning. Our results agree with their study. Further Chakrabarti *et al*., (2008) confirmed that "Assam Valley" along Brahmaputra River experiences maximum number of thunderstorm events. Lower Assam is more prone to these events as compared to upper and South Assam. A recent study by Tyagi (2007) shows a significant increase of thunderstorm activity over Northeast India, West Bengal, south Peninsula and Jammu region. In the month of April during the period from 1200 UTC to 1500 UTC, occurrence of Cb clouds with anvil are more prone over Goa and adjoining South Konkan and Goa with reported 1-3 days as seen in Figs. 3(c&d). Rao and Ramamurti (1968) have studied mean distribution of surface temperature at surface level. Mean daily Maximum temperature suggests a large contrast between air over land and Sea in the month of April. Prevailing winds are favourable to the Sea breeze on the west coast which results in lower temperature on a good part of the west coast. North of 15° N along the west coast, there is a narrow strip to the east of Western Ghats where April is hottest month.

Fig. 4(b) shows Cb cloud with anvil dominant over Kerala. Ranalkar and Chaudhari (2009) have demonstrated high spatial distribution of lightning flash density over southern peninsular India, especially over Kerala. They have attributed this to westward movement of synoptic scale systems such as cyclonic circulations or troughs of low pressure from the southwestern parts of the Bay of Bengal to the Arabian Sea during later part of the pre-monsoon season. Our results show that on an average 7 to 10 days report occurrence of Cb clouds with anvil over Kerala at 1200 UTC [Fig. 4(c)]. This indicates frequent occurrence of Cb clouds with anvil and possibility of peak thunderstorm activity. Lightning study by Ranalkar and Chaudhary (2009) has also shown lightning flash densities over Orissa and adjoining Jharkhand and Gangetic West Bengal. This agrees with our observations. Our results show that the spatial areas of Chhattisgarh and adjoining Vidharbha, Orissa and Gangetic West Bengal and adjoining areas of Jharkhand and Bihar have reported frequent occurrence of Cb clouds with anvil (on an average 3 to 10 days). Ranalkar and Chaudhary (2009) have also examined the reason for the rise in intense thunderstorms and lightning flash densities over Northeast India and Bangladesh. Fig. 4(c) shows that the belt comprising SHWB, Assam and Meghalaya covering Guwahati and Shillong have reported Cb clouds with anvil (on an average 5 to 7 days) and belt comprising regions of Tripura and adjoining Mizoram extending to states of Nagaland and Manipur up to Dibrugarh have reported Cb clouds with anvil (on an average 5 to 7 days). These observations confirm with lightning study by Ranalkar and Chaudhary (2009) indicating peak thunderstorm activity. It has also been observed in their lightning study that lightning flash densities concentrate over Himachal Pradesh, Uttarakhand, Punjab and adjoining Jammu & Kashmir. It is seen in our results from Fig. 4(c) at 1200 UTC that the belt (Himachal Pradesh and adjoining Jammu & Kashmir, Uttarakhand and adjoining West UP) is prone to occurrence of Cb clouds with anvil and thunderstorm activity.

Figs. (2-4) reflects development of Cb clouds (with anvil) around 1200 UTC and its subsequent decrease during early morning. This agrees with Gambheer and Bhat (2001). They have examined the diurnal variation of the deep cloud systems over Indian region using INSAT-1B pixel data. Their study indicated the growth of the cloud areas during night hours and their decrease drastically in the early morning hours Figs. 2-4(d-f).

Figs. 4(c-e) exhibit prominent areas of Cb clouds (with anvil) over Deccan Plateau and adjoining plains of Andhra Pradesh and east Maharashtra. Study by Rao and Ramamurti (1968) has shown by April mean daily temperatures of the order of 33 °C to 35 °C covering the Deccan Plateau and it is also noticed for the month of May.

5. Conclusions

Considering the Climatology, the following observational aspects are noted for the Cb clouds with anvil over India:

(*i*) Cb clouds with anvil with a threshold of 1 okta have captured the potential areas over India of Cb development activity. During March, at 0600 UTC, Northeast India shows frequent Cb clouds with anvil development. At 0900 UTC, Development of Cb with anvil occurs over South Kerala and adjoining Tamil Nadu and Puducherry, North Coastal Andhra Pradesh and Orissa, Tripura and adjoining Mizoram. The spatial area extends to East Gangetic West Bengal. Significant frequent development of Cb clouds with anvil commences at 1200 UTC over above regions. Around 1800 UTC to 2100 UTC spatial coverage extends to East Rajasthan. Cb clouds with anvil with threshold of 1 okta have reported in the range 1-15 days over India at 0000 UTC and 0300 UTC in 31 years.

(*ii*) Significant observation during April is high frequency of Cb clouds with anvil development is noticed at 1200 UTC over the belt along West coast from Konkan and Goa to Southern Peninsula, belt along East coast from North Coastal Andhra Pradesh to Gangetic West Bengal, SHWB and Northeast India. However, spatial coverage of Cb clouds with anvil is decreasing temporally for the period from 1500 UTC to 2100 UTC over the above regions.

(*iii*) During May, from 0900 UTC onwards, frequent development of Cb clouds with anvil cells take place over Tamil Nadu and Puducherry and Coastal Andhra Pradesh. At around 1200 UTC, spatial coverage of Cb clouds with anvil extends to Saurashtra, Kutch and Diu, Konkan and Goa, Gangetic West Bengal and adjoining Bihar, East SHWB, Meghalaya, Tripura and adjoining Mizoram, Nagaland, Manipur and Upper Assam. Around 1500 UTC to 1800 UTC, convective clouds develop over South Interior Karnataka and adjoining Rayalaseema.

(*iv*) Maximum peak of convective cloud activity occur at 1200 UTC. The present study has revealed that there are certain belts of frequent occurrence of Cb clouds with anvil over India which shows both spatial and temporal characteristics as season progresses. Further there are five prominent belts of Cb clouds prevalence during May which is the month of peak thunderstorm activity.

(*v*) The frequencies of number of observations of Cb clouds with anvil over the 101 Class I surface observatories show an increase in days as the season progresses.

(*vi*) The formation of Cb clouds with anvil exhibits the diurnal tendency of growth of cloud areas and show drastic decrease in the early morning hours.

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