Forecasting of Severe Weather Events Over India

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Abstract Forecasting severe weather events is of immense value since it can help alleviate (if not mitigate) the disastrous impacts to a certain extent. While accurate and precise forecasting is a great challenge, the advances in recent decades in the NWP in India have shown improved accuracy and reliability in the forecasting capabilities, especially for severe weather events. Improved observations, monitoring, modelling and forecasting capabilities in recent years in India have helped in early detection and warning for severe weather events. This Chapter documents the recent developments in India, and NCMRWF in particular, in forecasting (i) Heavy Rainfall (ii) Tropical Cyclones (iii) Thunderstorms and Hailstorms (iv) Heat and Cold Waves (v) Fog and Visibility.

1 Introduction

Severe weather is an extreme meteorological event or phenomenon, which represents a real hazard (to human life and property). The definition of severe weather is most often impacted based, and usually defined by "local/regional" thresholds that are related to the inability of the "local/regional" populations to safely conduct their normal business, to the point of being life threatening. Naturally, the set of severe weather phenomena is different in different geophysical environments (different physical processes and antecedent conditions are in play). In general, severe weather includes events like (category 1) heavy rain, strong wind/ wind gusts, hail, lightning, tornadoes, flash floods and extreme temperature. Some of the more localized events are suggested as (category 2) snow storms, thunderstorms, dust/sand storms, sea swell/ tsunamis/storm surges and extended areas of fog for transport (aviation especially). In this chapter, an overview of some of the severe weather events in India is presented with a brief discussion on the prediction or early warning capability and know-how used in India.

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2 Heavy Rainfall Events

Heavy rains are the most common natural disasters which affect the human society, the environment and the economy. They are generally associated with deep convective systems and produce copious rainfall in a short period of time (a few hours). As per the IMD definitions (Table 1), heavy rainfall is reported at a place when the accumulated rainfall in a day exceeds 7 cm. If the rainfall in a day exceeds 12 cm, then it is reported as very heavy rainfall.

The Indian subcontinent is highly vulnerable to heavy rainfall events. Most of the heavy and extreme rainfall events occur during the southwest monsoon season (June to September, JJAS), the Western Ghats (WGs), North-Eastern (NE) states (Assam, Meghalaya, Mizoram, Arunachal Pradesh, Sikkim, Manipur and Tripura) of India and central India are the most prominent regions of heavy rainfall. Central India receives rainfall mainly due to the Low-Pressure Systems (LPS) and Monsoon Depressions (MD) that form over the Bay of Bengal (BoB) and move towards the west north-westward during JJAS (and only on very few occasions do these LPS and MDs move towards northward and produce a significant amount of rainfall over the NE states. The WGs and the NE states of India are the regions which are characterized by steep orography and therefore the heavy rainfall in these regions is often due to the forced ascent of air parcels over the mountains.

Recently, India has witnessed some unprecedented heavy rainfall events that caused flooding and landslides. The heavy rainfall in Mumbai (26 July 2005), Kedarnath (Uttarakhand) in June 2013, heavy rains and flooding in Chennai (2 Dec 2015), flooding in Madhya Pradesh during July–August 2016 and Mount Abu in Gujarat (July 2017) are some of the examples of severe weather/extreme rainfall events. The most recent unprecedented heavy rainfall occurred over Kerala during August 2018 (1–20 August) resulting in large flooding with the death of more than 400 people and affecting millions of people. According to the India Meteorological Department

Table 1 IMD classification of 24-h accumulated rainfall

	Terminology	Rainfall Range in (cm)	Percentile
1	Very light rainfall	Trace-0.25	
2	Light rainfall	Up to 1	Up to 65
3	Moderate rainfall	2–6	65.0–95.0
4	Heavy rainfall	7–11	95.0–99.0
5	Very heavy rainfall	12–20	99.0–99.9
6	Extremely heavy rainfall	≤ 21	>99.9
7	Exceptionally heavy rainfall	When the amount is a value near about the highest recorded rainfall at or near the station for the month or season. However, this term will be used only when the actual rainfall amount exceeds 12 cm	

(IMD), rainfall over Kerala during August (1–19 August) was 164% above normal thus making it the fourth highest record August rainfall (+94%). Similarly in some of the neighbouring districts of Karnataka state, heavy rains caused widespread flooding and landslides. Figure 1a shows the spatial distribution of the rainfall along the west coast of India, accumulated during 7–17 August 2018 based on the satellite and gauge merged rainfall analysis. The IMD-NCMRWF satellite + gauge merged (NSGM) rainfall analysis shows the highest observed rainfall amounts exceeding 100 cm over several areas in Kerala and coastal Karnataka (Fig. 1a).

NCMRWF provides real-time forecast based on NWP models for up to 10 days. Figure 1b shows accumulated rainfall during 7–17 August 2018 as predicted by NCMRWF's NWP model. A comparison with observations (Fig. 1a) suggests that the model (Fig. 1b) successfully predicted the increased rainfall amount over Kerala and coastal Karnataka. A detailed analysis of the forecasting and validation for the Kerala event is presented by Ashrit et al. (2020).

Although the prediction of these heavy rainfall events and scientific understanding of the processes responsible for these events have been improved continuously, there are still many challenges associated with its prediction like where (location), when (time), and how much (intensity) precipitation will occur. The reported improvement is attributed to increased horizontal and vertical resolutions as well as improved physics parameterization schemes in NWP models. However, the major credit for the substantial improvements in weather forecasting goes to the sophisticated data assimilation (DA) systems which utilize satellite data.
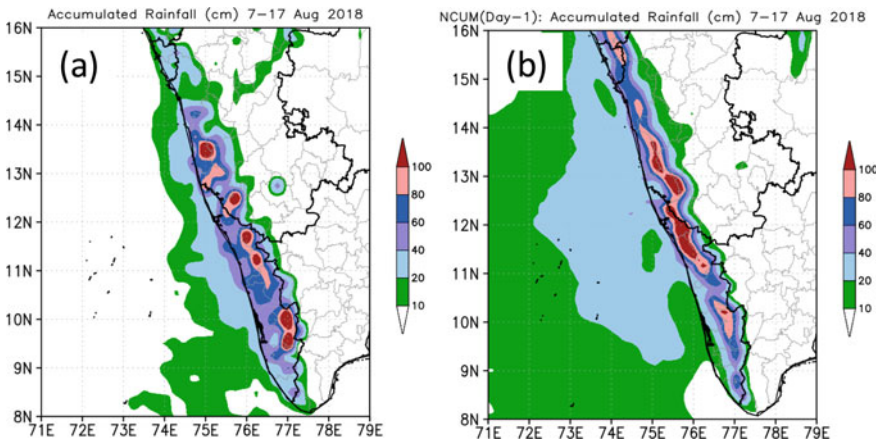
Fig. 1 Accumulated rainfall during 7–17 Aug 2018 over coastal Karnataka and Kerala. **a** Observed. **b** NCMRWF Model forecast

3 Tropical Cyclones in the North Indian Ocean

Tropical cyclones are intense circular storms that originate over warm tropical oceans and are characterized by low pressure at the centre of the storm, string winds, and heavy rainfall. These weather systems draw most of their energy from the sea surface and maintain their strength as long as it remains over warm waters (>26 °C). As soon as a cyclone makes landfall it tends to lose its strength and gradually dissipates. Cyclonic systems usually move from east to west due to the upper level steering flow. They are the major natural hazards that affect the coastal region of India. In view of the serious risk posed to life, property and infrastructure, the availability of reliable and timely information about the probability of formation of tropical cyclones, their location, movement, intensification, and landfall become very crucial for disaster management and mitigation.

Tropical cyclones over the North Indian Ocean are categorized as (Table 2):

In the coastal areas with the approach of a tropical cyclone, there are strong winds, torrential rains and storm surges which is an elevation of the sea surface that can reach up to 6 m (20 ft) above normal levels. Such a combination of high winds and water makes cyclones a serious hazard for coastal areas in tropical and subtropical areas of the world.

The Indian subcontinent, with a total coastline of about 7516 km and almost 40% of the population living within 100 km of this coastline, is exposed to nearly 10% of the world's tropical cyclones making it one of the worst cyclone-affected areas. On an average, the Bay of Bengal and Arabian sea are affected by about 5–6 tropical cyclones each year out of which 2–3 cyclones may reach the intensity of a severe cyclonic storm. There are two definite seasons of tropical cyclones in the North Indian Ocean (NIO), i.e. from May to June and from September to the middle of December. In recent years, there have been many instances of severe to very severe tropical cyclones affecting both the Bay of Bengal as well as the Arabian Sea, for example, 'Phailin' in 2013, 'Hudhud' in 2014, 'Chapala' in 2015, 'Vardah' in 2016, 'Mora' and 'Ockhi' in 2017, and 'Mekunu' in 2018. In the year 2018 alone there were 7 tropical cyclones observed in the NIO out of which 5 were in the severe to very severe category. Figure 2 shows the plot of tropical cyclones in the Indian Ocean

Table 2 Tropical cyclone categories in NIO based on maximum sustained windspeed

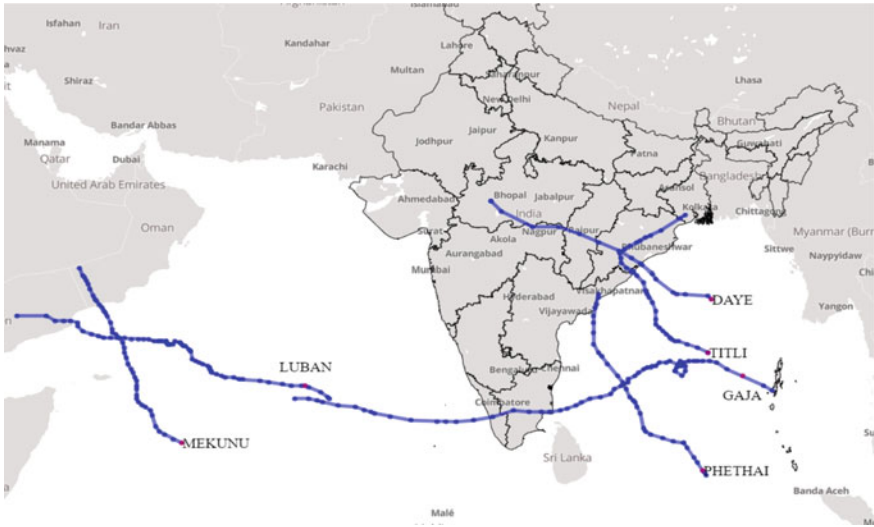| Category	Wind speed
Depressions	(31 km/h ≤ wind ≤ 50 km/h)
Deep depressions	(51 km/h ≤ wind ≤ 62 km/h)
Cyclonic storms	(63 km/h ≤ wind ≤ 88 km/h)
Severe cyclonic storms	(89 km/h ≤ wind ≤ 117 km/h)
Very severe cyclonic Storms	(118 km/h ≤ wind ≤ 165 km/h)
Extremely severe cyclonic storms	(166 km/h ≤ wind ≤ 220 km/h)
Super cyclones	(221 km/h ≤ wind)

Fig. 2 Tropical Cyclones affecting the North Indian Ocean during 2018

during 2018. In India, IMD is the operational agency which gives all cyclone-related warnings and forecasts for all the countries adjoining the North Indian Ocean.

3.1 Forecasting Tropical Cyclones at NCMRWF

The loss of life and property caused due to tropical cyclones is particularly high in densely populated areas, usually when the forecasts are inaccurate or are not given well ahead of time. In the last decade or so there have been many advances in the field of numerical weather prediction (NWP) which have resulted in an improvement in the forecasts of tropical cyclone tracks. All over the world, there are several numerical weather prediction models that are used by different meteorological agencies in giving forecasts (usually up to 5 days) for cyclones.

At the National Centre for Medium Range Weather Forecasting (NCMRWF), the operational weather prediction model is adapted from the Unified Model (UK Met Office) and is known as NCUM, which has a horizontal resolution of 12 km. The output of this model comes in the form of winds, mean sea level pressure, temperature, rainfall, etc. These basic variables are then used to compute the current and future locations of a tropical cyclone as well as the various hazards associated with it like the increase in wind speed as well as heavy rainfall. Output from this model is also used to calculate the landfall time and location for a given cyclone, which is further used in issuing out the evacuation or preparedness warnings to the general public by the IMD. Due to the high horizontal resolution of the NCUM model, it is also very useful in predicting the strength/intensity of a cyclone. This intensity is usually
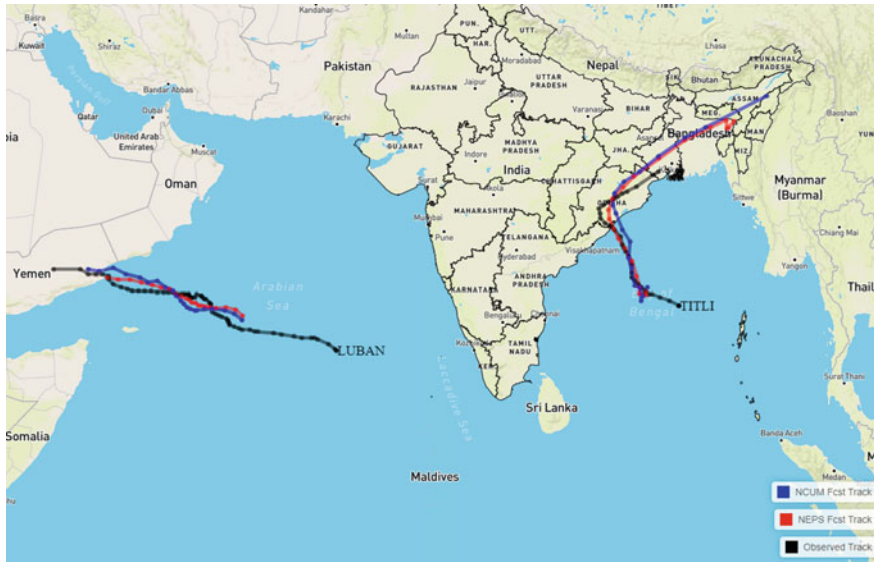
Fig. 3 Observed and forecast tracks for two very severe cyclones affecting the North Indian Ocean during 2018 (Titli and Luban)

measured in terms of the maximum winds that are seen within the cyclonic storm. Figure 3 shows the observed and forecast tracks for 2 very severe cyclonic storms Titli (8–12 October 2018) and Luban (6–15 October 2018) observed in 2018. The forecast tracks are from NCUM and the Ensemble prediction System, NEPS (mean track), two global models operational at NCMRWF.

3.2 Forecast Track Errors

For the two cyclonic systems, the NCUM and NEPS forecast track errors in Km are shown in Tables 3 and 4. The errors are computed against the IMDs' best track data. For the cases of VSCS Titli (Table 3), it is found that the lowest initial position error is 54 km in NEPS mean and slightly higher value of 58 km in NCUM. In NCUM all 00 and 12 UTC analyses show initial position errors lower than 70 km except for 12 UTC analyses on 8th Oct where the initial position errors is 189 km. The NCUM and NEPS mean track errors are comparable up to 48 h. For the Arabian Sea VSCS Luban, the NCUM, and NEPS (ensemble mean) forecast track errors suggest that the mean initial position error in NCUM is 43 km and in NEPS it is 67 km. The lowest initial position error is 11 km in NCUM and 12 km in NEPS mean (00UTC 8th Oct 2018). NEPS mean shows a very large initial position error (>350 km) on 6th Oct 12 UTC. Similarly, NCUM also shows a large error of 12 UTC on 8th Oct (109 km)

Table 3 Forecast track errors (in Km) for VSCS Luban from 3 to 13 Oct 2018. NCUM and NEPS track errors are based on 00UTC and 12UTC (numbers in the brackets indicate the number of cases)

	0	24	48	72	96	120
NCUM	43(12)	60(14)	125(17)	148(17)	186(17)	285(14)
NEPS	67(13)	56(14)	97(14)	138(13)	171(10)	245(9)

Table 4 Forecast track Errors (in Km) for VSCS Titli from 6 to 12 Oct 2018. NCUM and NEPS track errors are based on 00UTC and 12UTC (numbers in the brackets indicate the number of cases)

	0	24	48	72	96	120
NCUM	58(8)	99(8)	153(9)	142(8)	148(6)	183(3)
NEPS	54(7)	99(9)	135(9)	172(8)	165(6)	237(4)

and 00 UTC on 9 Oct 2018 (90 km). The NEPS mean track errors are lower at all lead times after 48 h.

3.3 Forecasting Landfall

The 850 hPa winds at the time of landfall of VSCS Titli over Odisha are shown in Fig. 4 for analysis and Day-2 forecast (top panels). Intense winds (>40kts) near the coast are well predicted in the Day-2 forecast. Similarly, the rainfall forecast (bottom) indicates the accurate location of peak rainfall over the coast. The regions affected by heavy rains >8 and 16 cm/day over Odisha, parts of AP and West Bengal are all accurately represented in the Day-2 forecast. Model tends to overestimate the rainfall amount; however, the location is accurately predicted. A similar analysis for the case of VSCS Luban is presented in Fig. 5.

The VSCS Luban made landfall at around 5:30–6:00 UTC on 14 Oct 2018). The forecasts based on 11th Oct predicted landfall 6 h early while the forecast based on 12th and 13th Oct had almost no landfall time error. For VSCS Titli, which made landfall at around 23UTC of 10th-00 UTC of 11 Oct 2018, the landfall time errors in the forecast based on 8th, 9th and 10th Oct is about 12 h, + 6 h and 0 h, respectively.

3.4 Four-Stage Warning Strategy of India Meteorological Department

Cyclone Warning Division (CWD) of IMD, New Delhi is the nodal agency in India for issuing the cyclone-related alerts and warnings. Additionally, the Area Cyclone Warning Centres (ACWC) and Cyclone Warning Centres (CWCs) play a crucial role
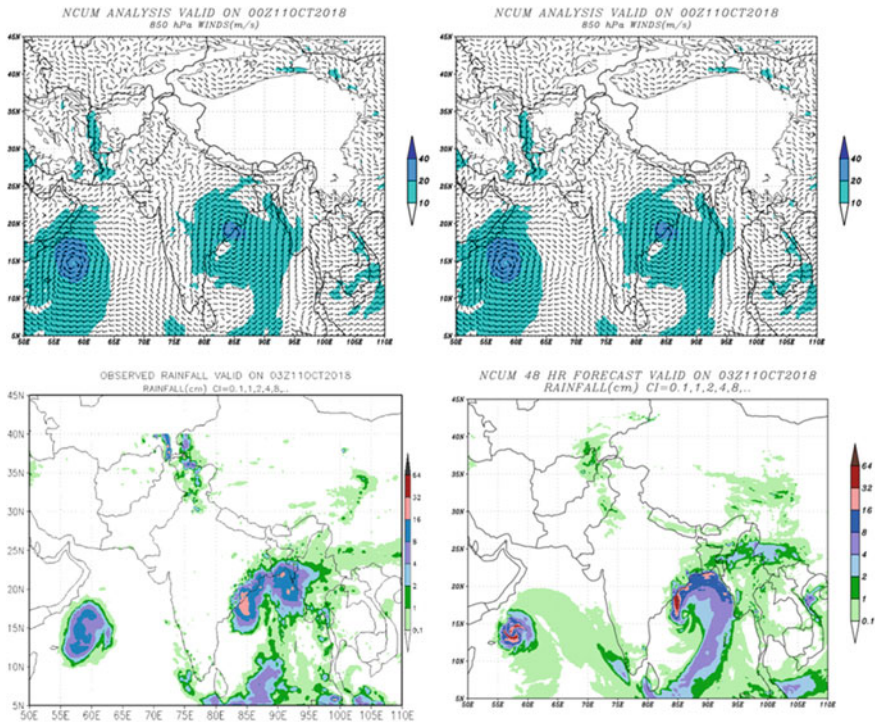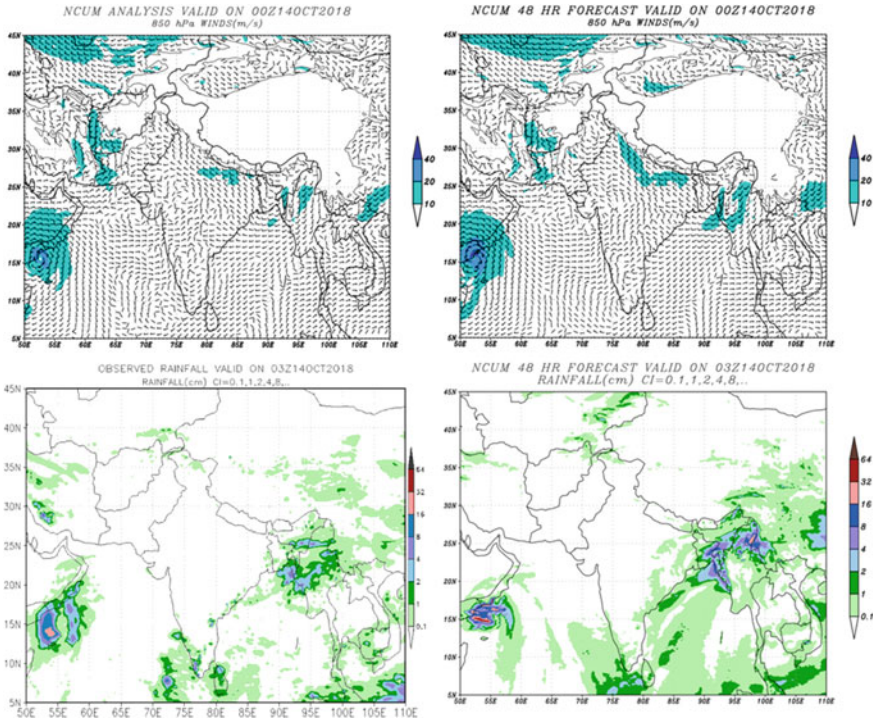
Fig. 4 Observed (left) and Day-2 forecast (right) 850 hPa winds (top) and rainfall (bottom) valid at the time of the landfall over Odisha for VSCS Titli on 11th Oct 2018

in the dissemination of regional and local warnings. The cyclone warnings are issued to state government officials in four stages.

Different colour codes are being used since post-monsoon season of 2006 to indicate the different stages of the cyclone warning in the bulletins as desired by the NDMA. Cyclone Alert (Yellow), Cyclone Warning (Orange) and Post-Landfall Outlook (Red). During disturbed weather over the Bay of Bengal and the Arabian Sea, the ports likely to be affected are warned by concerned ACWCs/CWCs by advising the port authorities through port warnings to hoist appropriate Storm Warning Signals. IMD also issues "**Fleet Forecast**" for the Indian Navy, Coastal Bulletins for Indian coastal areas covering up to 75 km from the coastline and sea area bulletins for the sea areas beyond 75 km. The special warnings are issued for fishermen four times a day in normal weather and every three hours in accordance with the four-stage warning in case of disturbed weather.

For the general public, the coastal residents and fishermen are warned by State Government officials and broadcast warnings through All India Radio and National Television (Doordarshan) telecast programmes in national and regional hook-up (Table 5).

Fig. 5 Observed (left) and Day-2 forecast (right) 850 hPa winds (top) and rainfall (bottom) valid at the time of the landfall over Yamen for VSCS Luban on 14th Oct 2018

3.5 Tropical Cyclone Monitoring/Warning Using Satellites

Satellite information is very important for tracking and determining the intensity trends of tropical cyclones. When a system is well offshore and out of effective radar range, forecasters use satellite imagery to continuously track the storm's movement and development. Figure 6 shows the Meteosat-7 visible imagery of VSCS 'Phailin' on 12 Oct 2013 06UTC (left) On the right Meteosat-7 IR image with 12.5 km ASCAT winds overlay for Cyclone Hudhud on 10 October 03:00 UTC is shown. The satellite imagery gives information about the top of the storm and also about the wind speeds over the ocean surface. These are crucial for monitoring the formation and development of storms and are used to pinpoint the storm centre. Tropical Cyclone forecasters use both visible and infrared satellite imagery to track the motion and cloud patterns of cyclones and infrared to monitor cloud-top temperatures. The forecasters also pay attention to the sea surface temperature. Cyclones passing over warmer (*cooler*) water pick up energy and intensify (*weaken*). For a cyclone to form the sea surface temperature needs to be at least 26 °C.

As per the IMDs Standard Operating Procedure (SOP; IMD 2013), 1-hourly Satellite Bulletins (based on satellite cloud imagery data and derived products) are made at

Table 5 Four stages of cyclone warning strategy operational in IMD

Stages	Warning	Information	Issued by	Target agency
First stage 72 h in advance	Pre-cyclone Watch	Early warning about the development of a cyclonic disturbance in the NIO and its likely intensification into a tropical cyclone and the coastal belt likely to experience adverse weather	Director General of Meteorology	Cabinet secretary and other senior officers of the Government of India including the Chief Secretaries of concerned maritime states
Second stage 48 h in advance	Cyclone alert	information on the location and intensity of the storm likely direction of its movement, intensification, coastal districts likely to experience adverse weather and advice to fishermen, general public, media and disaster managers	ACWCs/CWCs and CWD at HQ	
Third stage 24 h in advance	Cyclone warning	Landfall point is forecast at 3 hourly interval giving the latest position of cyclone and its intensity, likely point and time of landfall, associated heavy rainfall, strong wind and storm surge along with their impact	ACWCs/CWCs/and CWD at HQ	Advice to the general public, media, fishermen and disaster managers
Fourth stage 12 h in advance	Post-landfall outlook	Likely direction of movement of the cyclone after its landfall and adverse weather likely to be experienced in the interior areas at least 12 h in advance of the expected time of landfall	ACWCs/CWCs/and CWD at HQ	
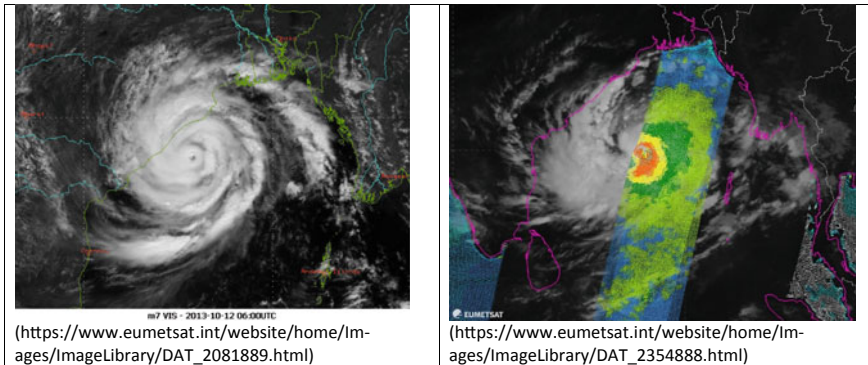
Fig. 6 On left Bay of Bengal VSCS 'Phailin' visible imagery from METEOSAT-7 on 12th Oct 2013 06UTC. On the right Meteosat-7 IR image with 12.5 km ASCAT winds overlay for Cyclone Hudhud on 10 October 03:00 UTC. Imagery shows the area with hurricane force winds in the centre along with tight circulation centre

the Satellite Meteorology Division of IMD, New Delhi. In these bulletins, the centre and intensity of a cyclone as estimated by "Dvorak Technique", its past motion and amount of convection associated with tropical cyclones and other characteristic features are described.

Ultimately, the assimilation of data from Indian satellites (e.g. INSAT-3D, Megha Tropiques, SARAL) in the numerical weather prediction (NWP) models carried out for improved representation of tropical cyclone environment in the initial conditions which yield improved prediction of cyclone track, intensity, rainfall in the NWP models.

3.6 Use of RADARS for Monitoring and Warning Tropical Cyclones

IMD has a network of over 27 radars spread all over the country as in Fig. 7. They are categorized mainly as:

- S and C Band Radars for cyclone detection are installed along the coast. Eleven numbers of S-Band high power radars are located along the east and west coasts of India and are used primarily for the detection of cyclones approaching the Indian Coasts. Some of these radars are also used for the detection of storms and other severe weather phenomena for use in local forecasting. The effective range of these radars is 400 km.
- X Band radars for storm detection are installed at airports for the detection of localized phenomena such as thunderstorms, dust storms and squalls. The effective range is 150 km.

(http://www.imd.gov.in/broadcast/DWRnetwork.png)
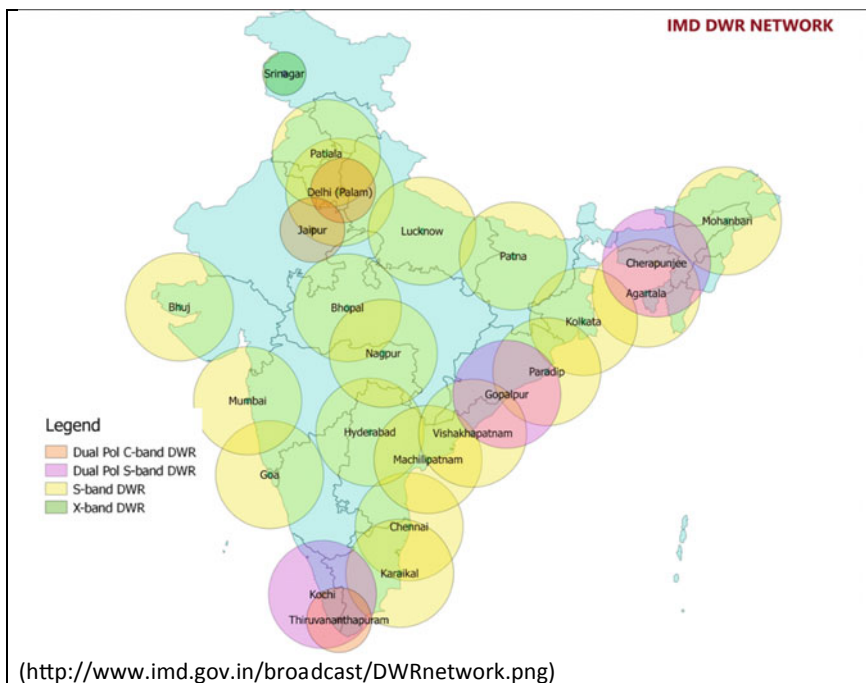
Fig. 7 IMD's Doppler Weather Radar network over India

- IMD also has a network of multipurpose radars known as MULTIMET Radars operating in the X Band. These were dual-purpose radars used for tracking the radiosonde balloon as well as detecting storms.

The radar network of IMD is now being upgraded with doppler weather radar technology replacing conventional radars. IMD is also installing C band polarimetric doppler weather radars and the first two are installed in DELHI and JAIPUR. Eventually, the network in India will comprise 55 doppler weather radars covering entire India.

For the case of VSCS Hudhud, the DWR Reflectivity is shown in Fig. 8 as the system is crossing the coast on 12 Oct 2014 over the city. The eye of the cyclone is clearly seen in the DWR imagery. This image from Doppler Radar of Vizag (taken 02:20) shows Vizag at the (+) mark. The image shows the eyewall and eye (the place where the strongest winds and heaviest rainfall take place). So, the eyewall is about to hit Vizag and the coastal areas around it. The image shows the VSCS Hudhud crossing the coast. This will be the period when the rains will be stopping, almost (the image below shows a blue-shaded region which is the eye where rains vanish), and winds will also decrease until the eye passes. However, just after this eye passes, the weather once again turns severe with a complete reversal of wind.
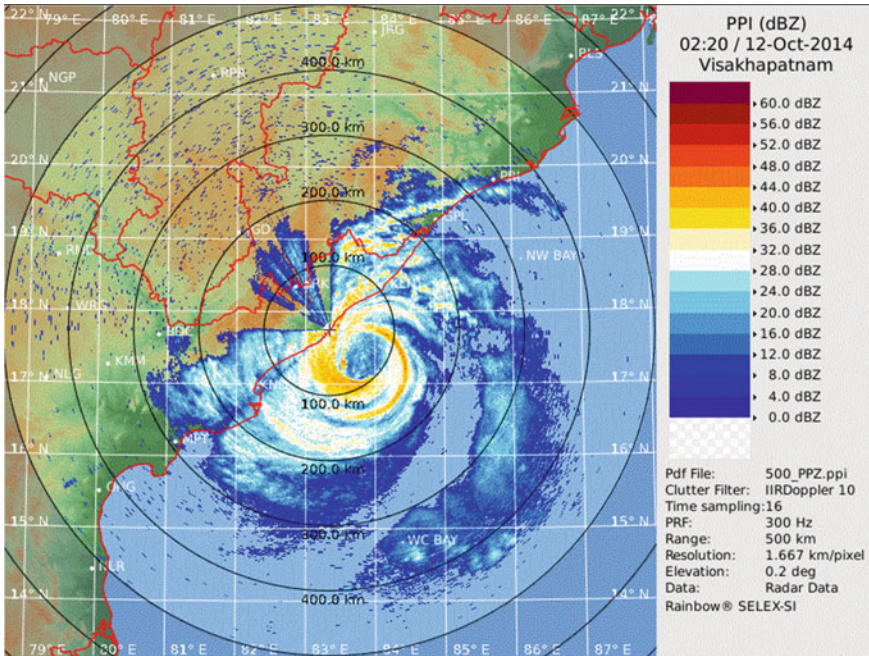
Fig. 8 Visakhapatnam DWR reflectivity during Cyclone Hudhud while crossing the coast over city on 12th Oct 2014

4 Thunderstorms and Hailstorms

A thunderstorm is a violent short-lived weather disturbance. It is associated with high-impact weather phenomena like lightning, thunder, dense clouds, heavy rain or hail, and strong gusty winds. These cause loss of life and damage to crops and property. Recently, India has witnessed many thunderstorm events a few to be named are, a severe thunderstorm over north India on 2 May 2018 in which more than 130 people died and on 21 April 2015 over Bihar which took the lives of 65 people. National Crime Records Bureau (NCRB) indicates that 9.86% of the total number of deaths in India attributed to nature (317,259) is due to lightning alone. Similar significant fraction of loss of life and damage to crops and the aviation sector are associated with other phenomena associated with thunderstorms, such as downbursts, high winds and hailstorms. During pre-monsoon season (March–May) Gangetic West Bengal and surrounding areas get severe thunderstorms called Nor'westers, which are locally called as 'Kal-Baisaki'. Northwest India gets convective dust storms called locally as 'Andhi'. These dust storms are generally associated with strong dry winds and reduced visibility (almost nil). When downpours associated with thunderstorms are very heavy and of very short duration it is called 'cloud burst'. It is defined as rainfall of more than 10 cm in 1 h.
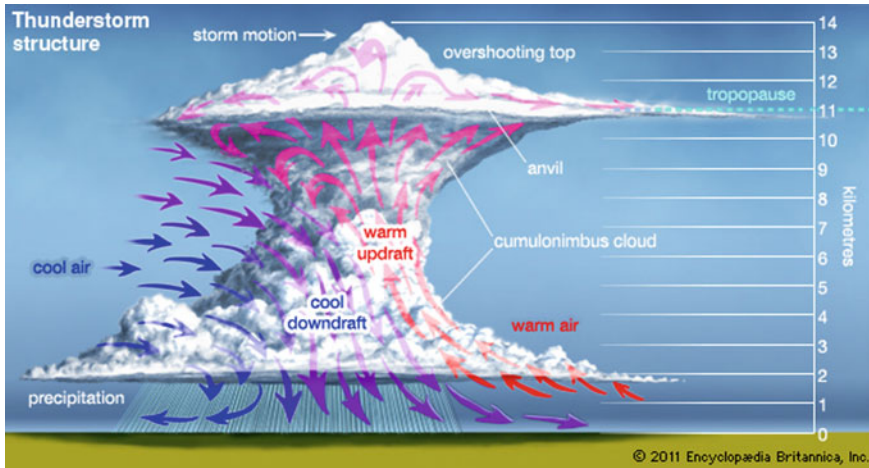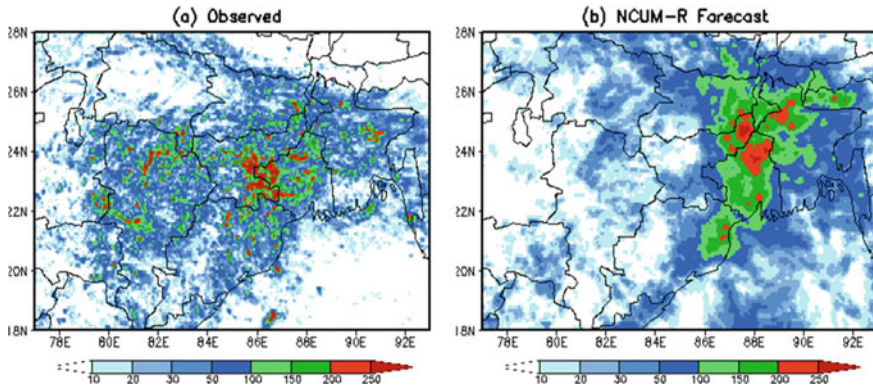
Fig. 9 Structure of a fully mature thunderstorm

In general, thunderstorms have a spatial extent of a few kilometres and a life span of less than an hour. Thunderstorms originate mainly during the summer season, warm days of the season, and warm hours of the day. Warm, moist and rising unstable air is the most important factor in the development of thunderstorms. Besides the convective mechanism, warm and moist winds also rise and become unstable due to orographic obstacles (Fig. 9).

4.1 Forecasting Thunderstorm

A natural calamity is beyond human control but numerical weather prediction (NWP) models can be used to provide forecasting guidance a few days in advance to minimize the losses incurred due to it. NCMRWF being a numerical weather forecasting centre runs Unified Model up to 10 days in advance to provide guidance to weather forecasters to advice the general public. Depending on the weather phenomenon and its severity, suitable weather parameters are selected for this purpose. For forecasting thunderstorms atmospheric instability parameters like Total Totals Index (TTI > 45), Showalter Index (SWI < 0), KI (>35), lifted index (LI < −1), convective available potential energy (CAPE high values) and convective inhibition (CIN low values) are useful. These parameters are calculated from NWP model running at NCMRWF. On 7 February 2019, Delhi, NCR and adjoining areas witnessed a severe hailstorm (Fig. 10a). In Fig. 10b IMD's weather warning issued for different types of severe weather over north India has been highlighted. NCMRWF model predicted values of TTI, KI, CAPE and CIN as 57, 36, 1469 and 15, respectively, (Fig. 10c and d) indicate severe thunderstorm activity over a large part of the north and northwest India.

Fig. 10 **a** A glimpse of hailstorm event on February 7, 2019 (photo credit: Manisha Pandey/India Today). **b** IMD weather warning. **c** and **d** NCMRWF model predicted TTI and Skew-T chart

4.2 Forecasting Lightning

Lightning strikes are the biggest natural killers in India, causing more than 2,000 deaths each year, according to the top experts from the IMD and the NDMA. India has witnessed an increasing death toll and damages due to lightning bolts over the past few years. Despite improved understanding, monitoring and prediction capabilities brought about by scientific and technological progress, lightning and thunderstorms still cause widespread loss of life and property every year mainly due to a communication gap which does not result in last mile connectivity. With the joint initiative of scientists from the IMD, IITM and NCMRWF, a lightning warning system was

Fig. 11 Observed (left) and NCUM-R forecast (right) 24 h total lightening flash counts during May 2021

developed in 2018, having a location-specific forecast of up to 48 h about the occurrence of thunderstorms, lightning strikes, squalls, gusty winds or hailstorms. The country is now capable of having 'real-time' information about lightning updated every 5 min to alert the people about potential threats. The models developed by the Ministry of Earth Sciences are very definite and are utilized by forecasters around the country to provide detailed information for each district in the country every three hours. Figure 11 shows the comparison of observed and NCMRWF model (NCUM-R) predicted 24 h lightning count over eastern India covering Bihar, Jharkhand, Chhattisgarh, Odisha and West Bengal. The enhanced lightning activity over the West Bengal region is accurately predicted in the model. Lightning activity is underestimated in Chhattisgarh. The forecasters use these products for early warning of lightning.

5 Heat/Cold Waves

Temperature conditions, which vary from extremely hot to chilly weather, differ from place to place. In fact, people living in a place for a long get acclimatized to the normal weather/climate of that place/region. For instance, in the cold climate region (extratropical regions or high-level stations), a day temperature of more than 30 °C may be a hot day for the local residents whereas this temperature in the warm climate region may present the feeling of comfortable weather. In the equatorial and tropical regions, locals are accustomed to warm/hot weather. Comfortable temperature range for inland and coastal stations of the same climate regimes may also differ substantially due to varying humidity levels and wind flow.

Similarly, people in cold climate conditions are acclimatized to rather low temperatures and threshold values for cold wave conditions in those regions are much

lower than for people living in warm climates. Thus, health-related problems due to heat/cold waves in the extra-tropical countries are different, compared to those in the tropics. India Meteorological Department (IMD) is mandated to provide heat/cold wave advisories to help decision-making by the various sectors to minimize these risks and potential damages.
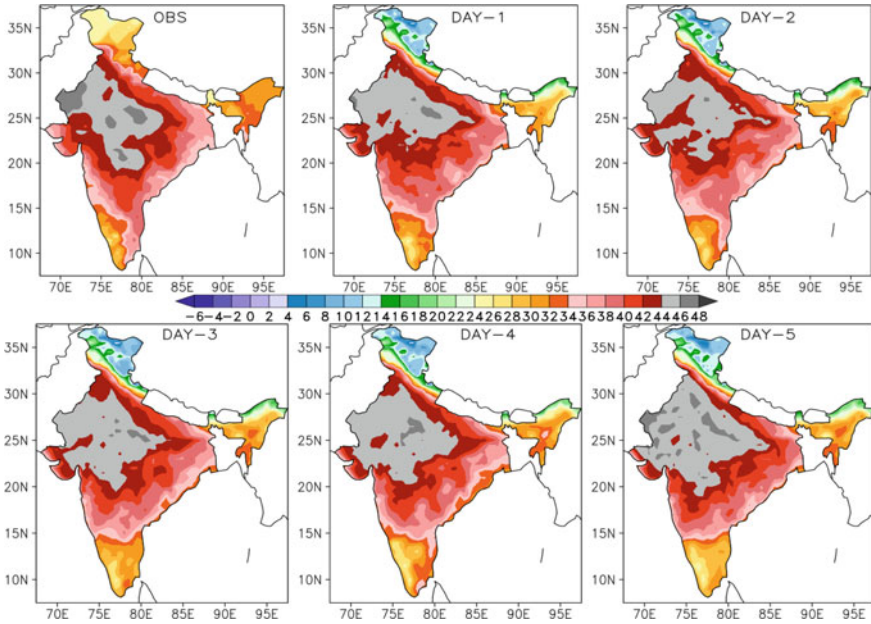
5.1 Heat Waves

Heat wave is a pervasive meteorological phenomenon resulting in the mortality of people, agricultural losses, and increases in many risks such as health-related risks, wildfires, power and water shortage and accidents, amongst others. As per the WMO guidelines (WMO 2018).

A period of marked unusual hot weather (maximum, minimum and daily average temperature) over a region persisting at least three* consecutive days during the warm period of the year based on local (station-based) climatological conditions, with thermal conditions recorded above given thresholds.

As per the IMD terminology, heat wave is considered if the maximum temperature of a station reaches at least 40 °C or more for plains and at least 30 °C or more for Hilly regions. When actual TMAX remains 45 °C or more irrespective of normal TMAX, heat waves occur (Nair et al., this book).

As per WMO (2018), a heat wave differs from warm spells. Similar to heat waves, warm spells are defined as a persistent period of abnormally warm weather. A warm spell can similarly be defined in terms of the 90th or 95th percentile of daily maximum temperature (T_{max}). A warm spell occurs at any time of the year, whereas heat waves can only occur in the warm season. Figure 12 shows the spatial distributions of IMD's observed and NCUM Model forecast T_{max} valid on 28 May 2018. This figure is an example of the prevailing heat wave conditions over parts of Rajasthan, Madhya Pradesh, Uttar Pradesh, Delhi, Haryana, Punjab and some parts of Maharashtra. The observed maxima of T_{max} (>42 °C) are seen over a wide region over central and western parts of India. NWP Models do feature the capability to forecast severe heat wave conditions. They can be effective tools of guidance for forecasters.

NCMRWF Model forecast of maximum temperatures for all cases of $T_{max} > 40$ C is evaluated for an entire MAM season during 2017 (Fig. 13). The forecast verification is presented in the form of a spatial map of the Probability of Detection (POD) and Equitable Threat Score (ETS) in Fig. 13. The appendix provides the detailed formula for the verification metrics. POD gives the fraction of the observed events that were correctly forecasted. It varies from 0 to 1 with 1 representing perfect forecast. On the other hand, ETS measures the fraction of observed events that were correctly predicted, adjusted for hits associated with random chance (for example, it is easier to correctly forecast rain occurrence in a wet climate than in a dry climate). The POD values excess of 0.6 can be considered skilful over large parts of India. The ETS values also indicate reasonable skill in predicting high temperatures during the MAM season.

Fig. 12 Observed and model forecast T$_{max}$ on 28th May 2018
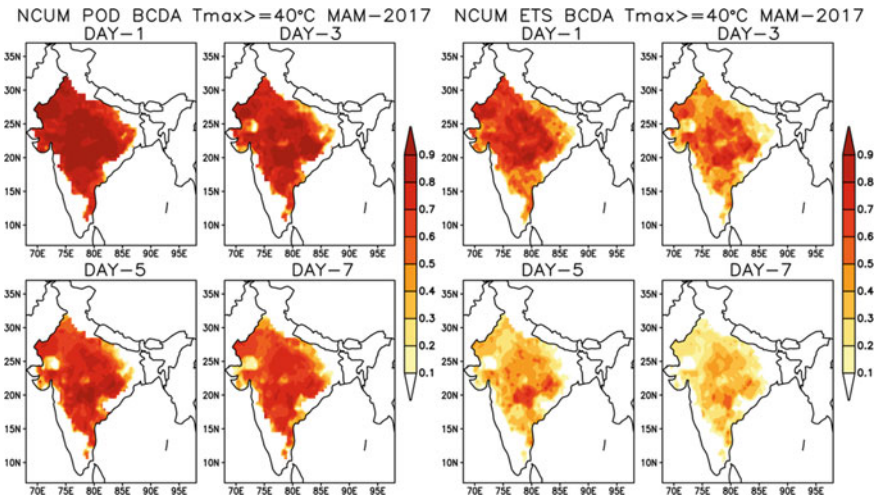
Fig. 13 Probability of Detection (POD; left) and Equitable threat Score (ETS; right) for forecast T$_{max}$ > 40C during MAM-2017

Higher daily peak temperatures and longer, more intense heat waves are becomingly increasingly frequent globally due to climate change. India too is feeling the impact of climate change in terms of increased instances of heat waves which are more intense in nature with each passing year, and have a devastating impact on human health thereby increasing the number of heat wave casualties. As per NDMA (2016), there were over 1000 reported heat wave-related deaths in India every year from 2010 to 2015 and over 22,000 deaths during 1992–2015.

5.2   Heat Action Plan (HAP)

Many states are affected during the Heat wave season, such as the state of Andhra Pradesh, Telangana, Odisha, Gujarat, Rajasthan, Madhya Pradesh, Uttar Pradesh, Vidarbha region of Maharashtra, Bihar, Jharkhand and Delhi. NDMA's Heat Action Plan (HAP) provides a framework for Indian cities to protect their citizens from extreme heat. Ahmedabad was among the first city to prepare a heat wave action plan in 2015. The heat wave action plan aims to provide a framework for implementation, coordination and evaluation of extreme heat response activities in cities/towns in India that reduces the negative impact of extreme heat. The Plan's primary objective is to alert those populations at risk of heat-related illness in places where extreme heat conditions either exist or are imminent and to take appropriate precautions, which are at high risk. Preventive heat management and administrative action need to be taken by city administration authorities.

The heat wave action plan is intended to mobilize individuals and communities to help protect their neighbours, friends, relatives, and themselves against avoidable health problems during spells of very hot weather. Broadcast media and alerting agencies may also find this plan useful. Severe and extended heat waves can also disrupt general, social and economic services. For this reason, Government agencies will have a critical role to play in preparing and responding to heat waves at a local level, working closely with health and other related departments on long-term strategic plans. Details of strategies can be found in NDMA (2016). Some of the key components include:

- Establish Early Warning System and Inter-Agency Coordination to alert residents on predicted high and extreme temperatures.
- Capacity building/training programme for health care professionals at the local level to recognize and respond to heat-related illnesses, particularly during extreme heat events.
- Public Awareness and community outreach
- Collaboration with non-government and civil society organizations.

5.3   Criteria for Cold Wave

A cold wave is a meteorological event generally characterized by a sharp drop of air temperature near the surface, leading to extremely low values, steep rise of pressure and strengthening of wind speed, or associated with hazardous weather like frost and icing. It often causes severe impacts on human health, agriculture and high heating costs, and can even result in mortality for human beings and livestock.

As per the IMD terminology, a cold wave is considered when the minimum temperature is 10 °C or less for plains and 0 °C or less for Hilly regions (Smitha A Nair et al., this book).

In January 2017 entire north India was devastated by a cold wave. This occurrence had a severe effect on several North Indian states, including Himachal Pradesh, Jammu and Kashmir, Punjab, Harayana, Rajasthan, and Uttar Pradesh. The lowest temperature in Gulmarg due to the cold wave was recorded at − 12.4 C. The banks of Dal Lake in Srinagar froze. Keylong of Himachal Pradesh and Kargil of Jammu and Kashmir witnessed low temperatures of − 13.9 °C and − 15.6 °C, respectively. At least 40 people died as a result of the January 2017 cold wave.

During 10–15 Jan 2017, the entire northern part of India was under the grip of a severe cold wave spell. Figure 14 shows the observed and model predicted Tmin valid on 13 Jan 2017. As in the observations, model forecasts show a large part of northern and central India featuring the Tmin values lower than about 5 °C. The models could predict the cold waves 3–4 days in advance. Such model-based products are crucial for the forecasters to monitor and forecast severe cold wave events.

The NCMRWF Model forecast of maximum temperatures for all cases of Tmin < 10 °C is evaluated for an entire DJF season during 2016–17 (Fig. 15). The forecast verification is presented in the form of a spatial map of the Probability of Detection (POD) and Equitable Threat Score (ETS) in Fig. 15. The POD values higher than 0.6 clearly indicate high POD over large parts of central and northern India. The ETS values are relatively lower indicating relatively lower skill in predicting the lower Tmin values during winter.

6   Fog/Visibility

The impact of fog on the daily lives of human beings has significantly increased during recent decades due to increasing air, marine and road traffic. The financial and human losses related to fog and low visibility become comparable to the losses from other weather events such as cyclones. Fog and associated low visibility conditions over any region cause significant impacts on the human activities and adversely affect the economy (Gultepe et al. 2007). Fog events lead to deaths, damage to property and delays worldwide. The number of deaths in the USA in fog-related traffic accidents in the period 1982–1991 was more than twice that due to the combination of flash floods, hurricanes, lightning and tornadoes (Rosenfled 1996). The British Airports Authority
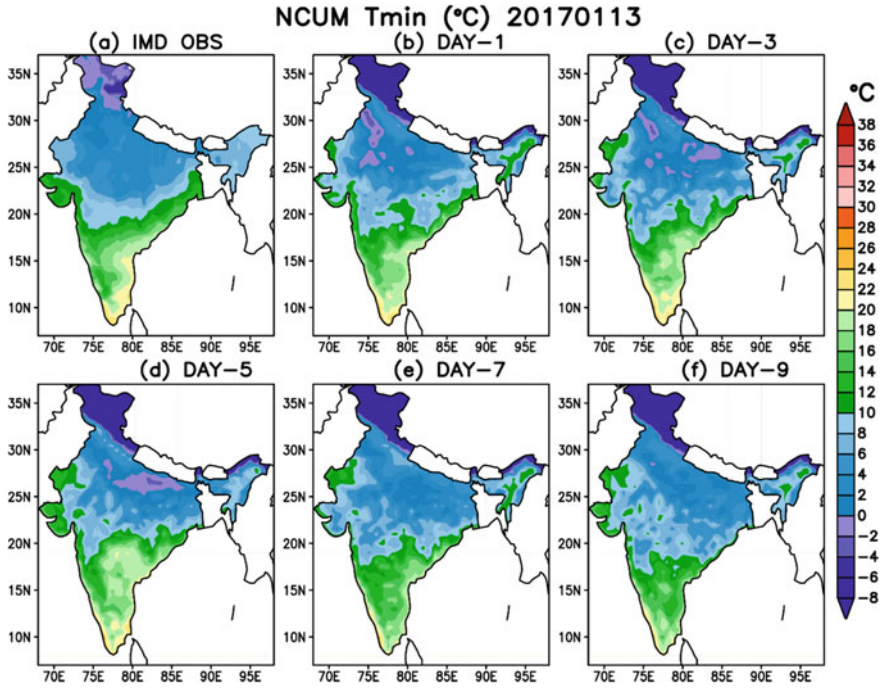
Fig. 14 Observed and model forecast T$_{min}$ on 13th Jan 2017
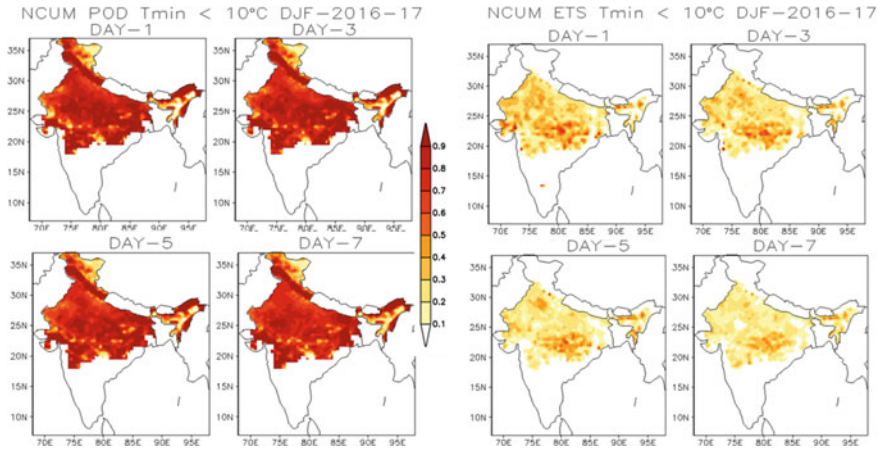
Fig. 15 Probability of Detection (POD;) and Equitable threat Score (ETS; right) for forecast T$_{min}$ < 10C during DJF-2016–17

cancelled nearly half the flights at Heathrow Airport in December 2006. The Indira Gandhi International Airport (IGIA) in New Delhi, experienced the highest number of fog hours during the months of December and January 2008–2009, which disrupted aviation services severely (Jenamani and Tyagi 2011).

The techniques for fog predictions can be categorized as manual, statistical and numerical modelling. In manual techniques, atmospheric profiles from radiosonde or numerical weather prediction (NWP) model and surface observations are interpreted at forecasting location to estimate fog point. Statistical techniques rely on a training period of data which connects forecast profiles, local observations and observed visibility. The prediction of fog with NWP models has long been a challenge and success is also very limited mainly due to the complex processes involved in fog formation. However, continuous efforts have been made in improving models for the accurate prediction of fog and visibility.

A number of 1-D models such as COBEL and Air Mass Transformation Model have achieved some success in forecasting fog. However, the utility of these models is limited in practice as they do not incorporate the large-scale meteorological conditions that affect the genesis, evolution and dissipation of fog. Thus, a three-dimensional (3-D) model which incorporates processes like horizontal pressure gradient, advection and diffusion is required for predicting fog. Mesoscale models such as Fifth-Generation NCAR/Penn State Mesoscale Model (MM5) and Weather Research Forecasting (WRF) were developed and used to forecast fog, especially the low visibility in fog by different researchers. These models use parameterization schemes to forecast visibility as they do not have detailed microphysical processes. The liquid water content (LWC)/ice water content (IWC), temperature or relative humidity is often used to parameterize visibility in these models.

There are operational models globally which predict visibility. The HIRLAM model at Danish Meteorological Institute (DMI) (Peterson and Neilson 2000) is one such model which predicts visibility at 2 m height using the variables such as relative humidity, temperature and cloud cover. The Rapid Update Cycle (RUC) model of the USA, calculates visibility from prognostic relative humidity, cloud and hydrometeor fields (Smironova et al. 2000). However, the visibility of any region also depends on the aerosol content of that region. In HIRLAM-DMI constant aerosol concentration is assumed whereas the RUC model neglects aerosol. The operational global model of NCMRWF known as NCUM also predicts visibility.

Visibility forecasts from NCUM are shared with India Meteorological Department (IMD) every year under the Forecast Demonstration Project (FDP) during the winter season (December–February). The spatial extent of fog over any area is identified using the satellite observations. Ground-based and conventional observational networks use horizontal visibility (Vis) to identify fog. If observed visibility at a particular location is $\leq$ 1 km, then it is considered as foggy (WMO manual 2003). Figure 16 shows the comparison of the visibility forecast from NCUM with INSAT-3D fog image and METAR visibility observations for 28 December 2014. Different types of fog are identified based on the visibility values. Visibility forecasts at Amritsar, Delhi, Lucknow and Varanasi are verified with METAR observations in Fig. 17.
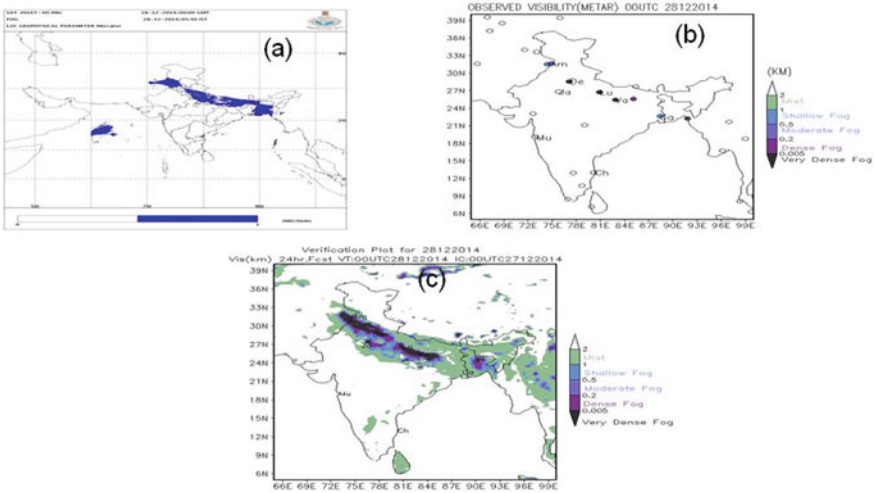
Fig. 16 Obsrved fog from **a** INSAT-3D, **b** Visibility from METARS and **c** Day-1 forecast of visibility from NCUM on 28th Dec 2014
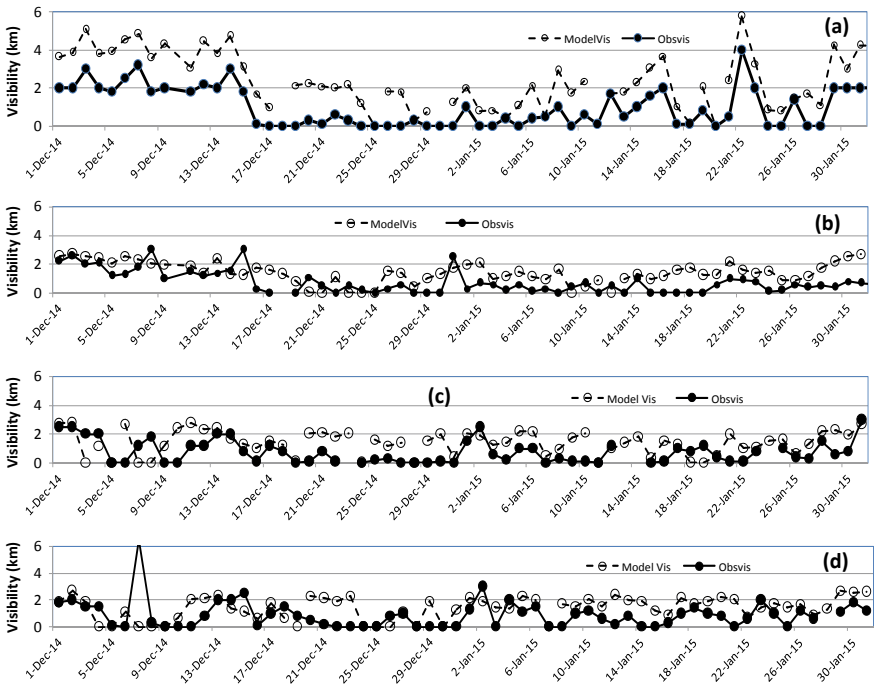
Fig. 17 Comparison of Day-1 forecasts of Visibility from NCUM with Observations at **a** Amritsar, **b** Delhi, **c** Lucknow and **d** Varanasi during Dec 2014–Jan 2015

7   Conclusions

Severe weather events often have devastating impacts on "local/regional" populations and their normal businesses. Understandably they are different in different geophysical environments Generally severe weather includes events like heavy rain, strong wind/wind gusts, hail, lightning, tornadoes, flash floods and extreme temperature. Some of the more localized events are snow storms, thunderstorms, dust/sand storms, sea swell/tsunamis/storm surge and extended area of fog for transport (aviation especially). Forecasting for severe weather events is of immense value since it can help alleviate (if not mitigate) the disastrous impacts to a certain extent. While accurate and precise forecasting is a great challenge, the advances in the recent decade in the NWP in India have shown improved accuracy and reliability in the forecasting capabilities, especially for severe weather events. This chapter has documented the glimpses of successful forecasting of severe weather events over India.

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