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Latest Approaches to Thunderstorm/Lightning and Severe Weather Forecasting using High Resolution Numerical Model

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ABSTRACT

In India, lightning is responsible for at least 10% of the total deaths caused by natural calamities. Recently, it is noticed that, there is an increasing trend of lightning activity due to combined positive effect of aerosol and thermodynamics. In this backdrop, there is an urgent need of developing a technique of forecasting lightning flashes during thunderstorms. This research has important implications for adopting proper precautionary measures over the Indian region. Here, we have computed Lightning Potential Index (LPI) as a measure of the potential for charge generation and separation that leads to lightning flashes, using best suitable physics and model strategies in a cloud resolving model. Guidance of Global Forecast System (GFS ~12.5Km) by deriving various thermodynamic indices has been achieved and based on these outlook, forecasting of lightning and thunderstorm event has been attempted using WRF-ARW model derived LPI in cloud resolving scale(1km). This study invokes the idea of initiating probabilistic forecast of lightning using GFST1534 and WRF in real time. Thus, it has a great societal importance for the aviation sector and public safety.

Keywords: *Lightning, Thunderstorm, Lightning flashes, Lightning Potential Index and Forecast.*

1. Introduction

Lightning discharge is a meteorological phenomenon and the result of electric activity in thunderstorms. Across the globe, it is a major cause of natural calamity; destroys public properties. Thunderstorms associated with lightning, gusty wind, rainfall and hail are one of the disastrous weather events that affect various parts of the Indian region mostly during the pre-monsoon months (March-April-May-June). Unfortunately, besides some purely empirical methods, there was hardly any mechanism which provides a forecast to issue a warning prior to the occurrence of lightning. In this present endeavor, there is a strong need of developing a technique of prediction of lightning, heavy winds and other associated parameters for adopting proper precautionary measures over the Indian region.

Lightning is known to have strong microphysical origin (Adamo et al., 2007) which is important for charge separation processes that helps in generation of electric field. It is generally believed that the charge centers in thunderclouds are located in the region where ice phase is actively involved in the electrification process (Saunders et al., 1994, 2006; Williams et al. 2002; Yair et al. 2008 and Siingh et al. 2008). In presence of supercooled liquid water, rebounding collisions between graupel particles and cloud ice crystals cause charge generations (Takahashi, 1978; Saunders, 2008). This non-inductive charging mechanism is widely believed to be the dominant process for the generation and separation of charge in thunderclouds (Mason and Dash, 2000; Mansell et al., 2005, Saunders, 2008). The electrical activity and rainfall are associated with the microphysics and dynamics of deep convective clouds (Williams et al., 1989). A positive correlation between lightning and precipitating ice in cloud is also reported (Sherwood et al., 2006, Deierling et al., 2008). Though there exists a conventional approach of forecasting the probability of TSs using thermodynamic instability indices (such as Lifted Index, K Index, Total-Total Index, Surface Lifted Index, Humidity Index, Bulk Richardson Number, CAPE, CINE and Cloud Physics Thunder Parameter etc.) (Mukhopadhyay et al., 2003), it is not based on the microphysics of charge separation in thunderclouds and eventually cannot resolve the cloud scale structures properly. Yair et al., (2008) and Khain et al. (2008) introduced an index called, Lightning Potential Index (LPI), which is a measure of the potential for charge generation and separation that leads to lightning flashes in convective TSs. Lynn and Yair, (2010) also proposed that from the model simulations the LPI can be used to predict the lightning flashes. Although it is an empirical relation since it consists of cloud-microphysical parameters and therefore should be independent of geographical location. Forecasting the electrical activity of a storm is a difficult task primarily because of the complex electrical structure of a thundercloud, which depends on the result of microphysical and macrophysical processes occurring simultaneously within the clouds (Saunders, 2008). These processes are poorly resolved in numerical models. As the explicit prediction of the electrical activity in storms is computationally expensive, these complex electrical processes are not incorporated into atmospheric models (Barthe et al. 2010, Zepka et al. 2014). Till now, the numerical forecast of lightning is not perfect in terms of location and timing as compared to observation. Owing to its high economic impact, heightened emphasis has been laid all over the world in the last two decades towards improving the community's ability to forecast lightning using numerical weather prediction (NWP) model (McCaul et al. 2009, Wong et al. 2013, Giannaros et al. 2015).

It is evident that the Indian subcontinent (see their Figure 6(b), Christian et al., 2003) is a lightning prone region (mainly East Central India (CI), North-East India (NE) and Southern Peninsula (SP) (Rao and Raman, 1961; and Litta and Mohankumar, 2007) with varied lightning intensities associated with TSs. The TSs also depict a wide range of characteristics over different parts of India (Mukhopadhyay et al. 2005; Halder and Mukhopadhyay, 2016). In the absence of any systems to provide guidance of lightning especially to village and urban population, the society is vulnerable to this natural menace. Keeping this in background, it is felt that a large scale NWP guidance of lightning and severe weather phenomenon using numerical model like Global Forecast System (GFS ~ 12.5Km) GFS could be worth exploring and then detailed forecast of the guided probable region of storm using WRF model in cloud resolving scale(1km) may add a valuable direction for the forecasters. Application of state-of-the art numerical model and its sensitivity to different microphysical schemes have been tested for TSs over India by several researchers (Rajeevan et al. 2010; Halder and Mukhopadhyay, 2016). However, an approach based on the estimation of LPI has not been attempted so far using hydrometeors as proxy parameters for Indian region. In this study, with the use of GFS and WRF-ARW cloud resolving model (in 1km), an attempt has been made to develop a frame work to make forecast of severe storm at least 1day in advance. Calculating conventional indices like (K Index, TT Index, Cape, Layer Mean Relative Humidity, SWEAT index, wind gust and Supercell composite parameter (SCP) from short range forecast of GFS a probable area and time of occurrence of severe storm can be guessed. To make a more space-time specific accurate prediction, initialized with GFS initial and boundary conditions with appropriate physics options prediction of conventional indices, maximum reflectivity, lightning potential Index by WRF-ARW model has been achieved in 1 km.

2. Data, Model Design and Methodology

2.1 Data and model used in the present study

The non-hydrostatic, fully compressible Advanced Research Weather Research and Forecasting (WRF-ARW) (Skamarock et al., 2008), atmospheric model, version 3.7.1 developed by National Center for Atmospheric Research (NCAR) is used in this present study. The model is run in four domains with 27, 9, 3 and 1 km as horizontal resolution. Calculation of LPI is performed using model derived dynamical and microphysical parameters. Experiments started with initializing with GFS analysis as initial condition of (0.5^0 X 0.5^0) resolutions with random combination of different physics parameterization options. The model showed very less skill with these combinations. In order to further improve the skill of the model,

Table 1. Different sensitivity Experiments conducted using WRF model to find a suitable combination of different physical parameterization schemes for thunderstorm prediction. (Bold letters indicate the final chosen configuration)

Initial Condition Sensitivity	1. GFS Analysis (0. 5^0 X 0.5^0) 2. GFS Forecast (0.25^0 X 0.25^0) 3. **GFST1534 Forecast (0.125^0 X 0.125^0)**
Planetary Boundary Layer Scheme	1. **Yonsei University (YSU)** 2. Mellor-Yamada-Janjic(MYJ) 3. Quasi-Normal Scale Elimination(QNSE)
Microphysics Sensitivity	1. **Morrison** 2. Thompson 3. WDM6
Cumulus Sensitivity	1. **Kain Fritsch(KF)** 2. Betts-Miller-Janjic (BMJ) 3. Grell-Freitas Ensemble (GF)
No of vertical levels	1. 31 2. **45** 3. 52
LU/LC data	1. USGS 2. **MODIS** 3. NRSC

Microphysics, Cumulus Parameterization sensitivity experiments (Table 1) are conducted simultaneously. Morrison microphysics (Morrison, 2005) and KF *(*Kain, 2004*)* cumulus scheme's performance was satisfactory and this configuration is fixed for further sensitivity experiments of PBL schemes. YSU, being better among other PBL schemes, is used for initial and boundary condition data sensitivity experiments. GFST1534 (res ~12 Km, Global Forecast System (Mukhopadhyay et al., 2019) now run by India Meteorological Department (IMD) as initial and boundary conditions gave better results over GFS analysis initial conditions and same is used to carry out the vertical level sensitivity experiments. The boundary conditions are updated every 3hourly with GFST1534 forecast fields and output is saved at 30min interval. Proper representation of Land Use and Land Cover (LU/LC) is also important for improving the model skill. Finally, 45 vertical levels and best combination (Morrison-KF-YSU-GFST1534), are used for LU/LC sensitivity. Thus MODIS and NRSC LU/LC give similar results. In this region, thunderstorms mainly occur in afternoon time. Experiments with the initialization time both with 00UTC of same day and 12UTC of earlier day are also tested. Model performance is better in producing forecast of lightning with 12 hours lead time with 00UTC GFST1534 initial condition. Doing several sensitivity experiments of physical parameterization schemes, best suitable scheme is decided and then with these combinations numerous thunderstorm events have been simulated. Details of the physical parameterization schemes used in these experiments are provided in ST-1.

2.2 Methods for the calculation of LPI

It is evident that production of cloud ice and mixed-phase hydrometers is imperative for correct estimation of LPI (Yair et al., 2008). LPI has been calculated using WRF model output with existing explicit microphysical schemes (discussed in Section 2.1). For that, model simulated grid scale updraft velocity and microphysical fields within the charge separation region of clouds between (0 oC and - 20 ^{o}C) are utilized in offline mode, where the non-inductive mechanism involving collisions of ice and graupel particles in the presence of supercooled water is most effective (Saunders, 2008). LPI is defined as the volume integral of the total mass flux of ice and liquid water within the "charging zone" in a developing thundercloud in units of (J kg^{-1}) as per Lynn and Yair, (2008). The calculation of LPI depends on the vertical velocity and also the function of cloud hydrometeors (mixing ratio of cloud ice, snow, graupel and cloud water). The formulation of ice fractional mixing ratio for LPI derivation is obtained from Lynn and Yair (2008*)*. The evolution of LPI (space and time) from the cloud-resolving model can also provide probabilistic forecast of lightning flashes. The formulations used in these experiments to derive LPI are provided in Appendix-1.

2.3. Method for calculation of Supercell Composite Parameter (SCP)

As per Carbin et al. (2015), SCP is defined as:

$$SCP = \frac{CAPE}{1000} Jkg^{-1} \times \frac{SRH}{50} m^{-2}s^{-2} \times \frac{BWD}{20} ms^{-1}$$

Here CAPE is calculated within 0–180-hPa-layer above ground (which is “most unstable”), Storm Relative Helicity (SRH) is calculated between 0-3km, Bulk Wind Shear (BWD) is computed from the u and v winds between model’s two levels such as 0–30-hPa-above-ground and 500 hPa. SCP ≥ 1 are associated with environments conducive to thunderstorm updraft persistence and rotation.

3. Results and Discussion

From early researches (Penki and Kamra, 2013) and (Halder and Mukhopadhyay, 2016) we know that, wide ranges of meteorological and environmental conditions and their interactions with topography of land surface and terrain heights modulate the convective motions of the atmosphere. These lead to the formation of thundercloud with great diversity in their microphysical and dynamical characteristics in different TS prone regions of India (Halder and Mukhopadhyay, 2016). Lightning Location Network data mainly obtained over Southern Peninsula for the period 2017 and 2018 gives the detail characteristics, diurnal variations of the storm. Keeping the in homogeneities of the storm behavior in mind, their model timing strategies are adopted in this current research. The simulations of lightning events occurred during pre-monsoon (March, April and May) months of 2017

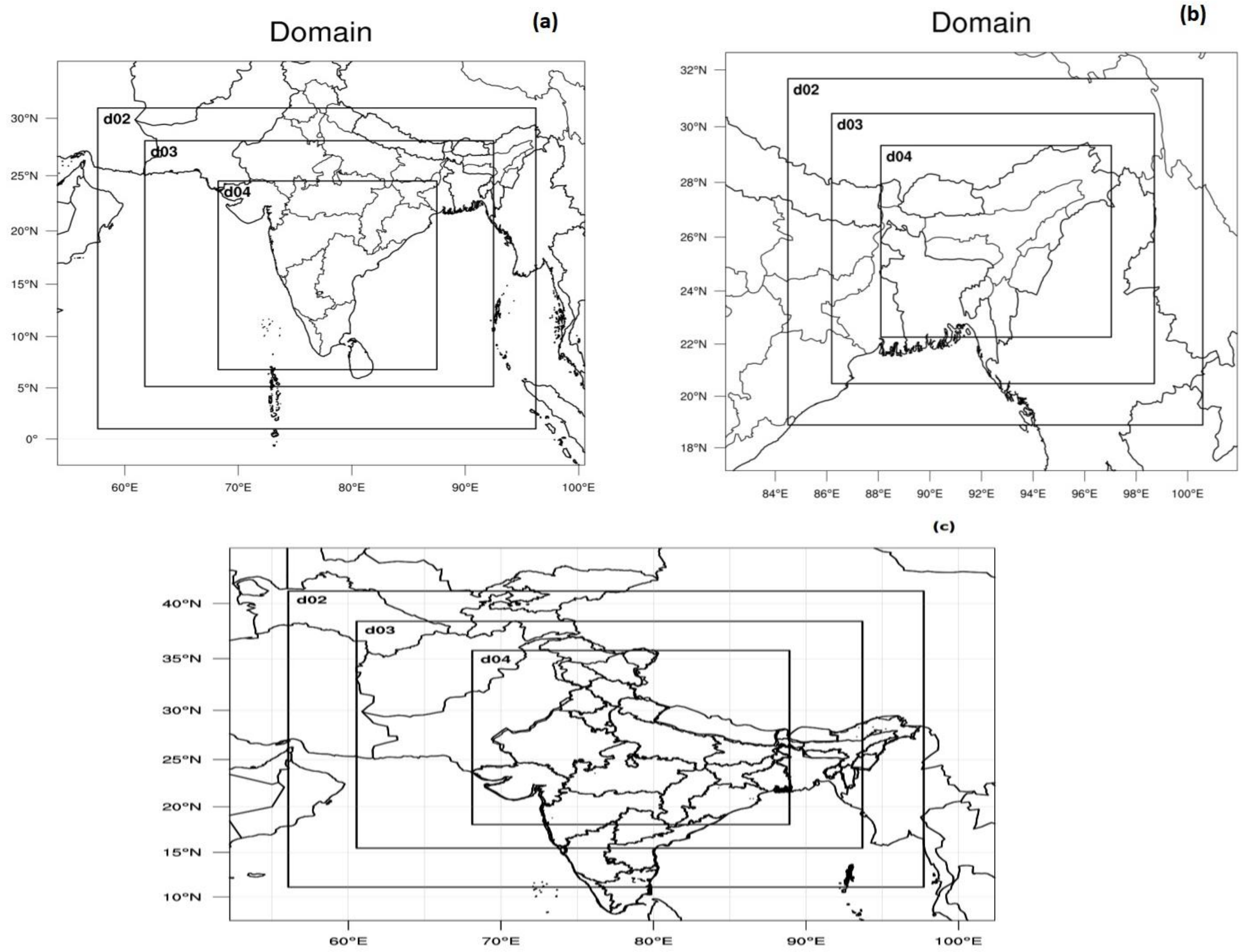

Figure 1: WRF model domain configuration for 24 Apr2018 in (a) Southern Peninsula & (b) North East India and 13May 2018 (c) North India.

and 2018 over India have been carried out using WRF-ARW V3.7.1 with initial and boundary conditions from GFST1534 (~12.5km) for these different regions (namely, Southern Peninsula (Figure 1a), North East India (Figure 1b) and North India covering Northwest and Central India (Figure 1c). The impacts of initial conditions are tested for the events both at 00UTC and 12UTC initial and boundary conditions. The probable lightning prone regions are verified with observed lightning obtained from Lightning Location Network (LLN) data. LLN can accurately detect the location of occurrence of lightning and forewarn the public at least 1-2 hours prior to the occurrence of the thunderstorm. After this numerous experiments, best suited model configuration and physics options are finalized and based on that, forecast of TS and lightning is achieved. Analyzing the severity and spread of thunderstorm and lightning over different regions, experiments for two TS events are showed here.

From FDP report obtained from IMD and satellite figures obtained from Kalpana and JAXA Real Time Rainfall Watch the detailed characteristics of these storms are found. From the realized past 24 hours TS data mentioned in FDP report, IMD, it is known, that TS associated with squall and lightning occurred during 1300 IST to 20.30 IST of 24th April, 2018, over various parts of southern peninsula namely coastal Karnataka, stations like Bengaluru and surrounding North and South Interior Karnataka region. At Bengaluru, during 1400 IST to 1430 IST there was a squall. In Figure 2a, observations from satellite cloud cover (overlapped with the clod top temperatures in red contours) around 1700 IST showed that there is a deep convective system in coastal Andhra Pradesh and South and Interior Kerala and Karnataka. 24 hour accumulated Lightning Location Network (LLN) data shows (Figure 2e) the presence of vigorous lightning activity over coastal Andhra Pradesh, South and Interior Kerala and Karnataka. An attempt has been adopted to provide large scale guidance using GFS model output. Supercell Composite Parameter (SCP) Index has been calculated. Due to page limitation, SCP at only 13UTC i.e., around 1830 IST has been shown in Figure 2b. GFS at 12.5 Km also could capture the convective event. From Carbin et al 2016, SCP>=1 is associated to environments conducive to thunderstorm updraft persistence and rotation. WRF-ARW at 1 Km also could capture the event realistically. Accumulated LPI for 05UTC to 15UTC shows there is proven probability of lightning in coastal region of Andhra Pradesh, Interior Karnataka, and Kerala. In many regions, LPI is nearly 10 or higher, showing deep convection (Figure 2c). LPI, from FDP report it is also noticed that on 24th April, there was thunderstorm and lightning in North Eastern State mainly in Gangtok, Guwahati, Agartala. LPI obtained from cloud resolving simulation of North Eastern India also realistically capture the event. Figure2d shows around Gangtok, Jalpaiguri, Kuwahati, Agartala, Lengpui, Shilchor, highest likelihood of lightning by the accumulated LPI during the time period 05UTC-15UTC, which has occurred in reality also. As the sensors of LLN were not fully operational in North East India during April 2018, lightning activity was not observed in LLN data.

On 13th May 2018, there was vigorous convective activity in whole North India, covering Punjab, Uttar Pradesh, Jharkhand, Chhattisgarh, South West Bengal etc. According to IMD report (shown in Table 2) rain and thundershower along with gusty wind observed over at most places over Uttarakhand, East Uttar Pradesh, Bihar, Jharkhand, West Bengal, at many places over Himachal Pradesh, Chattishgarh and few places over Jammu & Kashmir, West Uttar Pradesh, Haryana, Delhi, East Madhya Pradesh, Orissa and isolated paces of Punjab and West Madhya Pradesh Figure 3a is the satellite cloud picture obtained from JAXA Real Time Rainfall watch at 1500UTC. This depicts that there is deep convective cloud all around the Northern and central states along with Orissa and West Bengal. SCP obtained from GFS also shows the similar pattern all over the observed convective regions showing threat of occurring thunderstorm and lightning. Here in Figure 3b, GFST1534 model forecasted SCP index at 15UTC of 13May18 with initial condition 00UTC13May18 has been shown. WRF in 1 km initialised with 00UTC GFST1534 initial conditions also could capture this event realistically. Figure 3b shows the probable zone of lightning during 03 UTC 13 May 18 – 03 UTC 14 May 18, which closely match with the observed locations of convective activity in satellite image and IMD’s observed weather table (Table 2). The severity of lightning also captured by LPI >10 J/kg at many places. Thus these approaches of large scale NWP guidance by GFST1534 and forecast of LPI by WRF in cloud resolving scale may add valuable inputs to the forecasters in real time, which has a great societal benefit.

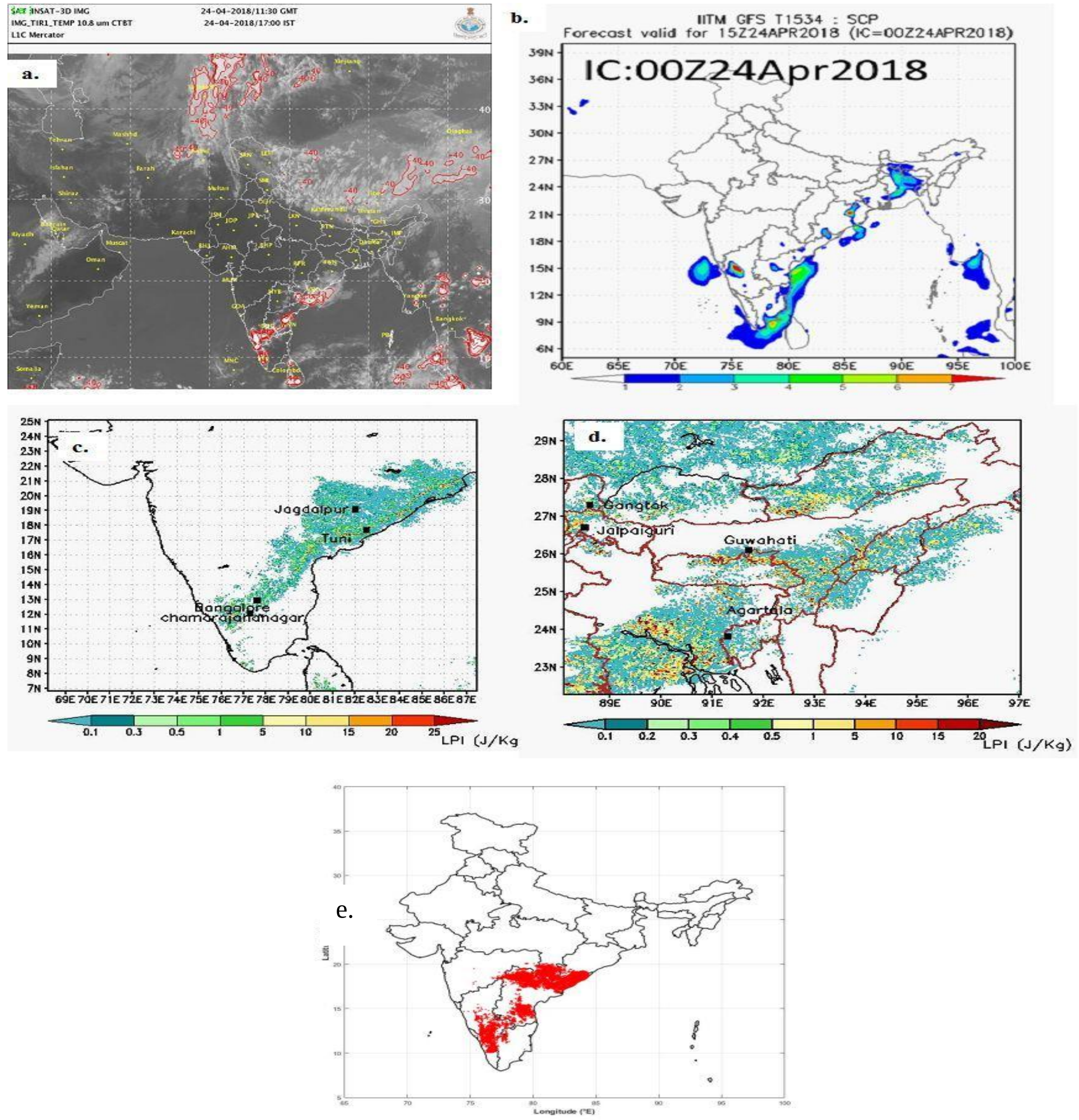

Figure 2: (a) INSAT-3D Satellite cloud picture (overlapped with the cloud top temperature contours in red color. Contours represent the cloud top temperatures less than -40^{0}C) at 11.30 UTC of 24 April 2018 b) GFST1534 model forecasted Supercell Composite Parameter (SCP)) index at 15UTC of 24April 2018 with initial condition 00UTC 24Apr2018. WRF model forecasted accumulated Lightning Potential Index (LPI) from 05UTC-15UTC of 24April 2018 for (c) Southern Peninsula India and (d) East India. (e) Total observed Lighting obtained from LLN data on 24 April 2018.

Table 2. Weather according to IMD, during past 24 hours ending at 8.30 IST of 14th May 2018.

S. No	Sub-Division	Forecast Warnings	Realized weather (highest rain at 0830hrs of 14May2018)
1.	Andaman& Nico Island		
2.	Arunachal Pradesh		
3.	Assam & Meghalaya	TS+GW	TS+GW
4.	Naga Mani, Mizo& Tripura		
5.	Sub-HIM W. Beng &Sikkim		
6.	Gangetic West Bengal	TS+GW	TS+GW (Canning-6)
7.	Odisha	TS+Squall	TS+GW (Chandbali-6)
8.	Jharkhand	TS+GW	TS+GW(Daltanganj-2)
9.	Bihar		
10.	East Uttar Pradesh	TS+GW	TS+Squall(Gorakhpur-3)
11.	West Uttar Pradesh	TS+GW	TS+Squall(Barelly-2)
12.	Uttarakhand	TS+Squal	TS+Squall
13.	Haryana CHD & Delhi	TS+GW	TS+GW+Squall (Ambala-2)
14.	Punjab	TS+GW	TS+GW (Patiala-1)
15.	Himachal Pradesh	TS+Squall	TS+GW (Solan-3)
16.	Jammu &Kashmir	TS+GW	TS+GW
17.	West Rajasthan	DS	DS
18.	East Rajasthan	DS	DS
19.	West Madhya Pradesh	TS+GW	TS+GW
20.	East Madhya Pradesh	TS+GW	TS+GW
21.	Gujarat Region D.D. & N.H		
22.	Saurastra Kutch & Diu		
23.	Konkan & Goa		
24.	Madhya Maharashtra		
25.	Marathawada		
26.	Vidarbha	TS+GW	TS+GW
27.	Chattishgarh	TS+GW	TS+GW
28.	Coastal Andhra Pradesh	TS+GW	TS+GW
29.	Telangana	TS+GW	TS
30.	Rayalseema	TS+GW	TS+GW
31.	Tamilnadu &Puducherry	TS+GW+HR	TS+GW(Kakinada-3)
32.	Coastal Karnataka		TS+GW(Mangalore-5)
33.	North Int Karnataka		TS+GW(Belgum-5)
34.	South Int. Karnataka	TS+GW	TS+GW
35.	Kerala	TS+GW+HR	TS+GW (Thiruvananthapuram-6)
36.	Lakshadwep		

Legends: TS= Thunderstorm, GW= Gusty winds and HR=Heavy Rain

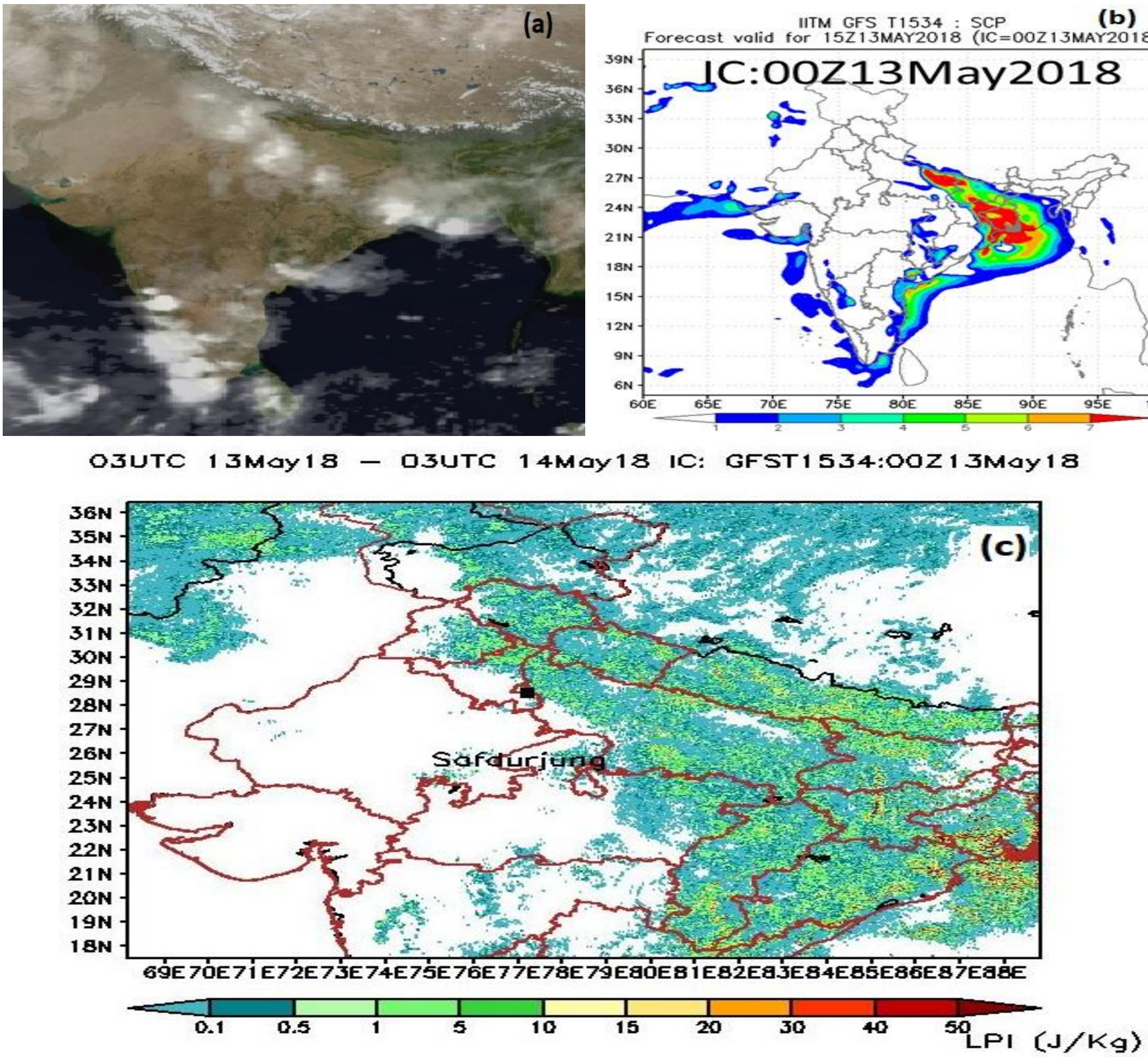

Figure 3: (a) Satellite cloud picture obtained from JAXA Realtime Rainfall watch at 15UTC of 13May 2018, (b) GFST1534 model forecatsed Supercell Composite Parameter (SCP) index at 15UTC of 13May 2018 with initial condition 00UTC13May 2018. (c) WRF model Forecasted 24hrs accumulated Lightning Potential Index (LPI) from 03UTC 13May to 03 UTC 14May for North India.

4. Conclusions

Combination of a day ahead guidance of large scale GFST1534 model derived SCP and WRF-ARW derived LPI in the cloud resolving scale can predict the thunderstorm and associated lightning events realistically. In this study, it is found that the performance of initial conditions at 00UTC for the forecasting of thunderstorm event at various regions is reasonably well. Generally, to avoid the cold start problem, 6 hour spin up is needed. The finding from this study highlights that using LPI index obtained from WRF in cloud resolving scale lightning events can be predicted at least in 12 hours advance and warning and mitigation strategies can be developed well in advance. Large scale guidance using SCP also will help in guessing the probable zone and time of convective activity. This study can set the pathway of the idea of initiating probabilistic forecast of lightning using Global Ensemble Forecast System T1534 (GEFST1534) and WRF in real time. Finally, we may conclude that our results highlight the strong need of proper model strategy, better initial conditions and suitable physics options in the model for better lightning forecast.

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Appendix 1: Formulation for LPI calculation

The basic formulation is as follows [*Lynn and Yair* 2008; *Yair et al. 2010*]:

$$LPI = \frac{1}{V}\iiint \in \omega^2 dxdydz \qquad (1)$$

Here, V is the volume of air in the layer between 0^oC and -20^oC, ω is the vertical wind component (m s^{-1}), and $\in$ is the function of cloud hydrometeors like q_s, q_i and q_g are the model-computed mass mixing ratios for snow, cloud ice, and graupel respectively (in kg kg^{-1}). $\in$ is a dimensionless number that has a value between 0 and 1 and is defined by [*Lynn and Yair* 2008] as

$$\in = 2\left(Q_i Q_l\right)^{0.5} / \left(Q_i + Q_l\right) \qquad (2)$$

Q_l is the total liquid water mass mixing ratio (kg kg-1) and Q_i is the ice fractional mixing ratio (kg kg-1) defined by [*Lynn and Yair* 2008] as

$$Q_i = q_g \left[\left(\left(q_s q_g\right)^{0.5} / \left(q_s + q_g\right)\right) + \left(\left(q_i q_g\right)^{0.5} / \left(q_i + q_g\right)\right)\right] \qquad (3)$$

In essence, $\in$ is a scaling factor for the cloud updraft and attains a maximum value when the mixing ratios of supercooled liquid water and of the combined ice species (the total of cloud ice, graupel, and snow) are equal. Calculation of the LPI from the cloud-resolving atmospheric model output fields can provide maps of the microphysics based potential for electrical activity and lightning flashes.