Seasonal Predictability of Lightning Over the Global Hotspot Regions

Chandrima Mallick1,2, Anupam Hazra1, Subodh K. Saha1,2, Hemantkumar S. Chaudhari1,2, Samir Pokhrel1, Mahen Konwar1, Ushnanshu Dutta1,2, Greeshma M. Mohan1, and K. Gayatri Vani1

Abstract  Skillful seasonal prediction of lightning is crucial over several global hotspot regions, as it causes severe damages to infrastructures and losses of human life. While major emphasis has been given for predicting rainfall, prediction of lightning in one season advance remained uncommon, owing to the nature of problem, which is short-lived local phenomenon. Here we show that on seasonal time scale, lightning over the major global hotspot regions is strongly tied with slowly varying global predictors (e.g., El Niño and Southern Oscillation). Moreover, the sub-seasonal variance of lightning is highly correlated with global predictors, suggesting a seminal role played by the global climate modes in shaping the local land-atmosphere interactions, which eventually affects seasonal lightning variability. It is shown that seasonal predictability of lightning over the hotspot is comparable to that of seasonal rainfall, opens up an avenue for reliable seasonal forecasting of lightning for special awareness and preventive measures.

Plain Language Summary  Lightning, atmospheric hazards have an impact on the loss of human life, forest fire, health, agriculture, and economy across the globe. However, due to its chaotic nature, the tendency of seasonal forecasting of lightning is considered not viable as the understanding of the predictability of lightning is still incomplete. Here, we have explored the possibility of seasonal forecasting of lightning activity and provided a scientific basis as the lightning flashes are found to be tied with slowly varying remote forcings (e.g., El Niño and Southern Oscillation, or other global predictors). Correlation of flash count with different indices (Nino, Pacific decadal oscillation, North Atlantic oscillation, and Extra tropics, etc.) demonstrate the potential of seasonal forecasting of lightning. The multiple regression analysis enhances the skill. The climatology of lightning flash density from the Goddard Earth observing system model is compared with observation. The pattern correlation between observation and model is very high (∼0.7) over global tropics hints at the predictability of lightning flashes on a seasonal time scale. Therefore, better climate models that capture crucial couplings between ocean, atmosphere, and land processes could make skillful predictions of lightning and opens up a possibility for lightning forecast in one season advance.

1. Introduction

Lightning is one of the most powerful, all-pervasive atmospheric hazards. Lightning fatalities over India (Mahapatra et al., 2018; Accidental Deaths and Suicides in India (ADSI) Report, Govt. of India) result in severe societal and economic consequences as lightning affects aviation, telecommunication, agriculture, electricity, and many more sectors. Keeping in mind the lifetime injuries, physiological trauma, disabilities that are caused by lightning (e.g., Mahapatra et al., 2018; Singh and Singh, 2015), an accurate or better formulation of predicting lightning activities is of utmost significance. The major question asked here is whether the global hotspots of lightning activities across the globe are associated with the remote forcing for example, El Niño and Southern Oscillation (ENSO), Pacific decadal oscillation (PDO), North Atlantic oscillation (NAO), Atlantic multidecadal oscillation (AMO), and extra tropics (ET).

The seasonal forecasting of hail and tornado occurrence, which are the severe weather phenomena associated with the deep convective systems are examined over the United States of America (Elsner & Widen, 2014; Wu et al., 2011). Lightning activity is also a typical phenomenon of severe weather characterized by strong convection (van den Broeke et al., 2005), where instability, strong vertical updraft, wind shear, and availability of moisture are the primary conditions. The higher predictability of tropical climate than extra tropics was laid
by the scientific basis of pioneering work on Indian summer monsoon (ISM) predictability by Charney and Shukla (1981). The large heat capacity in the ocean can give the climate system a memory, which can affect the atmospheric deviations lasting for months to years and the scientific basis of prediction lies in the predictability established by the conditions of the ocean and land surface (Wang et al., 2005). The physical basis for seasonal prediction in the tropics is that the low-frequency component of variability is primarily governed by slowly varying boundary forcing (e.g., sea surface temperature (SST), soil moisture, snow cover, and more; Charney & Shukla, 1981).

Recent studies have also unraveled that the high-frequency sub-seasonal fluctuation of ISM rainfall (ISMR), so far considered chaotic, is partly predictable as it is tied with ENSO (Dutta et al., 2021; Saha, Hazra et al., 2019; Saha, Konwar et al., 2021). In recent years, the associations of lightning and thunderstorm activities with the ENSO and various other large-scale modes of atmospheric and oceanic variability such as NAO, the Quasi-Bien- nial oscillation, and the Indian Ocean dipole (IOD) are reported (Bovalo et al., 2012; de Pablo & Soroiano, 2007; Dowdy, 2016). Dowdy (2016) has demonstrated that ENSO has the strongest relationship with lightning activity and a weak relationship with other modes of variability during each season. Chronis et al. (2008) have also shown the relationship of global lightning climatology in response to the ENSO cycle. Thus it is revealed that lightning and thunderstorm activity are predictable for several months in advance in various regions throughout the world including the region of the tropics (Dowdy, 2016; Lopez, 2016). Muñoz et al., (2016) highlighted that the predictive skill of lightning density is higher than typical values for rainfall amounts in North-Western Venezuela regions.

Over the Indian subcontinent, lightning flashes mostly occur during the pre-monsoon and post-monsoon season due to favorable atmospheric conditions, for example, instability in the atmosphere, strong vertical updraft, wind shear, and availability of moisture (Barth et al., 2012; Barthe et al., 2010; Kamra, 1985; Latham et al., 2004; Mohan et al., 2021). The flash rate is assumed to be proportional to the maximum vertical updraft velocity, fourth power of cloud dimension (where graupel exists along with snow, ice, and cloud water), and also becomes directly proportional to the fifth power of the cloud top height (Williams, 1985). Seasonal distributions of lightning activity have been explored in several studies (Kandalgaonkar, 2005; Ranalkar and Chaudhari, 2009; Tinmaker et al., 2010). In the El-Niño (La-Nina) period of the pre-monsoon and monsoon seasons over India, there is an increase (decrease) in the flash density as compared to the Non-ENSO period (Ahmad & Ghosh, 2017; Ramesh Kumar and Kamra, 2012; Sreenath et al., 2021). In another study, Kulkarni (2015) has revealed that for rainfall prediction atmospheric electricity can be used as a proxy parameter.

Therefore, in the present endeavor, we attempt to find the potential feasibility of reliable seasonal forecasting of lightning over global hotspots along with India as a sub-set. Here, we seek the predictability of seasonal lightning and not the maximum prediction limit. The following questions are attempted to address here:

1. Is there any correlation of lightning over different global hotspots with different indices (Niño, NAO, PDO, AMO, and ET)?
2. Are the seasonal occurrences of lightning activities over global tropics and India is associated (i.e., teleconnection) with slowly varying predictable components (e.g., SST over Niño areas or any other global predictors, NAO, PDO, AMO, and ET)?
3. Whether sub-seasonal variance (i.e., a vigor of convection) is linked with slowly varying predictable components (e.g., SST over Niño areas or any other global predictors, NAO, PDO, AMO, ET, and more)?

The hypothesis is that lightning flashes can be predicted if the mean and sub-seasonal fluctuation is found to be tied with slowly varying remote global predictors. Here, we have tried to investigate the possible relationship of lightning with the large-scale modes of variability (i.e., ENSO, NAO, PDO, AMO, ET, and more) as these phenomena are predictable at least a season well in advance.

2. Data and Methods

The satellite-based two lightning sensors on the tropical rainfall measuring mission (TRMM) satellite: Lighting imaging sensor (LIS) and optical transient detector (OTD) from NASA (Cecil et al., 2014) are used in this study from 1997 to 2013 (17 years). The daily gridded lightning flash densities generated from a combination of the LIS and OTD data (available from http://thunder.nsstc.nasa.gov; Blakeslee, 2021; Mach et al., 2007) which has a spatial resolution of $2.5^\circ \times 2.5^\circ$ is used to elucidate the distribution of lightning strikes, it’s mean and variability.
The year-to-year variation in the mean lightning flash counts for March to May (MAM) and June to September (JJAS) seasons are evaluated over the study regions. The interannual variability of lightning flash can give an insight into the year-to-year variation of lightning on the seasonal time scale. The observational data sets of SST from HadISST (Rayner et al., 2003) are used to understand the relation of lightning with large-scale processes. It is well known that lightning has a strong relationship with cloud top temperatures (CTTs) (Liu et al., 2012). Therefore, the CTT data from Modern-Era retrospective analysis for research and applications version 2 (MERRA2; Gelaro et al., 2017) are also used to find the correlation with large scale predictors (i.e., SST) over the global tropics. Posselt et al. (2012) have shown that CTT from MERRA-analyzed exhibit good agreement with Clouds and the Earth’s radiant energy system data. The rainfall data from the global precipitation and climatology project (GPCP; Adler et al., 2003) is also used to calculate the correlation with lightning. The JJAS mean climatology of rainfall from GPCP is compared with TRMM data. The pattern correlation of rainfall between these two products over central India (lon: 72°E–88°E; lat: 18°N–28°N) and all India (lon: 70°E–90°E; lat: 10°N–30°N) region is ~0.97. Pattern correlation over the global tropics ((lon: 0–360; lat: 40°S–40°N) is ~0.99 (Dutta et al., 2021). The data of fatalities over India due to natural disasters are obtained from the “ADSI Report” published by National Crime Records Bureau (NCRB) data, Govt. of India ([https://ncrb.gov.in/] for the years 2002–2019 (36th to 53rd series). Merchant et al. (2019) have shown that the teleconnections are large-scale atmospheric variability patterns that result from changes in slowly varying forcing mechanisms like SST, soil moisture, etc. The climatic relationships or teleconnection with global predictors like ENSO, NAO, AMO, PDO, and ET of certain variables over large distances may provide predictability of those variables (Borah et al., 2020; Chattopadhayay et al., 2015; Mock, 2014). The multiple linear regression analysis is also used to present the combined indices. The combined effect of different indices (e.g., ENSO, NAO, AMO, PDO, and ET) on flashes of lightning (FL) can be obtained by the multiple linear regression analysis techniques. The multiple linear regression analysis (Alexopoulos, 2010; Saha, Konwar et al., 2021) has been applied in this study as shown in the following Equation 1:

$$FL = C_0 + C_1Nino_{1+2} + C_2Nino_3 + C_3Nino_{3.4} + C_4NAO + C_5AMO + C_6PDO + C_7ET,$$

where $C_0$ = intercept and $C_1, C_2, \ldots, C_7$ = Regression coefficients.

3. Results

3.1. Seasonal Mean Climatology of Lightning Over Global Hotspot Regions and Lightning Variability of the Indian Subcontinent

The seasonal mean climatology of lightning flashes over major hotspot regions over global tropics and India are represented in Figures 1a and 1b and Figures 1c and 1d during MAM and JJAS respectively. Two major global lightning hotspot regions are selected over North America (Region 3: 110°W–71°W; 5°N–43°N) and Africa (Region 4: 8°E–35°E; 12°S–15°N) as shown in Figures 1a and 1c. Similarly, over India two more lightning hotspot regions are identified: (a) East and north-East (Region 1: 82°E–94°E; 20°N–28°N) (b) North-West (Region 2: 68°E–80°E; 25°N–38°N), which are marked in Figures 1b and 1d. These lightning global hotspots are consistent with earlier studies (Choudhury et al., 2020; Zipser et al., 2006; and references therein). The lightning flash density is also calculated following Finney et al. (2014) and Stolz et al. (2021) from (Goddard Earth observing system, GEOS) model to compare MAM and JJAS climatology with observation (Figures 1e–1h). We have used 17 years (1997–2013) data from the GEOS model, and a brief description of the model is presented in the supporting text. There is a marginal underestimation in the lightning flashes calculated from the model as compared to observation, which may be due to the biases in many climate models to capture deep convection realistically (Dutta et al., 2021; Hazra et al., 2017). The pattern correlation between observation and model is high over the global tropics (~0.71 in MAM and ~0.68 in JJAS, Figures 1e and 1g) and the south Asian region (~0.62 in MAM and ~0.54 in JJAS, Figures 1f and 1h). This result shows that lightning may be predictable on a seasonal time scale as it is linked with global predictors. The lightning flash density from observation and model is shown over continent only (ocean masked). It is also important to note that although the total accidental deaths due to natural disasters (e.g., Cyclone, flood, heat, and cold wave, lightning, landslide) over the Indian subcontinent decreases due to the advancement of technology and forecast system particularly cyclone, flood, heat, and cold wave, but deaths due to lightning is still increasing over the years (Figure 2a) and percentage of death increases (red line; Figure 2a) in recent years. The increasing trend of the percentage of death due to lightning (death due to lightning/total death by all-natural disasters × 100) has emerged as a new challenge of policymakers in recent
years (red line; Figure 2a). Therefore, seasonal prediction of lightning may achieve new importance for effective preparedness and mitigation activities.

To understand the usefulness of the lightning prediction in seasonal time scale over India, which is a sub-set of global lightning hotspot regions, first the year to year variation of seasonal mean lightning flash (averaged over Region 1 and Region 2) is analyzed for MAM (Figure 2b) and JJAS (Figure 2c) seasons. It is important to note that during MAM, lightning flash density is more (less) over Region 1 (Region 2) as seen in Figure 2b. On the other hand, during JJAS, Region 2 experiences more lightning as compared to Region 1 (Figure 2c). The El-Niño and La-Nina years obtained from monsoon online of Indian Institute of Tropical Meteorology (https://mol.tropmet.res.in/monsoon-interannual-timeseries/), which is based on All-India area-weighted mean summer monsoon rainfall are marked as stars in red (indigo; Figure 2b). The percentage of interannual variability of lightning flash count during MAM and JJAS is also presented (Figures 2d and 2e). The prominent interannual variation of lightning flash counts indicates the importance and possibility of seasonal forecasting of lightning (Figures 2d and 2e). It is interesting to note that seasonal predictions are bound to the general trends/tendencies of the phenomena than the forecast of specific days. The tendencies of lightning for a particular season over specific regions are focused on seasonal prediction. But, we do not focus on forecasts for specific days.

Figure 1. Seasonal climatology of lightning flashes (count/km²/year) over global tropics (Indian Region) during March to May (MAM) (a and b) and June to September (JJAS) (c and d) during 1997–2013 from observation (tropical rainfall measuring mission-lighting imaging sensor) and calculated from Goddard Earth observing system model during MAM (e and f) and JJAS (g and h). Different regions are marked in the figure (East and north-East India, Region 1: 82°E–94°E; 20°N–28°N; north-West India, Region 2: 68°E–80°E; 25°N–38°N; North America Region 3: 110°W–71°W; 5°N–43°N) and Africa (Region 4: 8°E–35°E; 12°S–15°N).
3.2. Global Teleconnection of Lightning Over Global Hotspot Regions and SST

It can be hypothesized that the lightning flashes may be predictable one season in advance if it is tied to the slowly varying forcing (e.g., ENSO) and other global predictors (e.g., ET, PDO, NAO, and AMO). To investigate the linkages between lightning flash density and slowly varying predictable components, the mean lightning flash count averaged over the four lightning hotspot regions over global tropics are correlated with global SST (2 m Tempera-
ture) over the ocean (land) during MAM and JJAS (Figures 3 and 4). The correlation of mean lightning flash count and CTT averaged over Region 3 and Region 4 (box shown in Figures 1a and 1c) with global SST is calculated during MAM and JJAS (Figure 3). The deep convection over the study regions is verified by correlating the CTT averaged over Region 3 (Figures 3c3 and 3d3) and Region 4 (Figures 3c4 and 3d4) with SST during MAM and JJAS. Interestingly, an opposite strong correlation pattern is observed between lightning and CTT. This is because lightning flashes increases when CTT decreases (Figure not shown), which is also mentioned by previous studies (Liu et al., 2012; Price and Rind, 1992). The stronger correlation in lightning (Figure 3a3) and CTT (Figure 3c3) during MAM indicates the strongest relationship of large-scale global predictors and seasonal mean lightning flash density. The results reveal that lightning activity over Region 3 and Region 4 shows a strong teleconnection with global SST.

The different modes of variability and its linkage with lightning flashes are examined by correlating the area-averaged lightning flash counts (averaged over four regions) with different indices for MAM and JJAS as shown in Figures 3e and 3f. The ENSO (represented by the NINO4, NINO3.4, NINO3, NINO1 + 2 index), the NAO, AMO, PDO, and ET are considered in the present study. The lightning activity is more in the years of negative IOD and positive IOD than normal years, as Unnikrishnan et al. (2021) reported. They also found that the enhancement of lightning activity is more in negative IOD years than positive IOD years. We have also done the multiple regression analysis for both lightning and rainfall over selected global lightning hotspot regions (Region 1, Region 2, Region 3, and Region 4) along with all India (lon: 68°E–98°E, lat: 8°N–38°N) to get the combined correlation coefficient and depicted in Figures 3g and 3h for MAM and JJAS. The linear multiple regression analysis demonstrates that there is a strong correlation over Region 1 ($R$ ∼ 0.74), Region 2 ($R$ ∼ 0.42), Region 3 ($R$ ∼ 0.72), and Region 4 ($R$ ∼ 0.72) along with all India ($R$ ∼ 0.55) during MAM for lightning. Interestingly, the correlation value for lightning ($R$ ∼ 0.74) in MAM over Region 1 is greater than rainfall ($R$ ∼ 0.65). During MAM and JJAS the multiple regression of rainfall and lightning are very strong in all the regions (Figures 3g and 3h). Multiple correlation/co-variance of lightning with SST of several regions/predictors quantify the co-variability of the seasonal anomaly of lightning with the combined influence of the predictors (Figures 3g and 3h). It is interesting to note that during JJAS, the combined correlation coefficient over Region 2 is significantly high ($R$ ∼ 0.8). However, the correlation value over Region 2 is less during MAM ($R$ ∼ 0.42) than in the other regions, which might be related to orography, as Kamra and Ramesh Kumar (2020) highlighted. They reported that the Himalayas over the North-West (Region 2) region play a crucial role in lightning activity due to solar heating and moisture availability.

A similar teleconnection between lightning and global SST over India, a sub-set of global lightning hotspot regions is also investigated to find the linkages between lightning flash density and global predictors. The mean lightning flash count averaged over Region 1 and Region 2 are correlated with global SST (2 m temperature) over the ocean (land) during MAM and JJAS (Figures 4a1–4d1, and Figures 4a2–4d2). The results show a strong and the most widespread relationship to lightning activity with the different modes of variability. The strongest positive correlation in the MAM is observed in the NINO4 region followed by the NINO3.4 index for Region 1 (Figure 4a1). On the other hand, the relationship for Region 1 is rather weak (not significant) over the NINO4 or NINO3.4 during JJAS, but a significant negative correlation is noted over the NINO1+2 indices (Figure 4b1). Similarly, the CTT averaged over Region 1 is correlated with SST (Figures 4c1 and 4d1) during MAM and JJAS to demonstrate the role of deep convection over the regions. On the other hand, the strong negative correlation pattern is also noticed in lightning and CTT over Region 1 and Region 2 as it is well known that lightning flashes increase when CTT decreases (Liu et al., 2012; Price and Rind, 1992). The stronger correlation in lightning (Figure 4a1) and CTT (Figure 4c1) during MAM indicates the strongest relationship of large-scale global predictors and seasonal mean lightning flash density. The pre-monsoon CTT over Region 2 has a similar relationship (Figure 4c2) as seen in Region 1 (Figure 4c1). The results also point out that the pre-monsoon seasons (MAM), lightning activity increases in association with the El-Nino condition over Region 1. Interestingly, the JJAS (MAM) mean climatology of lightning flash density is stronger over Region 2 (Region 1) as already seen in Figure 1. Similarly, during JJAS, CTT over Region 2 depicts the strongest negative correlation in the NINO index (Figure 4b2). We have calculated lightning flash density for the El-Nino and La-Nina composite years for MAM and JJAS seasons (Figures 4e and 4f). The difference between El-Nino and La-Nina (El-Nino minus La-Nina) are shown in Figures 4e and 4f for MAM and JJAS, respectively. These results demonstrate that lightning flash counts lead to an increase over Region 1 during MAM in the El-Nino condition. On the other hand, lightning flash density increases during JJAS in La-Nina conditions over Region 2. The results are valuable in the perspective of seasonal forecasting of lightning for the preparedness in advance.
The synoptic variance (period less than 10 days) of lightning flash counts averaged over study Region 1 is correlated with SST over the ocean during MAM and JJAS (Figure S1 in Supporting Information). The numbers of synoptic events (e.g., depressions, cyclone, etc.) during MAM and JJAS from 1997 to 2013 are shown in Table S1 in Supporting Information.

Figure 3. Correlation of mean lightning flash count (cloud top temperature; unit: K) averaged over two selected global lightning hot spot regions, Region 3 (a3, b3, c3, and d3) and Region 4 (a4, b4, c4, and d4) with global sea surface temperature (SST) during March to May (MAM) and June to September (JJAS). (e, f): The correlation coefficients of lightning averaged over different study regions with SST over different boxes (Nino 1 + 2, Nino 3, Nino 3.4, Nino 4, North Atlantic oscillation, Atlantic multidecadal oscillation, Pacific decadal oscillation, and extra tropics) across the globe for MAM (e) and JJAS (f) season. (g and h): The multiple correlation ($R$) for lightning and rainfall all regions (Region 1 to Region 4) and all India (68°E–98°E; 8°N–38°N) are shown for MAM and JJAS. The dashed line shows 90% significance level.

The synoptic variance (period less than 10 days) of lightning flash counts averaged over study Region 1 is correlated with SST over the ocean during MAM and JJAS (Figure S1 in Supporting Information). The numbers of synoptic events (e.g., depressions, cyclone, etc.) during MAM and JJAS from 1997 to 2013 are shown in Table S1 in Supporting Information along with the seasonal mean of total lightning flashes av-
eraged over Region 1 from observation (TRMM-LIS) and model (GEOS). The correlation of mean lightning flash counts averaged over different study regions with global rainfall during MAM and JJAS are also present in Figure S2 in Supporting Information S1. It is interesting to note that lightning over Region 1 (Region 2) is positively (negatively) correlated with rainfall over the Niño region during MAM (JJAS). The results also demonstrate that there is high predictability of lightning one season in advance, which is comparable to that of seasonal rainfall.

4. Summary and Conclusion

We have explored the possibility of the seasonal prediction of lightning and thunderstorm activity over the Indian subcontinent in this present study. Generally, for the seasonal predictions, we do not focus on forecasts of specific days instead look for general trends/tendencies/possibilities over specific regions for a season ahead, which may help to give warnings/alerts for that area (regions) well in advance. We emphasize that the seasonal anomaly of lightning can be predicted (i.e., predictability exists) because it shows a strong association with slowly varying
boundary forcing such as SST, which serves as a predictor for relatively faster-evolving processes (e.g., rainfall, lightning). In particular, the extra-tropical SST influences and the strong association of the AMO with MAM and JJAS lightning flash density are equally crucial sources of predictability along with ENSO. The sub-seasonal variances of lightning flash density with global SST reveal a strong positive correlation between them. This again corroborates that lightning flash density over the Indian subcontinent (Region 1) is tied to the slow varying predictable component (e.g., SST). Hence, reliable seasonal forecasting of lightning flashes over India as well as over other global hotspot regions is achievable as the mean and sub-seasonal variances of lightning are found highly linked with global predictors.

This opens up a new avenue for the most difficult and essential atmospheric hazards and would be helpful to save lives, the economy of a populous country like India. Here, we have focused on the two global lightning hotspot regions (North America and Africa) and as a sub-set of global tropics specific interest over the Indian subcontinent to demonstrate the feasibility of seasonal forecasting of lightning with a proper scientific basis. The multiple regression analysis demonstrates that seasonal lightning is predictable in all four regions of the global tropics. Over East India, lightning is predictable at ~56% (R = 0.75) during pre-monsoon and an average of ~62% (R = 0.79) over all India for monsoon. The multiple correlations of rainfall are also high ~74% (R = 0.86) over all India for pre-monsoon along with other regions of global tropics. The different modes of variability and its linkage with lightning flashes are examined by doing of lightning flash count (averaged over study region) with different indices for two seasons (pre-monsoon, MAM, and Monsoon, JJAS). The new research will motivate the researcher to pick up the challenging problem with the dynamical model and suitable lightning parameterizations for the lightning/thunderstorm activity forecast on the seasonal timescale.

Data Availability Statement

All data used in this study are freely available. The daily gridded lightning flash densities data for the time period 1997 to 2013 generated from a combination of the LIS and OTD on the Tropical Rainfall Measuring Mission (TRMM) LIS/OTD, GPCP data sets used here. Authors acknowledge National Crime Records Bureau (NCRB), Govt. of India (https://ncrb.gov.in/) for the data of total fatalities by natural disasters along with death due to lightning over India available from the “Accidental Deaths & Suicides in India (ADSI) Report,” Govt. of India published by for the years 2002–2019 (36th to 53rd series), CHAPTER – 1 (https://rsmcnewdelhi.imd.gov.in/en/adsi-reports-of-previous-years). We acknowledge HadISST (https://www.metoffice.gov.uk/hadobs/hadisst/), MERRA2 (https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/), Tropical Rainfall Measuring Mission (TRMM) LIS/OTD, GPCP data sets used here. Authors acknowledge National Crime Records Bureau (NCRB), Govt. of India (https://ncrb.gov.in/) for the data of total fatalities by natural disasters along with death due to lightning over India available from the “Accidental Deaths & Suicides in India (ADSI) Report,” Govt. of India published by for the years 2002–2019 (36th to 53rd series), CHAPTER – 1 (https://ncrb.gov.in/en/adsi-reports-of-previous-years). The low, depression, cyclone data are available in “Cyclone eAtlas - IMD” (http://14.139.191.203/login.aspx?ReturnUrl=%2fViewByParam.aspx) and http://www.imdchennai.gov.in/cyclone_eatlas.htm. The data are also available at https://mausam.imd.gov.in/imd_latest/contents/cyclone.php. The reports are available at (https://rsmcnewdelhi.imd.gov.in/report.php?internal_menu=Mjc=).

Acknowledgments

We thank MoES, the Government of India, Director IITM for the support to carry out this work. We also acknowledge HadISST (https://www.metoffice.gov.uk/hadobs/hadisst/), MERRA2 (https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/), Tropical Rainfall Measuring Mission (TRMM) LIS/OTD, GPCP data sets used here. Authors acknowledge National Crime Records Bureau (NCRB), Govt. of India (https://ncrb.gov.in/) for the data of total fatalities by natural disasters along with death due to lightning over India available from the “Accidental Deaths & Suicides in India (ADSI) Report,” Govt. of India published by for the years 2002–2019 (36th to 53rd series), CHAPTER – 1 (https://ncrb.gov.in/en/adsi-reports-of-previous-years). The challenging problem with the dynamical model and suitable lightning parameterizations for the lightning/thunderstorm activity forecast on the seasonal timescale.

References

Adler, R. F., Huffman, G. J., Chang, A., Ferraro, R., Xie, P. P., & Janowiak, J. (2003). The version-2 global precipitation climatology project (GPCP) monthly precipitation analysis (1979-present). Journal of Hydrometeorology, 4(6), 1147–1167. https://doi.org/10.1175/1525-7541(2003)004<1147:TVGPCP>2.0.CO;2
Ahmad, A., & Ghosh, M. (2017). Variability of lightning activity over India on ENSO time scales. Advances in Space Research, 60(11), 2379–2388. https://doi.org/10.1016/j.asr.2017.09.018
Alexopoulos, E. C. (2010). Introduction to multivariate regression analysis. HIPPOKRATA 2010, 14(Suppl 1), 23–28.
Barth, M. C., Lee, J., Hodzic, A., Pfister, G., Skamarock, W. C., Worden, J., et al. (2012). Thunderstorms and upper troposphere chemistry during the early stages of the 2006 north American Monsoon. Atmospheric Chemistry and Physics, 12(22), 11003–11026. https://doi.org/10.5194/acp-12-11003-2012
Barthe, C., Deierling, W., & Barth, M. C. (2010). Estimation of total lightning from various storm parameters: A cloud-resolving model study. Journal of Geophysical Research: Atmospheres, 115(C4), 1–17. https://doi.org/10.1029/2009JD014405
Blakeslee, R. J. (2021). Lightning imaging sensor (LIS) on TRMM science data. The NASA Global Hydrology Resource Center DAAC. https://doi.org/10.5067/LIS/LISDATA201
References From the Supporting Information

Bacmeister, J. T., Suarez, M. J., & Robertson, F. R. (2006). Rain re-evaporation, boundary layer-convection interactions, and pacific rainfall patterns in an AGCM. Journal of the Atmospheric Sciences, 63, 3383–3403. https://doi.org/10.1175/JAS3791.1

Barahona, D., Molod, A., Bacmeister, J., Nenes, A., Gettelman, A., Morrison, H., et al. (2014). Development of two-moment cloud microphysics for liquid and ice within the NASA Goddard Earth observing system model (GEOS-5). Geoscientific Model Development, 7, 1733–1766. https://doi.org/10.5194/gmd-7-1733-2014

Chou, M. D., & Suarez, M. (1994). An efficient thermal infrared radiation parameterization for use in general circulation models. In Vol. 3 of NASA Tech. Memorandum 104606. NASA Goddard Space Flight Center.

Chou, M. D., Suarez, M., Ho, C. H., Yan, M. H., & Lee, K. T. (1992). A solar radiation model for use in climate studies. Journal of the Atmospheric Sciences, 49, 762–772.

Cyclone eAtlas – IMD Version 2.0 (2011). Tracks of cyclones and depressions over North Indian Ocean, (from 1891 onwards). Technical Note. Cyclone Warning & Research centre India Meteorological Department Regional Meteorological Centre.

Moorthi, S., & Suarez, M. J. (1992). Relaxed Arakawa-Schubert: A parameterization of moist convection for general circulation models. Monthly Weather Review, 120, 978–1002. https://doi.org/10.1175/1520-0493(1992)120<0978:RASAPO>2.0.CO;2

Rienecker, M. M., Suarez, M. J., Todling, R., Bacmeister, J., Takacs, L., Liu, H.-C., et al. (2008). The GEOS-5 data assimilation system—Documentation of versions 5.0.1 and 5.1.0, and 5.2.0. NASA Tech Rep Ser Glob Model Data Assim NASA/TM-2008-104606 27.

Slingo, J. (1987). The development and verification of a cloud prediction scheme for the ECMWF model. Quarterly Journal of the Royal Meteorological Society, 113, 899–927.

Tiedtke, M. (1993). Representation of clouds in large-scale models. Monthly Weather Review, 121, 3040. https://doi.org/10.1175/1520-0493(1993)121<3040:ROCILS>2.0.CO;2