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LIGHTNING–METEOROLOGY RELATIONSHIPS OVER SRI LANKA AND INDONESIA: A MACHINE LEARNING APPROACH

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ABSTRACT

The relationship between lightning flashes (LF) and various meteorological parameters is analyzed using lightning data from 1995 to 2014. The meteorological parameters considered in this study include aerosol optical depth (AOD), precipitation (P), relative humidity (Rh), convective available potential energy (CAPE), effective cloud droplet size (CER), total precipitable water (TPW), cloud fraction (CF), cloud top temperature (CTT), Richardson number (RN), cloud ice water content (CIWC), and cloud liquid water content (CLWC). This study examines two regions with distinct climates: Sri Lanka (R1) and Indonesia (R2). Results show lower lightning activity in R1 (15.5 flashes/km^2/year) than in R2 (21.8 flashes/km^2/year), with both peaking in April. Furthermore, the study evaluates the effectiveness of different regression techniques in modeling lightning activity. The Support Vector (SV) regression model performs best for Sri Lanka, while the Random Forest (RF) regression model emerges as the most suitable approach for Indonesia.

Keywords: Lightning, Cloud, Regression, Model

1. INTRODUCTION

Lightning is a natural phenomenon resulting from charge separation within thunderclouds, occurring as either cloud-to-ground or intra-cloud lightning. Cloud-to-ground lightning involves charge exchange between clouds and the Earth's surface, while intra-cloud lightning occurs within clouds. Local weather influences lightning formation, particularly when contrasting air masses—dry-hot and cold-moist—converge, triggering thundercloud development Lal et al. (2024).

Though stratiform clouds can produce lightning, it is more frequent in cumulonimbus clouds, which accumulate sufficient charge to overcome air resistance Mansell et al. (2010). Lightning is common in various weather events, including thunderstorms, wildfires, volcanic eruptions, snowstorms, and hurricanes, but is most frequent in convective cumulonimbus clouds Mistovich et al. (2008), Aslar et al. (2001), Verma et al. (2021), Williams & Sátori (2004). Strong convection within these clouds enhances lightning activity, making thunderstorms particularly destructive and hazardous to people and infrastructure.

Around 78% of global lightning activity occurs in the tropical belt (30°S–30°N), especially across Southeast Asia, Africa, and South America Turman & Edgar (1982) Price (2008). Convective storms are more variable over land than oceans Zipser (2003). Studies indicate an increasing lightning trend over Indonesia and Sri Lanka Maduranga et al. (2018), Denov et al. (2023), Moron et al. (2010), alongside a rise in lightning-related fatalities, injuries, and property damage in these regions over the past two decades Edirisinghe & Maduranga (2021).

Lightning strikes cause hundreds of fatalities and serious injuries worldwide each year, making it one of the most severe atmospheric hazards. Globally, over eight million lightning strikes occur daily, exceeding 100 per second Zipser (2003), Dowdy (2016), Singh et al. (2017), Mills et al. (2010), Jensen et al. (2021), Mushtaq et al. (2018), Orville & Huffines (1999), Okafor (2005).

Indonesia has one of the highest lightning-related fatality rates due to its tropical climate, high humidity, and frequent thunderstorms, particularly from November to March. Regions like Sumatra and Java experience intense lightning activity, influenced by volcanic mountains and warm, humid air from the Indian Ocean, with some areas recording up to 200 thunderstorm days annually Denov et al. (2023), Moron et al. (2010), Cummins et al. (2019), Denov et al. (2022), Hamid et al. (2001), Zoro & Mefiardhi (2005), Shubri et al. (2024). Similarly, Sri Lanka, being a tropical country, faces significant lightning threats, with annual fatalities and injuries averaging 18.40 and 16.50, respectively Edirisinghe & Maduranga (2021). Lightning activity in Sri Lanka peaks at 1600 UTC and is lowest in the morning Umakanth et al. (2024).

Lightning flashes are linked to convective rain, total column water vapor (TCWV), and relative humidity (RH) Dai et al. (2009), Zheng et al. (2020). Higher humidity increases hydrometeor concentrations and lifting speeds, intensifying lightning activity. Convective Available Potential Energy (CAPE) plays a crucial role in storm intensity, with higher CAPE values indicating stronger convection and increased lightning probability Jayaratne & Saunders (1983), Saunders (1993), Takahashi (1978), Williams et al. (1991). CAPE-driven instability fosters charge separation, promoting lightning formation Galanaki et al. (2015), Saha et al. (2017) , Dewan et al. (2018).

Studies Liou & Kar (2010), Louf et al. (2019), Siingh et al. (2015) show a strong correlation between CAPE and lightning, with surface temperature also playing a role, unlike outgoing longwave radiation. Seasonal variations influence lightning patterns, as seen in northeast India, where intense pre-monsoon storms produce severe lightning and strong winds Mukhopadhyay et al. (2009), Tyagi et al. (2012), To improve lightning forecasting in Sri Lanka and Indonesia, this study analyzes key environmental factors like CAPE, RH, cloud-top temperature, cloud fraction, and rainfall, using reliable lightning data.

2. MATERIALS AND METHODS

This study utilized multiple datasets. Lightning data (1995–2014) were obtained from the Lightning Imaging Sensor (LIS) onboard TRMM (https://ghrc.nsstc.nasa.gov/pub/lis/orbit_files/data/). Aerosol Optical Depth (AOD), Cloud Top Temperature (CTT), Cloud Effective Radius (CER), and Cloud Fraction (CF) were sourced from the MODIS MOD08_D3 V6.1 dataset (https://ladsweb.modaps.eosdis.nasa.gov/search/order/1/MODIS:Terra) with a grid resolution of 10×10 Kms. Rainfall data came from the GPM IMERG dataset, integrating radiometer and microwave sensor observations (https://gpm.nasa.gov/data/directory).

Additionally, atmospheric parameters such as relative humidity, total precipitable water (TPW), wind speed, cloud ice water content (CIWC), cloud liquid water content (CLWC), and temperature were retrieved from the Copernicus Climate Change Service (C3S) (Hersbach et al., 2020) at a 0.25° × 0.25° resolution (https://cds.climate.copernicus.eu/cdsapp#!/home). Using temperature and relative humidity values, we computed dew point temperature at all pressure levels and derived Convective Available Potential Energy (CAPE) and Richardson Number (RN) for each day.

- **Convective available potential energy (CAPE)**

The formula of Moncrieff and Miller (1976) is utilized to calculate CAPE.

$$CAPE = \int_x^y g[\frac{TV_{parcel} - TV_{env}}{TV_{env}}]\, dz \text{ --} \qquad (1)$$

Where 〖TV〗_parcel represents the parcel's virtual temperature and 〖TV〗_env represents the virtual temperature of the environment respectively. The levels of free convection and neutral buoyancy are represented by x and y. Z_f and Z_l stands for surface level and free convection.

(ii). Richardson Number (RN)

It is the ratio of buoyancy to vertical shear. The formula is used to calculate it.

RN= (CAPE)/0.5*(U)**2

Where U is the difference of wind speeds between mean wind from 0 – 6km and the lowest 500 m mean wind.

Low RN values indicate lower risk, while high RN values suggest intense multicell thunderstorms with frequent lightning Weisman & Klemp (1982), Thompson et al. (2003).

Weather forecasting relies on machine learning regression models to improve accuracy by processing large datasets, capturing nonlinear patterns, and adapting to changes. Model choice varies from simple decision trees to advanced methods like Random Forests and Gradient Boosting, which handle complexities and reduce overfitting. Gaussian Process Regression (GPR), a non-parametric method, outperforms traditional models in forecasting river temperatures and flow.

Regression tree models are robust and effective, particularly for non-linear interactions. As a supervised learning technique, Regression Tree (RT) uses ensemble learning, constructing multiple decision trees and averaging their predictions Liyew & Melese (2021).

Support Vector Machines (SVM) are supervised learning models for classification and regression. Introduced by Vapnik (1995), SVM is widely used for pattern recognition due to its ability to define optimal solutions and mitigate overfitting through structural risk minimization Farquad, & Bose (2012), Kumar et al. (2008).

The Radial Basis Function Network (RBFN) is a fully supervised learning algorithm for parametric estimation. It automatically adjusts the number of hidden layer neurons and prevents overfitting using the early stopping technique Lin & Chen (2004).

Ridge and Lasso regression are regularized techniques for meteorological variable prediction. Lasso regression, using L1 regularization, selects features and reduces overfitting, while Ridge regression, employing L2 regularization, minimizes coefficient size without feature selection Zaikarina et al. (2016). These methods were applied to analyze the relationship between lightning flashes and meteorological parameters, identifying the best correlation with TRMM LIS flashes.

We computed BIAS, correlation coefficient (CC), and root-mean-square error (RMSE) to assess the regression model's performance against ERA5 reanalysis data. The formulas, as presented by Wilks (2006), are:

$$BIAS = \frac{1}{n}\sum_{i=1}^{n}(o_i - f_i) \qquad (7)$$

$$CC = \frac{\sum_{i=1}^{n}(f_i - \acute{f})(o_i - \acute{o})}{\sqrt{\sum_{i=1}^{n}(f_i - \acute{f})^2}\sqrt{\sum_{i=1}^{n}(o_i - \acute{o})^2}} \qquad (8)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(f_i - o_i)^2}{n}} \qquad (9)$$

Where o_i and f_i are the observed and predicted values, respectively.

3. RESULTS AND DISCUSSIONS

The lightning flash climatology for the two study regions (R1 & R2) during 1995–2014 is shown in Fig. 1. R1 (Sri Lanka: 5.5°–10°N, 79°–83°E) recorded 0.04–0.06 flashes/km^2/day in the central, northwestern, western, and Sabaragamuwa regions, while the northern and north-central regions had 0.02–0.04 flashes/km^2/day. R2 (Indonesia: 5.75°S–10°N, 98.6°–105.6°E) saw 0.04–0.08 flashes/km^2/day in Lampung, South Sumatra, Bengkulu, and Jambi, whereas Riau and West Sumatra recorded 0.08–1 flashes/km^2/day.

Figure 1

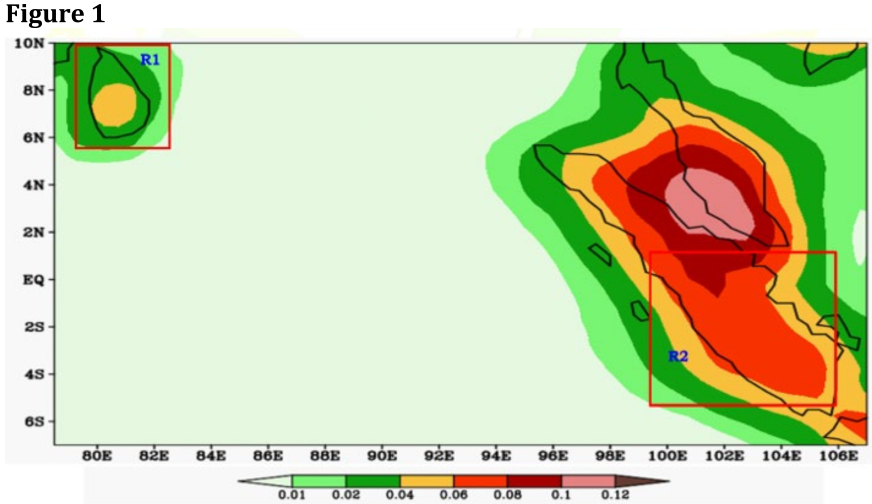

Figure 1 Spatial Plot of Lightning Flashes (Flashes/Km2 /Day) During 1995–2014

Figure 2

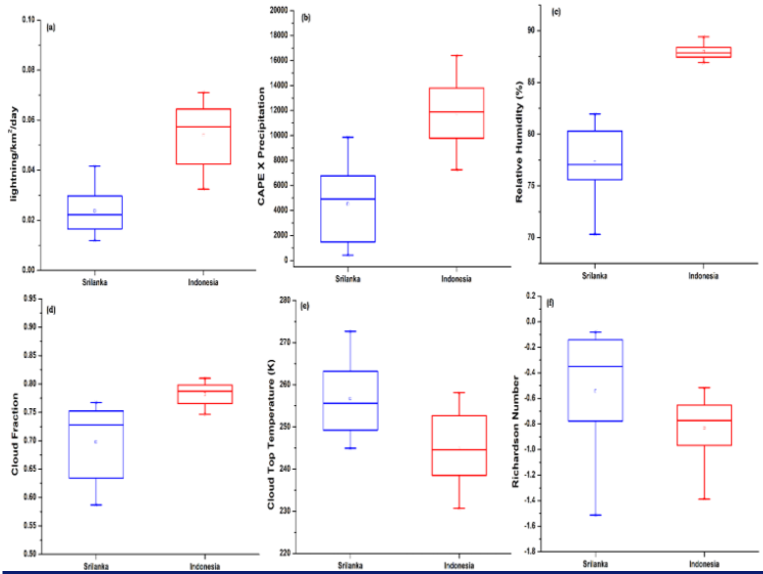

Figure 2 Box-and-Whisker plot of (a) Lightning, (b). CAPE X P, (c). Relative Humidity, (d). Cloud Fraction, (e). Cloud Top Temperature and (f). Richardson Number over Srilanka and Indonesia regions during 1995-2014.

To analyze the atmospheric parameters influencing lightning activity over Sri Lanka and Indonesia, box plots of lightning, CAPE × Precipitation, RH, CF, CTT, and RN are presented in Figure 2 The median (Q2), upper quartile (Q3), and upper whisker values indicate significantly higher lightning activity over Indonesia (0.055, 0.063, and 0.072 flashes/km^2/day) compared to Sri Lanka (0.025, 0.03, and 0.042 flashes/km^2/day). Similarly, CAPE × Precipitation is notably higher in Indonesia (Q2: 12000, Q3: 13800, upper whisker: 16500 J/kg/mm/day) than in Sri Lanka (5000, 7000, 10000 J/kg/mm/day). Higher values are also observed over Indonesia for RH (median: 87% vs. 77%), CF (0.78 vs. 0.73), and CTT (243K vs. 255K). These differences suggest stronger convective activity over Indonesia.

4. VERTICAL DISTRIBUTIONS

Figure 3

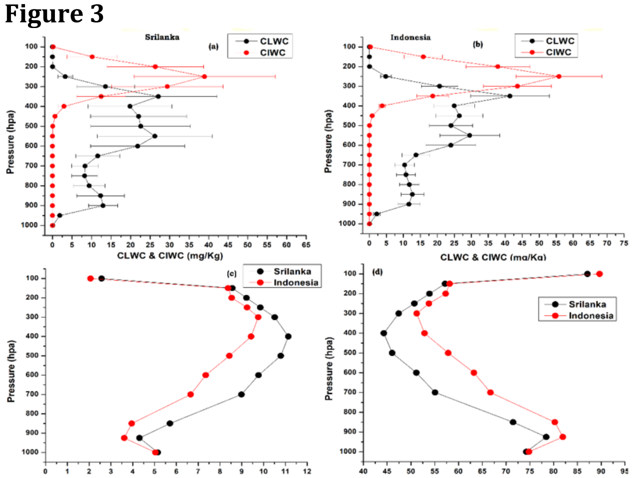

Figure 3 Vertical Distributions of Mean (A). CIWC, (B). CLWC, (C). Dew Point Depression (K) and (D). Relative Humidity During 1995-2014 Over Srilanka and Indonesia Regions.

To understand the response of mixed-phase processes within clouds, we analyzed Cloud Ice Water Content (CIWC) and Cloud Liquid Water Content (CLWC) across two regions, Sri Lanka and Indonesia. Figure 3 shows the mean CIWC and CLWC profiles with error bars, where intersecting black and red lines indicate mixed-phase regions.

For Sri Lanka, CIWC peaked at 250 hPa (40 mg/kg), while CLWC exhibited three peaks: 900 hPa (13 mg/kg), 550 hPa (26 mg/kg), and 350 hPa (26 mg/kg). The mixed-phase region (20 mg/kg) was observed between 300–400 hPa. In Indonesia, CIWC was higher at 250 hPa (55 mg/kg), and CLWC peaked at 850 hPa (12.5 mg/kg), 550 hPa (30 mg/kg), and 350 hPa (40 mg/kg), with a mixed-phase region (30 mg/kg) spanning 200–400 hPa. The mixed-phase region was more prominent in Indonesia than in Sri Lanka.

These findings suggest an increase in mixed-phase and total water content (especially IWC) during the study period, potentially altering cloud microphysics and precipitation processes. The rise in IWC may be linked to atmospheric dynamics, thermodynamics, moisture availability, vertical updrafts, and large-scale atmospheric influences. Comparable atmospheric conditions during the same periods of the year further highlight the role of ice nuclei concentration DeMott et al. (2010), Murray et al. (2012),Pruppacher et al. (2010).

Figure 3 illustrates the dew point depression over regions R1 (Sri Lanka) and R2 (Indonesia). In both regions, values are around 5K at 1000 hPa, decreasing to ~4K at 950 hPa, then rising to 10–11K at 300–400 hPa, before dropping to ~2K at 100 hPa. This pattern indicates moist air between 1000–800 hPa, dry air from 800–300 hPa, and moist air again at upper levels (400–100 hPa), signifying strong atmospheric instability.

Figure 3 further supports this, showing high relative humidity (RH) between 1000–800 hPa, decreasing from 800–400 hPa, and rising again above 400 hPa. The combination of high RH and low dew point depression in the lower atmosphere over Indonesia suggests more intense convection and lightning activity compared to Sri Lanka.

5. DYNAMICS

Figure 4

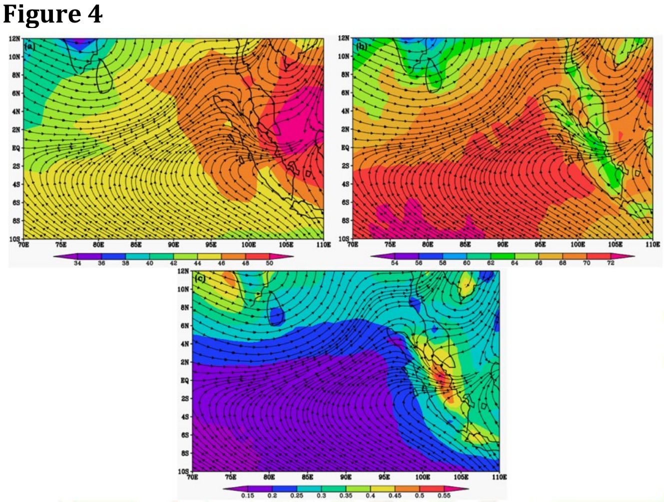

Figure 4 Mean spatial plot of (a). TPW (shaded), (b). RH (shaded) and (c). AOD (shaded) with winds streamline during 1995-2014.

Figure 4 presents wind streamlines overlaid with Total Precipitable Water (TPW) using 255 km resolution ERA5 data. ERA5 analysis reveals that, during 1995–2014, moist air from the Indian Ocean is transported to Indonesia's west coast, with TPW values of 45–50 mm over East Indonesia and a southwesterly flow across Riau and West Sumatra. Over Sri Lanka, moist air also influences both coasts, but TPW values are lower (41–44 mm), contributing to reduced lightning activity compared to Indonesia.

Higher relative humidity (RH) values (62%–72%) are observed over Indonesia, with higher RH (66%–72%) along the east coast and lower RH (62%–66%) on the west coast. Moist air from the west interacts with drier air on the east, leading to wind convergence, especially over Riau and West Sumatra. In contrast, lower RH (58%–67%) is observed over the Indian Ocean off Indonesia's west coast Figure 4, consistent with AOD observations.

Higher AOD values (0.35–0.55) are observed on Indonesia's east coast compared to the west (0.25–0.35), positively influencing lightning activity. Over Sri Lanka, AOD is lower (0.2–0.35), with the southeastern region showing the least values (0.2–0.25) compared to other provinces Figure 4.

Figure 5

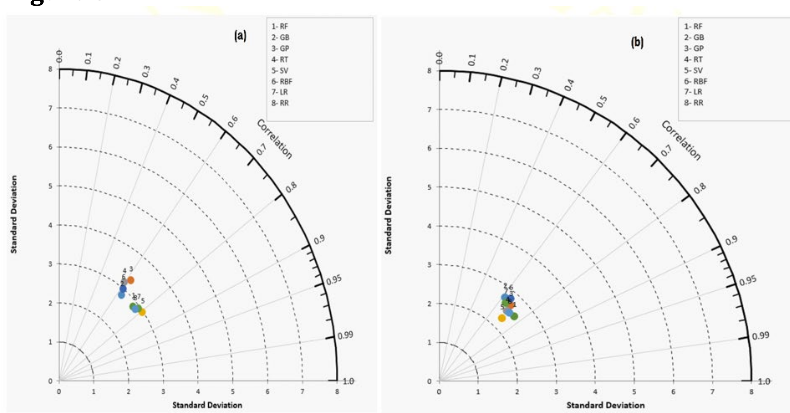

Figure 5 Taylor Diagram for All Regression Models Over (A). Srilanka Region, (B). Indonesia Region.

Machine learning-based regression models play a crucial role in weather forecasting. To assess their effectiveness across two regions, error statistics—standard deviation (STD), correlation coefficient (CC), and root mean square deviation (RMSD)—are analyzed against observed lightning data. These results are visualized using Taylor diagrams (Fig. 8a-b), which provide a comprehensive view of model performance.

In Sri Lanka Figure 5, the SV model demonstrates the best performance (CC = 0.81, STD = 2.98), followed by LR (CC = 0.78, STD = 2.95) and RR (CC = 0.77, STD = 2.86). The RF model also performs well (CC = 0.75, STD = 2.86). Other models (GB, GP, RBF) exhibit moderate accuracy, while the RT model shows the weakest performance (CC = 0.60, STD = 3.15).

In Indonesia Figure 5, the RF model outperforms others (CC = 0.76, STD = 2.55), followed by RR (CC = 0.72, STD = 2.52) and SV (CC = 0.71, STD = 2.28). The RT and GP models show moderate accuracy, whereas RBF and LR perform slightly worse. The GB model has the lowest performance (CC = 0.62, STD = 2.74).

These findings highlight the varying effectiveness of regression models across different regions, emphasizing the superiority of SV and RF models in Sri Lanka and Indonesia, respectively.

6. CONCLUSIONS AND RECOMMENDATIONS

The study examines the relationship between meteorological parameters and lightning activity over Sri Lanka and Indonesia (1995–2014), emphasizing the role of regression models. Findings reveal higher lightning activity in Indonesia (0.08–1 flashes/km^2/day) than Sri Lanka (0.02–0.04 flashes/km^2/day), with northern Sri Lanka and the Riau-West Sumatra regions of Indonesia experiencing the most lightning.

Higher CAPE × P values (16500 J·kg^{-1}·mm·day^{-1} in Indonesia vs. 10000 in Sri Lanka) align with increased relative humidity (89% vs. 82%) and cloud fraction (0.81 vs. 0.76). Indonesian thunderclouds are colder, with a lower CTT(min) (230 K vs. 245 K). The study identifies ice and liquid water content in the mixed-phase zone as key lightning indicators, alongside rainfall and dew point depression patterns.

Moist air from Indonesia's west coast interacts with dry air from the east, leading to wind convergence over Riau and West Sumatra, supported by higher AOD values (0.35–0.55 east coast vs. 0.25–0.35 west coast). Among regression models, Random Forest performs best for Indonesia, while Support Vector Regression is more effective for Sri Lanka.

CONFLICT OF INTERESTS

None.

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REFERENCES

Aslar, A. K., Soran, A., Yildiz, Y., & Isik, Y. (2001). Epidemiology, Morbidity, Mortality, and Treatment of Lightning Injuries in A Turkish Burns Unit. International Journal of Clinical Practice, 55(8), 502–504. https://doi.org/10.1111/j.1742-1241.2001.tb11110.x

Christian, H. J., Blakeslee, R. J., Boccippio, D. J., Boeck, W. L., Buechler, D. E., Driscoll, K. T., Goodman, S. J., Hall, J. M., Koshak, W. J., Mach, D. M., & Stewart, M. F. (2003). Global Frequency and Distribution of Lightning As Observed from Space By the Optical Transient Detector. Journal of Geophysical Research: Atmospheres, 108(D1), ACL-4. https://doi.org/10.1029/2002JD002347

Cummins, K. L., Wilson, J. G., & Eichenbaum, A. S. (2019). The Impact of Cloud-To-Ground Lightning Type on the Differences in Return Stroke Peak Current

Over Land and Ocean. IEEE Access, 7, 174774–174781. https://doi.org/10.1109/ACCESS.2019.2956685

Dai, J., Wang, Y., Chen, L., Tao, L., Gu, J., Wang, J., Xu, X., Lin, H., & Gu, Y. (2009). A Comparison of Lightning Activity and Convective Indices Over Some Monsoon-Prone Areas of China. Atmospheric Research, 91(2–4), 438–452. https://doi.org/10.1016/j.atmosres.2008.08.002

DeMott, P. J., Prenni, A. J., Liu, X., Kreidenweis, S. M., Petters, M. D., Twohy, C. H., Richardson, M. S., Eidhammer, T., & Rogers, D. (2010). Predicting Global Atmospheric Ice Nuclei Distributions and Their Impacts On Climate. Proceedings of the National Academy of Sciences, 107(25), 11217–11222. https://doi.org/10.1073/pnas.0910818107

Denov, B., Hidayat, S., & Zoro, R. (2022). Tropical Lightning Peak Current Measurement At West Java, Indonesia. In 2022 36th International Conference on Lightning Protection (ICLP) (pp. 364–368). IEEE. https://doi.org/10.1109/ICLP56858.2022.9942478

Denov, B., Hidayat, S., Suwarno, & Zoro, R. (2023). A Method To Obtain Lightning Peak Current in Indonesia. Energies, 16(17), 6342. https://doi.org/10.3390/en16176342

Dewan, A., Ongee, E. T., Rafiuddin, M., Rahman, M. M., & Mahmood, R. (2018). Lightning Activity Associated With Precipitation and Cape Over Bangladesh. International Journal of Climatology, 38(4), 1649–1660. https://doi.org/10.1002/joc.5286

Dowdy, A. J. (2016). Seasonal forecasting of Lightning and Thunderstorm Activity in Tropical and Temperate Regions of the World. Scientific Reports, 6, 20874. https://doi.org/10.1038/srep20874

Edirisinghe, M., & Maduranga, U. G. D. (2021). Distribution of Lightning Accidents in Sri Lanka from 1974 To 2019 Using the Desinventar Database. ISPRS International Journal of Geo-Information, 10(3), 117. https://doi.org/10.3390/ijgi10030117

Farquad, M. A. H., & Bose, I. (2012). Preprocessing Unbalanced Data Using Support Vector Machine. Decision Support Systems, 53(1), 226–233. https://doi.org/10.1016/j.dss.2012.01.016

Galanaki, E., Kotroni, V., Lagouvardos, K., & Argiriou, A. (2015). A Ten-Year Analysis of Cloud-To-Ground Lightning Activity Over the Eastern Mediterranean Region. Atmospheric Research, 166, 213–222. https://doi.org/10.1016/j.atmosres.2015.07.008

Grbić, R., Kurtagić, D., & Slišković, D. (2013). Stream Water Temperature Prediction Based on Gaussian Process Regression. Expert Systems with Applications, 40(18), 7407–7414. https://doi.org/10.1016/j.eswa.2013.06.077

Hamid, E. Y., Kawasaki, Z. I., & Mardiana, R. (2001). Impact of the 1997–98 El Niño Event on Lightning Activity Over Indonesia. Geophysical Research Letters, 28(1), 147–150. https://doi.org/10.1029/2000GL011374

Hashiguchi, H., Yamamoto, M. K., Yamamoto, M., Mori, S., Yamanaka, M. D., Carbone, R. E., & Tuttle, J. D. (2013). Cloud Episode Propagation Over the Indonesian Maritime Continent from 10 Years of Infrared Brightness Temperature Observations. Atmospheric Research, 120, 268–286. https://doi.org/10.1016/j.atmosres.2012.09.004

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., & Simmons, A. (2020). The ERA5 Global Reanalysis. Quarterly Journal of the Royal Meteorological Society, 146(730), 1999–2049. https://doi.org/10.1002/qj.3803

Jayaratne, E. R., & Saunders, C. P. R. (1983). Charge on Ice Crystals In Laboratory Clouds. Journal of Geophysical Research: Oceans, 88(C9), 5494–5496. https://doi.org/10.1029/JC088iC09p05494

Jensen, J. D., Thurman, J., & Vincent, A. (2021). Lightning Injuries. In StatPearls. Publishing LLC.

Khan, M. W., Ahmad, S., Dahri, Z. H., Syed, Z., Ahmad, K., Khan, F., & Azmat, M. (2023). Development of High-Resolution Daily Gridded Precipitation and Temperature Dataset for Potohar Plateau of Indus Basin. Theoretical and Applied Climatology, 154(3), 1179–1201. https://doi.org/10.1007/s00704-023-04626-7

Kumar, M., Gromiha, M. M., & Raghava, G. P. S. (2008). Prediction of RNA Binding Sites in A Protein Using SVM and PSSM Profile. Proteins: Structure, Function, and Bioinformatics, 71(1), 189–194. https://doi.org/10.1002/prot.21677

Lal, D. M., Umakanth, N., Domkawale, M. A., Gopalakrishnan, V., Srivastava, M. K., & Pawar, S. D. (2024). Association of Lightning With LCL, EL, Humidity At 850 Mb and At 200 Mb During Various CAPE, Over Northern India. Science of The Total Environment, 915, 169947. https://doi.org/10.1016/j.scitotenv.2024.169947

Lin, G. F., & Chen, L. H. (2004). A Non-Linear Rainfall-Runoff Model Using Radial Basis Function Network. Journal of Hydrology, 289(1–4), 1–8. https://doi.org/10.1016/j.jhydrol.2003.10.015

Liou, Y. A., & Kar, S. K. (2010). Study of Cloud-To-Ground Lightning and Precipitation and Their Seasonal and Geographical Characteristics Over Taiwan. Atmospheric Research, 95(2–3), 115–122. https://doi.org/10.1016/j.atmosres.2009.08.016

Liyew, C. M., & Melese, H. A. (2021). Machine Learning Techniques To Predict Daily Rainfall Amount. Journal of Big Data, 8, 1–11. https://doi.org/10.1186/s40537-021-00545-4

Louf, V., Jakob, C., Protat, A., Bergemann, M., & Narsey, S. (2019). The Relationship of Cloud Number and Size With Their Large-Scale Environment in Deep Tropical Convection. Geophysical Research Letters, 46(15), 9203–9212. https://doi.org/10.1029/2019GL083964

Maduranga, U. D., Edirisinghe, M., & Gamage, L. V. (2018). Annual Variation Trend of Lightning Flash Activities Over Sri Lanka. World Science News, 114, 256–264. https://doi.org/10.3390/ijgi12020067

Mansell, E. R., Ziegler, C. L., & Bruning, E. C. (2010). Simulated Electrification of A Small Thunderstorm With Two-Moment Bulk Microphysics. Journal of the Atmospheric Sciences, 67(1), 171–194. https://doi.org/10.1175/2009JAS2965.1

Mills, B., Unrau, D., Pentelow, L., & Spring, K. (2010). Assessment of Lightning-Related Damage and Disruption in Canada. Natural Hazards, 52, 481–499. https://doi.org/10.1007/s11069-009-9391-2

Mistovich, J. J., Krost, W. S., & Limmer, D. D. (2008). Beyond the Basics: Lightning-Strike Injuries. EMS Magazine, 37(3), 82–87.

Moncrieff, M. W., Miller, M. J. (1976). The Dynamics and Simulation of Tropical Cumulonimbus and Squall Lines. Quarterly Journal of the Royal Meteorological Society, 102(432), 373–394. https://doi.org/10.1002/qj.49710243208

Moron, V., Robertson, A. W., & Qian, J. H. (2010). Local Versus Regional-Scale Characteristics of Monsoon Onset and Post-Onset Rainfall Over Indonesia. Climate Dynamics, 34, 281–299. https://doi.org/10.1007/s00382-009-0547-2

Mukhopadhyay, P., Mahakur, M., & Singh, H. A. K. (2009). The Interaction of Large Scale and Mesoscale Environment Leading To Formation of Intense Thunderstorms Over Kolkata Part I: Doppler Radar And Satellite Observations. Journal of Earth System Science, 118, 441–466. https://doi.org/10.1007/s12040-009-0046-1

Murray, B. J., O'Sullivan, D., Atkinson, J. D., & Webb, M. E. (2012). Ice Nucleation By Particles Immersed in Supercooled Cloud Droplets. Chemical Society Reviews, 41(19), 6519–6554. https://doi.org/10.1039/C2CS35200A

Mushtaq, F., Lala, M. G. N., & Anand, A. (2018). Spatio-Temporal Variability of Lightning Activity Over J&K Region and Its Relationship With Topography, Vegetation Cover, and Absorbing Aerosol Index (AAI). Journal of Atmospheric and Solar-Terrestrial Physics, 179, 281–292. https://doi.org/10.1016/j.jastp.2018.08.011

Okafor, U. V. (2005). Lightning Injuries and Acute Renal Failure: A Review. Renal Failure, 27(2), 129–134. https://doi.org/10.1081/JDI-48216

Orville, R. E., Huffines, G. R. (1999). Lightning Ground Flash Measurements Over the Contiguous United States: 1995–97. Monthly Weather Review, 127(11), 2693–2703. https://doi.org/10.1175/1520-0493(1999)127<2693:LGFMOT>2.0.CO;2

Pawar, S. D., Lal, D. M., & Murugavel, P. (2012). Lightning Characteristics Over Central India During the Indian Summer Monsoon. Atmospheric Research, 106, 44–49. https://doi.org/10.1016/j.atmosres.2011.11.007

Price, C. (2009). Thunderstorms, Lightning, and Climate Change. In Springer Netherlands (pp. 521–535). https://doi.org/10.1007/978-1-4020-9079-0_24

Pruppacher, H. R., Klett, J. D., & Pruppacher, H. R. (2010). Historical Review. Microphysics of Clouds and Precipitation, 1–9. https://doi.org/10.1007/978-0-306-48100-0

Saha, U., Siingh, D., Kamra, A. K., Galanaki, E., Maitra, A., Singh, R. P., Singh, A. K., Chakraborty, S., & Singh, R. (2017). On the Association of Lightning Activity and Projected Change in Climate Over the Indian Subcontinent. Atmospheric Research, 183, 173–190. https://doi.org/10.1016/j.atmosres.2016.09.001

Saunders, C. P. R. (1993). A Review of Thunderstorm Electrification Processes. Journal of Applied Meteorology and Climatology, 32(4), 642–655. https://doi.org/10.1175/1520-0450(1993)032<0642:AROTEP>2.0.CO;2

Shubri, A. R., Vonnisa, M., & Marzuki, M. (2024). Influence of Aerosols on Lightning Activities in Java Island, Indonesia. Trends in Sciences, 21(2), 7214. https://doi.org/10.48048/tis.2024.7214

Shubri, A. R., Vonnisa, M., & Marzuki, M. (2024). Influence of Aerosols on Lightning Activities in Java Island, Indonesia. Trends in Sciences, 21(2), 7214–7214. https://doi.org/10.48048/tis.2024.7214

Siingh, D., Singh, R. P., Kumar, S., Dharmaraj, T., Singh, A. K., Singh, A. K., Patil, M. N., & Singh, S. (2015). Lightning and Middle Atmospheric Discharges in the Atmosphere. Journal of Atmospheric and Solar-Terrestrial Physics, 134, 78–101. https://doi.org/10.1016/j.jastp.2015.10.001

Singh, O., Bhardwaj, P., & Singh, J. (2017). Distribution of Lightning Casualties Over Maharashtra, India. Journal of Indian Geophysical Union, 21(5), 415–424.

Sun, A. Y., Wang, D., & Xu, X. (2014). Monthly Streamflow Forecasting Using Gaussian Process Regression. Journal of Hydrology, 511, 72–81. https://doi.org/10.1016/j.jhydrol.2014.01.023

Takahashi, T. (1978). Riming Electrification As A Charge Generation Mechanism in Thunderstorms. Journal of Atmospheric Sciences, 35(8), 1536–1548. https://doi.org/10.1175/1520-0469(1978)035<1536:REAACG>2.0.CO;2

Thompson, R. L., Edwards, R., Hart, J. A., Elmore, K. L., & Markowski, P. (2003). Close Proximity Soundings Within Supercell Environments Obtained from the Rapid Update Cycle. Weather and Forecasting, 18(6), 1243–1261. https://doi.org/10.1175/1520-0434(2003)018<1243:CPSWSE>2.0.CO;2

Turman, B. N., Edgar, B. C. (1982). Global Lightning Distributions At Dawn and Dusk. Journal of Geophysical Research: Oceans, 87(C2), 1191–1206. https://doi.org/10.1029/JC087iC02p01191

Tyagi, A., Sikka, D. R., Goyal, S., & Bhowmick, M. (2012). A Satellite-Based Study of Pre-Monsoon Thunderstorms (Nor'westers) Over Eastern India and Their Organization Into Mesoscale Convective Complexes. Mausam, 63(1), 29–54. https://doi.org/10.54302/mausam.v63i1.1446

Umakanth, N., Chandrasekhar, A. V., Smitha, A. S. S., Vasantha, B., Rao, K. S., Koutavarapu, R., & Rao, M. C. (2024). Lightning Activity and Its Connection With Weather-Related Parameters Over Sri Lanka. Acta Geophysica, 1–21. https://doi.org/10.1007/s11600-024-01442-z

Vapnik, V. N. (1995). The Nature of Statistical Learning Theory (334). https://doi.org/10.1007/978-1-4757-2440-0

Verma, S., Yadava, P. K., Lal, D. M., Mall, R. K., Kumar, H., & Payra, S. (2021). Role Of Lightning Nox In Ozone Formation: A Review. Pure and Applied Geophysics, 178, 1425–1443. https://doi.org/10.1007/s00024-021-02710-5

Weisman, M. L., Klemp, J. B. (1982). The Dependence of Numerically Simulated Convective Storms on Vertical Wind Shear and Buoyancy. Monthly Weather Review, 110(6), 504–520. https://doi.org/10.1175/1520-0493(1982)110<0504:TDONSC>2.0.CO;2

Wilks, D. S. (2006). Statistical Methods in the Atmospheric Sciences (2nd ed.). Academic Press.

Williams, E. R., Sátori, G. (2004). Lightning, Thermodynamic, and Hydrological Comparison of the Two Tropical Continental Chimneys. Journal of Atmospheric and Solar-Terrestrial Physics, 66(13-14), 1213–1231. https://doi.org/10.1016/j.jastp.2004.05.015

Williams, E. R., Zhang, R., & Rydock, J. (1991). Mixed-Phase Microphysics And Cloud Electrification. Journal of Atmospheric Sciences, 48(19), 2195–2203. https://doi.org/10.1175/1520-0469(1991)048<2195:MPMACE>2.0.CO;2

Yadava, P. K., Soni, M., Verma, S., Kumar, H., Sharma, A., & Payra, S. (2020). The Major Lightning Regions and Associated Casualties Over India. Natural Hazards, 101, 217–229. https://doi.org/10.1007/s11069-020-03870-8

Zaikarina, H., Djuraidah, A., & Wigena, A. H. (2016). Lasso and Ridge Quantile Regression Using Cross-Validation To Estimate Extreme Rainfall. Global Journal of Pure and Applied Mathematics, 12(3), 3305–3314.

Zheng, D., Zhang, Y., Yao, W., Wang, F., Lyu, W., Meng, Q., Fan, X., Ma, Y., & Yang, J. (2020). Lightning and Deep Convective Activities Over the Tibetan Plateau. National Science Review, 7(3), 487–488. https://doi.org/10.1093/nsr/nwz182

Zipser, E. J. (2003). Some Views on "Hot Towers" After 50 Years of Tropical Field Programs and Two Years of TRMM Data. Meteorological Monographs, 29(51), 49–58. https://doi.org/10.1175/0065-9401(2003)029<0049:CSVOHT>2.0.CO;2

Zoro, R., Mefiardhi, R. (2005). Lightning Performance on Overhead Distribution Lines: Field Observation At West Java-Indonesia. In 2005 International

Power Engineering Conference (pp. 1–205). IEEE. https://doi.org/10.1109/IPEC.2005.206906