Conceptual Design of Extreme Weather Observation using Lightning Detection Network and Micro-Satellite for EWS over Indonesian Territory

Purwadi
BBTMC - BPPT
Jakarta, Indonesia
purwadi5178@bppt.go.id

Andi Eka Sakya
BBTMC - BPPT
Jakarta, Indonesia
halda.aditya@bppt.go.id

Tri Handoko Seto
BBTMC - BPPT
Jakarta, Indonesia
tri.handoko@bppt.go.id

Bayu Hak
BBTMC - BPPT
Jakarta, Indonesia
bayuhak3@gmail.com

Yukihiro Takahashi
Department of Cosmoscience
Hokkaido University
Sapporo, Japan
yukihiro@sci.hokudai.ac.jp

Erwin Mulyana
BBTMC - BPPT
Jakarta, Indonesia
Erwin.mulyana@bppt.go.id

Halda Aditya Belgaman
BBTMC - BPPT
Jakarta, Indonesia
halda.aditya@bppt.go.id

Mitsuteru Sato
Department of Cosmoscience
Hokkaido University
Sapporo, Japan
msato@ep.sci.hokudai.ac.jp

Findy Renggono
BBTMC - BPPT
Jakarta, Indonesia
findy.renggono@bppt.go.id

***Abstract*—In the last 10 years, based on Indonesia's National Disaster Management Agency (BNPB) data, the number of hydro-meteorological disasters have been increasing. These hydro-meteorological disasters mainly pertain to flood, landslide, wildfire, Small Scale Tornado (SST), among others. High intensity rainfall is an extreme weather condition that is considered as one of the causes of hydrological disasters. Previous researches have mentioned lightning as a good proxy for storm activity. This research aimed to develop an observation and prediction methodology for extreme weather events such as torrential rain based on the combination of continuous lightning measurement and on-demand by surface lightning detection network with remote sensing instrument, a micro-satellite owned by ASEAN countries and Japan. Indonesia already has a network of lightning detection devices that use Very Low Frequencies (VLF) but not too dense. This research will lead to a new methodology in hydro meteorological disaster mitigation, and strengthen and complement already operational extreme weather early warning systems.**

Keywords—disaster, torrential rainfall, lightning, Lightning observation, mitigation

I. INTRODUCTION

The number of hydro-meteorological disasters, such as floods, landslides, tornadoes, droughts, and forest and land fires, in Indonesia have continued to increase in the past 10 years. Based on National Disaster Management Agency (BNPB) data, more than 700 hydro-meteorological disasters have occurred until in the end of the first quarter of 2019, as shown in figure 1.

Hydro-meteorological disasters in the first quarter of 2019 have caused a considerable number of losses, both lives and infrastructures. Table 1 explains number of losses due to hydro-meteorological disaster during the first quarter of 2019. Majority of these disasters were Small Scale Tornado (SST), floods, and landslides, and creating high number of death tolls. Rainfall intensity was seemed to be as the main cause of floods and landslide that happened over the disaster location.

Indonesia's Agency for Meteorology, Geophysics, and Climatology (BMKG) had already established an Early warning system for extreme weather spread throughout Indonesia. The system was based on "traditional" ground measurements, weather radar and satellite data observations. The weakness of this system was the limitations of observation using weather radar, such as coverage, cloud height, and the high cost of maintenance. Meanwhile, satellite cloud cover observations tend to leave high error values due to cloud peak values which sometimes do not represent cloud types.

By the end of 2020, the Indonesian Space Agency (LAPAN) will own a micro satellite named LAPAN A-4 equipped with an infrared camera developed by Hokkaido University[1]. This camera is able to produce high-resolution image that can be converted to cloud peak temperature. High resolution infrared images will certainly improve understanding of the development of cumulus clouds observed from above, and more accurately predict the speed of cloud expansion.

978-1-7281-5077-2/19/$31.00 ©2019 IEEE

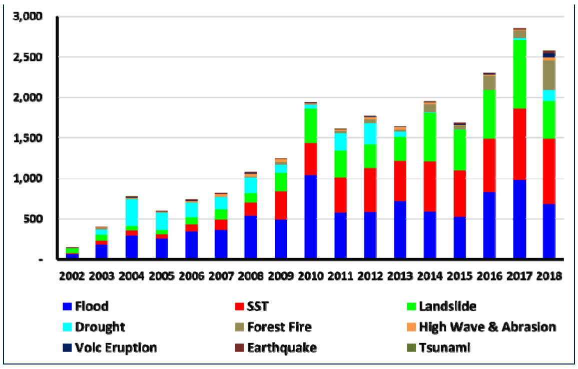

Fig. 1. Disaster trends in past the 10 years in Indonesia

TABLE I. NUMBER OF LOSSES FROM HYDROLOGICAL DISASTER IN INDONESIA IN THE FIRST QUARTER OF 2019 (SOURCE: DIBI.BNPB.GO.ID).

TYPE OF DISASTER	NO EVENTS	VICTIM			HOUSE – DAMAGED				FACILITY – DAMAGED		
		Loss	Injuries	Displcd	Heavily	Medium	Light	Sunken	Health	Worship	Edctn
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Flood	225	96	81	192,541	663	100	1,779	62,763	6	63	105
Landslide	241	42	53	1,275	74	71	336	0	2	10	12
Flash Flood	4	2	1	0	6	1	21	0	0	0	0
SST	383	2	72	6,901	419	805	4,316	0	4	32	30
Forest Fire	30	1	0	0	0	0	0	0	0	0	0
TOTAL	**883**	**143**	**207**	**200,717**	**1,162**	**977**	**357**	**62,763**	**12**	**105**	**147**

The speed of cloud expandability has long been known to have strong correlation with updraft conditions within the cloud. Strong updraft will potentially grow into storm seeds that also contain thunders and/or lightning and significantly indicate heavy rain intensity. Detection of lightning location will therefore help identify active cloud and updraft, and thus can serve as possible proxy for potential heavy rain intensity in certain areas.

In this research, the authors will briefly present an outline of their research on detecting lightning for extreme weather precursor and its application in Japan. Next the paper discusses the possibility of using this methodology in Indonesia that continues to experience an increase in hydro-meteorology disasters within the last 5 years. This paper focuses on the design of integrating this methodology with Indonesia's existing hydro-meteorological early warning system.

II. LITERATURE REVIEW

Lightning occurs as a result of static displacement that is sufficiently large on the sides of the cloud, raising different potentials on several sides of the cloud as well as sides inside the clouds, against other clouds, and clouds against the earth. Lightning is divided into three categories: intra-cloud (IC), cloud-to-cloud (CC), and cloud-to-ground (CG).

Lightning emits different electromagnetic waves as a result of different processes in the discharge, either low in Hz or high in several hundred MHz [2, 3]. Lightning is initiated much like ladder steps finding its release. In this process, lightning emits Very High Frequency (VHF) electromagnetic waves and the released lightning occur when the electromagnetic potential difference reach the target, either the earth surface or another cloud. T. Kudo (2014) stated that continuing current occurs in millisecond after a lightning strike occurs [4].

The estimated location of a lightning can be determined in two ways: Direct Finding (DF) and Time of Arrival (ToA) [5, 6, 7]. Peak current and charge moment change during the occurrence of CG can be calculated by the electromagnetic wave that are emitted at VLF and ELF ranges, respectively [5, 8, 9, 10].

Lightning that occur inside a cloud is as a result of electrification within the cloud and is caused by the friction between ice crystals and cloud droplets. Therefore, cloud dynamic has an important role and can be correlated with the electrification process. [11], stated that electrification inside a cloud occurs when the cloud reaches freezing level at cloud growth speed of more than 8 m/s.

Previous researchers have denoted significant proportional correlation between lightning frequencies and heavy rainfall [12, 13, 14]. Some researchers in Indonesia reiterated the intense relationship between lightning and convective cloud activities and rainfall amount [15, 16, 17]. [18] concluded that the number of CG activities had very good correlation with hail and graupel occurrences, which was indicated by weather radar echo of more than 35dBZ. Other related researches re-emphasized notable correlation between lightning (IC+CG) with severe weather, such as high wind, hail, and tornado [19, 20, 21].

Satellite images can show distribution and cloud type. Further researches have successfully estimated cloud height from infrared image data obtained through satellite. Hamada et. al., 2008 used split-window and probability density function (PDF) method to determine cloud type from infrared image at 10.8 µm and at 12 µm wavelength using fifth Geostationary Meteorological Satellite (GMS-5) [22]. Further, Hamada et. al., 2010 estimated cloud height using the same wavelength but from a different satellite, the Geostationary multifunctional transport satellite (MTSAT-1R) [23]. Meanwhile [24] measured cloud height using infrared image from Feng Yun 2 (FY2) satellite and compared it with weather radar data.

III. DATA AND METHODOLOGY

A. Lightning Geolocation

Strong dynamic thunderstorm clouds often results in a collection of similar charges on certain sides of cumulonimbus clouds. If this charging energy is large enough and exceeds the air isolation threshold between charges in the cloud to the ground, it will trigger a natural phenomenon of lightning from cloud to ground (cloud to ground/CG). This type of CG lightning discharges electromagnetic waves, one of them is in the Very Low Frequency (VLF) range. VLF signals can be detected up to ~5000 kilometers. Based on this VLF signal, several lightning parameters, such as location of lightning, peak currents, and charge moment change (CMC), can be measured [4]. Because the frequency of discharge is closely correlated with cloud dynamics, those parameters could be used to determine the level of potential hazards caused by cumulonimbus clouds [19s].

In this research, a conceptual design of lightning observation is proposed to cover the entire territory of Indonesia using V-POTEKA lightning detectors that use an in-situ observing apparatus of the device. This observation equipment is Japanese made and capable of measuring CG Lightning up to 3000 Km. V-POTEKA uses 3G network for data communication and is synchronized with a satellite GPS within the range of 100 us resolution. For this purpose, 3 (three) V-POTEKA have been installed to fulfill the essential minimum requirement to measure the Time-of-Arrival (ToA).

ToA is the time difference received between 2 (two) stations. As shown in Figure 2, t0 is the time the lightning strikes. In certain intervals, the electromagnetic waves emitted by the lightning will reach station A and station B in time tA and tB, respectively. Therefore, the difference in the timing of receiving electromagnetic waves from stations A and B is tA & tB and can be represented as tA-tB.

The location of the lightning based on the time difference between tA & tB is the points that are shown on the A & B red line. It can be interpreted that the A & B red line is the possible location of a lightning that occurs with the time difference ΔtA & B, called ToA lines. By adding 1 more station location, station C, 3 (three) ToA lines are obtained as illustrated in Figure 3. The estimated location of the lightning is the cross section of these lines.

With the V-POTEKA lightning detector capable of observing lightning in the range of 3000 km, approximately 5 V-POTEKA are needed to cover the entire territory of Indonesia (Figure 4). As shown in Figure 5, the simulation of geo-location error had been created by every 3 stations (Figure 5), with an ambiguity of about 20 to 40 km of geolocation range.

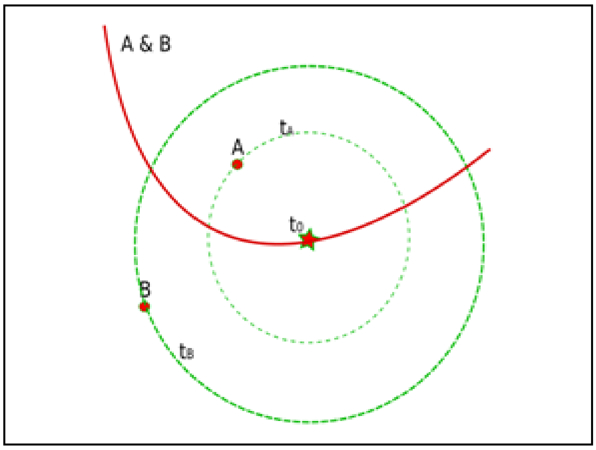

Fig. 2. Illustration of Time of Arrival (ToA).

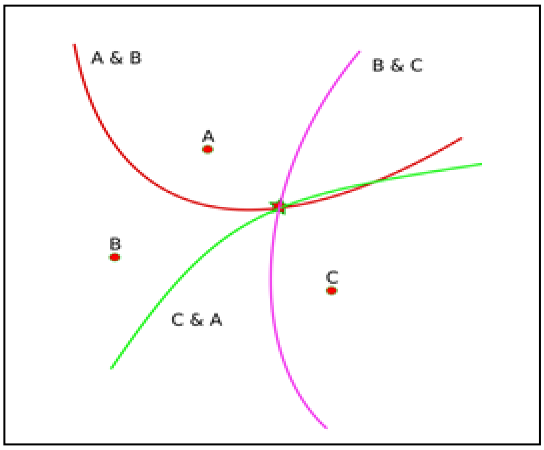

Fig. 3. Estimation of lightning location using Time of Arrival method.

B. Cloud Cover

Thunderstorm cloud convection can be observed by the updraft intensity represented by the speed of cloud expandability. The geostationary Himawari-8 satellite provides a 2-kilometer resolution brightness temperature image over Indonesian territory every 10 minutes. Using this satellite, the cloud shape detail cannot be acquired. Thus, the research used the thermal infrared sensor (TIS) camera designed by Hokkaido University that will be installed in LAPAN-A4 satellite. This TIS camera is able to provide 180-meter resolution at 500 kilometers from the orbit with an accuracy 4 Kelvin. In that satellite orbit, the TIS camera will provide a 54 x 42 kilometer Field of View that will sufficiently capture the surface temperature of thunderstorm clouds.

Assuming that the surface temperature of cloud follows ambient temperature, the cloud height can be estimated, considering that ambient temperature can be estimated using radiosonde or numerical modeling. From several brightness temperature images which have been measured by LAPAN-A4 in specific interval times, the cloud growth speed can be measured. The concept of cloud top height and cloud growth speed measurement are illustrated in figure 6.

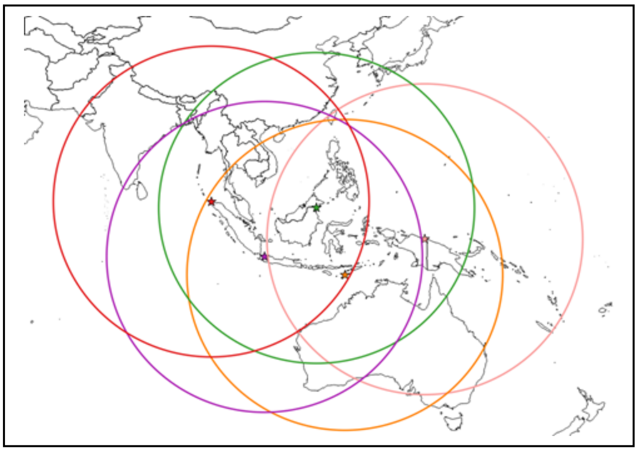

Fig. 4. Lightning Observation Network Scenario to cover entire Indonesian territory.

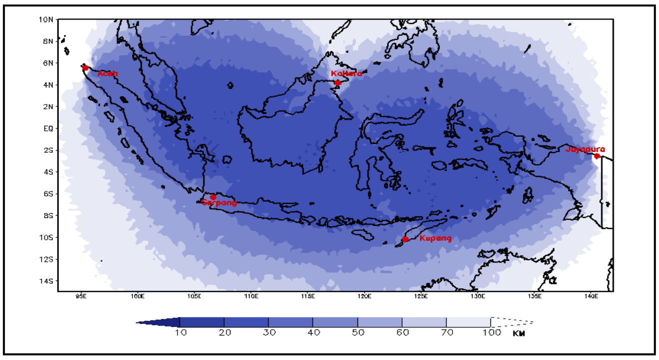

Fig. 5. Geolocation Simulation Error.

C. Combine Observation

The combination of lightning detection network and cloud brightness temperature movement from space (shown in Fig. 7) is able to detect thunderstorm clouds over the entire area of Indonesia not detected by radar. The VLF signal that is emitted by lightning from a cloud will be detected by a lightning sensor. The ToA and amplitude of the detected signal will then be recorded and sent to the computer server using available and ready internet connection. The computer server is able to estimate the geo-location of the lightning based on a minimum of 3 ToA data from 3 different stations. The first lightning that is detected will be the reference for the microsatellite to observe the area. The microsatellite takes an image of the specific relevant brightness temperature and send it to the computer server. The server will analyze the lightning parameter data, such as frequency of occurrences, peak currents, and charge moment change, and cloud parameter collected from the brightness parameter observation, such as cloud growth speed and cloud volume. This analysis will create a prediction of thunderstorm cloud hazards, such as hail, thunder, heavy rainfall, and microburst at several to ten minutes before they occur.

Fig. 6. Concept of cloud top height and cloud growth speed measurement.

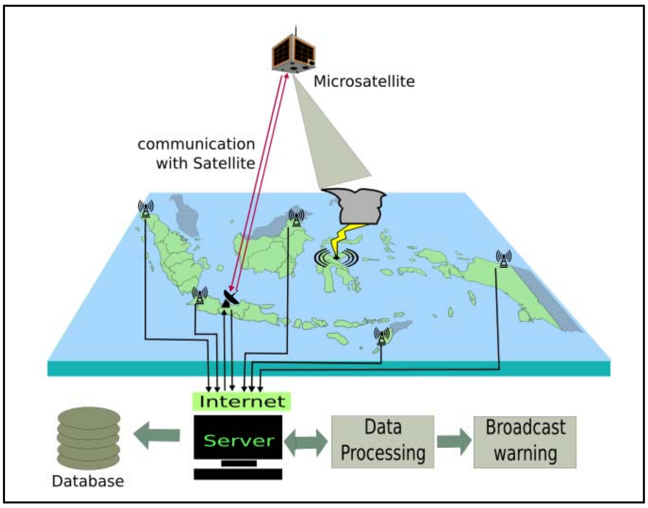

Fig. 7. Concept of cloud top height and cloud growth speed measurement.

IV. Discussion and Conclusion

A. Discussion

Indonesia, as a tropical maritime country, reaching ~5300 km from Sabang in the west to Merauke in the east, has a wet tropical climate that potentially provides the environment for thunderstorm clouds to massively expand. This type of cloud is a potential cause of disaster, such as hail, hurricanes, lightning strikes, and heavy rains that could further cause floods and landslides [20]. This type of cloud is easily observed in Indonesia using weather radar, but Indonesia's large area would require many radars, which would become very costly to accommodate.

An effective and efficient alternative for cloud observation is using remote sensing satellite. The Himawari-8 satellite from the Japanese Government has a resolution of 2 kilometers and the collaboration has enabled Indonesia to observe its clouds. However, the observed image results are have not sufficiently describe the potential dangers of each thunderstorm cloud. Indonesia needs additional parameters, such as lightning location, frequency of occurrence, peak currents, charge moment change, among others, to better predict potential hazards and level of thunderstorm clouds.

As described above in Fig. 5, lightning observation over the entire Indonesia area can be supported by 5 V-POTEKA lightning detectors that have been placed in Aceh, Serpong-Tangerang Selatan, Nunukan-Kalimantan Utara, Kupang, and Jayapura.

The geo-location range of error is between 20-40 kilometers, which is still considerably large for a single thunderstorm that usually extend up to ~100 km^2 [24]. A combination of V-POTEKA measurement, with FoV 54x24 km, can support the observation of a single thunderstorm cloud activity. Thus, the geo-location error can presumably be reduced through the incorporation of FoV of TIS camera image.

This proposed system can deliver observation results on lightning parameters such as frequency, peak current, and charge moment change, cloud top height, and cloud growth speed. Previous studies have shown that lightning activity is correlated with severe weather [19, 20, 21], and that cloud growth speed affects thunderstorm cloud electrification.

The integration of 'existing and common' weather observation systems with the capturing of complete measurements of the early stage of thunderstorm developments will be able to better predict potential hydro-meteorological hazards, such as heavy rain, and contribute to the improvement of extreme weather forecast.

The implementation of this concept to cover the entire area of Indonesia requires a number of specifically-designed micro-satellites in orbit and temporal resolution to TIS cameras that have been used by LAPAN-A4. However, development of space technology for remote sensing is pacing slowly in Indonesia, thus the country would need to create a scenario to develop its space technology strategy [26].

978-1-7281-5077-2/19/$31.00 ©2019 IEEE

B. Conclusion

The research reviewed lightning location detection in correlation with the expandability of active clouds using micro-satellite network in Japan. Active clouds tend to be closely associated with updraft, which indicate extreme weather potential, such as heavy rain or cyclone. Therefore, this methodology can be used as a proxy for potential hydro-meteorological hazards. The possibility to expand this methodology for extreme weather early warning system have been sought in conjunction with the need to complement Indonesia's existing system.

The proposed integrated design discussed in this research has also taken into consideration Indonesia's plan to launch its micro-satellite by the end of 2020, one of the highlight intended for lightning detection.

ACKNOWLEDGMENT *(Heading 5)*

This work was supported by Japan Society for the Promotion of Science (JSPS), Core-to-Core Program, B. Asia-Africa Science Platforms, by Japan Science and Technology Agency(JST) together with Technology and Higher Education(RISTEKDIKTI) of the of Indonesia under the e-ASIA Joint Research Program, and by Japan International Cooperation Agency (JICA) and JST, SATREPS.

REFERENCES

[1] M. A. Saifudin, A. Karim and Mujtahid 2018 LAPAN-A4 Concept and Design for Earth Observation and Maritime Monitoring Missions IEEE International Conference on Aerospace Electronics and Remote Sensing Technology (ICARES) pp. 1-5.

[2] Burke, C.P., and D.L. Jones 1992 On the polarity of and continuing currents in unusually large lightning flashes deduced from ELF event Journal of Atmospheric and Solar-Terrestrial Physics 54 pp 531-540

[3] Weidman C.D, Krider E.P 1986 The amplitude spectra of lightning radiation fields in the internal from 1 to20 MHz Radio Science 21 pp 964-970

[4] Kudo T 2014 A Study of lightning magnitudes and thunderstorm activity based on the observation of VLF sferics (Hokkaido University, Faculty of Science)

[5] Yamashita K, Takahashi Y, Sato M., Kase H. 2011 Improvement in lightning geolocation by time-of-arrival method using global ELF network data Journal of Geophysic Research 116 pp 1-12

[6] Said R. K, Inan U.S., and Cummins K. L. 2010 Long-range lightning geolocation using a VLF radio atmospheric waveform bank Journalof Geophysics Research 115

[7] Krider E. P, Pifer A.E, and Vance D. L 1980 Lightning direction finding system for forest fire detection Bulettin of the American Meteorology Society 61 pp 980-986

[8] Sato M, Tsuchiya F., Honma H., Tsurushima D., Takahashi Y. 2013 Lightning Current Measurements Based on ELF Magnetic Field Observations paper presented to the Asia Pacific Radio Science Conference (AP-RASC 2013) Sep. 3-7 2013 Taipei Taiwan.

[9] Cummer S.A, Lyons W.A., and Stanley M.A. 2013 Three years of lightning impulse charge moment change measurements in United States J. Geophys. Res. Atmos 118 pp 5178-5189

[10] Narita, T., T. Yamada, A. Mochizuki,, E. Zaima, and M. Ishii, 2000, Observation of current waveshapes of lightning strokes on transmission towers, IEEE Transactions on Power Delivery 15 pp 429-435

[11] Krehbiel P.R. 1986 The electrical structure of thunderstorms, in The Earth's Electrical Environment (E.P. Krider et al., eds. Washington, DC: National Academy Press, pp 263)

[12] Tapia A., Smith J. A., Dixon M. 1998 Estimation of Convective Rainfall from Lightning Observations Journal Applied Meteorology 37 pp 1497-1509.

[13] Carey L. D, Rutledge S. A. 2000 The relationship between precipitation and lightning in tropical island convection: A C-band polarimetric radar study Mon. Wea. Rev. 128 pp 2687-2710.

[14] Soula S, Chauzy S. 2001 Some aspects of the correlation between lightning and rain activities in thunderstorms Atmospheric Research 56 pp 355–373.

[15] Fansury G.H Mustofa M.A. 2013 Hubungan aktivitas Petir Cloud-to-Ground (CG) dengan Curah Hujan di Bogor (Institut Teknologi Bandung)

[16] Fitriani R, Wahyu T.W. 2013 Hubungan antara Aktivitas Petir CG (Cloud-to-Ground) dan Awan Konvektif (studi Kasus Wilayah Jawa Barat) (Institut Teknologi Bandung)

[17] Muiz K, Dupe Z.L Riawan E. 2015 Studi Karakteristik Petir Jenis Cloud-To-Ground (CG) Sebagai Indikator Hujan Ekstrem di Wilayah Sumatera Utara (Institut Teknologi Bandung)

[18] Seity Y, Soula S Tabary P and Scialom G 2003 The convective strorm system during IOP 2a of MAP: Cloud-to-ground lightning flash production to dynamics and microphysics Quarterly Journal of the Royal Meteorology Society 129 pp 523-542

[19] Williams E, Boldi B, Matlin A., Weber M., Hodanish S., Sharp D., Goodman S., Raghavan R., Buechler D. 1999 The behavior of total lightning activity in severe Florida Thunderstorms Atmospheric Research 51 pp 245-265.

[20] Goodman S J, Blakeslee R., Christian H., Koshak W., Bailey J., Hall J., McCaul E., Buechler D., Darden C., Burks J., Bradshaw T., and Gatlin P. 2005 The North Alabama Lightning Mapping Array: Recent severe storm observations and future prospects Atmospheric Research 76 pp 423-437

[21] MacGorman D. R, Burgess D.W., Mazur V., Rust W.D., Taylor W.L., and Johnson B.C. 1989 Lightning rates relative to tornadic storm evolution on 22 May 1981 Journal of Atmospheric Science 46 pp 221-250.

[22] Hamada A, Nishi N., Iwasaki S., Ohno Y., Kumagai H., and Okamoto H. 2008 Cloud type and top height estimation for tropical upper-tropospheric clouds using GMS-5 split-window measurements combined with cloud radar measurements Journal of Applied Meteorology and Climatology 4 pp 57–60

[23] Hamada A, Nishi N. 2010 Development of a Cloud-Top Height Estimation Method by Geostationary Satellite Split-Window Measurements Trained with CloudSat Data Journal of Applied Meteorology and Climatology 4 pp 2035–2049, doi:10.1175/2010JAMC2287.1.

[24] Wang C, Zheng D., Zhang Y., and Liu L. 2017 Relationship between lightning activity and vertical airflow characteristics in thunderstorms Atmospheric Research 191 pp 12–19.

[25] Rakov V.A, Uman M.A 2003 Lightning physics and effect (Cambridge University press: Cambridge)

[26] Agustan, Sadly, M., Yulianto, S., Sutrisno, D., Bintoro, O. B., & Alhasanah, F. (2018, September). Participatory Scenario Planning for Indonesian Space Industry in 2025. In 2018 IEEE International Conference on Aerospace Electronics and Remote Sensing Technology (ICARES))pp. 1-6