Distribution of winter lightning around the world using Blitzortung

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***Abstract*—In this study, Blitzortung, a lightning location system, was used to investigate lightning trends in the areas covered in North America, Europe, Japan, and Australia to ascertain the distribution of summer and winter lightning. Two conditions, continental cold air and warm ocean currents, which are known to cause winter lightning in Japan, were investigated in other areas that are prone to winter lightning, with results showing that these conditions were also met in the Gulf of Mexico and Atlantic Ocean in North America, the Mediterranean Sea and Norway in Europe, the Sea of Japan and the Pacific Ocean off the coast of Ibaraki Prefecture, and the Tasman Sea. These results suggest that winter lightning occurs in areas with continental cold air to the west and warm ocean currents to the east, which lie at latitudes of 25° north and south or higher. The extent to which cold continental air is related to areas experiencing winter lightning has also been elucidated.**

Keywords*— *LLS, time of arrival technique, VLF, winter lightning, world

I. INTRODUCTION

The Blitzortung projects[1][2][3] aim to achieve a global-scale, high-precision lightning location network using inexpensive IT technology. The project was initiated in 2012 by Professor Egon Wanke and his colleagues at Heinrich Heine University in Germany. It is operated by volunteers who solder and build receiving stations and connect them to the network. Lightning data, including the lightning location coordinates, are available free of charge on the Internet in real time.

In this study, lightning location system (LLS) in Blitzortung was used to determine the distribution, analyze the distribution characteristics, and discuss the causes of winter lightning from a meteorological perspective.

II. OVERVIEW OF THE LIGHTNING LOCATION SYSTEM

Several weather and electric power companies have developed commercial LLSs, and publicly available data cover a wide area, however, detailed data are either private or not free of charge. An overview of LLSs is presented in Table 1. Meanwhile, advances in IT have facilitated the control of devices and sensors in networks, while also allowing for the use of more affordable devices, this led to the Blitzortung project, which aims to create a global, highly accurate lightning location network using inexpensive receiving stations and IT technology. Receiving stations for lightning locations are primarily deployed in the United States, Europe, and Oceania, and approximately 2300 receiving stations have been registered as of December 2018, with approximately half (1100) in operation. The stations receive very low-frequency (VLF) electromagnetic waves generated by lightning, which propagate long distances. Lightning at night, in particular, can sometimes be detected at distances over 5000 km from the utilized receiving stations, this enables the elucidation of lightning locations in the United States, Europe, Oceania, and Asia. The main performance features are a detection efficiency of 12%-39% compared to commercial LLS, a location accuracy of 1.4 km, and a coverage range as shown in Fig. 2, as shown in [2]. This study used Blitzortung data, as participants in the program can use the data free of charge.

TABLE 1. Overview of lightning position systems both in Japan and worldwide

System	**Frequency**	**Method**	**Operator**	**Free/ Fee**	**Area**
JLDN	LF	TOA+MDF	Company	Fee	Japan
Electric Power Co.	LF	TOA+MDF	Company	------	Japan
LIDEN	LF	TOA+MDF	Government	Fee	Japan
WWLLN	VLF	TOA	University	------	World
GDL360	VLF	TOA	Company	Fee	World
Blitzortung	VLF	TOA	Volunteer	Free	World

A. Lightning location principle

Blitzortung, an LLS, uses the time-of-arrival (TOA) technique as its lightning location principle, in which the difference between the time of arrival of electromagnetic waves generated by lightning.

B. System configuration

The Blitzortung system consisted of a magnetic field antenna/amplifier, an electric field antenna/amplifier, GPS, GLONASS, and a controller. The magnetic field and electric field antennae receive the magnetic and electric field components of the VLF electromagnetic waves generated by lightning. A trigger was activated when the magnitude exceeded a particular threshold, at which point the time, coordinates of the receiving station, and waveform were recorded. These data were then sent to a server via UDP, and the lightning waveforms observed at six or more stations were statistically processed to minimize errors, allowing the lightning location to be estimated. The lightning location was displayed in real time. Spherical coordinates were used to calculate the distance. The times at the receiving stations were synchronized using GPS and GLONASS.

C. *Receiving station locations*

The global locations of the receiving stations are shown in Fig. 1. As of December 2018, approximately 2300 systems have been registered worldwide. Europe had the highest number of systems (over 800), followed by the United States and Australia, with approximately 1100 systems operating worldwide. Fig. 2 shows the density of the Blitzortung receiving stations, with greener colors indicating higher density. Dark green areas in Europe, North America, Oceania, and Japan indicate high receiving station density and high lightning detection rates. In contrast, lighter green areas in Africa, South America, and eastern Eurasia are associated with lower receiving station density and lower lightning detection rates.

III. GLOBAL LIGHTNING DISTRIBUTION

Global lightning distributions were created using satellite lightning capture[4] and the WWLLN[5]. However, in this study, the monthly global lightning distribution for 2017 was created using Blitzortung. Fig. 4 shows the distribution from January to June, whereas Fig. 5 shows the distribution from July to December, with red circles indicating the locations at which winter lightning was estimated.

Fig. 1 Distribution map of receiving stations around the world

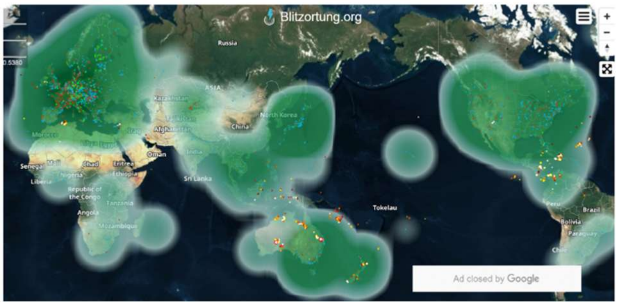


Fig.2 Blitzortung coverage area

Note that all the data are plotted on the map, and the resulting image does not show a density distribution. Data outside the coverage area in Fig. 2 could not be evaluated, therefore, the areas covered in North America, Europe, Japan, and Australia were the focus of this study.

A. *Overall trends*

In the Northern Hemisphere, summer lightning occurs from June to September, winter lightning occurs from January to March and November to December, and lightning occurs in spring and autumn. In the Southern Hemisphere, where the seasons are reversed, summer lightning occurs roughly from January to April, and winter lightning occurs from June to September. The main factors that cause summer lightning include the sun's heating of the Earth's surface, cold air in the upper atmosphere, and high temperature gradients caused by cold fronts resulting from the passage of low-pressure pressure. Winter lightning is generally caused by high seawater temperatures and high temperature gradients caused by the outflow of cold continental air or the formation of cold fronts due to the passage of low pressure, which also causes a high temperature gradient. Lightning in spring and autumn also occurs when cold air arrives in the upper atmosphere or when a cold front creates a high temperature gradient due to the passage of low pressure.

B. *Characteristics in North America*

Lightning strikes the southeastern part of the North American continent from November to January and gradually spreads northward in February and March, extending all the way near the Canadian border. However, fewer lightning strikes are observed on the west side of the country at this point. Lightning strikes spread across North America in March and April, covering the entire country and reaching the Northwest Territories (Great Slave Lake) in Canada from May to August. The seawater temperature in the Gulf of Mexico is around 20–25 °C in winter. In November 2017, lightning strikes also occurred along the Pacific coast of Washington State, presumably due to the warm Alaska Current and cold easterly winds.

C. *Characteristics in Europe, the Middle East, and Africa*

Lightning strikes occurred from October to March along the Mediterranean coasts of Spain, Italy, and Greece, with similar observations in Turkey, Israel, and Syria in the Middle East and Algeria, Libya, and Egypt in North Africa. Seawater temperatures in the Mediterranean Sea are high in winter, ranging from 10 to 20 °C. The presence of fulgurite, a mineral found in the Libyan Desert, suggests the occurrence of lightning strikes in this region. At the same time, lightning strikes also occur in the Persian Gulf in the Middle East from November to March, where the seawater is 15–20 °C in winter, and cold air from continental Saudi Arabia is thought to destabilize the atmosphere.

Lightning strikes occurred along the coast of Norway from November to March and across Europe, including the entire Scandinavian Peninsula, from June to September.

In the Atlantic Ocean, lightning strikes are almost nonexistent from January to August but are frequent from September to December, this is thought to be due to the influence of Icelandic law, which causes severe weather disruptions from autumn to winter, resulting in frequent lightning strikes.

D. Characteristics in Japan

Lightning strikes occur from November to March along the coast of the Sea of Japan and in the Pacific Ocean off the coast of Ibaraki Prefecture, but are rare over land. The Tsushima Warm Current flows through the Sea of Japan. Cold air caused by radiative cooling from the Eurasian continent flows into the Sea of Japan, destabilizing the atmosphere and causing cumulonimbus clouds to form, resulting in lightning strikes. The cold air that passes through the Sea of Japan then crosses the Japanese Archipelago and flows along the Pacific coast of Ibaraki Prefecture. The warm Kuroshio Current flows through this area, causing atmospheric instability and lightning strikes. The seawater temperature in the Sea of Japan is 5–15 °C in winter.

Lightning strikes occur throughout Japan from April to September, both on land and at sea.

E. Characteristics in Australia

Australia is located in the Southern Hemisphere, thus, its seasons are reversed compared to the Northern Hemisphere, with summer from October to April, and lightning strikes occurring throughout Australia during this period. Lightning strikes decrease in northwestern Australia in May and across the Australian continent during winter from June to September. However, winter lightning has been observed in the Tasman Sea between the Australian continent and New Zealand. The seawater temperature in the Tasman Sea is 12–13 °C during the winter months, resulting in a warm current. Lightning strikes also occur in the Great Australian Bight, where the tropical Leeuwin Current, East Australian Current, and cold Antarctic Circumpolar Current intersect in the southern Australian continent in July and August. Lightning strikes also occur throughout Australia during the Southern Hemisphere summer months from October to December.

F. Positional relationship between ocean currents and continents

The factors that cause winter lightning in Japan are as follows: Cold air caused by radiative cooling from the Eurasian continent flows over the Sea of Japan, and the warm, moist Tsushima Warm Current creates atmospheric instability, leading to the formation of cumulonimbus clouds and lightning strikes. From this perspective, an examination of the monthly lightning trends is shown in Figs. 4 and 5, which show the global distribution of lightning strikes. Specifically, the presence of cold air and warm ocean currents from the continent in four areas where winter lightning occurs, namely: (1) the Florida Peninsula and Gulf of Mexico, (2) the Mediterranean Sea and coast of Norway, (3) the Sea of Japan and Pacific Ocean off the coast of Ibaraki Prefecture, and (4) the Tasman Sea, was investigated.

The locations of warm and cold ocean currents worldwide are shown in Fig. 3, with red representing warm ocean currents and blue representing cold ocean currents. The map was compared with the locations of winter lightning at the four locations mentioned above. (1) The Florida Current and the Caribbean Current are warm in the Florida Peninsula and the Gulf of Mexico. (2) The Mediterranean Sea is warm despite the lack of major ocean currents. The coast of Norway also has warm ocean currents in the form of the Norwegian Current and the North Atlantic Current. (3) The Sea of Japan has the Tsushima Current, and the Pacific Ocean off the coast of Ibaraki Prefecture has the Kuroshio Current, both of which are warm ocean currents. (4) The Tasman Sea experiences a warm East Australian current. As mentioned, lightning strikes are generated in areas with continental land to the west and warm ocean currents to the east.

Next, we examined whether the locations were supplied with cold air that flowed in due to radiative cooling from the continent, with the following results: (1) North America, (2) Europe, Greenland, and Iceland, (3) Eurasia, and (4) Australia to the west and northwest of the winter lightning occurrence areas. These regions have the same positional relationships in that the continents cool the air in winter owing to radiative cooling, and the cool air is blown eastward by the westerly winds. Therefore, all four locations have a continent to the west, an ocean area in which cold air is cooled by radiative cooling in winter, and warm ocean currents. When these conditions are satisfied, the atmosphere becomes unstable, resulting in lightning strikes. This phenomenon causes winter lightning in Japan.

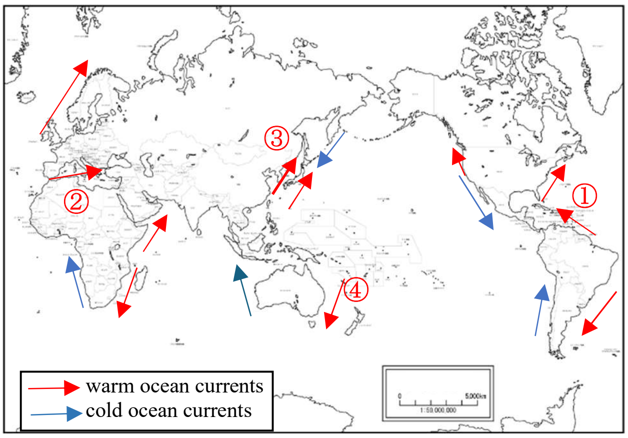
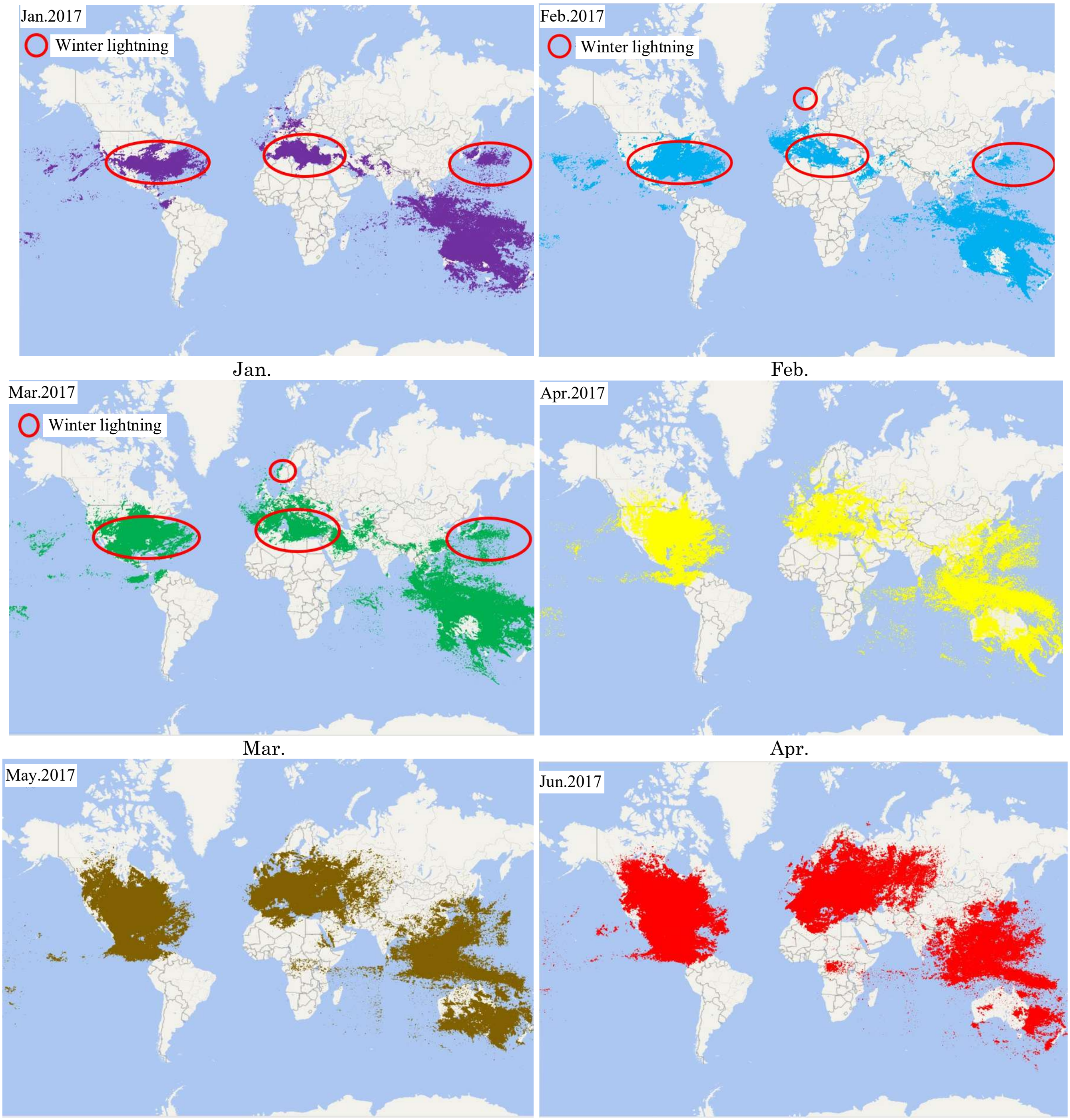


Fig.3 World Ocean Currents

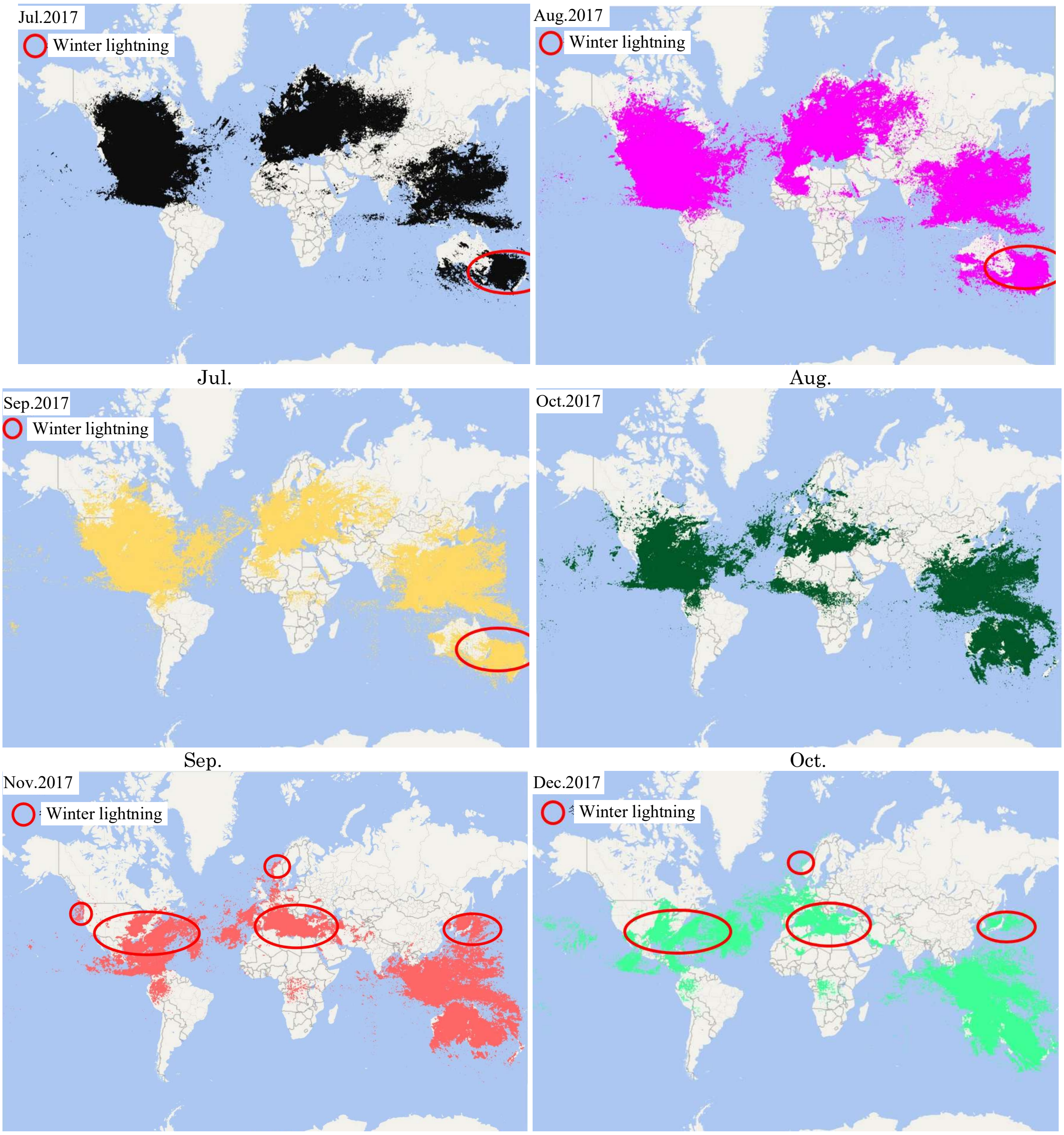


Jan. Feb.

Mar. Apr.

May. Jun.

Fig. 4 Monthly lightning distribution obtained using Blitzortung (January to June 2017)



Jul. Aug.

Sep. Oct.

Nov. Dec.

Fig.5 Monthly lightning distribution obtained using Blitzortung (July to December 2017)

G. Distance from the occurrence area to the continent:

The distance from the continent to the location of the winter lightning was then calculated to determine the extent to which the inflow of cold air from the continent affected lightning formation.

・North America, Atlantic Ocean: The distance from North Carolina to the winter lightning occurrence area in the Atlantic Ocean is within 2000 km.

Mediterranean Sea: A comparison was impossible because no ocean was on the eastern side.

・The distance from Greenland to the coast of Norway is within 1600 km.

・Sea of Japan: The distance from the Eurasian continent (North Korea) to the coast of Ibaraki Prefecture is within 2000 km. Winter lightning does not occur beyond this point.

・Tasman Sea: The distance from the east coast of Australia to New Zealand is within 2000 km. Winter lightning did not occur in New Zealand.

These results suggest that winter lightning occurs within approximately 2000 km of continental landmasses, presumably because the continent's cold air gradually warmed, reducing the temperature gradient.

H. Potential for winter lightning in other areas

Areas outside the Blitzortung area, where winter lightning may also occur, were examined based on the location on the continent and warm ocean currents. However, it was assumed that winter lightning would not occur within a latitude of 25° from the equator owing to weak radiative cooling and a gradual gradient between the overlying cold air and ocean temperature. Fig. 6 shows the positional relationships of the continents and the warm and cold ocean currents, with blue circles indicating areas in which winter lightning has already occurred, such as off the coast of Florida and Washington State in the United States, the Mediterranean Sea and Norway in Europe, the Sea of Japan and the Pacific Ocean off the coast of Ibaraki Prefecture, and the Tasman Sea. Orange circles indicate areas where winter lightning is unlikely to occur because the conditions of having a continent to the west and a warm current to the east of an ocean bordering a continent are not met. The specific locations included Peru, Chile, Portugal, Senegal, Angola, Oman, India, Myanmar, and the western coast of Australia.

Two areas that also meet both conditions but are outside the Blitzortung area, namely, the oceanic areas between Africa and Madagascar and the coast off Brazil, are indicated by red circles. These areas meet the criteria but are outside the Blitzortung location area, thus, the results for these regions cannot be obtained using this system..

Winter lightning in the Sea of Japan is often positive and upward, thus, a literature review was conducted on the characteristics of winter lightning in the Mediterranean Sea, with reports indicating that superbolts are common in the Mediterranean Sea during winter[6], 30 % of winter lightning is positive[7], upward lightning is common in wind power plants on the Mediterranean side of Spain[8]. Camera observations of wind power plants in Croatia showed that upward lightning accounts for 96 % of lightning[9]. Despite the limited information, upward lightning is thought to be common in wind power plants around the Mediterranean Sea during winter.

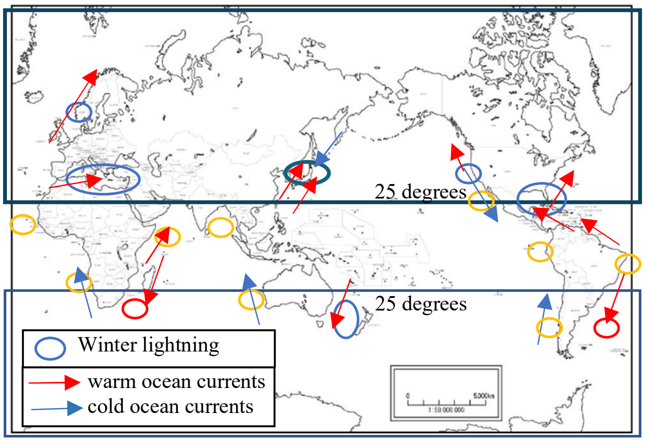


Fig.6 Location of winter lightning

IV. CONCLUSION

Blitzortung, an LLS, examined the lightning trends in North America, Europe, Japan, and Australia. An investigation was conducted to determine whether the two conditions for winter lightning in Japan, cold continental air and warm ocean currents, were satisfied, with particular attention paid to areas where winter lightning has been shown to occur. The results showed that these conditions were met in the Gulf of Mexico and the Atlantic Ocean in North America, the Mediterranean Sea and Norway, the Sea of Japan and the Pacific Ocean off the coast of Ibaraki Prefecture, and the Tasman Sea. Therefore, it is presumed that winter lightning occurs in areas at 25° north and south or higher latitudes, where there is continental cold air to the west and warm ocean currents to the east. An investigation of the extent to which continental cold air is related to winter lightning showed that the range of influence extended to approximately 2000 km in all areas. However, it is unclear whether the electrical characteristics are the same as those of winter lightning in the Sea of Japan, and further investigation is required.

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