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Relationship between aerological stability and charge amount of upward lightning hitting wind turbines in winter

Mikihisa SAITO
CRIEPI
Yokosuka, Japan
mikihisa@criepi.denken.or.jp

Masaru ISHII
The University of Tokyo
Tokyo, Japan

***Abstract*—Aerological data of the days, when upward lightning flashes with large charge transfer in winter were observed, were analyzed. Indices used for the evaluation of stability of air in summer, are not suitable to apply to winter lighting condition, however, some combinations of parameters derived from arerological data seem to be related to the days when upward flashes occur, including occurrence of energetic upward flashes.**

Keywords—lightning, winter lightning, aerological data, upward lightning, wind turbine

I. Introduction

Lightning flashes hitting tall structures in winter in the coastal area of the Sea of Japan are mostly upward lightning [Ishii, M. et al., 2009, 2011, 2013, 2014; Natsuno et al., 2010; NEDO report, 2015; Saito and Ishii, 2016, 2017a, 2017b]. Characteristics of such upward lightning in winter are different from those of downward lightning observed in summer, especially in the current parameters.

Lightning currents were directly observed at 27 wind turbines in Japan in the 5-year research project, from 2008 to 2013, of NEDO (New Energy and Industrial Technology Development Organization), Japan. The extensive observation provides statistical data on lightning currents flow into wind turbines by direct lightning hits, and facilitates improvement of lightning protection of wind turbines. The ratio of the flashes with transferred charge exceeding 300 C, which may threat wind turbines, was 4% [NEDO report, 2015; Saito and Ishii, 2016].

Classification of weather pattern related to severity of winter thunderstorms by using the weather chart was tried [NEDO report, 2015], however, automatic classification of weather charts is still difficult. In summer, likeliness of occurrence of thunderstorms are evaluated from aerological data by using such indices as Showalter index, Total totals, SWEAT index and K index etc. [Vogel, S., et al.,2016a, 2016b, 2017a, 2017b ; Fujisawa, G., and R. Kawamura(2005)], though, these indices are reportedly not quite suitable for winter lightning condition [G. Fujisawa, and R. Kawamura(2005)].

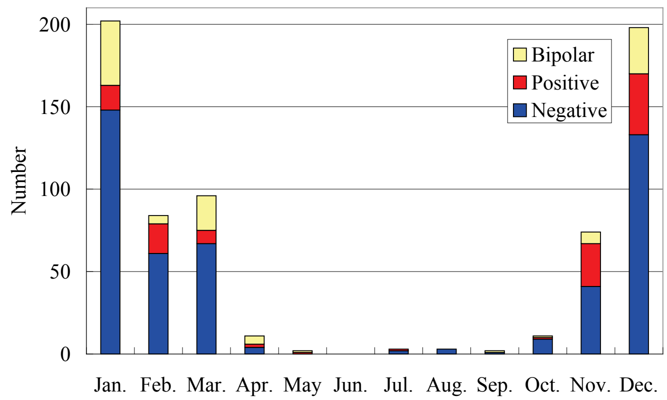
This paper reports on the parameters extracted from aerological data on the days when upward lighting flashes hit wind turbines in winter, and for those when upward flashes with large charge transfer were observed.

II. Data Subject to Analysis

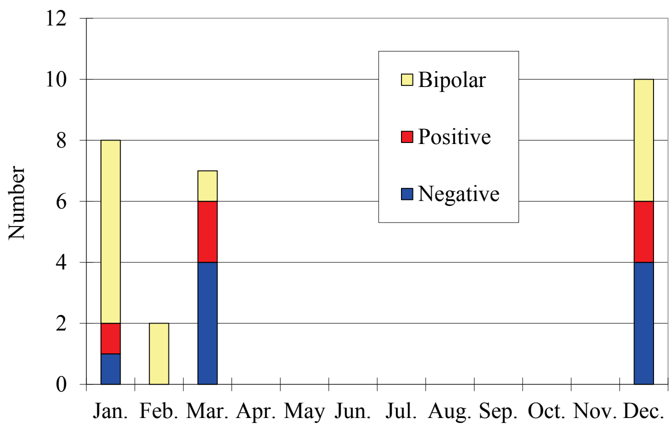
676 lightning currents were observed during 5 seasons from October to April at the NEDO research project [NEDO report, 2015; Saito and Ishii, 2016]. In other months, only 10 data were recorded as shown in Fig. 1(a), although observation was carried out through the year.

Almost all of recorded currents were associated with upward lightning, and in this paper, the 676 lightning currents are classified as winter lightning. 27 lightning flashes with transferred charge exceeding 300 C were observed in winter months from December to March only, as seen in Fig. 1(b), and the tendency of monthly distributions of these two figures is somewhat different. This suggests that there may be difference in charge structures of thunderclouds in winter between majority of thunderclouds and those produce energetic upward lightning. Fig. 2 shows differences in the polarity of flashes belonging to these two groups, ordinary and energetic ones. Bipolar flashes are the majority in the energetic flashes.

The aerological data were observed at upper air observatories in Japan every 12 hours (9h JST, 21h JST). So upward flashes observed in a half-day bin (12hours) are grouped to form one datum. As the majority of observed upward flashes were on Honshu Island, the data obtained on this island only are analysed. Consequently, 327 half-day aerological data from November to March, on days upward flashes were observed, are analysed.

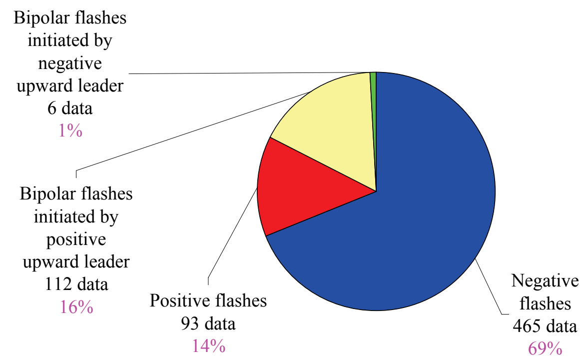


(a) All flashes (686 data).

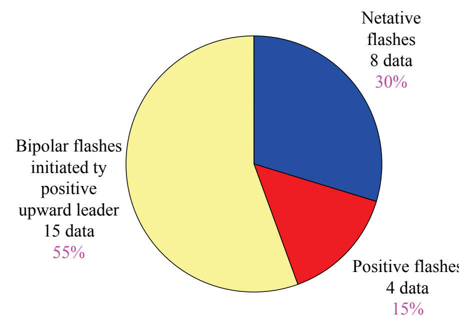


(b) Exceeding 300 C (27 data).

Fig. 1 Monthly variation of number of observed current data.



(a) All flashes observed in winter (676 data).



(b) Flashes with charge amount exceeding 300 C (27 data).

Fig. 2 Ratios of polarities of upward winter lightning flashes dependent on the amount of transferred charge.

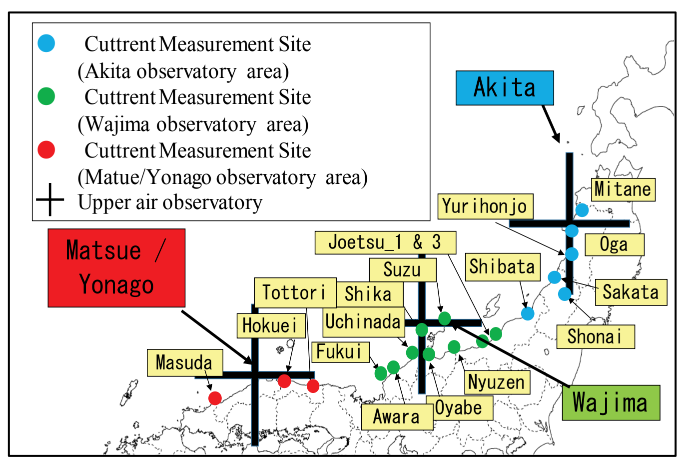


Fig. 3 Locations of instrumented wind turbines and upper air observatories in the coastal area of the Sea of Japan.

Aerological data [http://weather.uwyo.edu/upperair/] obtained at three upper air observatories are used, and data from instrumented wind turbines are analyzed in conjunction with the data from the closest upper air observatory. Observed lightning flashes are put in the half-day bin with the closest observation time of upper air data. The locations of wind turbines and upper air observatories are shown in Fig. 3. Among the analyzed 327 half-days, 23 half-days had flashes with transferred charge exceeding 300 C. The distribution of observed maximum charge amount during a half day for the 327 half-days are shown in Fig.4.

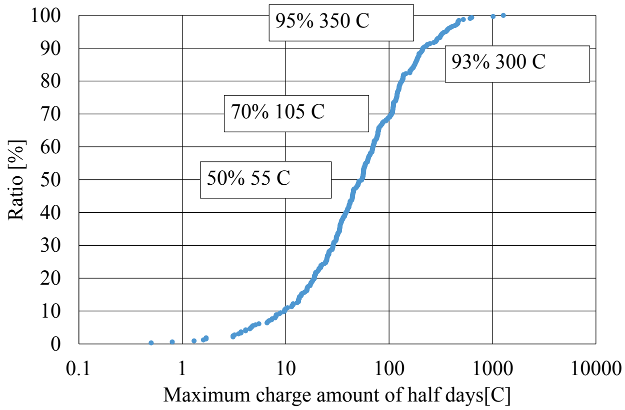
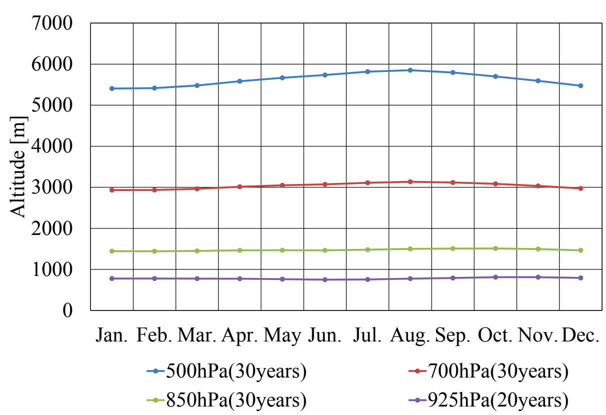


Fig. 4. Cumulative distribution of maximum transferred charge of an upward flash in a half day.

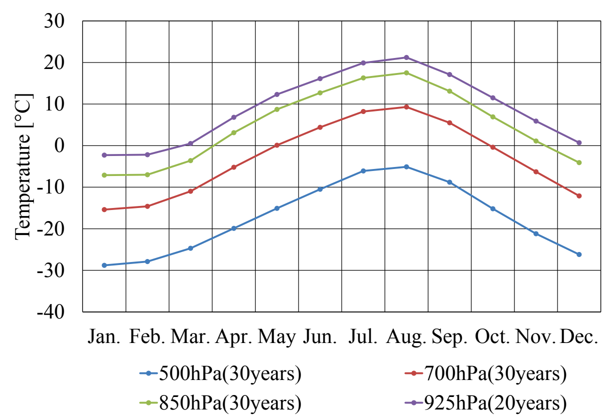
III. MONTHLY VARIATION OF METEOROLOGIAL DATA

Fig. 5 shows averaged monthly variations of meteorological parameters at each atmospheric pressure level at Wajima Observatory. Fig. 6 shows the atmospheric stability for the 327 half days, evaluated by using various indices employing criteria for prediction of occurrence of thunderstorms in the convective season. The thresholds of each criterion are shown in Table 2 [http://weather.uky.edu/kind.html]. As shown in Fig. 6, the judgements are not successful in both populations of all flashes and of energetic flashes except by Total Totals. Total Totals shows better judgement, however, there is not clear distinction between the ordinary and energetic flashes.

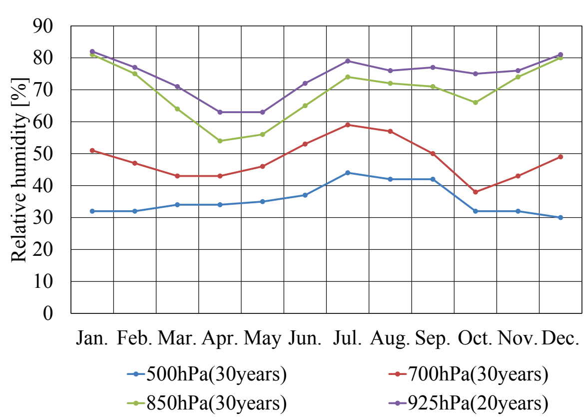
The reason for the poor results except by Total Totals may be difference between the convective and non-convective seasons in altitudes where charge separation actively occurs. Minus 10°C isotherm level, which is the temperature height, where charge in thunderclouds frequently accumulates regardless of the season [Ishii, M. et al., 2011], considerably varies dependent on the season.



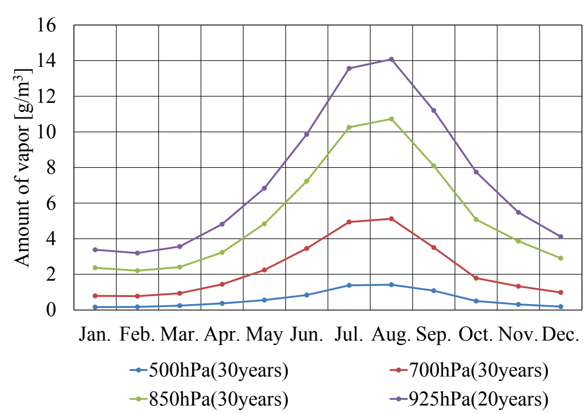
(a) Altitude.



(b) Temperature.

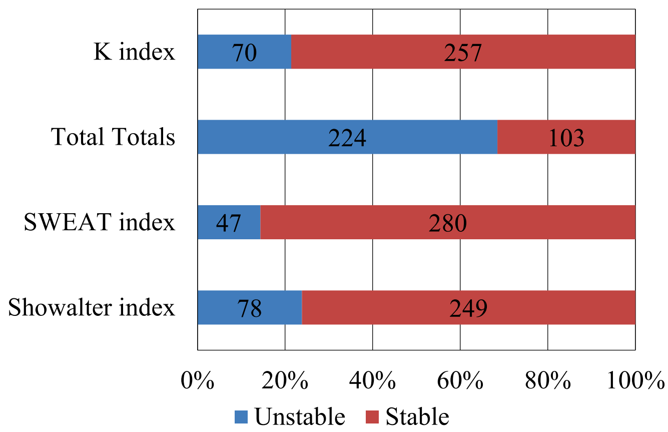


(c) Relative humidity.

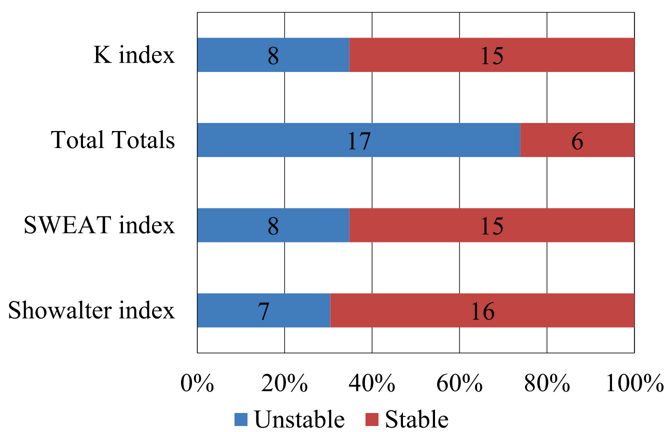


(d) Amount of water vapor estimated from (b) and (c).

Fig. 5 Averaged monthly variations of meteorological parameters at Wajima Observatory.



(a) Applied to all flash data.



(b) Applied to flashes exceeding 300C.

Fig. 6 Analyzed stability by using various indices when upward winter lightning occurred, by employing criteria for prediction of occurrence of thunderstorms in convective season.

The height of –10°C is around 500hPa in typical summer (August) and is around 850 hPa in typical winter (January) in Japan, whereas the indices used to evaluate atmospheric stability are mainly calculated by using aerological conditions between 850 hPa and 500 hPa. Amount of water vapor in the atmosphere is important for formation of cloud particles, and is mostly from the surface of warm current in the Sea of Japan at winter lightning condition in Japan. This situation and meteorological parameters at each pressure level are quite different between summer and winter in Japan. Thus, criteria to judge stability useful in the convective season will need modification for winter condition.

Table 2 Thresholds of classifications used to produce Fig. 6.

K index	Unstable > 18 > Stable
Total Totals	Unstable > 43 > Stable
SWEAT index	Unstable > 272 > Stable
Showalter index	Unstable < 4 < Stable

Considering the different condition between summer and winter, each index is calculated by using the adjusted levels shown in Table 3 and formulae (1)~(4). The results for indices calculated by using the adjusted levels are shown in Fig. 7.

Level adjusted K-index

$$= T(925\ \text{hPa}) + Td(925\ \text{hPa}) - T(700\ \text{hPa}) - DD(850\ \text{hPa}) \quad (1)$$

Level adjusted Total Totals

$$= T(925\ \text{hPa}) + Td(925\ \text{hPa}) - 2[T(700\ \text{hPa})] \quad (2)$$

Level adjusted SWEAT Index

$$= 12[Td(925\ \text{hPa})] + 20\,(TT' - 49) + 2[f(925\ \text{hPa})] + f(700\ \text{hPa}) + 125(S' + 0.2) \quad (3)$$

Level adjusted Showalter Index

$$= T(700\ \text{hPa}) - Tp\ (\text{from } 925\ \text{hPa to } 700\ \text{hPa}) \quad (4)$$

Here, T is temperature, Td is dew point temperature, DD is dew point depression, TT' is level adjusted Total totals, f is wind speed, S' is wind shear between 700 hPa and 925 hPa, and Tp is temperature of lifted parcel .

Regarding K-index, it heavily relies on T and Td at low altitude (850 hPa at conventional, 925 hPa at level adjusted). Thus, the values stay stable in winter. Note that T and Td in low altitudes do not change much in winter because of wet updraft from the Sea of Japan as seen in Fig. 5(c). At the level adjusted values, T and Td at the low altitude are slightly higher than those of the conventional values. The differences of T(700 hPa) and T (925 hPa), however, are slightly smaller than the conventional values (between 500 hPa and 850 hPa) as seen in Fig. 3(b). Consequently the values move to a more stable side at the level adjusted values.

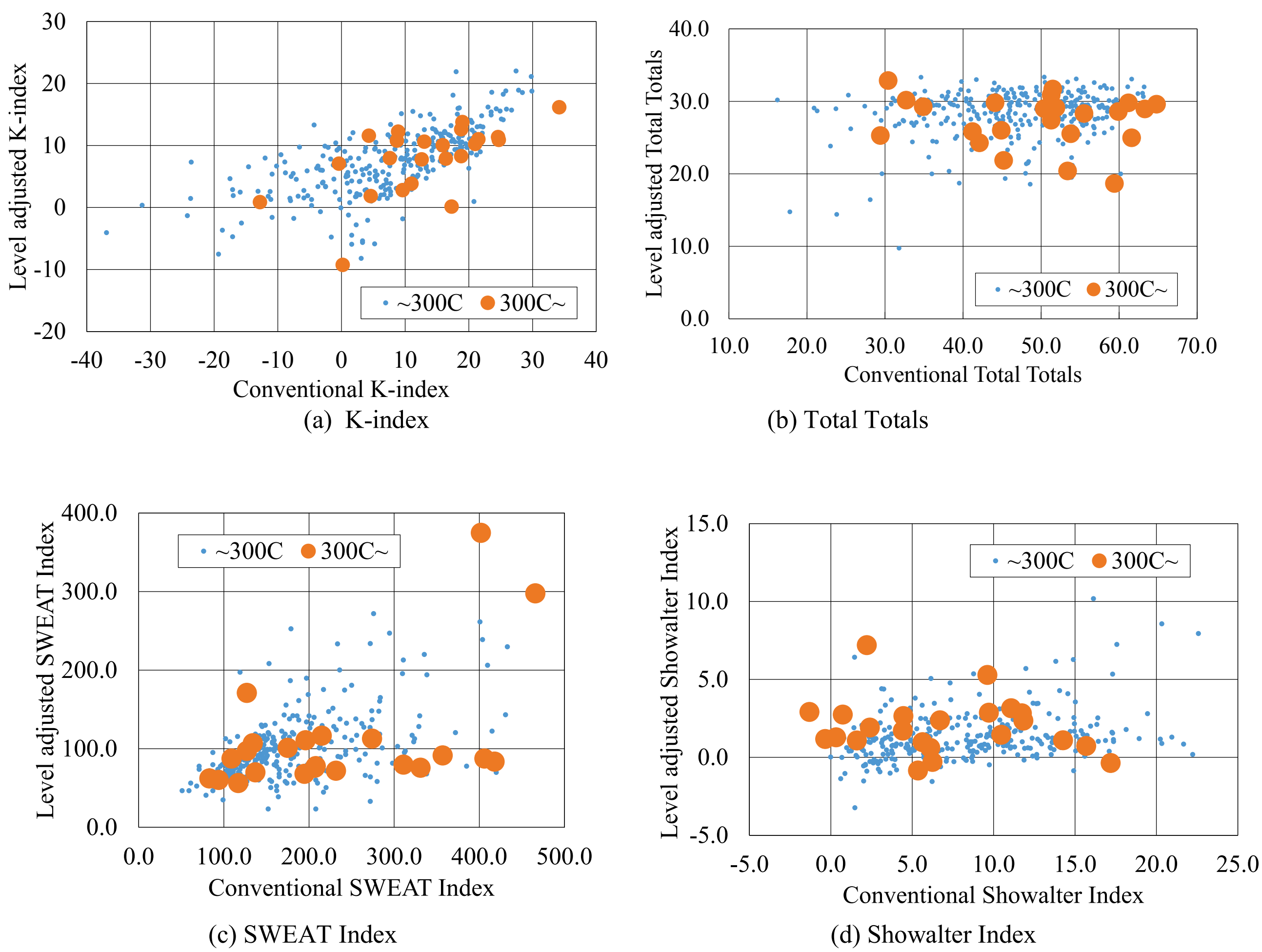
Table 3 Conventional and adjusted levels employed to produce Fig.7

Conventional indices		Level adjusted indices
500 hPa	→	700 hPa
700 hPa	→	850 hPa
850 hPa	→	925 hPa

At Total Totals, it judges the condition is unstable if the air is humid. Thus, the values are on the unstable side when lightning flashes are observed. At level adjusted values, however, differences of T (700 hPa) and T(925 hPa) are slightly smaller than for the conventional values (between 500 hPa and 850 hPa) as seen in Fig. 3(b). Thus, the level adjusted values move to a more stable side.

Regarding SWEAT Index, it heavily relies on the values of low level Td (850 hPa in conventional evaluation, 925 hPa in level adjusted) and the values of Total Totals. Thus, the level adjusted values move to more stable side because the level adjusted Total Totals also move to stable sides as is explained above.

At Showalter index, the conventional values are stable because; 1) T(500 hPa) is too cold to evaluate instability, 2) the moist adiabatic lapse rate and the dry adiabatic lapse rate are quite close at temperatures between 850 hPa and 500 hPa levels in winter as seen in Fig. 3 (b). Thus, conventional values are on the stable side. The level adjusted index, however, shows better performance to evaluate stability of winter lightning condition, and the calculated values of the index move to unstable sides. Fig. 8 shows the stability evaluated by the level adjusted Showalter index by using the same threshold shown in Table 2. Most half days are evaluated as unstable when upward flashes hit wind turbines.



(a) K-index

(b) Total Totals

(c) SWEAT Index

(d) Showalter Index

Fig. 7 Comparison of conventional indices and level adjusted indices.

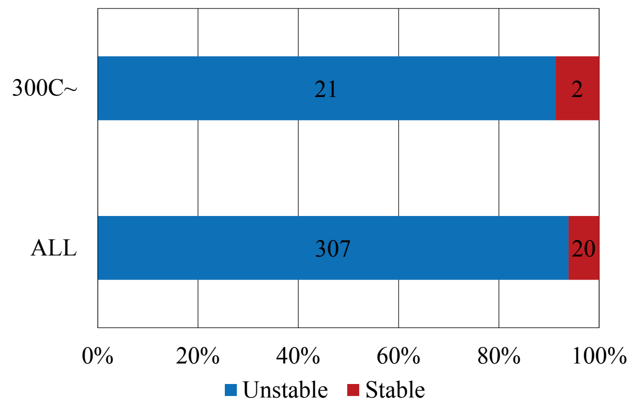


Fig. 8 Stability at winter thunderstorms by using level-adjusted Showalter index.

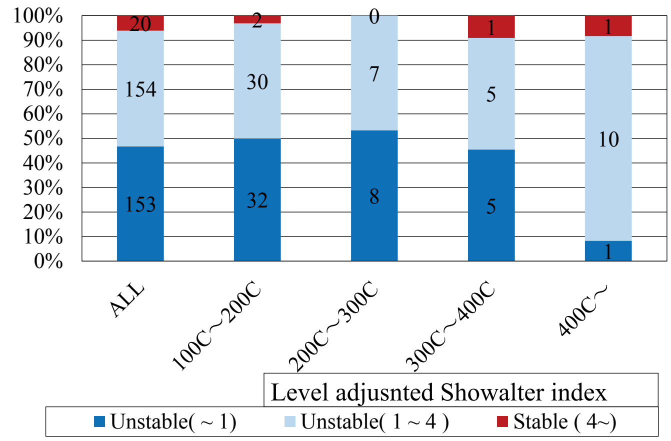


Fig. 10 Distribution of maximum charge amounts.

IV. Energetic Upward Flashes in Winter

As shown in Fig. 8, the most half days are evaluated as unstable by the modified Showalter index, however, there is not much difference in the index for half days with and without upward flashes associated with charge transfer over 300 C.

Fig. 9 and Fig. 10 show the relationship between the charge amount in a half day and the corresponding modified Showalter index of the half day. Most of the energetic flashes exceeding 400 C were observed on the half day, when the modified Showalter index is in between 1 and 4.

This result suggests that upward flashes with extremely large charge transfer tend to occur in the less convective condition among days with unstable air. This concentration of half days with energetic flashes on days of less active convection agrees to the tendency of the study using LLS data [Vogel, S. et al. 2017b] that energetic upward flashes more likely to occur at thunderstorms of moderate activity.

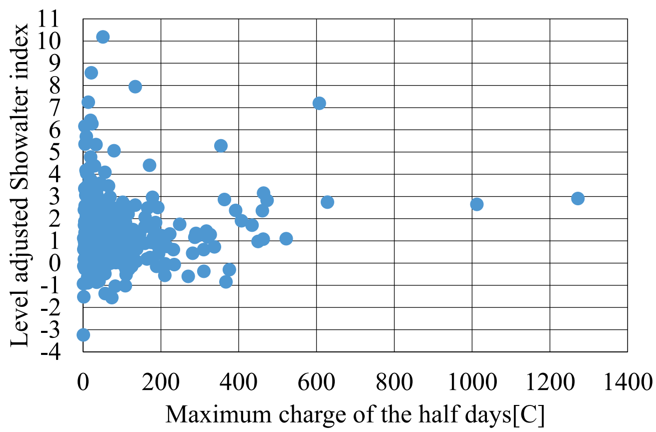


Fig. 9 Relationship between maximum charge amounts and level adjusted Showalter index.

V. Conclusion

Aerological data when upward flashes were observed at instrumented wind turbines on the coast of the Sea of Japan in winter are analyzed. Criteria to calculate indices to evaluate atmospheric stability in the convective season are not suitable to evaluate condition of winter thunderstorms; however, by modifying the calculation condition, Showalter index turns out to be effective in evaluating stability in winter. Moreover, days of storms which produce energetic lightning flashes seem be separated by using this modified Showalter index. Such flashes associated with large charge transfer were observed more frequently when activity of convection was moderate.

Acknowledgment

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