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Title: Characterization of Lightning Occurrence in Alaska Using Various Weather Indices for Lightning Forecasting

Authors' name with affiliations and addresses:

1. Murad Ahmed Farukh

Doctoral student, Graduate School of Engineering, Hokkaido University,

Kita-ku, N13 W8, Sapporo, Hokkaido 060-8628, Japan.

E-mail: maf_bau@yahoo.com

2. Hiroshi Hayasaka

Associate Professor, Graduate School of Engineering, Hokkaido University,

Kita-ku, N13 W8, Sapporo, Hokkaido 060-8628, Japan.

E-mail: hhaya@eng.hokudai.ac.jp

3. Keiji Kimura

Associate Professor, Graduate School of Information Science and Technology,

Hokkaido University, Kita-ku, N14 W9, Sapporo, Hokkaido 060-0814, Japan.

E-mail: kimura@ssi.ist.hokudai.ac.jp

Brief title: **Weather Indices for Lightning Forecasting in Alaska**

Characterization of Lightning Occurrence in Alaska Using Various Weather Indices for Lightning Forecasting

Abstract

Alaska lost 10% of its forest area due to vigorous forest fires in 2004 and 2005. Repeated lightning-caused forest fires annoy residents and influencing earth's atmosphere in every fire season. The authors have reported on the weather conditions of Alaska's most severe lightning occurrence in mid June 2005. This paper examines a range of weather indices like soar, instability, 'dry lightning' and others to the factors that could clearly explain lightning characteristics in Alaska. First, lightning occurrence days from May to September were classified into 'non or small lightning' days and 'lightning' days to determine threshold values. Second, 'lightning' days were categorized into 'less severe', 'severe', 'very severe', and 'extremely severe' to notice controlling factors on the lightning severity. Based on this analysis, the lifted index (LIFT) was selected as sensitive to assess upper air instability, and Te_{850} (environmental temperature at 850hPa) was selected as sensitive to assess warm and moist air masses. Finally, the possibilities of lightning forecasts in Alaska are discussed using lightning occurrence and LIFT and Te_{850} in 2005. As there is a time-lag between LIFT measurements (14:00) and the lightning peak (~17:00), and around one day time-lag between Te_{850} and lightning occurrence, lightning forecasts using LIFT and Te_{850} could provide a simply applicable forecast index for Alaska.

Key words: Lightning severity, LIFT, Environmental temperatures, Ordinary cell thunderstorm, Moisture

1. Introduction

Recent wildland fires in Alaska have become numerous since around 1990 and burn off about 4,000 km^2 of forests annually. Lightning caused wildland fires are responsible for more than 90% of these annual burnt areas in Alaska (Shulski et al. [1]), and play an important role in boreal forest regeneration. Thunderstorms and the resultant lightning is a very important factor in the boreal forest fire regime through its influence as a fire starting mechanism.

In Alaska, at the beginning of the 21st century lightning activity increased significantly not only due to increases in the efficiency and aerial coverage of lightning detection sensors, but also due to abrupt changes in weather conditions. However, there are still only few studies regarding lightning weather conditions in Alaska. Price and Rind [2] found that, in association with increased global air temperatures of 4ºC, global mean lightning activity increased by 26%. The influence of the changes in surface air temperature on the seasonal variation in lightning activity was studied by Williams [3][4][5][6][7]. It was found that Alaskan lightning strikes were mostly due to convection from surface heating rather than large-scale synoptic forcing (Sullivan [8]; Biswas and Jayaweera [9]; Reap [10]). Dissing and Verbyla [11] reported on the spatial patterns of lightning strikes in relation to elevation and vegetation in Alaska. Previous work by Reap [12] has shown a diurnal variability in the lightning strike count in which the maximum was observed from three to six hours after solar noon. Reap [10] also found that the peak positive count was one hour behind the maximum negative count. Rorig and Furguson [13][14] used radiosonde data to predict occurrences of ‘dry’ (thunderstorms that produce <2.5mm precipitation) and ‘wet’ (thunderstorms that produce ≥2.5mm precipitation) lightning. Their MM5 mesoscale model is currently run in real time by the Northwest Regional Modeling Consortium (NWRMC) through the University of Washington, Department of Atmospheric Sciences. The MM5 real time model is applied to forecast the risk of dry convection (output from the Penn State/National Center

for Atmospheric Research (NCAR)) and is now used by several researchers. Anderson [15], Holle et al. [16], Reap [17], and Reap and Foster [18] calculated a 'K index' from radiosonde data and suggested that model as a good indicator of airmass thunderstorm occurrence.

During the last about two and half decades, more than one million lightning flashes were detected in Alaska. Richmond and Shy [19] partially explained some of the causes of the extraordinary lightning occurrence in 2004. Previous work by the authors (Farukh et al. [20]) showed the background to the largest lightning occurrence in the middle of June 2005. But studies of Alaskan lightning trends and lightning weather pattern analyses are scarce. Therefore, this study analyzes lightning data, radiosonde data, and weather maps of Alaska during the years from 1986 to 2009, and classifies lightning occurrences into several categories. An attempt is made to discuss the recent lightning magnitudes of Alaska, and to determine control factors of the categorized lightning occurrences to predict the onset and severity of lightning in Alaska.

2. Data and Methods

2.1. Lightning Detection, Lightning Data and Study Areas

The Bureau of Land Management, Alaska Fire Service (AFS [21]) operates an automated network of cloud-to-ground (CG) lightning sensors. The asterisks in **Fig. 1** show the locations of the 9 lightning detection sensors in Alaska. The lightning detection sensors have been in operation since 1976, and a lightning flash is reported only if detected by more than one of the sensors. The positional accuracy of estimated lightning locations varies with the number of detectors sensing the lightning and the geometry, but it is assumed to be 2–4 km at best with a detection efficiency of 60-80% in interior Alaska (Dissing and Verbyla [11]).

The daily lightning data from 1986 to 2009 were obtained from the Alaska Interagency Coordination Center (AICC [22]) of AFS with missing data for 1987 and 1989. The data from the AFS contained the computed location or coordinates, dates, times, signal strength,

and polarity etc. for each lightning flash that is detected over the large area from the Bering Strait to the Canadian mountainous areas (135ºW to 179ºW Longitude), and from the tundra area in the Arctic region to the forest area on the southeast coast (70ºN to 50ºN Latitude).

[Position of Fig. 1.]

The large rectangle in **Fig. 1** shows the study area (S_I) of 806,785 km^2 covering North Latitudes from 62º to 68.5º and West Longitudes from 141º to 163º. This area, from the south of the Brooks Range to the north of the Alaska Range is characterized by comparatively hot summers having enough available moisture to fuel thunderstorms due to large-scale advection (Reap [12], Sullivan [8]). **Fig. 1** also depicts a smaller rectangle (S_F) of 222,600 km^2 and this area was used to assess the lightning conditions surrounding Fairbanks (62-66ºN and 142-151ºW).

2.2. Surface and Radiosonde data

Even with both the surface and 'radiosonde' (upper air) data for Fairbanks it is not possible to explain all Alaskan weather changes but it can be used to explain most of the weather changes in the eastern part of interior Alaska. Weather data from Fairbanks Airport were chosen as representative of Alaskan weather because it may be expected to be the most reliable and has been available for the longest period. Weather data were obtained from the Alaska Climate Research Center [23], Fairbanks and from the Summary of Day Data of the National Climatic Data Center [24], and were analyzed. To investigate the variability of thunderstorms influenced by weather patterns, this study used monthly, weekly, and daily sea level, 925hPa, 850hPa, 700hPa, 500hPa and 300hPa weather maps from the NCEP/NCAR re-analysis data, USA (Kalnay et al. [25]).

Radiosonde data of the Fairbanks radiosonde station (stations in Alaska are shown in **Fig. 1** using circles) from 1986 to 2009 were derived from ground level to the 100hPa level from the University of Wyoming webpage [26]. The radiosonde parameters considered were air and

dew point temperatures, geopotential height, wind direction, and relative humidity of the 925hPa, 850hPa, 700hPa, 500hPa and 300hPa levels.

3. Lightning Occurrence - Tendency and Categorization

3.1. Lightning Tendency

In Alaska, the variability in the number of lightning flashes between individual years is high. In 1996, the total number of annual lightning flashes for the S_I study area was around 13,000. But extremely large numbers of lightning flashes of around 120,000 were recorded in each of 2004, 2005, and 2007. There is an about four times difference between the severe lightning numbers of these three years and the average number of around 31,000. Around 99% of lightning flashes occur from May to August in Alaska, while 90% occur in June and July, and the most frequent lightning flash period is from around the middle of June to around the middle of July. The daily lightning incidence from May to August 1986 to 2009 showed that the numbers of days with daily flash numbers above 1,000 were 241 (~10% of the total 2,460 days from May to August of the last 22 years). The numbers of lightning flashes on these 241 days are detailed in the bar graph in **Fig. 2** to demonstrate the chronological daily lightning flash ranking. The top two largest daily flash peaks were recorded in 2005 with 13,027 flashes on June 15 and 12,017 flashes on June 30. These values are the largest daily total flash numbers ever detected in June in the 22 years of lightning records. More than 5,000 flashes/day are seen only in the present decade (2000-2009) possibly due to abrupt climate changes.

[Position of Fig. 2.]

3.2. Lightning Categorization

The daily lightning flash incidences from May to August of the last 22 years show 34% days with ‘0’ flashes and 56% days with ‘1~999’ flashes (**Fig. 3**). The 34% days with ‘0’ flashes is a relatively large number because the days from May to August are considered here. As a

result, the ‘0 flash’ and ‘1~999 flash’ days comprised 90% of the days from May to August, and therefore, in the following these 90% of the days are considered as days with a ‘non or small lightning’ incidence and the remaining 10% of the days as ‘lightning’ days. Further, the authors classified the ‘lightning’ days into 4 categories to determine the factors controlling the lightning severity. Based on daily lightning flash numbers these four categories are shown with the two-pointed arrows in **Fig. 2** and in **Table 1**.

[Position of Fig. 3.]

The 4 categories of ‘lightning’ days are termed as ‘Less Severe’ (1,000~2,999 flashes/day), ‘Severe’ (3,000~5,999 flashes/day), ‘Very Severe’ (6,000~8,999 flashes/day), and ‘Extremely Severe’ (≥9,000 flashes/day), and will hereafter be termed as ‘Cat. L_1’, ‘Cat. L_2’, ‘Cat. L_3’, and ‘Cat. L_4’, respectively. To show the changes in weather conditions for the lightning days categorized in this manner, the ‘non or small lightning’ category (Cat. L_0) is added here and, the overall categorization is summarized in **Table 1**.

[Position of Table. 1.]

4. Lightning Occurrence Conditions in Alaska

4.1. Assessing Severe Lightning Conditions

Several indices and parameters like surface and upper air temperatures, soar indices, dry lightning indices, stability indices, and others were selected to assess the atmospheric conditions at the severe lightning occurrences in Alaska, and are listed in **Table 2**.

[Position of Table. 2.]

A vertical cross section of the atmospheric layers for June 15, 2005 when the extremely severe lightning (Cat. L_4) occurred are shown using a Skew-T Log-P diagram (hereafter ‘emagram’) in **Fig. 4**. The emagram contains pressure heights, vertical profiles of the environmental temperature (T_e) and the dew point temperature (T_d) as well as air parcel temperature (T_p), and other information for this extraordinary day.

[Position of Fig. 4.]

From **Fig. 4** the following noteworthy atmospheric conditions were observed and could be affecting the unique occurrences on the Cat. L_4 lightning occurrence day June 15, 2005:

(i) surface instability by upward warm air flow could be created by the higher T_{max} (a ~32ºC), (ii) the upward warm air could create an unstable lower layer of the atmosphere at around 1,470 m height, (iii) the very small CINS (-23 J/kg) indicates an unstable area at around 1,500 m with high convective activity, (iv) the relatively large CAPE (424 J/kg) indicates a high instability from around 3,000 m to 9,200 m that could enhance the possibility of thunderstorms, (v) the $\Delta Te_{850\text{-}500}$ of around 32ºC indicates higher instabilities from around 1,470 m to 5,650 m, (vi) the DD_{850} (9ºC) and DD_{700} (5ºC) represent an abundance of moisture and humidity from around 1,470~3,000 m that could supply fuel for vigorous thunderstorm formation, (vii) the highly unstable and moist layers (KINX: a ~30) from around 1,470 m to 5,650 m indicates a 60% possibility of 'over thunderstorm' development, and higher convective activity with lift rates of about 5.6 m/s, (viii) the highly unstable upper layer (LIFT:-2.1) at around 5,650 m shows a 0 to 20% probability of air mass thunderstorm development.

4.2. Surface Weather Conditions

The mean values of T_{max}, precipitation and precipitable water for the five different categories from Cat. L_0 to Cat. L_4 lightning occurrence days are shown in **Fig. 5**. The precipitable water is not part of the so-called surface weather conditions but it is closely related to precipitation and is included here.

From **Fig. 5**, the threshold value of T_{max} for lightning to occur may be defined as around 24ºC, as T_{max} increased from around 22ºC for Cat. L_0 to around 24ºC for Cat. L_1. This suggests that the usual lightning season in Alaska starts around the middle of June and ends around the top of August, and is affected by the long summer daylight period at high latitudes. **Fig. 5** also

shows that T_{max} increased from 24ºC for Cat. L_1 to around 30ºC for Cat. L_3 and Cat. L_4, which suggests the most severe thunderstorm occurs at a T_{max} of around 30ºC. Price and Rind [27] found that surface air temperature is a parameter leading to more instability in the lower atmosphere and could increase the amount of lightning. For interior Alaska more than 2,000 daily strikes were reported when T_{max} goes above 21ºC (McGuiney et al. [28]). Therefore, T_{max} could be an indicator for predicting Cat. L_3 and Cat. L_4 lightning occurrences in Alaska.

[Position of Fig. 5.]

The threshold values for precipitation and precipitable water for lightning to occur can also be postulated with **Fig. 5**. They are around 2 mm (Cat. L_1) and 18 mm (Cat. L_1), respectively. These values suggest: (i) Cat. L_1 to Cat. L_4 lightning is associated with almost all of the summer precipitation in Alaska, (ii) considerable precipitation in Alaska could occur when precipitable water reaches values larger than around 18 mm and T_{max} exceeds 24ºC, (iii) the significant increases of precipitation from Cat. L_1 to Cat. L_4 implies that larger thunderstorms could bring higher amounts of rainfall, and (iv) higher amounts of precipitable water would also support the occurrence of larger thunderstorms.

4.3. Pressure and Temperature at Various Heights

4.3.1. Pressure Heights

Fig. 6 shows the 1,000hPa, 850hPa and 500hPa pressure heights for Cat. L_0 to Cat. L_4 which may reveal: (i) the depression to below around 45 m (Cat. L_1) for the 1,000hPa level could be assumed as the threshold value for the development of a ‘low’ near the surface layer, (ii) this considerable depression near the surface layer, below around 1,000 m height from Cat. L_0 to Cat. L_1 implies growth of the ‘low’. From Cat. L_1 to Cat. L_3, the existence of the ‘low’ is very prominent, but for Cat. L_4 the mean height of the ‘low’ increased slightly. Even the mean height increased there were still a strong ‘low’ at the extremely severe Cat. L_4, (iii) a considerable rise in pressure above around 1,000 m height at 850hPa and 500hPa implies the

growth of a 'high'. From Cat. L_1 to Cat. L_4, the height of 850hPa increased about 60 m and 500hPa about 90 m, (iv) the co-occurrence of both of these depression and rise conditions of pressure heights clearly shows the vertical structure of the Alaskan 'thermal low' formation.

[Position of Fig. 6.]

The Alaskan 'thermal low' could be a reliable indicator for assessing Cat. L_4 lightning occurrences. This 'thermal low' could develop mainly due to a significant temperature rise in the lower atmospheric layers below around the 1,000hPa height. At the same time, the considerable rise in pressure in the middle and upper atmospheric layers above around the 900hPa height was also present for the Alaskan 'thermal low' [20]. Wagtendonk and Cayan [29] have reported high lightning occurrences to be associated with increased geopotential height patterns in California.

4.3.2. Temperatures at Various Heights and 'Dry Lightning' Indices

Fig. 7 shows temperatures at 850hPa (Te_{850}), 700hPa (Te_{700}), and 500hPa (Te_{500}), and dew point temperatures at 850hPa (Td_{850}) and 700hPa (Td_{700}) to describe the effect of the temperatures aloft and of the moisture on lightning severity. From Cat. L_1 of **Fig. 7** the threshold *Te* values for 850hPa, 700hPa, and 500hPa were around 8ºC, -3ºC, and -20ºC, respectively. The threshold values for *Td* were 2ºC for 850hPa and -7ºC for 700hPa.

The considerable increases in the aloft temperatures from Cat. L_0 to Cat. L_1 are clearly shown in **Fig. 7**. The temperature increases suggest that these *Te* parameters are good indicators for assessing thunderstorm onsets in Alaska. From Cat. L_1 to L_4, the temperatures increased by 3.4ºC at 850hPa, 2.5ºC at 700hPa, and 1.4ºC at 500hPa implying warmer aloft atmospheric conditions for Cat. L_3 and Cat. L_4 lightning occurrences.

The Td_{850} and Td_{700} curves are nearly flat from Cat. L_1 to Cat. L_4, but increase sharply from Cat. L_0 to Cat. L_1. These increases were due to the presence of very large amounts of low and

mid level moisture during thunderstorm onsets. These parameters could be considered as useful indicators of lightning onset in Alaska.

[Position of Fig. 7.]

Rorig and Ferguson [13][14] used the '850hPa and 500hPa temperature difference' (hereafter, $\Delta Te_{850\text{-}500}$) and the '850hPa dew point depression' (hereafter, DD_{850}) to describe convective days as 'dry' and 'wet' for the Pacific northwest. These parameters were useful and physically meaningful indicators in estimating the risk of dry convection. Rorig et al. [30], and Rorig and Ferguson [13][14] also studied the '700hPa and 500hPa temperature difference' (hereafter, $\Delta Te_{700\text{-}500}$) and the '700hPa dew point depression' (hereafter, DD_{700}) for the western US and found significant differences on 'dry' and 'wet' days. It was suggested that DD_{700} is an effective indicator of available moisture which is important in determining whether thunderstorms will produce significant rainfall that reaches the ground.

As 'dry lightning' (accompanying precipitation <2.5mm) indices, the authors have also used $\Delta Te_{850\text{-}500}$ and $\Delta Te_{700\text{-}500}$ to assess atmospheric instability, and DD_{850} and DD_{700} to assess 850hPa and 700hPa moisture profiles for Fairbanks, Alaska. The computation equations (*1~4*) for these parameters along with definitions of their symbols are given in Appendix 1.

The above 'dry lightning' indices in relation to different lightning categories are shown in **Fig. 8**. From this figure the threshold value for $\Delta Te_{850\text{-}500}$ could be assumed as 27ºC (Cat. L_1) and was not a very effective indicator for lightning onsets, but ≥30ºC was good for assessing Cat. L_3 and Cat. L_4 lightning occurrences. Conversely, $\Delta Te_{700\text{-}500}$ could be a good indicator for thunderstorm initiation (the threshold value is assumed as 16ºC), as it showed around a 3ºC temperature increase from Cat. L_0 to Cat. L_1. The DD_{850} and DD_{700} values could be regarded as useful indicators to describe Cat. L_3 and Cat. L_4 as they represent moisture inflows during a large number of lightning occurrences, that provide the thunderstorms with energy by the release of latent heat through condensation (Grice and Comisky [31]).

[Position of Fig. 8.]

4.4. Soar Indices (KINX and LIFT)

Equations (*5~6*) used to calculate the 'K index' (KINX) and the 'Lifted index' (LIFT) are provided in Appendix 1, and the values for Cat. L_0 to Cat. L_4 conditions are shown in **Fig. 9**.

The KINX values suggest the moisture condition as well as the stability of the air. Because $\Delta Te_{850\text{-}500}$ is proportional to the average lapse rate, Td_{850} shows low levels of moisture, and DD_{700} is a measure of the saturation. Thus, KINX provides a suitable assessment for the stability of the air and the saturation conditions by considering the existing temperature and moisture.

The changes in the three components of KINX, Td_{850}, $\Delta Te_{850\text{-}500}$, and DD_{700} are shown in **Figs. 7** and **8**, respectively, and the threshold value for KINX could be defined as around 25 (Cat. L_1) from **Fig. 9**. The almost flat KINX curve from Cat. L_2 to Cat. L_4 suggest that KINX may be useful to distinguish lightning occurrence conditions because there is a considerable change between Cat. L_0 and Cat. L_1.

[Position of Fig. 9.]

The LIFT represents the temperature difference between an air parcel lifted adiabatically and the temperature of the environment at 500hPa, and when LIFT becomes negative, it would indicate that the atmosphere is unstable.

We may define the threshold value for LIFT as around 0.5 (Cat. L_1) from **Fig. 9**. The change in LIFT from Cat. L_1 to Cat. L_4 were from 1 to -2. This apparent decrease could explain the severity of lightning from Cat. L_1 to Cat. L_4. Therefore, LIFT appears to be a useful indicator for assessing the occurrence and severity of lightning in Alaska.

4.5. Stability Indices

Several stability indices like CAPE, CINS, and SHOW for different categories of lightning occurrences were computed using equations *7~9* (as given in Appendix 1) and the results are depicted in **Fig. 10**.

The CAPE is the amount of positive buoyant energy from the middle to upper layers of the atmosphere and a good indicator for predicting severe weather. Considering the change from Cat. L_0 to Cat. L_1 in **Fig. 10**, the threshold values for CAPE could be defined as around 115 J/kg (Cat. L_1). The CAPE was found as an important indicator for the lightning onset as it increased by 87 J/kg from the Cat. L_0 to Cat. L_1 conditions. The CAPE value also increased significantly from Cat. L_1 to Cat. L_4. This implies higher instability from the middle to upper layers during larger thunderstorms and the resultant severe lightning occurrences.

The CINS is the amount of negative buoyant energy from the lower to middle layers of the atmosphere and it is an index of convective activity. From **Fig. 10** the threshold value of CINS could be considered to be around -10 J/kg, as the CINS decreased from -0.9 for Cat. L_0 to -10.7 for Cat. L_1 conditions, and hence it could be used to indicate the severity of convective activity. The decrease of CINS from -11 J/kg for Cat. L_1 to -39 J/kg for Cat. L_4 suggests instability with higher convective activity during larger thunderstorm occurrences.

[Position of Fig. 10.]

The SHOW is a measure of the stability of the atmosphere and is determined by a dry-adiabatically raised air parcel from 850hPa. **Fig. 10** suggest that the threshold value for SHOW could be below 2 (Cat. L_1). The SHOW decrease from 6.2 to 2.1 for Cat. L_0 to Cat. L_1 conditions was an indication of instability from 850hPa to 500hPa. The lower SHOW values (<1) from Cat. L_2 to Cat. L_4 could explain the relatively higher atmospheric instability during large thunderstorm occurrences, and may be a useful indicator for the thunderstorm onset and development.

4.6. Horizontal Temperature Distribution at 850hPa and Moisture Streaming

Fig. 11 shows horizontal temperature distribution maps for 850hPa in June 2005 and 2006 to demonstrate typical monthly temperature patterns for Cat. L_4 and Cat. L_1 to Cat. L_2 lightning occurrences, respectively.

For Alaskan lightning to become active, the horizontal temperature distribution is a very important factor causing atmospheric instability. **Fig. 11** shows a very large 'warmer air mass' over Alaska at 850hPa mostly surrounded by cooler air masses. This warmer air mass was warmer than the north and southwest cooler air masses by around 9ºC and showed sharp temperature gradients in all directions. The average temperature at the center of this warmer air mass was around 3~4ºC higher than a similar period with average lightning incidence (Cat. L_1 to Cat. L_2) like June 2006. Further, the persistence of the central much warmer zone over interior Alaska was a distinguishing pattern for a Cat. L_4 lightning occurrence. Thus, it may be said that the formation of very extensive warmer air masses over interior Alaska with sharp temperature gradients around this warmer zone is one indicator of enhanced increased instability that could lead to severe lightning.

[Position of Fig. 11.]

In Alaska, the height of the 'tropopause' increases during the summer while the usual summer weather pattern is a 'Thermal low/Ocean high' pattern. However, a 'Thermal low/Ocean low' pattern was seen for the Cat. L_4 lightning occurrences [20]. This suggests one of the causes of Cat. L_4 lightning was the existence of the 'Ocean low' ('Aleutian low' and/or 'low on Gulf of Alaska') which could supply sufficient moisture into the interior of Alaska from the south or southwest oceans. During Cat. L_4 lightning occurrences in the middle of June 2005, a coupling of this 'Ocean low' with a 'low on interior Alaska' were noticed and that could induce a substantial moisture flow into interior Alaska. Another pattern was the

‘high’ over the Beaufort Sea of north of Alaska which could bring cool air masses with tiny amounts of moisture into the interior of Alaska from the Arctic Ocean.

4.7. Summary of the Various Indices and Parameters

Above the paper provided an evaluation of important indices and parameters by considering the absolute value differences between Cat. L_0 to Cat. L_1 to determine threshold values, and the gradient of the curves from Cat. L_1 to Cat. L_4 as shown in **Fig. 5** to **10**. The results of this evaluation are summarized in **Table 3** using three symbols, ‘O’, ‘Δ’, and ‘X’ standing for ‘effective’, ‘moderately effective’ and ‘not so effective’.

[Position of Table. 3.]

Among the indices and parameters in **Table 3**, LIFT appears as one of the most effective indices that could be used to express both the onset of lightning weather as well as to explain the severity of lightning occurrences. To visualize this further, the daily changes in the number of lightning flashes and LIFT from DN 140 to 220 of 2005 are shown in **Fig. 12**. It must be noted here that there is an around 3 hour time-lag between the LIFT data measurements by radiosonde at 14:00 and the occurrence of the lightning peak at around 17:00. Thus, the LIFT data for 2:00 AST (Alaska Standard Time) and 14:00 AST are included in **Fig. 12**.

[Position of Fig. 12.]

The exponential function the correlation coefficient showed a relatively low interaction ($R^2 = 0.39$) between LIFT and the lightning occurrences. Thus, based on the threshold value of LIFT (0.5) days of DN 140 to 220 (81 days) were divided into two groups, ‘active lightning days’ (LIFT below 0.5) and ‘little lightning days’ (LIFT above 0.5). The number of ‘active lightning days’ was 37 (~46%) out of the 81 days but include 27,302 (82%) lightning flashes of the 33,159 total. Among these, there were 17 severe lightning days (>1,000 flashes/day) of which 14 days (~82%) corresponded to ‘active lightning days’. Among the 27,302 flashes

22% occurred when LIFT was 0.5 to -0.99, 30% occurred when LIFT was -1 to -1.99, and the rest, 48%, occurred when LIFT was -2 to lower. Thus, it could be concluded that lightning activity due to the lifting mechanism via surface heating (mainly for Alaska) could occur when LIFT values remain in the range between 0 to -2, and that severe lightning could take place when LIFT goes below -2.

[Position of Fig. 13.]

The daily changes of Te_{850} and lightning flashes from DN 140 to 220 of 2005 are shown in **Fig. 13** to better visualize the effect of Te_{850} on the lightning occurrence. Here, the mean of Te_{850} from 1986 to 2009 along with the standard deviation curves (± SD) are also shown. Similar to LIFT in **Fig. 12**, the days from DN 140 to 220 in **Fig. 13** were also divided into two groups, namely 'warm days' and 'cool days' using the threshold value of Te_{850} (8ºC). The two groups clearly showed quite different lightning occurrence incidences. There were 43 (53%) 'warm days' out of the 81 and these included 27,239 (82%) flashes out of the total 33,159 flashes. The eight days with the most lightning in 2005 had 1,315 to 3,751 flashes under a warm Te_{850}, above 9.2ºC. For these days with heavy lightning, the mean temperature was 11.3ºC and most of the Te_{850} values exceeded temperatures of one plus the SD temperatures. These characteristics in the lightning occurrence tendency would support Te_{850} as an effective lightning index for Alaska.

4.8. Possibility of Lightning Forecasts for Alaska Using LIFT and Te_{850}

Based on the above results, the authors attempted to develop a simple forecasting index using LIFT and Te_{850}. Firstly, curve fitting by an exponential function was applied to obtain the optimum correlation between LIFT and lightning occurrences. This curve fitting was used as the number of lightning flashes changes from zero to more than 1,000 depending on the daily weather conditions. The radical change in lightning incidence was mainly caused by a latent heat release of moisture and this accelerates the upward flow dramatically. The authors used

the exponential function here by replacing the ‘0’ number of lightning flashes with ‘1’ as a matter of convenience. Thus, a total of 12 days out of the 81 days were assigned to have 1 lightning flash.

Secondly, correlation between LIFT and lightning occurrence using the exponential function showed the equation $y = 115.94e^{-0.51x}$ with $R^2 = 0.42$, where y and x stand for the number of lightning flashes and LIFT, respectively.

Thirdly, the correlation between Te_{850} and lightning occurrence gave $y = 7.75e^{0.27x}$ with $R^2 = 0.13$. It has been found that lightning in May and June tended to occur just after Te_{850} became warmer (**Fig. 13**). In addition, there may be around a one day time-lag between Te_{850} and lightning occurrence.

The LIFT showed relatively higher R^2 than Te_{850} and the authors tried to determine a new forecasting index by a combination of the LIFT and Te_{850} parameters. Therefore, various combination equations of LIFT and Te_{850} were evaluated by R^2, and the following may be proposed as an index to forecast lightning in Alaska:

$$\textit{Lightning Forecast Index (LFI)} = f \times Te_{850}\,(N\text{-}1) - LIFT\,(N)$$

where f is a weighting coefficient (here, 0.7 is used), ‘*N-1*’ and ‘*N*’ stand for ‘data of the previous day’ and ‘data of the current day’, respectively, the ‘-’ for LIFT is due to the negative correlation.

[Position of Fig. 14.]

This proposed ‘combination equation of LIFT and Te_{850}’ or LFI showed $y = 10.32e^{0.43x}$ with a relatively high R^2 of *0.55* (**Fig. 14**). Though this kind of combination equation can not explain the severe lightning occurrences well, it would be useful in explaining characteristics of the lightning occurrences in Alaska.

5. Conclusions

This study carefully examined a range of weather parameters and indices like soar, instability, 'dry lightning', and others to establish factors that most sensitively shows the lightning characteristics in Alaska. For this purpose, a categorized lightning severity analysis was carried out. Based on the results of the analysis, 'LIFT' and 'Te_{850}' were selected as the most sensitive parameters among the various factors. The sensitivities were examined by comparing daily changes in LIFT and Te_{850} with lightning occurrence during the fire season (81 days) in 2005. Finally, a simple lightning forecast index is proposed. The conclusions may be summarized as follows:

1. The LIFT parameter was the most sensitive among the factors investigated, such as SHOW and CAPE, to assess the upper air instability. In addition, LIFT can be calculated more simply than other parameters.
2. A total of 81 days of the fire season in 2005 were divided into two groups, 'active lightning days' and 'little lightning days' by using a threshold value (0.5) of LIFT. The percentage of 'active lightning days' was 46% (37 days out of 81) but included 82% (27,302 flashes out of 33,159) of the total recorded lightning flashes in the 81 days.
3. The LIFT value could solely explain the lightning occurrence and severity in Alaska with a relatively high correlation ($R^2 = 0.42$) when using an exponential function.
4. The Te_{850} (environmental temperature at 850hPa) was the most sensitive factor to assess the existence of warm and moist air masses.
5. Like with LIFT, the Te_{850} enabled a division of the 2005 fire season into two by using a threshold value (8ºC). The percentage of 'warm days' (Te_{850} > 8ºC) was 53% (43 days out of 81) and included 82% (27,239 out of 33,159 lightning flashes) of the total

number of lightning flashes here. These numbers are very similar to the two way division with LIFT.

6. The proposed lightning forecast index showed a good correlation ($R^2 = 0.55$) but still does not explain the large incidences of lightning occurrences (>1,000 flashes/day) well. To improve this, further information such as upper air moisture, flow conditions, and other parameters should be considered.
7. This study shows that almost all of the summer precipitation in Alaska is brought by large thunderstorms. This implies that larger thunderstorms in Alaska are not the so-called ‘dry-thunderstorms’.

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References

[1] M. Shulski, G. Wendler, S. Alden and N. Larkin, "Alaska`s Exceptional 2004 Fire Season", 6th Symposium on Fire & Forest Meteorology, Canmore, 2005.

[2] C. Price and D. Rind. "Lightning activity in a greenhouse world". Proceedings of the 11th Conference on Fire and Forest Meteorology 11, pp. 598-604, 1991.

[3] E. Williams, "The Schumann resonance: a global tropical thermometer", Science, 256, pp. 1184-1187, 1992.

[4] E. Williams, "Global circuit response to seasonal variations in global surface air temperature", Mon. Wea. Rev., pp. 1917-1929, 1994.

[5] E. Williams, "Global circuit response to temperature on distinct time scales: a status report, in Atmos. Ionos. Electromag. Phenomena associated with Earthquakes", Ed. M. Hayakawa, TERRAPUB, Tokyo, pp. 939-949, 1999.

[6] E. Williams, "Lightning and climate: a review", Atmos. Res., 76, pp. 272-287, 2005.

[7] E. Williams, "The global electrical circuit: A review", Atmos. Res., 91, pp. 140-152, 2009.

[8] W. Sullivan, "Low level convergence and thunderstorms in Alaska", Mon. Wea. Rev., 91, pp. 82-92, 1963.

[9] K. Biswas and K. Jayaweera, "NOAA-3 satellite observations of thunderstorms in Alaska", Mon. Wea. Rev., 104, pp. 292-297, 1976.

[10] R. M. Reap, "Climatology characteristics and objective prediction of thunderstorms over Alaska", Wea. Forec. 6, pp. 309-319, 1991.

[11] D. Dissing and D. L. Verbyla, "Spatial patterns of lightning strikes in interior Alaska and their relations to elevation and vegetation", Can. J. For. Res., 33, pp. 770-782, 2003.

[12] R. M. Reap, "Evaluation of cloud-to-ground lightning data from the western United States for the 1983-84 summer seasons", J. App. Meteor. 25, pp. 785-799, 1986.

[13] M. L. Rorig and S.A. Ferguson, "Characteristics of lightning and wildland fire ignition in the Pacific Northwest", J. App. Meteor. 38, pp. 1565-1575, 1999.

[14] M. L. Rorig and S.A. Ferguson, "The 2000 fire season: lightning-caused fires", J. App. Meteor. 41, pp. 786-791, 2002.

[15] K. R. Anderson, "Models to predict lightning occurrence and frequency over Alberta", M. Sc. Thesis, University of Alberta, Edmonton, Alta, 1991.

[16] R. L. Holle, A. I. Watson, R. E. Lopez, K. W. Howard, R. Ortiz and L. Li, "Meteorological studies to improve short-range forecasting of lightning/thunderstorms within the Kennedy Space Center area", Final Report, NOAA, National Severe Storms Laboratory to Office of Space Flight, NASA, Boulder, Colo, 1992.

[17] R. M. Reap, "Analysis and prediction of lightning strike distributions associated with synoptic map types over Florida", Mon. Weather Rev. 122, pp. 1698-1715, 1994.

[18] R. M. Reap and D. S. Foster, "Automated 12-36 hour probability forecasts of thunderstorms and severe local storms", J. App. Meteor. 18, pp. 1304-13015, 1979.

[19] M. Richmond and T. Shy, "An extraordinary summer in the interior of Alaska", Proceedings of the 85th AMS Annual Meeting, San Diego, CA, p.1.5, 2005.

[20] M. A. Farukh, H. Hayasaka and K. Kimura, "Recent Severe Lightning Occurrences in Alaska – the case of June 2005 –" Journal of Disaster Research, 6(2), 2011, In Press.

[21] Alaska Fire Service (AFS), 2010. http://fire.ak.blm.gov/afs/

[22] Alaska Interagency Coordination Center (AICC), 2010. http://afsmaps.blm.gov/imf_lightning/imf.jsp?site=lightning

[23] Alaska Climate Research Center, 2010. http://climate.gi.alaska.edu/Climate/Location/Interior/Fairbanks.html

[24] National Climatic Data Center, 2010. http://www.wrcc.dri.edu/cgi-bin/rawMAIN.pl?akAFAI

[25] E. Kalnay and Coauthors, "The NCEP/NCAR 40-year reanalysis project", Bull. Amer. Meteor. Soc., 77, pp. 437-470, 1996.

[26] University of Wyoming, Department of Atmospheric Science, 2010. http://weather.uwyo.edu/upperair/sounding.html?region=seasia

[27] C. Price and D. Rind. “The impact of a 2 x CO_2 climate on lightning caused fires”. Journal of Climate 7, pp. 1484-1494, 1994.
[28] E. McGuiney, M. Shulski and G. Wendler, “Alaska lightning climatology and application to wildfire science”,
Proceedings of the 85th AMS Annual Meeting, San Diego, CA, p.2.14, 2005.
[29] J. W. Van Wagtendonk and D.R. Cayan, “Temporal and spatial distribution of lightning in California in relation to large-scale weather patterns”, Fire Ecology 4(1), pp. 34-56, 2008.
[30] M. L. Rorig, S.A. Ferguson and S. McKay, “Forecasting dry lightning in the western United States”, Proceedings of the 5th Symposium on Fire and Forest Meteorology, Orlando, FL, p.1.4, 2003.
[31] G. K. Grice and A.L. Comisky, “Thunderstorm Climatology of Alaska”, NOAA Technical Memo, NWS AR-14, p. 36, 1976.

Caption list of illustrations and Table, and Appendix

Fig. 1. The location of the lightning detection sensors, radiosonde stations, and study areas S_I (large rectangle) and S_F in Alaska (small rectangle)

Fig. 2. Daily lightning flash incidence from May to August 1986 to 2009

Fig. 3. Categorization of lightning days based on lightning flashes/day from May to August since 1986 to 2009

Fig. 4. Indices and parameters for the extremely severe (Cat. L_4) lightning conditions on June 15, 2005 in Alaska

Fig. 5. T_{max}, precipitation, and precipitable water for the different categories of lightning occurrences

Fig. 6. Pressure height at 1,000hPa, 850hPa and 500hPa for the different categories of lightning occurrences

Fig. 7. Te_{850}, Te_{700}, Te_{500}, and Td_{850}, Td_{700} for the different categories of lightning occurrences

Fig. 8. $\Delta Te_{850\text{-}500}$, $\Delta Te_{700\text{-}500}$, and DD_{850}, DD_{700} for the different categories of lightning occurrences

Fig. 9. KINX and LIFT for the different categories of lightning occurrences

Fig. 10. CAPE, CINS and SHOW for the different categories of lightning occurrences

Fig. 11. Monthly mean 850hPa temperature maps in June of 2005 and 2006

Fig. 12. Daily changes in the number of lightning flashes and LIFT (2:00 and 14:00 AST) from DN 140 to 220 in 2005 for study area S_F

Fig. 13. Daily changes in the number of lightning flashes and Te_{850} from DN 140 to 220 in 2005 for study area S_F

Fig. 14. Relationship between number of lightning flashes and LFI

Table 1: Categorization of lightning occurrences in Alaska

Table 2: Indices and parameters assessing lightning conditions in Alaska

Table 3: Indices and parameters to evaluate lightning conditions in Alaska

Appendix 1. List of equations used to calculate various indices

(I)

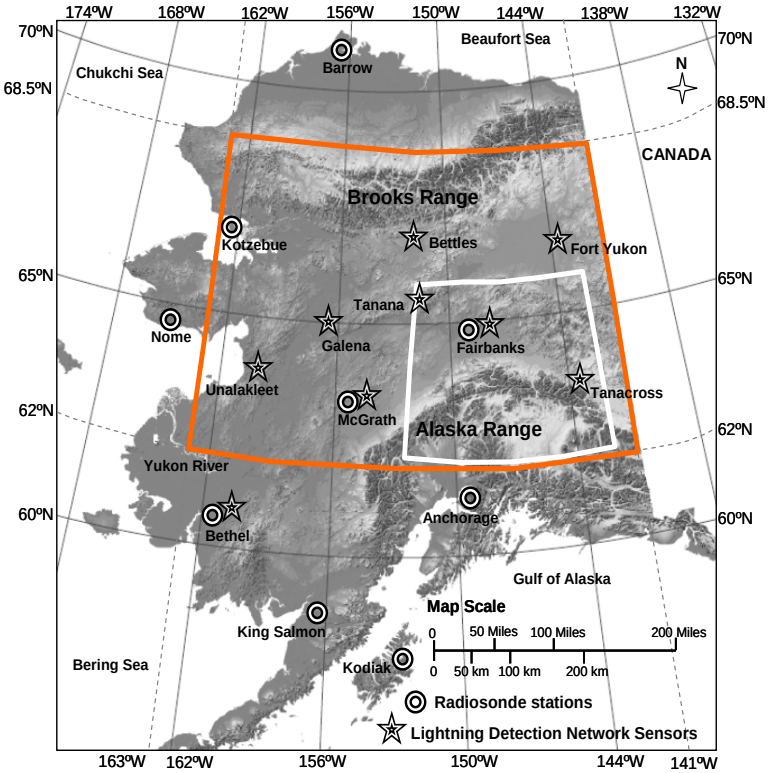


Fig. 1. The location of the lightning detection sensors, radiosonde stations, and study areas S_I (large rectangle) and S_F in Alaska (small rectangle)

(II)

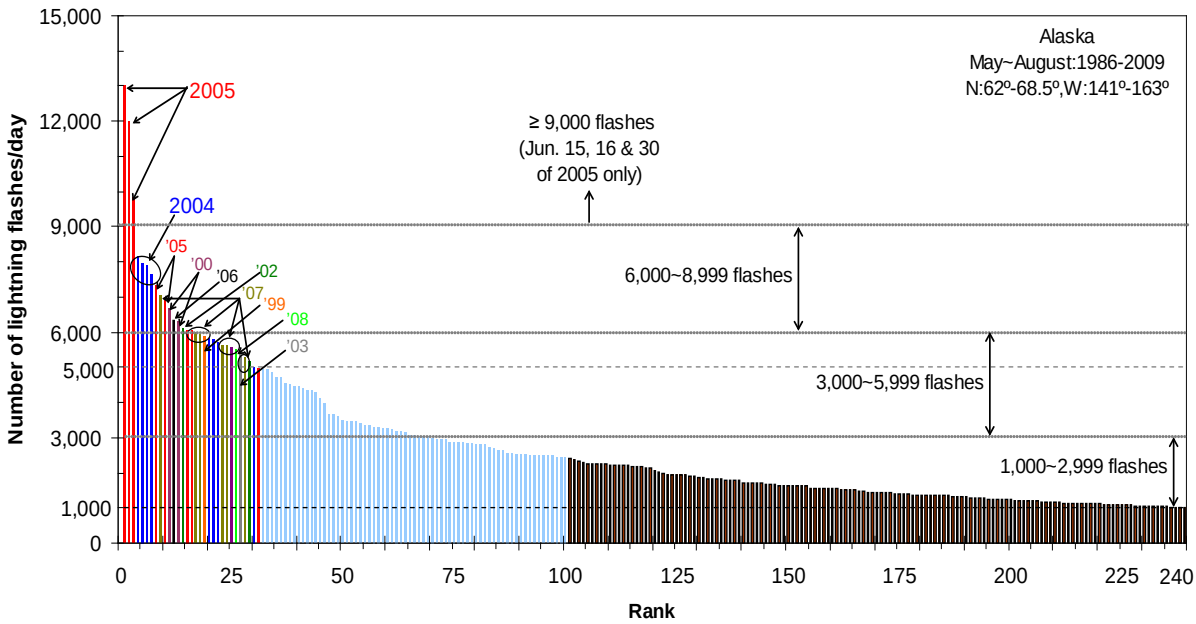


Fig. 2. Daily lightning flash incidence from May to August 1986 to 2009

(III)

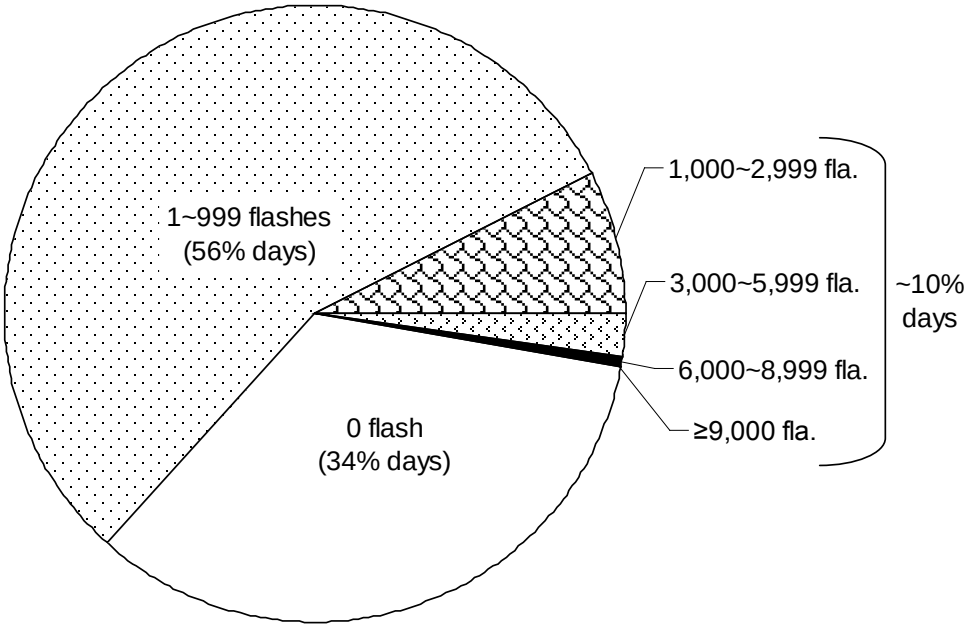


Fig. 3. Categorization of lightning days based on lightning flashes/day from May to August since 1986 to 2009

(IV)

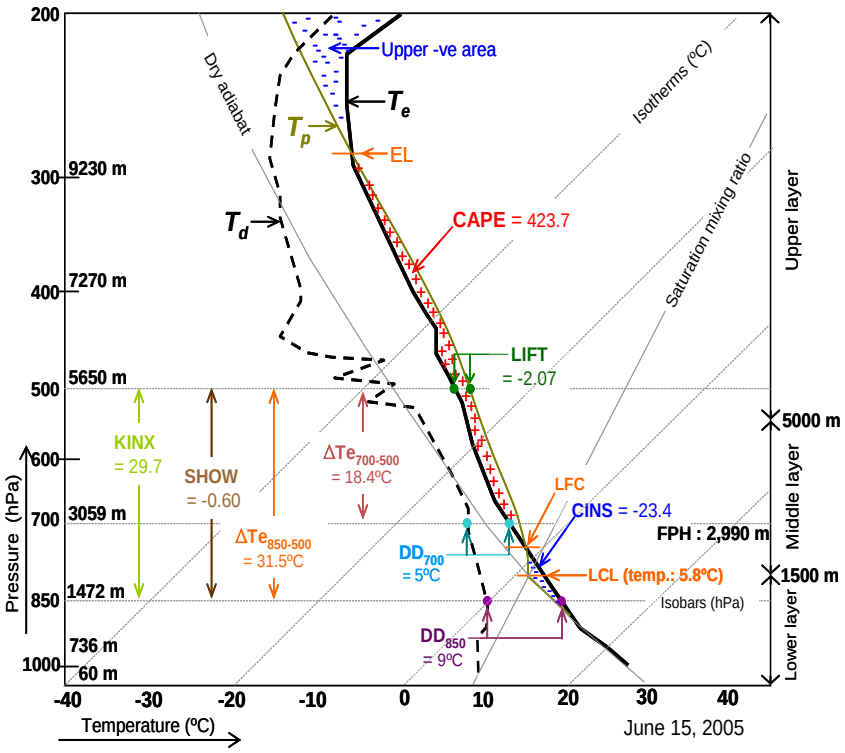


Fig. 4. Indices and parameters for the extremely severe (Cat. L_4) lightning conditions on June 15, 2005 in Alaska

(V)

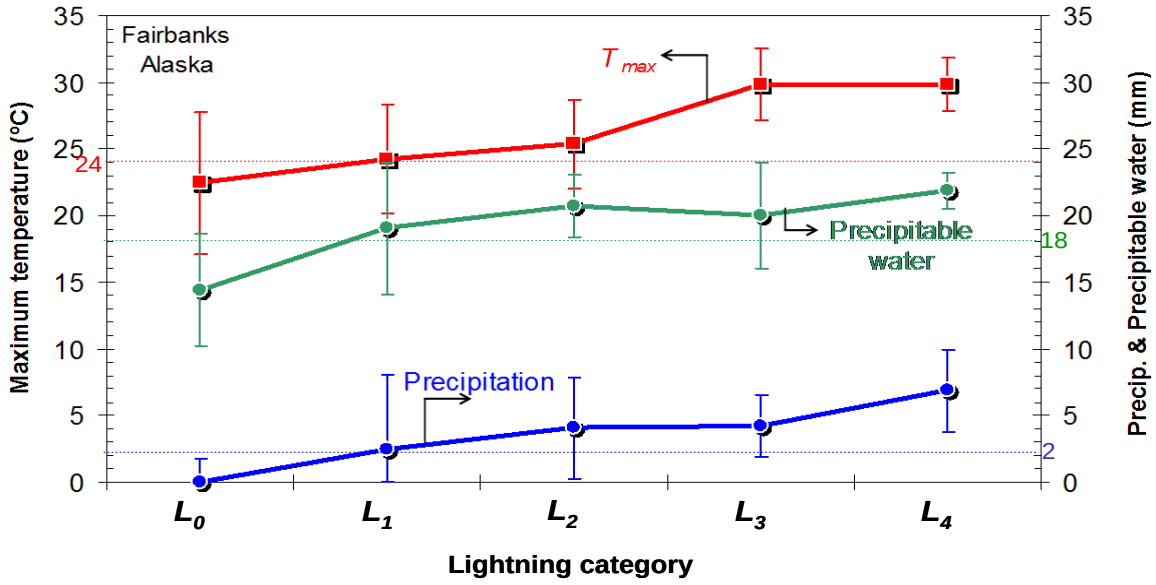


Fig. 5. T_{max}, precipitation, and precipitable water for the different categories of lightning occurrences

[Representative author: **Murad Ahmed Farukh**]

(VI)

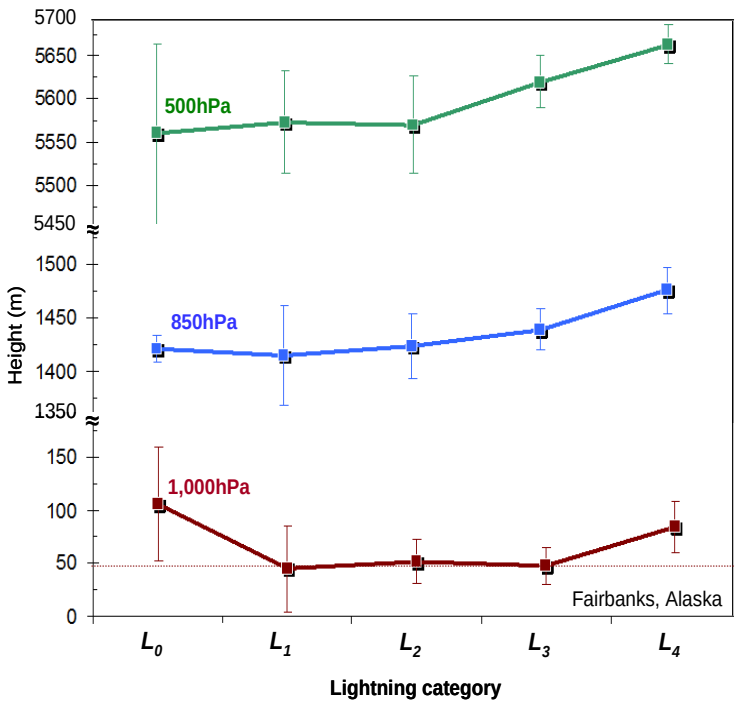


Fig. 6. Pressure height at 1,000hPa, 850hPa and 500hPa for the different categories of lightning occurrences

(VII)

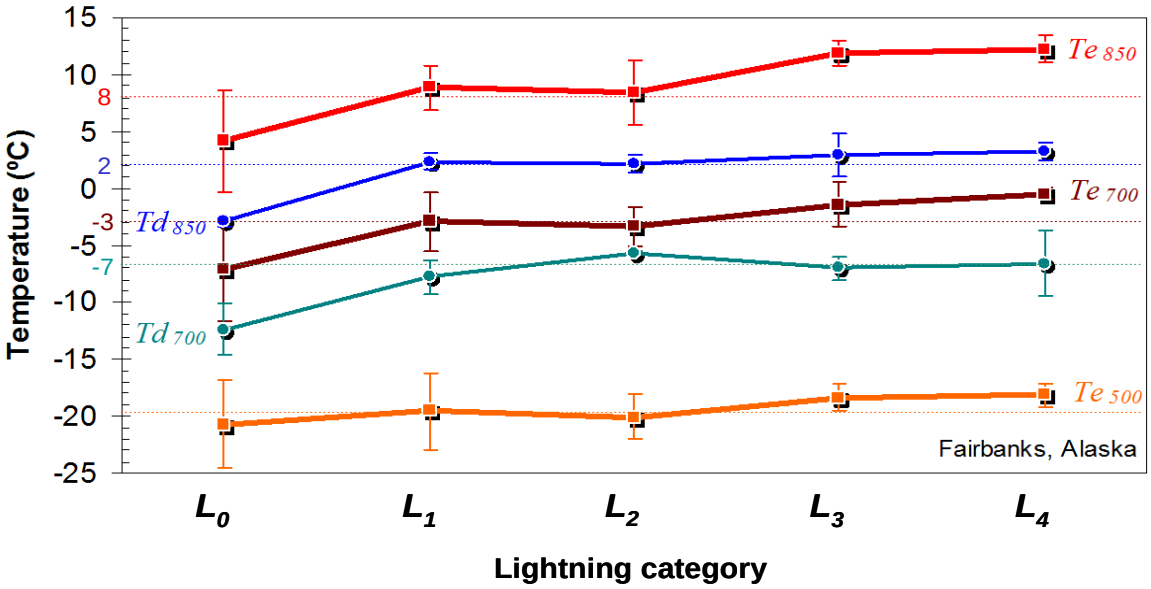


Fig. 7. Te_{850}, Te_{700}, Te_{500}, and Td_{850}, Td_{700} for the different categories of lightning occurrences

(VIII)

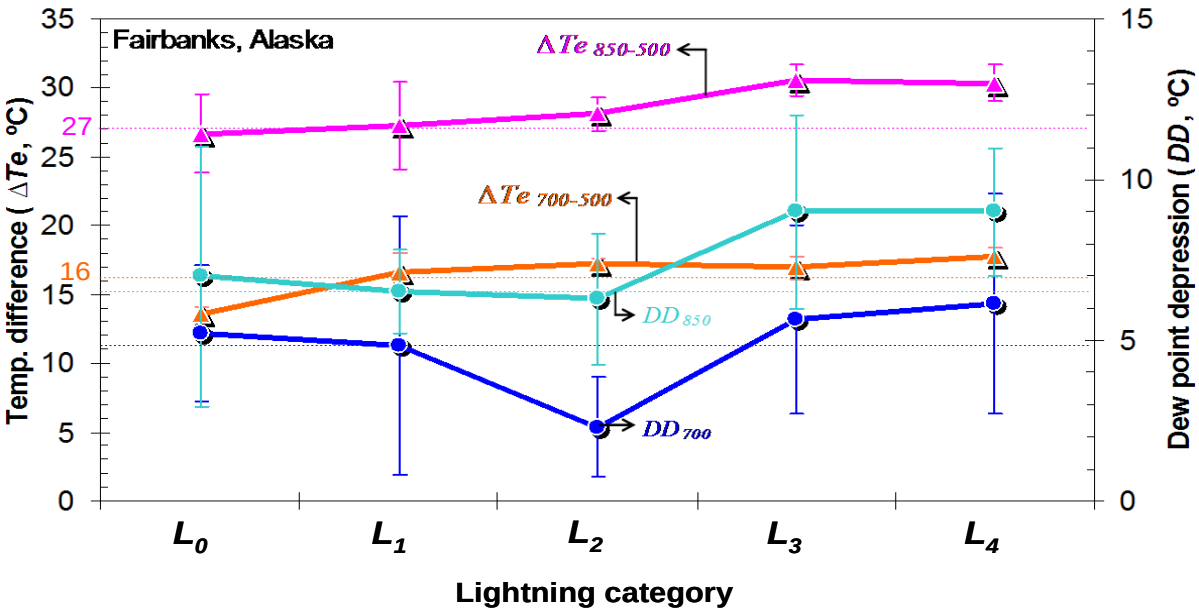


Fig. 8. $\Delta Te_{850\text{-}500}$, $\Delta Te_{700\text{-}500}$, and DD_{850}, DD_{700} for the different categories of lightning occurrences

(IX)

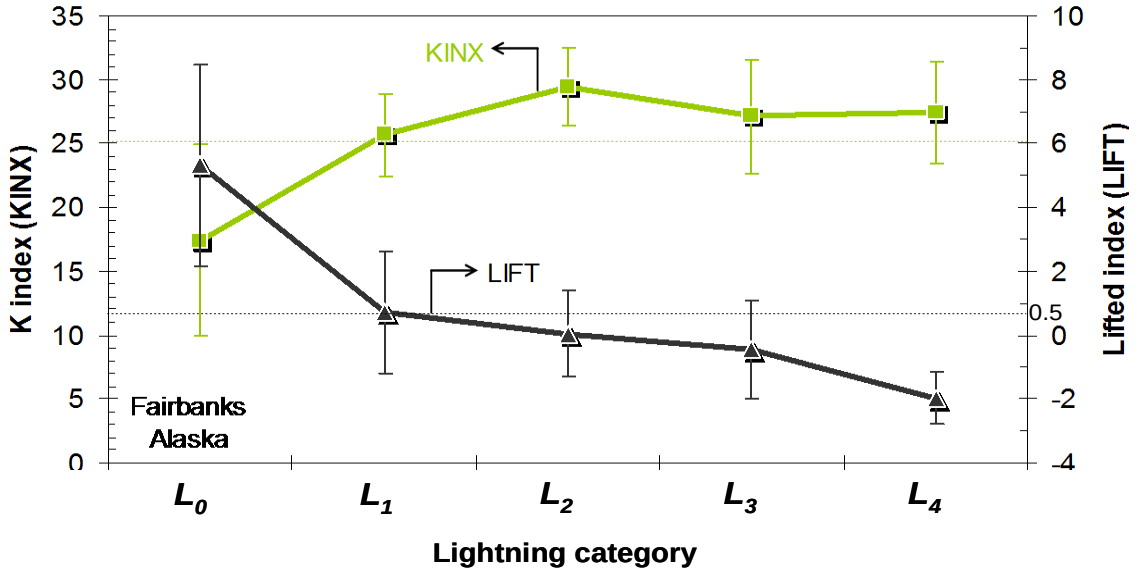


Fig. 9. KINX and LIFT for the different categories of lightning occurrences

(X)

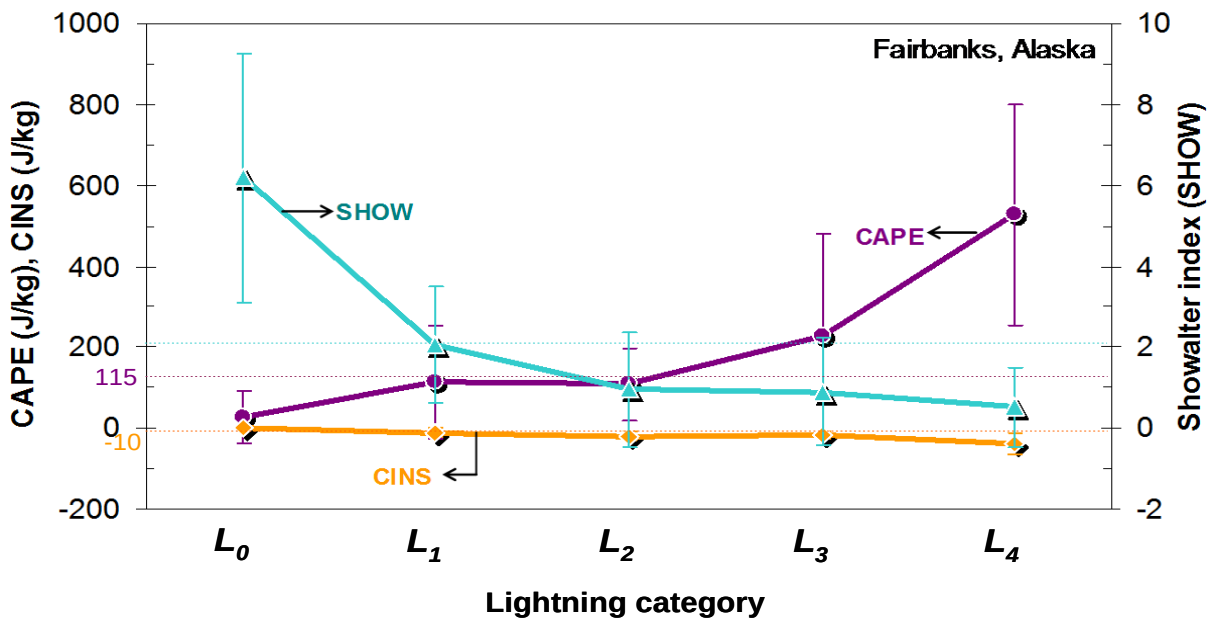


Fig. 10. CAPE, CINS and SHOW for the different categories of lightning occurrences

(XI)

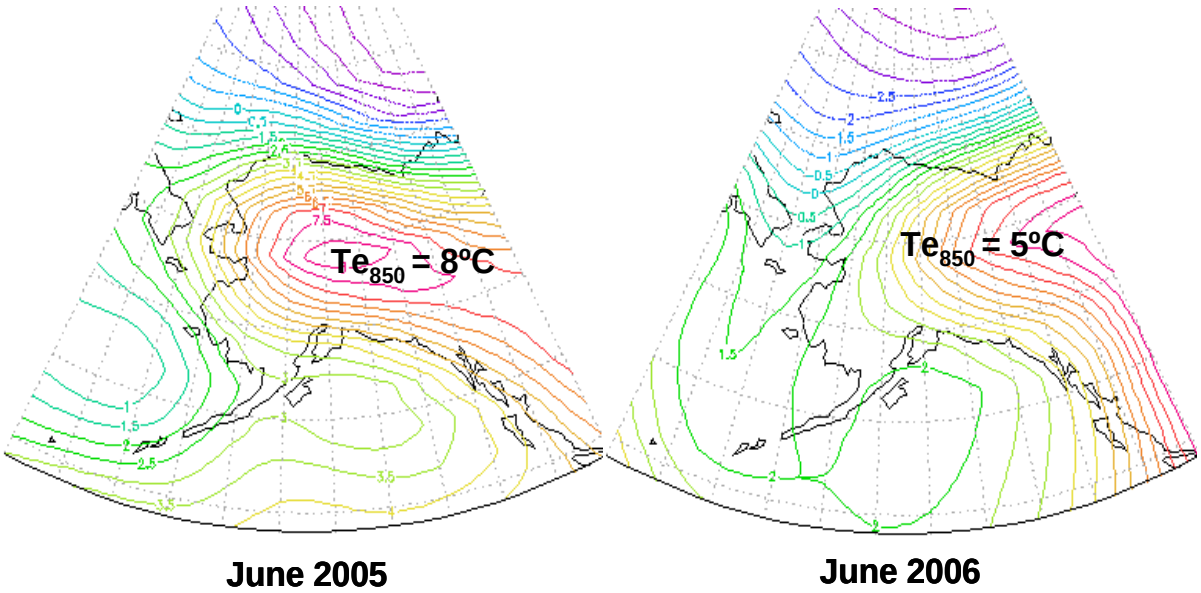
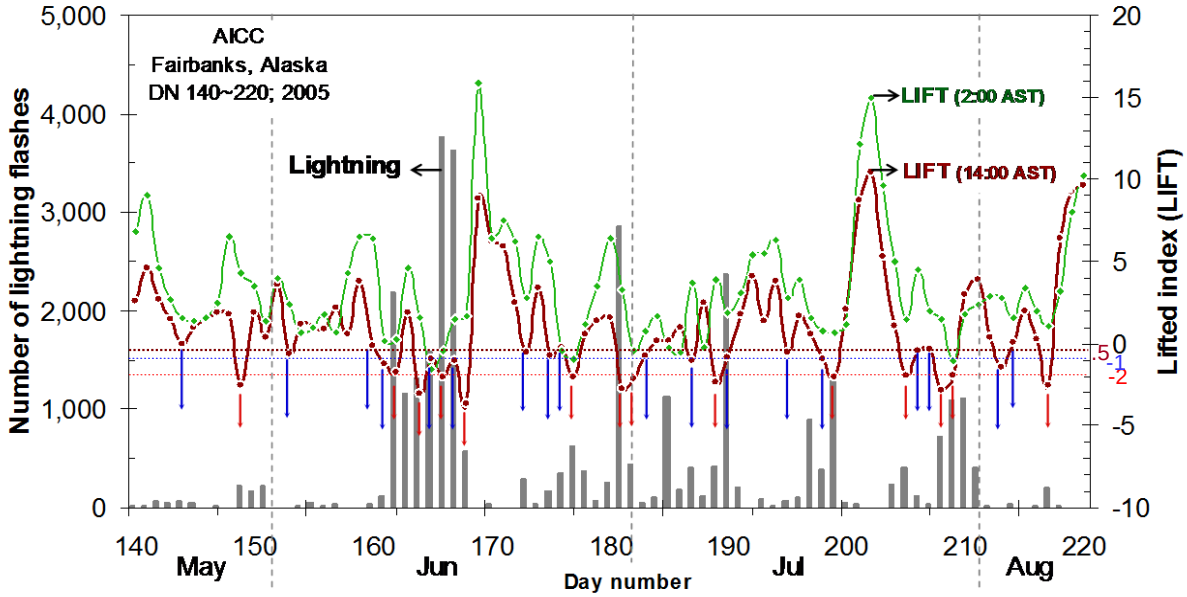


Fig. 11. Monthly mean 850hPa temperature maps in June of 2005 and 2006

(XII)



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(XIII)

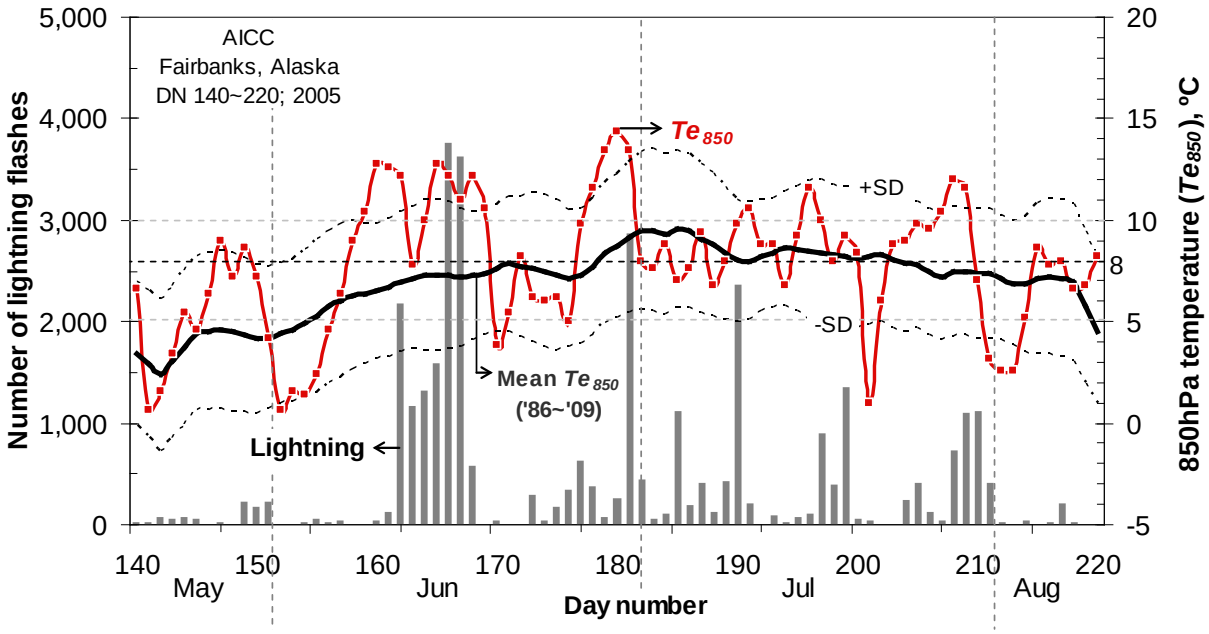

Fig. 13. Daily changes in the number of lightning flashes and Te_{850} from DN 140 to 220 in 2005 for study area S_F

(XIV)

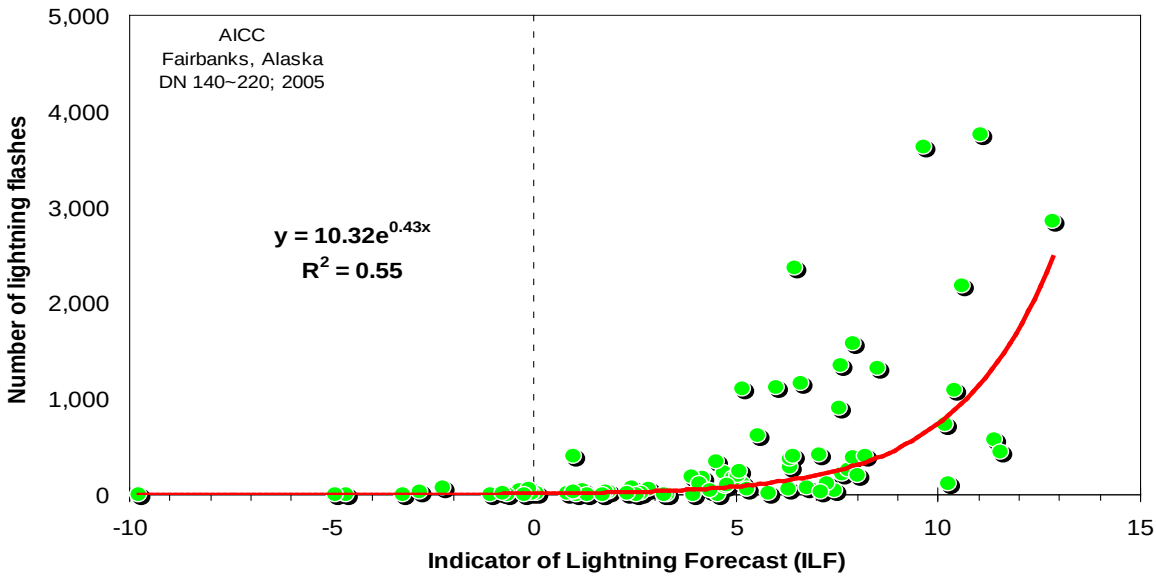

Fig. 14. Relationship between number of lightning flashes and LFI

(I) **Table 1**: Categorization of lightning occurrences in Alaska

(May~August: 1986-2009; Coverage: N 62º-68.5º, W 141º-163º)

	Lightning Category						**TOTAL**
	Extremely Severe (L_4)	**Very Severe (L_3)**	**Severe (L_2)**	**Less Severe (L_1)**	**Small lightning (L_0)**		
Lightning flashes/day	≥ 9,000	6,000~8,999	3,000~5,999	1,000~2,999	1~999	0	-
Number of days	3	13	53	172	1,307	912	2,460
Average flashes/day	11,625	6,961	4,281	1,733	191	0	24,791

(II) **Table 2**: Indices and parameters assessing lightning conditions in Alaska

Indices/ Parameters	**Assessing Conditions**	**Indices/ Parameters**	**Assessing Conditions**
Temperature		Dry lightning	
T_{max}	Maximum temp., surface	$\Delta Te_{850\text{-}500}$	Temp. difference, 850hPa & 500hPa
Te_{850}	Environmental temp., 850hPa	DD_{850}	Moisture & Humidity, 850hPa
Te_{700}	Environmental temp., 700hPa	$\Delta Te_{700\text{-}500}$	Temp. difference, 700hPa & 500hPa
Te_{500}	Environmental temp., 500hPa	DD_{700}	Moisture & Humidity, 700hPa
Soar		Stability	
KINX	Convective activity lift rate	CAPE	Instability
LIFT	Airmass thunderstorm probability	CINS	Stability, Convective activity
		SHOW	Instability

where KINX: K index, LIFT: Lifted index, *DD*: Dew point depression, CAPE: Convective Available Potential Energy, CINS: Convective Inhibition, SHOW: Showalter index

(III) **Table 3**: Indices and parameters to evaluate lightning conditions in Alaska

Indices/ Parameters	**Threshold values (Cat. L_1)**	**Lightning**		**Remarks**
		Onset	**Severity**	
LIFT	0.5	O	O	Airmass thunderstorm probability
CAPE (J/kg)	115	Δ	O	Indicates upper level instability
Te_{850} (ºC)	8	O	O	Indicates 850hPa instability
T_{max} (ºC)	24	X	O	Indicates surface instability

Appendix 1. List of equations used to calculate various indices

Eq. No.	Equation
(1)	$\Delta Te_{850\text{-}500} = Te_{850} - Te_{500}$
(2)	$\Delta Te_{700\text{-}500} = Te_{700} - Te_{500}$
(3)	$DD_{850} = Te_{850} - Td_{850}$
(4)	$DD_{700} = Te_{700} - Td_{700}$
(5)	$KINX = \Delta Te_{850\text{-}500} + Td_{850} - DD_{700}$
(6)	$LIFT = Te_{500} - Tp_{500}$
(7)	$CAPE = \int_{Zf}^{Zn} g\left\{(Tp - Te)/Te\right\}dz$
(8)	$CINS = \int_{\approx bottom}^{\approx top} g\left\{(Tp - Te)/Te\right\}dz$
(9)	$SHOW = Te_{500} - Tp_{850}$

List of symbols used in equations

Symbols	Description	Unit
$\Delta Te_{850\text{-}500}$	temperature difference between 850hPa and 500hPa	ºC
Te_{850}	environmental temperature at 850hPa	ºC
Te_{500}	environmental temperature at 500hPa	ºC
$\Delta Te_{700\text{-}500}$	temperature difference between 700hPa and 500hPa	ºC
Te_{700}	environmental temperature at 700hPa	ºC
DD_{850}	dew point depression at 850hPa	ºC
Td_{850}	dew point temperature at 850hPa	ºC
DD_{700}	dew point depression at 700hPa	ºC
Td_{700}	dew point temperature at 700hPa	ºC
Tp_{500}	temperature of air parcel lifted adiabatically to 500hPa height	ºC
Zf	height of the level of free convection (LFC)	m
Zn	height of equilibrium level (EL)	m
g	acceleration due to gravity	m/s^2
≈top	top altitudes of a CIN layer	m
≈bottom	bottom altitudes of a CIN layer	m
Tp_{850}	temperature of air parcel at 850hPa lifted dry-adiabatically to 500hPa height	ºC