Lightning in the Arctic

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Abstract:
WWLLN (World Wide Lightning Location Network) data on global lightning are used to investigate the increase of total lightning strokes at Arctic latitudes. We use the summertime data from June, July and August (JJA) which average >200,000 strokes each year above 65ºN for the years 2010 – 2020. We minimize the possible influence of WWLLN network detection efficiency increases by normalizing our results to the total global strokes during northern summer each year.

The ratio of strokes occurring above a given latitude, compared to total global strokes, increases with time, indicating that the Arctic is becoming more influenced by lightning. We compare the increasing fraction of strokes with the NOAA global temperature anomaly, and find that the fraction of strokes above 65ºN to total global strokes increases linearly with the temperature anomaly and grew by a factor of 3 as the anomaly increased from 0.65 to 0.95 degrees C.

Introduction

In August 2019 it was widely reported that multiple lightning strokes had been detected within just a few hundred miles from the North Pole (cf Freedman, 2019) Indeed, multiple reports in recent years show strong evidence that the Arctic is warming faster than expected (e.g. Carey 2012), the sea ice is melting (e.g. Dirk and Stroeve, 2016) as is the permafrost (e.g. Farquharson et al, 2019). One might assume that with global warming we would see an increase in global lightning, but this is both a controversial prediction and difficult to prove with existing global lightning data. In 2004 Williams discussed the expected and measured meteorology and climate variations on the frequency of lightning and concluded that the question was undecided about whether global lightning would increase or decrease as the planet warmed. Others have predicted an increase in lightning (Romps et al, 2014) or a decrease (Finney et al, 2018).

Another assumption one might have, now that we have global lightning monitoring in real time since 2004 (see http://wwlln.net), is that we should be able to simply count strokes and compare to the temperature rise. During the last decade, even the oldest global lightning location network has had such growth in its detection efficiency, that global inter-comparison between years is not simple. Because of the improving detection efficiency one might expect strong increases in lightning stroke counts even without any climate impacts.

In this paper we describe the global temperature increase and then look specifically at the lightning occurring at high northern latitudes over the last 11 years. Global lightning has a seasonal variation resulting in major lighting activity which is dominant in the summer hemisphere. Thus the major regions of lightning strokes switch from the northern mid-latitudes (June/July/August) to the southern mid-latitudes (in Dec/Jan/Feb) every year, while lightning activity in the tropics has a smaller annual total stroke variation. Furthermore we find few lightning strokes in the high Arctic outside of these summer months. Additionally we note that the southern hemisphere at high southern latitudes has very little lightning at any time of the year. There are some summer strokes near the Palmer Peninsula, Antarctica, but almost no strokes poleward of 65° S, and certainly not enough for a comprehensive statistical analysis, even though WWLLN has 5 stations in Antarctica. As such we consider only northern hemisphere summer data.

In this study we discuss the temperature and lightning data sets to be used and motivate the work with a global look at both the Earth's temperature anomaly as well as northern latitude lightning distributions. We then present an analysis using latitudinal and annual lightning variations to investigate the increasing fraction of global lightning which occurs at high latitudes. These lightning data are then compared to the three-month global temperature anomaly for northern hemisphere summer to arrive at a linear relationship between the fraction of global lightning occurring above 65°N, with the temperature increase. If this trend continues and the Earth has another 0.5°C global temperature increase, then the lightning stroke rate in the Arctic could increase by 100% from the 2020 stroke level.

Data Sets

Here we introduce the global temperature data set available from NOAA's National Centers for Environmental Information (NCEI) and the lightning data from WWLLN. NCEI tracks the Earth's temperature variations and has global temperature change data from 1880 to today (NOAA,2020). Figure 1 is a plot of the full globe, yearly temperature anomaly for JJA, showing the, now well known, steady increase of global temperature. Data used for these plots comes from over 1200 stations around the globe, and ocean data comes mostly from an extensive network of buoys (NCDC, 2020). The units are given in degrees C above the average temperature for the 20th century (0 degree line in Figure 1). We will concentrate on the yearly temperature anomaly changes corresponding to the 11 year time period of the WWLLN lightning data (2010 – 2020, toward the end of the plot in Figure 1) and use the global temperature data from the June-July-August (JJA) period each year corresponding to the summer time of the lightning data (NOAA, 2020b).

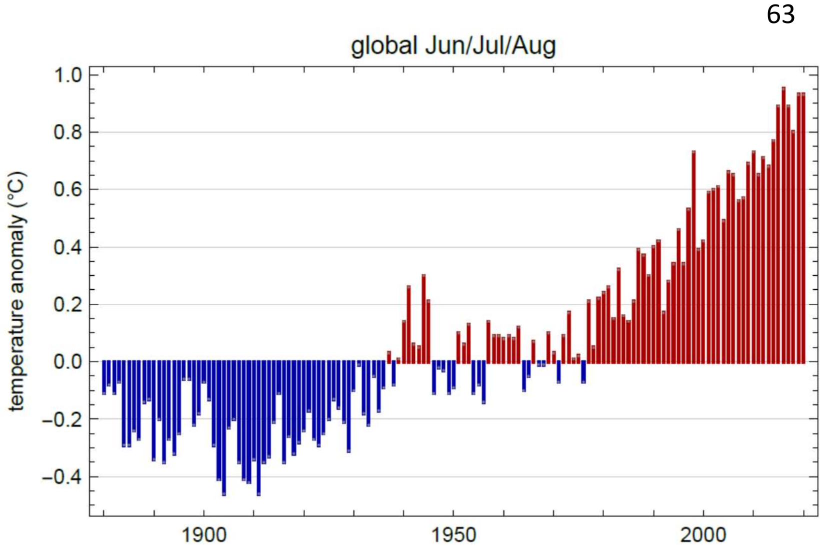

Figure 1. Global Temperature Anomaly for June, July and August

The WWLLN (World Wide Lightning Location Network) has been locating lightning strokes globally since 2004. The WWLLN uses the radio energy emitted by lightning (in the VLF - Very Low Frequency - range) and detected at receivers all over the world to locate lightning using the time of group arrival (Dowden et al, 2002, Rodger et al 2006, Hutchins et al, 2012, Virts et al, 2013). Lightning produces a strong, narrow impulse during each return stroke which results in the emission of radio frequency (RF) energy which peaks in the range of 10 to 15 kHz (e.g. Malan, 1963, Dowden et al, 2002). This narrow impulse, which can be recognized as a transient even at AM or FM radio band frequencies, produces a wave packet which propagates around the world in the Earth Ionosphere Wave Guide (EIWG). During propagation the wave packet spreads out in frequency by a process called dispersion, requiring a careful analysis of the wave packet to find the time of group arrival (TOGA) (Dowden et al, 2002). When the TOGA is measured with 100 ns absolute accuracy by several widely spaced receivers, it is possible to locate lightning to within < 5 km and within a few microseconds. Currently WWLLN locates 600,000 to 800,000 strokes globally every day, while in the past the detection efficiency was about 10% of what it is today. Here we use data from 2010 – 2020 to analyze the increase in high latitude lightning and concentrate on the northern summer months of JJA.

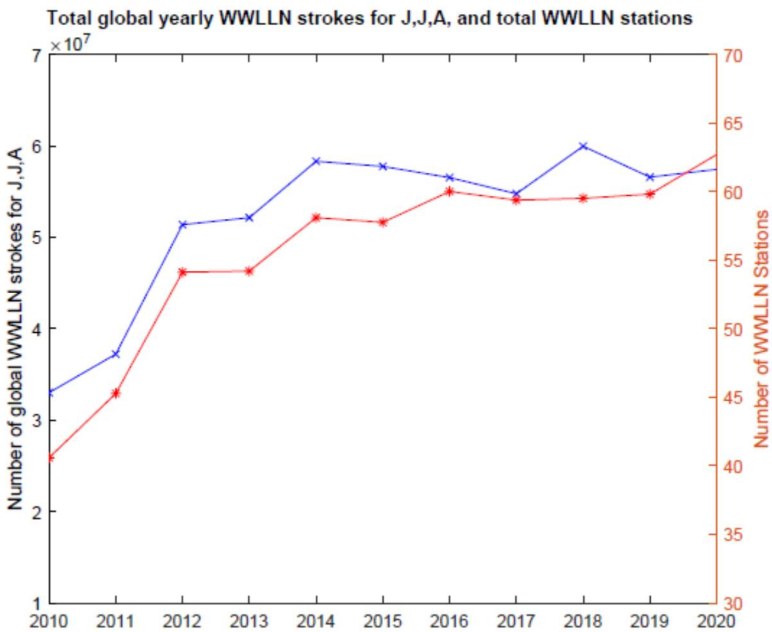

Figure 2. Number total global WWLLN strokes for June, July and August (blue) and the number of Active WWLLN Stations (Red)

Figure 2, for reference, shows the total, global strokes, each detected by 6 or more WWLLN stations, during JJA each year. Additionally Figure 2 shows the average number of WWLLN stations operating during those months (red line). We can see an increase in global strokes located with 6 or more WWLLN stations during these months, from 3.21×10^7 strokes in the northern summer in 2010 to about twice that beginning in 2014, and more or less steady after that. The red curve counts the average stations operating each year during the 92 days of the JJA months. Comparing the red to the blue curves one can see that the increase in strokes (blue) is closely associated with an increasing detection efficiency due to the increasing number of stations (red). However after 2014 the total global stroke count in Figure 2 varies by less than 10%, as does the station count. There is little or no lightning in the Arctic outside of northern summer time, hence we focus here on just those three months each year.

The distribution of high latitude lightning found during these 11 years is shown in Figure 3, which is a plot of just the strokes poleward of 75°N latitude. In Figure 3 we can see that the stroke distribution is dominated by lightning in the eastern hemisphere from about 70°E to 170°E, with relatively little lightning north of Canada/Alaska by comparison. This is probably due to the fact that mainland Canada is mostly south of 70°N, while mainland Russia reaches up to over 77°N, with substantial mainland Russia north of 70°N latitude.

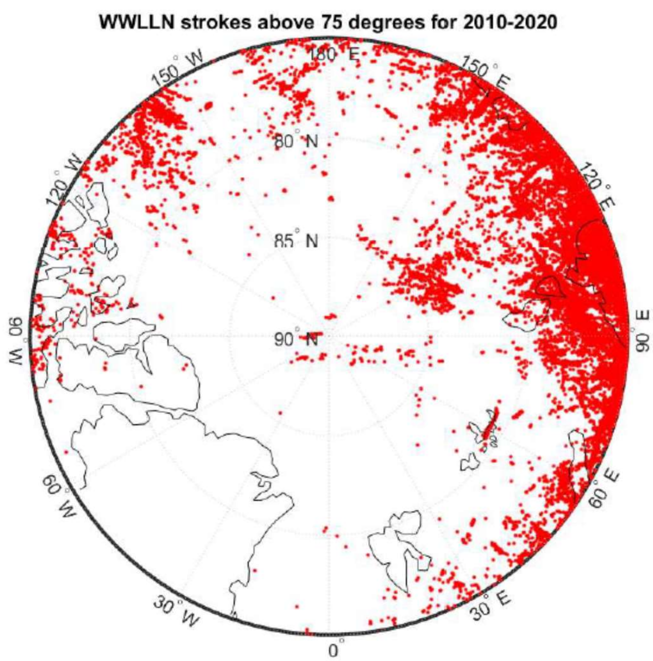

Figure 3 also shows some lightning activity extending up to very near the North Pole. In fact these WWLLN data include 28 strokes, well vetted in location and time which are within about 100 km of the North Pole which all occurred on 13 August 2019 (see Supplemental Material Table S1 for the actual strokes, and Figure S1 to see the WWLLN stations which located these strokes). This paper does not address the meteorology associated with this northern intrusion close to the pole, but it is clear that it is associated with an energetic, well organized event which lasted for hours and will be examined in a future study.

Figure 3. Global distribution of WWLLN strokes in June July and August for 2010 – 2020 above 75N

Analysis of High Latitude Lightning

Figure 4, with JJA WWLLN strokes poleward of 65N, shows stroke counts increasing over recent years (blue bars).The blue histogram data in his figure are not corrected for WWLLN detection efficiency, but report actual total strokes detected by 6 or more WWLLN stations during JJA from latitudes north of 65ºN. Looking at Figure 2 as a rough guide to the gross variation in WWLLN detection efficiency, we can adjust the stroke number each year by the ratio of average number of stations after 2014 (59.9 stations) to the actual number each year

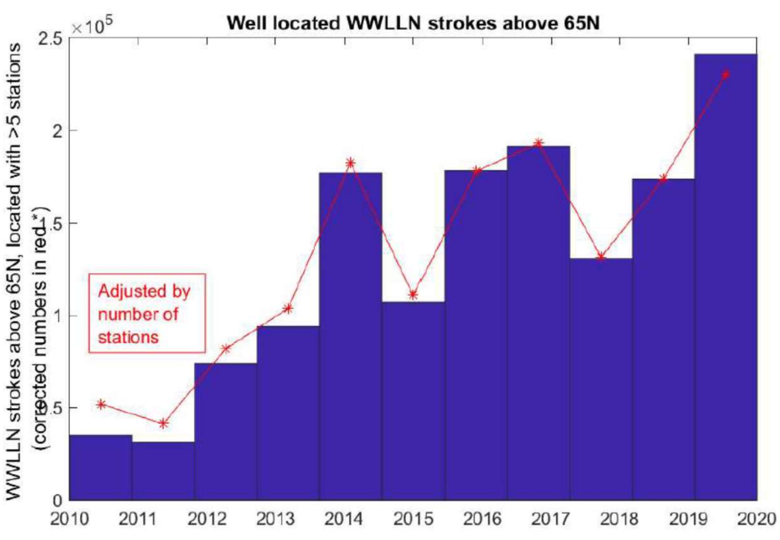

Figure 4. Well located WWLLN strokes above 65N (blue) and the red plot shows the adjustment based on total number of WWLLN stations

(from about 40 to 60 stations, see red line in Figure 2). The red line in Figure 4 is the result of this adjustment due to the increasing

number of WWLLN stations: with the primary effect being only a few tens of percent increases in the first few years. Here one can see that in Figure 4 the adjusted histogram (red line) still indicates a great increase in the number of WWLLN strokes north of 65° latitude over this 11 year period. So, there is no evidence from our growing station locations that the relative number of strokes detected in the Arctic would be favored in any way. In fact one might have expected a reduced ratio in the Arctic, due to increasing total global WWLLN stations, which are all outside the Arctic.

We plot in figure 5 (blue line) the fraction of total global strokes during JJA each year so that the increasing detection efficiency effect is minimized. In this Figure 5 the blue plot refers to the total well located strokes above 65°N normalized by the total number of WWLLN-observed global strokes in that summer time period. Comparing the blue line to the histogram or red line in Figure 4, one can see that the plot strongly reflects the increasing total strokes above 65°N, including the relative dips in 2015 and 2018. Thus Figure 5 is evidence that the fraction of global lightning occurring north of 65°N has increased by over a factor of 3 during this time period (from 0.002 to over 0.006 or 0.2% to 0.6%).

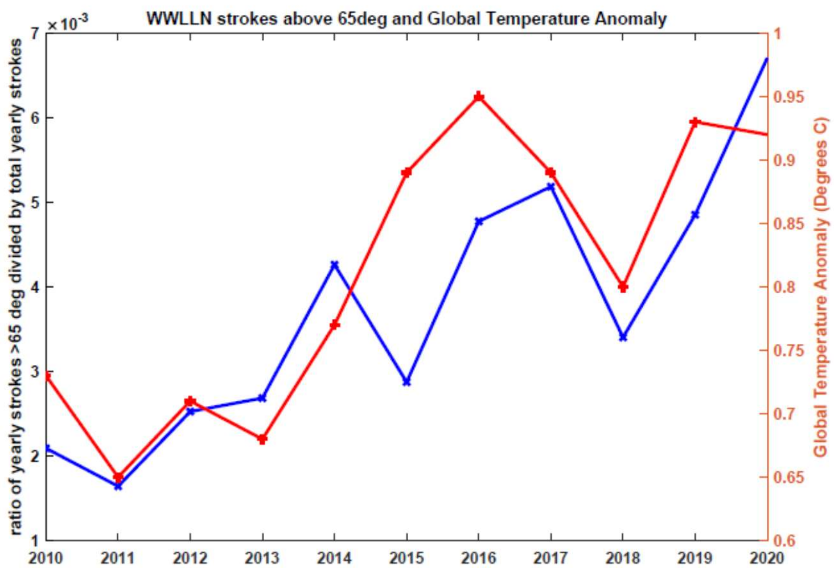

Figure 5. Ratio of the number of WWLLN strokes above 65N to the Total global WWLLN strokes (blue) and the Global Temperature Anomaly in degrees C, for June, July and August each year

Another point to make is that the increase is evident even just looking at the 7 year period from 2014 to 2020 when the WWLLN detection efficiency did not vary by more than 10% (as discussed above). We looked at three 10° latitude bands starting at 45°N and found the same trend in each separate band as shown for all strokes north of 65°N in figure 5 blue line (see Supplemental Material Figure S2 for the latitude bands detail).
Figure 5 also includes the three month (JJA) global temperature anomaly in degrees Celsius reported by NOAA (NOAA report 2020 and Table 1 below). These temperature anomaly data are from the same NOAA data set used in Figure 1. This Figure 5 demonstrates the strong similarity between the fraction of strokes above 65°N and the three month average global summer temperature anomaly for JJA for the 11 year period of the WWLLN stroke data.

There is obviously a correlation between the blue and red plots in Figure 5, which we quantify in Figure 6. At the very least, the two linear trends are consistent. In Figure 6 we see that the linear correlation coefficient is R= 0.802 and R^2=0.644. In this figure we can clearly see the increase in the fraction of total strokes occurring at high latitudes has increased by a factor of 3 during the temperature increase of 0.3 °C in the global 3-month average global temperature anomaly (from 0.65 to 0.95°C). As discussed in the introduction, the evidence and modeling regarding any possible global lightning increase with global temperature is mixed at best. The global WWLLN data in Figure 2 may show a slight upward trend from 2014 to 2020 when there was no clear trend in WWLLN detection efficiency. So, it is possible that total global strokes may indeed increase, but not by much compared to the large increase of Arctic lightning from 2010 to 2020 (as seen in Figure 4).

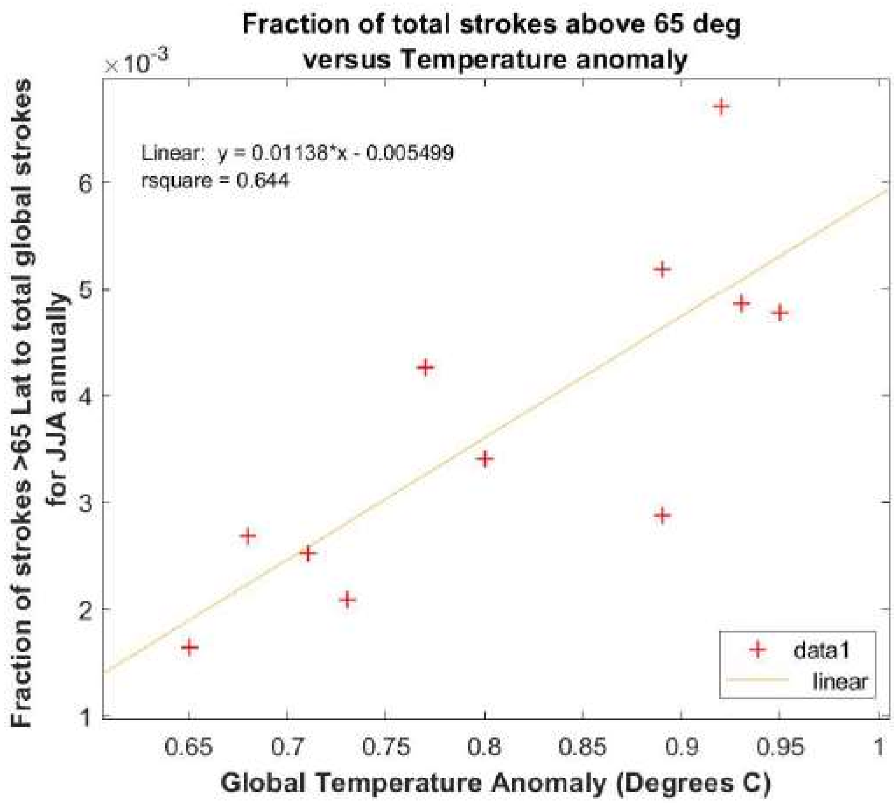

Figure 6. Direct comparison of the fraction of WWLLN strokes above 65N to total WWLLN strokes (Vertical Axis), and the Temperature Anomaly in Degrees C (Horizontal Axis)

To put this in raw terms we could say that if one thinks there are, say, 44 lightning strokes per second globally (e.g. Christian et al, 2003), which would be 0.35×10^9 strokes globally during three months of summer, then we can expect 0.006×350 million strokes = 2.1 million strokes to occur in the Arctic (all in the summer) or about 23,000 every day of JJA. We note that the total global strokes per second is not known from actual measurements from any network or spacecraft data set, but rather is projected from existing global lightning measurements (e.g. Christian et al, 2003). WWLLN has a detection efficiency variously identified as between 10 and 15 percent of all global strokes and currently up to 80% of all strong global lightning (Holzworth et al, 2019) , so we would expect to see 210,000 to 315,000 WWLLN strokes above 65° N every summer. In fact we directly measured 380,000 strokes in 2020 during JJA (the subset of those strokes above 75°N were plotted above in Figure (3).

We can ask what these numbers suggest for future Arctic lightning? We can use the regression line in Figure 6 to look out to a time in the future beginning from the current values in 2019-2020 (where the ratio is 0.0059) and the Temperature anomaly is 0.93ºC. Then, when the global temperature anomaly has increased by just 0.5ºC (to 1.45ºC) , the fraction of strokes in the Arctic (vertical axis figure 6) would increase to 0.011 or about 100% of the current total global lightning. This assumes the total global stroke rate does not change, but if the total global stroke rate increases, while the fraction in the Arctic also increases, then the total net increase in the Arctic could be much more.

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Table 1: Ratio of WWLLN strokes above 65°N and the 3-month summer Global Temperature anomaly

Year	Ratio	Temp Anomaly $^{\circ}$C
2010	0.002092	0.73
2011	0.001643	0.65
2012	0.002526	0.71
2013	0.002685	0.68
2014	0.004262	0.77
2015	0.002874	0.89
2016	0.004774	0.95
2017	0.005185	0.89
2018	0.003404	0.8
2019	0.004853	0.93
2020	0.006707	0.92

Temp Anomaly source (see NOAA, 2020b)