The WGLC global gridded lightning climatology and time series, 2022 update

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Abstract. Here we describe the 2022 update to the ~~WGLC global gridded lightning climatology~~ WWLLN Global gridded Lightning Climatology (WGLC) and timeseries (Kaplan and Lau, 2021), which extends the dataset with global lightning observations from 2021. This addition of new data means that the WGLC now contains 12 complete years of global lightning stroke observations covering 2010-2021. Slightly more lightning strokes (3%) were recorded in 2021 compared to the 2012-2020 mean of 218 million strokes yr^{-1}. In 2021, above-average lightning was recorded around the Gulf of Mexico, the Central Andes and Amazon Basin, West Africa, and over the central Mediterranean. Lower than average lightning density occurred in much of southern and East Africa, subtropical eastern South America, western Australia, and especially over the Straits of Malacca and the South China Sea. Because below-average global lightning was captured by WWLLN in 2010 and 2011 related to the build-out of the sensor network, we reprocessed the WGLC climatologies to cover the 10-year period from 2012-2021 and recommend these for applications needing climatological mean lightning fields. The updated WGLC datasets are available for download from Zenodo (Kaplan and Lau, 2022, https://doi.org/10.5281/zenodo.6007052).

1 Introduction

Global observations of lightning are made with by the World Wide Lightning Location Network (WWLLN) of very low frequency (VLF) radio sensors (http://wwlln.net; Rodger et al., 2004). In 2021, we published gridded fields of lightning density and power based on WWLLN observations for use in Earth System Modeling and other applications that covered the period 2010-2020 (Kaplan and Lau, 2021). This short communication is to document an update to the ~~WGLC~~ WWLLN Global Lightning Climatology (WGLC) gridded products that now includes data from 2021. We also describe the major features of lightning observed in 2021 compared to previous years.

2 Methods

The method for gridding the raw lightning stroke observations made by the WWLLN are described in detail in Kaplan and Lau (2021). We made no changes in this methodology in preparing the data update. Briefly, raw lightning observations are recorded with a latitude, longitude, and timestamp. Geographic data are nominally given with a precision of 10^{-4} decimal degrees, but the actual location accuracy of the WWLLN has been estimated at ca. 3.4 km (Rodger et al., 2005). The time of every lightning
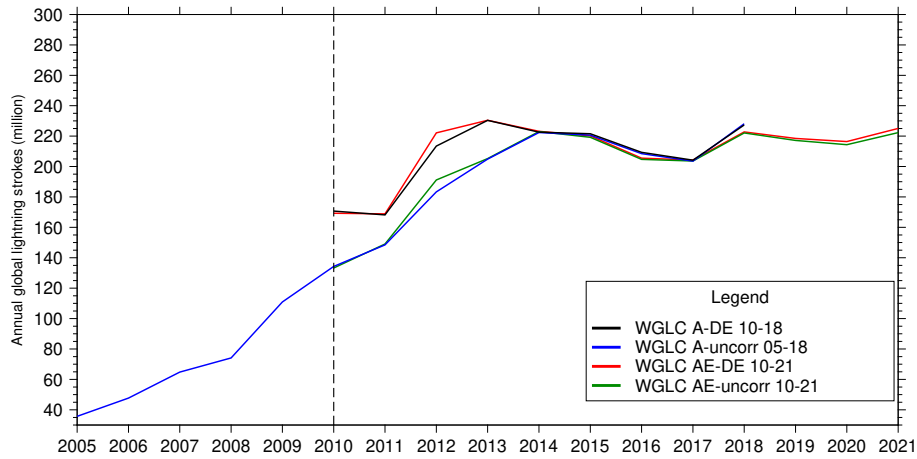
Figure 1. Total global lightning strokes from 2005 to 2021. WWLLN produces two sets of raw lightning stroke data: A (A-raw) and AE (AE-raw). The A-DE and AE-DE curves are adjusted for the WWLLN reported detection efficiency. Detection efficiency and AE data were produced starting in 2010. WWLLN "A" data (A-raw and A-DE) are shown for illustrative purposes and only up to 2018.

stroke is recorded to the nearest microsecond. Individual lightning stroke observations are summed on a geographic grid at the

25 desired spatial resolution (0.5 degree or 5 arc-minute), corrected for WWLLN detection efficiency using hourly gridded fields provided by the network, and aggregated into daily and monthly rasters.

Because below-average global lightning was captured by WWLLN in 2010 and 2011 related to the build-out of the sensor network (Fig. 1), we reprocessed the climatological mean fields for the WGLC to cover the 10-year period from 2012-2021. The WGLC is distributed as monthly timeseries at 0.5 degree and 5 arc-minute resolution, as a daily timeseries at 0.5 degree

30 resolution, and as climatological monthly means at 0.5 degree and 5 arc-minute. The data are distributed in CF-compliant netCDF (version 4) files.

2.1 Results

2.2 Trends in global lightning

Global lightning increased slightly between 2020 and 2021 from 216 to 225 million strokes, and 2021 was among the years

35 with the greatest amount of lightning observed over the past decade (Fig. 1), although not as high as the 230 million strokes recorded in 2013. Between 2012 and 2021, no obvious trend in global lightning strokes is visible in the timeseries that has been adjusted for detection efficiency. Interannual variability ranged from 204 to 230 million strokes ($1\sigma \pm 8.3$ million) over this period. The adjustment for detection efficiency has little effect on lightning observed in 2021, increasing the total by 2.75 million strokes or 1.2%.
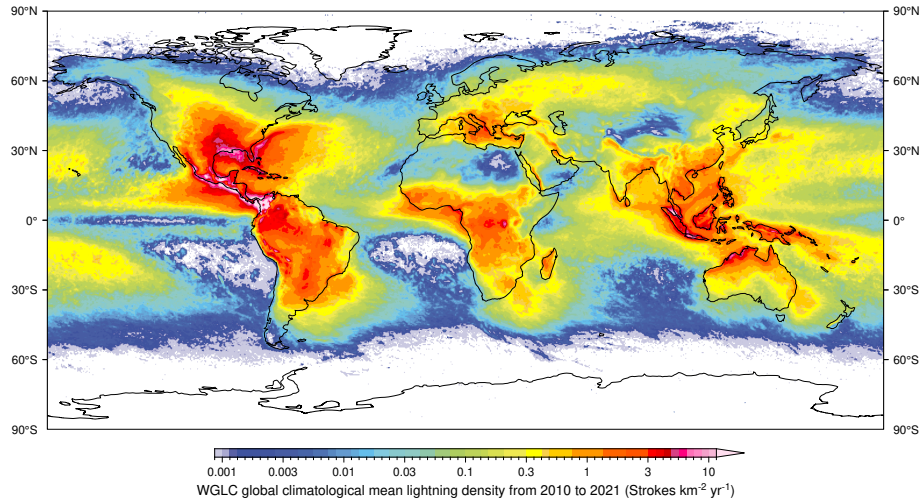
Figure 2. Climatological mean annual lightning stroke density (2012-2021).
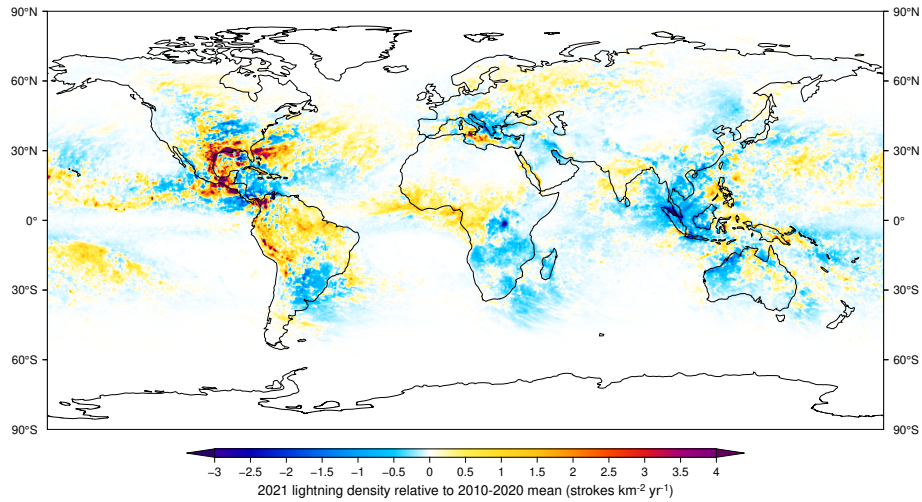
Figure 3. Difference between lightning observed in 2021 and the 2010-2020 climatological mean.

2.3 Lightning observed in 2021

The spatial patterns of the new climatological mean total annual lightning over the ten-year period 2012-2021 differ little from our previous dataset (Fig. 2; Kaplan and Lau, 2021). Lightning is observed over all of Earth's land surface with the exception of the Canadian high Arctic, Greenland, and Antarctica. Lightning is also ubiquitous over the oceans, except in the Arctic, northernmost Pacific, Southern Ocean, and in the subtropical gyres of the Southern Hemisphere. Large amounts of lightning are observed in the tropics and subtropics, particularly over the Americas and in parts of Island Southeast Asia. The greatest
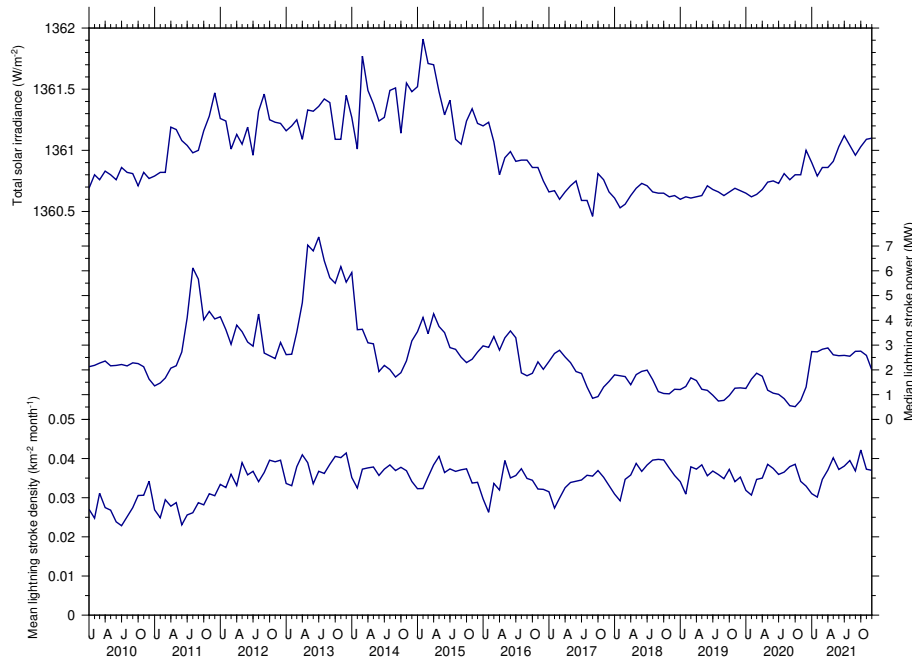
Figure 4. Timeseries of total solar irradiance (TSI; LASP, 2021), monthly median of WGLC global lightning stroke power, and monthly mean global lightning density.

lightning densities are in northwestern South America, Central America, and over the northern Gulf of Mexico and adjacent lands.

Despite the overall similarity in the spatial pattern of climatological mean lightning, there were some differences in 2021 compared to mean over preceding years (Figs. 3, S1). In 2021, more lightning than average was recorded in the Gulf of Mexico and surrounding lands, in the tropical Pacific north and south of the Equator, off the Atlantic coast of the southeastern United States, in southern Mexico and neighboring Central America, in the northern and central part of the Southern America, in the central Mediterranean Sea, and over West Africa, much of India, and the easternmost South China Sea. In contrast, less lightning was recorded in mainland and island Southeast Asia, particularly over the Straits of Malacca, Java, and the South China Sea. Less lightning than average is also apparent in Western Australia, west of Lake Victoria in East Africa and generally across eastern and southern Africa, in southeastern South America, and over the Caribbean Sea (Figs. 3). On a seasonal basis, more lightning strokes were detected over the United States and Central America during Northern Hemisphere summer and autumn (from May to October) and in the western part of the Amazon Basin during Southern Hemisphere summer (from November to February). In contrast, fewer lightning strokes were observed in the Strait of Malacca and northwest Australia from October to March (Fig. S2).

Figure 5. Timeseries of lightning over the major shipping lanes of the Bay of Bengal and South China Sea and adjacent areas (reference regions) following Thornton et al. (2017). The introduction of the IMO sulfur cap is in January 2020 is marked with a dashed line.

60 ## 2.4 Trends in stroke power

In 2021, stroke power increased slightly in comparison with previous years. Figure 4 shows monthly total solar irradiance, median lightning stroke power, and mean lightning stroke density from 2010 to 2021. Median stroke power shows substantial seasonal and interannual variability in the past decade, with a gradual decrease from a peak in March 2013 until the end of 2020. In 2021, mean annual median stroke power ranged between 2.0 and 2.8 MW throughout the year, a ca. 1 MW increase
65 over stroke power observed between 2017 and 2020. The geographic distribution of stroke power in 2021 was similar to that observed in previous years.

3 Discussion and Conclusions

We suggested previously that temporal trend in lightning stroke power could be related to total solar irradiance (TSI; Kaplan and Lau, 2021) and previous studies have suggested that there could be physical mechanisms linking lightning and the solar flux (Okike and Umahi, 2019; C
70 . The 2021 ~~saw substantial~~ lightning data do show a modest increase in median stroke power relative to the past few years, concomitant with increasing TSI in Solar Cycle 25 that started in early 2020. This increase in stroke power is intriguing, but it will likely take several more years of observations of both TSI and lightning to demonstrate an unequivocal link between these quantities.

The reductions in lightning over the Straits of Malacca and the South China Sea in 2021 compared to the 2010-2020 climatological mean (Fig. 3) are one of the most obvious features of the updated dataset. These major sea lanes in Southeast Asia have been recognized as lightning hotspots because aerosol emissions from shipping enhance convection and therefore lightning (Thornton et al., 2017). Analysis of the timeseries of lightning in and around the major Southeast Asian shipping lanes (Fig. 5) shows a general reduction in lightning over shipping lanes of the South China Sea since 2019 while lightning in the reference regions changed little; in the Indian Ocean the trend is less clear although there seems to be some more convergence between lightning density in the shipping lanes and neighboring clean-air regions from 2018. Thornton et al. (2017) showed long-term trends of increasing lightning in the shipping lanes that we can now see were clearly an artifact of the growing detection efficiency of the WWLLN in the early part of the first decade of the 21st century (Fig. 1.

Despite the ongoing COVID-19 pandemic, there is no indication that maritime trade decreased in 2021 relative to previous years (UNCTAD, 2021). On the other hand, the International Maritime Organization's Global Sulfur Cap (IMO 2020) came into force in 2020, limiting marine bunker fuel to a sulfur content of 0.5%. Several recent studies suggested that these new fuel standards would lead to significant reductions in marine PM2.5 emissions, particularly in East and Southeast Asia (Wang et al., 2021; Zhang et al., 2021; Sofiev et al., 2018). In addition to improving air quality, these new fuel standards may also have reduced the frequency of lightning, thereby presenting an additional benefit in terms of reduced hazards.

On the other hand, anomalously low lightning in southern Brazil, Uruguay, and northeastern Argentina, eastern and southern Africa, and Western Australia do not appear to be obviously related to transportation or industrial activity, although there is some indication that the ongoing COVID-19 pandemic may have led to reductions in pollution and therefore lightning (Liu et al., 2021). India , which was also severely affected by COVID-19, . India had greater-than-average lightning in 2021. These anomalies could are likely be related to changes in precipitation patterns or interannual variability in precipitation and other climatic factors, and deserve further study that is beyond the scope of this short communication.

We suggested previously that temporal trend in lightning stroke power could be related to total solar irradiance (TSI; Kaplan and Lau, 202 . The 2021 lightning data do show an increase in median stroke power over the past few years, concomitant with increasing TSI in Solar Cycle 25 that started in early 2020. This increase in stroke power is intriguing, but it will likely take several more years of observation of both TSI and lightning to demonstrate an unequivocal link between these quantities Although there is some indication that the ongoing COVID-19 pandemic may have led to reductions in pollution and therefore lightning (Liu et al., 2021), superficial examination of the WGLC does not reveal any immediately obvious correlations.

This 2022 update of the dataset WGLC demonstrates several features that underscore the utility of the WGLCdataset. The WWLLN network, at least after applying a detection efficiency correction, shows no long term trend in the number of lightning strokes recorded since 2012, and we now have ten years of quality lightning observations with which to construct global climatologies. The WGLC shows that lightning is detected worldwide, even in places with very low density including the Arctic and over the oceans. These data are useful for a range of purposes, including studies on air quality, With the availability of a decade of lightning data in the WGLC available in two spatial and three temporal resolutions, we may revisit the drivers of interannual variability in lightning summarized by Murray et al. (2012). A range of further studies could be performed in the future, even regionally, to investigate the role of climate variability and change, aerosol emissions, solar and cosmic radiation

on lightning density and stroke power. Such studies would be valuable from a risk management perspective, and add value
to a range of research that depends on the patterns and variability in lightning, including wildfire ignitions and the chemical
composition of the atmosphere~~, and wildfire ignitions~~. The WGLC is free to download and will continue to be updated annually
in the future.

4 Code availability

The code used for gridding the raw stroke counts, and progressive updates to the gridded data, are archived at https://github.com/ARVE-Research/WGLC.

5 Data availability

The WGLC gridded lightning density and power fields are distributed as a timeseries at daily and monthly resolution and as
a climatological monthly mean. The data are stored in netCDF format and are archived with Zenodo (Kaplan and Lau, 2022,
https://doi.org/10.5281/zenodo.6007052).

Author contributions. JOK conceived the datasets and developed the gridding process, and oversaw the evaluation. KHKL performed the
data preprocessing and gridding, and prepared the visualizations. Both authors contributed to writing the manuscript.

Competing interests. The authors declare that they have no competing interests.

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