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**Augmentation of a Global Dataset on Station Thunder Days**

1. **Introduction**

This memorandum is concerned with the worldwide documentation of thunder days as a standard meteorological observation. The definition of a thunder day is a day with thunder heard. Such observations have been underway in a systematic fashion since the 19th century (Brooks, 1925). The World Meteorological Organization (WMO) has twice played a key role as organizer of these global observations. Now that lightning has been recognized as Essential Climate Variable (ECV) by the Global Climate Observing System (GCOS) (Aich et al., 2018), , thunder days may serve a special purpose, and a third opportunity arises here for WMO as organizer.

Thunder days are a measure of lightning activity and such activity has been shown to be responsive to two recognized climate variables: surface air temperature and boundary layer aerosol. Evidence for the responsiveness of lightning to temperature has been demonstrated on several natural time scales: the diurnal (Price, 1993; Bailey et al., 2007; Markson, 2003; 2007; Markson and Price, 1999; Williams, 1999; Virts et al., 2013; Blakeslee et al., 2014)), the semiannual time scale (Williams, 1994; Füllekrug and Fraser-Smith, 1996), the annual time scale (Williams, 1994; Adlerman and Williams, 1996; Christian et al., 2003; Blakeslee et al., 2014) and the ENSO (El Nino Southern Oscillation) time scale (Williams, 1992; Hamid et al., 2001; Yoshida et al. 2007; Satori et al., 2009). Model calculations also suggest greater lightning in a warmer climate (Romps et al., 2014). In contrast to these broadly accepted theory of increasing lightning activity under global warming, a recent study projected a decrease of lightning due to a decrease of cloud ice content (Finney et al. 2018). In addition, the evidence for lightning response on the 11-year solar cycle time scale is conflicting (Brooks, 1934; Kleymenova, 1967; Fischer and Mühleisen, 1972; Christian et al., 2013; Pinto et al., 2013) and deserves further attention. An increasing body of evidence has shown that convective vigor and lightning activity are also enhanced by richer concentrations of cloud condensation nuclei (Rosenfeld et al., 2008; Bell et al., 2009; Mansell and Ziegler, 2013; Stolz et al., 2015; 2017; Altaratz et al., 2017; Thornton et al., 2017; Fan et al., 2018).

1. **Brief History of Thunder Days**

The “thunder day” was defined as a standard meteorological unit by the International Meteorological Committee in Vienna in 1873, and was further characterized with a symbol ‘T’ in Paris in 1896. Measurements of the Earth’ electric field over the oceans (Mauchly, 1923) and the emergence of a global signal in universal time, let to C.T.R. Wilson’s (1920) hypothesis for the global electrical circuit, maintained by the integrated contribution of electrified weather worldwide.. This development motivated Brooks (1925) in turn to make the first assessment of the global thunderstorm activity. A large dataset of 3265 surface stations with thunder day observations became the basis for the cornerstone of atmospheric electricity (Whipple, 1929; Whipple and Scrase, 1936). The recognized value of thunder days to mainstream meteorology led the WMO to assemble 3840 station data from 190 countries to produce a global monthly climatology (WMO, 1953, Part I), including global maps (Part II).

A second key WMO contribution toward an organized multi-station time series of thunder day data was facilitated by their collaboration with the United State Air Force in 1972 on the GSOD (Global Surface Observation of the Day) dataset (<ftp://ftp.ncdc.noaa.gov/pub/data/gsod> ); This compilation had new applicability to climate studies as it extends the global thunderstorm record back many decades before any lightning network observations are available.

Figure 1shows the evolution of archived station data in GSOD over the pull period of the dataset. In recent years, the number of stations reporting is greater than the station counts used to compute the global mean temperature (e.g., Hansen and Lebedeff, 1987). Evidently GSOD focused on archival going forward from the time of its inception, but little effort was devoted to collecting the station archives on thunder days from the period prior to 1972. Some enhancement of station collection occurred in the decade of the 1953 WMO report, but earlier data are scarce, and no data are in hand prior to 1929, when the existence of archived thunder day data are well documented. We have abundant evidence however that these data (Brooks, 1925) exist in the meteorological archives of individual countries.

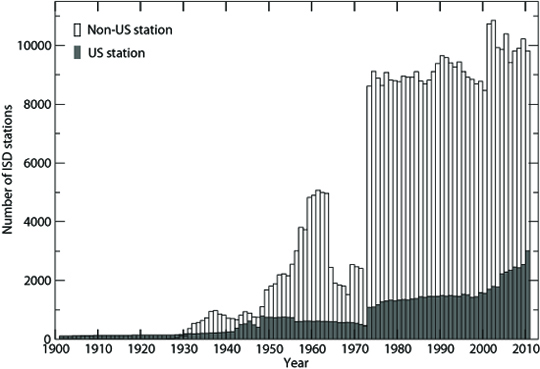


Figure 1: Number of reporting stations versus time for thunder days in the GSOD data set, established in 1972.

Beginning in the late 1990s, automatic weather stations came into widespread use, with a consequent reduction in the number of human observers in national weather services. This situation has led to a reduction in the number of stations reporting thunder days, though all airport stations worldwide continue the original practice.

1. **Comparisons with Modern Satellite Observations of Global Lightning Activity**

The continuous observation of global lightning activity is a desirable goal from the climate perspective (Williams, 2005) but has not yet been achieved. The optical observations of lightning from Low Earth Orbit are sufficient however to document the climatological variation of global lightning on the diurnal and seasonal time scales for which systematic global temperature variations are also present. The reliability of thunder days as a proxy for worldwide lightning activity can be judged by its behavior on natural time scales. The evidence for agreement on the diurnal time scale comes from the classical work on the global electrical circuit by Brooks (1925), Whipple (1929) and Whipple and Scrase (1936), in comparison with the modern satellite observations of Bailey et al. (2007) and Blakeslee et al. (2014). Comparisons on the seasonal time scale consist of calculations with the gridded WMO (1953) climatology (Williams, 1994) and comparisons with satellite optical observations in Christian et al. (2003). The semiannual variation is clearly present in both climatologies, when the near equatorial zone is examined. For the annual variation, the tendency for greater thunder day activity in NH summer is apparent, but the summertime maximum (August) is not evident in thunder day climatology (Williams, 1994). A possible explanation is that the number of flashes per thunder day in summer is greater in the baroclinic regions at higher latitude than in the quasi-barotropic region of the near equatorial region. This suggestion can be checked with Lightning Imaging Sensor and Optical Transient Detector (LIS/OTD) observations.

1. **Scientific Use of Thunder Day Observations**

Thunder day observations have been used extensively for the investigation of regional trends, for example in Australia (Kuleshov et al., 2002), in the Baltic countries (Enno et al., 2014), in Ontario, Canada (Huryn et al., 2016), in China (Chen et al., 2004; Wei et al., 2011), in Finland (Tuomi and Mäkelä, 2008), in Germany (Kunz et al., 2009), in Iran (Khalesi, 2014; Araghi et al., 2016; Ghavidel et al., 2017), in Nigeria (Ologunorisa and Chinago, 2004), in Poland (Bielec-Bakowska, 2003; Bielec-Bakowska and Lupikaza, 2009), in Russia (Garbatenko and Dulzon, 2001; Adzhiev and Adzhieva, 2009), in Alaska (Williams, 2009) and in the continental United States (Changnon and Hsu, 1984; Changnon, 1985; Changnon and Changnon, 2001). Correlated trends between thunder days and surface air temperature provide evidence for urban warming (Pinto, 2009; Pinto et al., 2013), as well as possible aerosol effects. ENSO variations in thunder day records, possibly linked with variations in both temperature and aerosol, have been considered by Pinto et al. (2015) in Brazil and by Kulkarni et al. (2015) in India. Brooks (1934), Kleymenova (1967), Fischer and Mühleisen, 1972; and Pinto et al. (2013) have all searched for the 11-year solar cycle in thunder day records of exceptional length, with varying success. Long-term increases in thunder days at stations on the Sea of Japan (Yamamoto et al., 2016) have been shown to accompany long-term increases in sea surface temperature there. Previously published thunder day observations in the USA by Changnon and Hsu (1984) and Changnon (1985)and by Gorbatenko and Dulzon (2001) overlap with the “big hiatus” in global warming in the period 1940 to 1976, and show flat or declining behavior, consistent with the behavior of global temperature (Williams et al., 2018). The global temperature has been shown to vary by 0.1 oC (peak-to-peak) on the 11-year solar cycle time scale (Camp and Tung, 2007; Tung and Camp, 2008; Zhou and Tung, 2013), substantially smaller than the temperature variations on the other natural time scales discussed previously (all on the order of 1 oC). All these latter studies have clear implications for climate change and global warming. The nature of scientific investigations involving thunder days can expand to global scale once a sufficiently long record at stations as numerous as those used for climatological studies (Brooks, 1925; WMO, 1953) is assembled from presently separate archives. This action also speaks to the need raised by Holzworth and Volland (1986) for a global geoelectric index, but for decades gone by. A resolution in such an archive at monthly time scale would fulfill many needs for climate studies (ENSO, 11-year solar cycle time scale, global warming), but a continuation of the practice in the GSOD dataset with daily/hourly resolution is certainly desirable.

1. **Recommendation for the WMO**

Large numbers of thunder day observations remain in the local data archives of thousands of meteorological stations worldwide (or in the respective government archives of the parent countries). Figure 1 shows evidence that these data missing from the GSOD archive are most prevalent in the period prior to 1972. Many of the observations prior to 1925 may be found in numerous references listed in Brooks (1925). A more comprehensive data collection would enable a number of climate investigations pertaining to lightning and thunderstorms that are not possible with relatively short-lived lightning network observations. A global trend analysis could be undertaken with a station total equal to or exceeding the count used to estimate the global mean temperature (e.g., Hansen and Lebedeff, 1987).

The main recommendation on the table is that the WMO engage with the thunder day issue a third time toward augmenting the global GSOD dataset on thunder days that they helped initiate in 1972.

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