When Is A Dust Storm Not A Dust Storm: Examining the Reliability of the Storm Events Database for Assessing the Incidence of Dust Storms in the USA

Karin Ardon-Dryer[1], Thomas E. Gill[2], and Daniel Tong[3]

[1]Texas Tech University
[2]University of Texas at El Paso
[3]George Mason University

November 22, 2022

Abstract

Dust is a meteorological phenomenon that has a strong impact on the environment, air quality, and human health. In the USA one of the most widely used databases of information on dust events is the Storm Events Database (SED). This project aims to examine the reliability and usefulness of the SED as a source for documenting the climatology of dust storms (DS) across the USA. While SED provides information potentially useful for understanding the frequency, distribution, and importance of DS across the USA, our analysis of DS from 2000 to 2020 shows that many DS were missing while some recorded events of less severe blowing dust (BLDU) in the SED were incorrectly reported as DS. Although the dust records from SED have been widely utilized to study dust related physical and societal issues, the limitations found in this study need to be taken into consideration in future studies.

Supplement

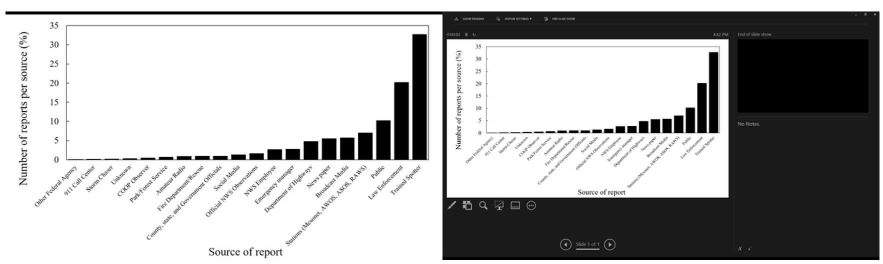

Figure S1. The frequency of each of the sources reported dust storm events in the storm database.

When Is A Dust Storm Not A Dust Storm: Examining the Reliability of the Storm Events Database for Assessing the Incidence of Dust Storms in the USA

K. Ardon-Dryer[1], T. E. Gill[2], and D. Q. Tong[3]

[1] Department of Geosciences, Texas Tech University, Lubbock TX, USA 79409
[2]Department of Earth, Environmental and Resource Sciences, The University of Texas at El Paso, El Paso, TX, USA 79968
[3]Department of Atmospheric, Oceanic and Earth Sciences / Center for Spatial Information Science and Systems, George Mason University, Fairfax, VA, USA 22030

Corresponding author: Karin Ardon-Dryer (karin.ardon-dryer@ttu.edu)

Key Points:

- Storm Events Database used as a database for significant weather across the USA is lacking many dust storm events.
- The dust storm database from the Storm Events Database contains many blowing dust events that should not be reported as dust storms.
- There is a need for a new database of dust events, that will include all levels of dust events (including blowing dust and dust storms).

Abstract

Dust is a meteorological phenomenon that has a strong impact on the environment, air quality, and human health. In the USA one of the most widely used databases of information on dust events is the Storm Events Database (SED). This project aims to examine the reliability and usefulness of the SED as a source for documenting the climatology of dust storms (DS) across the USA. While SED provides information potentially useful for understanding the frequency, distribution, and importance of DS across the USA, our analysis of DS from 2000 to 2020 shows that many DS were missing while some recorded events of less severe blowing dust (BLDU) in the SED were incorrectly reported as DS. Although the dust records from SED have been widely utilized to study dust related physical and societal issues, the limitations found in this study need to be taken into consideration in future studies.

Plain Language Summary

Dust is a weather phenomenon that has a strong impact on the environment, air quality, and human health. In the USA one of the widely used databases of dust events is the Storm Data publication and associated Storm Events Database (SED). This project aimed to examine the reliability and usefulness of the SED as a source for documenting the climatology dust storms (DS) across the USA. While this SED provides information potentially useful for understanding the frequency, distribution, and importance of DS across the USA, our analysis of DS from 2000 to 2020 shows that it is lacking many DS events, and that it contains events that should not have been reported as DS. Although this is the only existing dust database available for the USA as a whole, the issues found in this study hinder its efficiency, accuracy, and reliability.

1 Introduction

Atmospheric dust is a meteorological phenomenon caused by wind erosion of soil/sediment or suspension of particles from the land surface into the air by mechanical means (Goudie, 2014; Middleton, 2017). Dust is one of the most important natural contributors to atmospheric particulate matter (PM) (Shahsavani et al., 2012; Kelley et al., 2020; Ardon-Dryer et al., 2021). The increase of dust particles during dust events can affect solar radiation by absorbing and scattering the sun's radiation (Haywood et al., 2003), influence cloud formation (Bangert et al., 2012; Ardon-Dryer and Levin, 2014), have detrimental effects on the global economy (Tozer and Leys, 2013), as well as impacts on human well-being, safety, and health (Goudie, 2014; Ardon-Dryer et al., 2020).

According to the World Meteorological Organization (WMO), a Dust Storm (DS) is defined when the visibility is reduced by dust in the air to less than 1 km (UNEP, 2016; WMO, 2019). The USA Department of Transportation Federal Aviation Administration (FAA), based on guidance provided by the WMO, also uses the same guidelines (FAA, 2022). Operational weather warning in the USA National Weather Service (NWS) adopts more stringent criteria of visibility of 0.4 km (¼ mile) or less to report or warn of a DS (NWS, 2022a). Blowing dust (BLDU) or widespread dust (DU) is reported by the NWS (OFCM, 1995) as a less severe dust event characterized by airborne dust with higher visibility values up to 11.3 km (7 miles). In the 1990s and early 2000s, human weather observers in the USA were largely replaced by Automated Surface Observing Stations (ASOS). The ASOS system sometimes reports aerosol-related visibility degradation including dust simply as "haze" (HZ) (Bernier, 1995; Kelley and Ardon-

Dryer, 2021), defined by the NWS as aggregation in the atmosphere of very fine, widely dispersed, solid or liquid particles, or both, giving the air an opalescent appearance that subdues colors (Lee et al., 2012).

Since 1950, NOAA's National Center for Environmental Information (NCEI) and its predecessors have maintained the Storm Events Database (SED), used to populate an official publication titled Storm Data (NCEI, 2022). According to NCEI, the SED includes data on the occurrence of storms and other significant weather phenomena having sufficient intensity to cause loss of life, injuries, significant property damage, and/or disruption to commerce. Rare, unusual, weather phenomena that generate media attention, such as snow flurries in South Florida or the San Diego coastal area are also included in the SED. Other significant meteorological events, such as record maximum or minimum temperatures or precipitation that occur in connection with another event, may also be included. The most recent NWS instruction includes a category of events in SED called Dust Storm which is defined as strong winds over dry ground, with little or no vegetation, that lift particles of dust or sand, reducing visibility below locally/regionally established values (usually ¼ mile or less), which could result in a fatality, injury, damage, or major disruption of transportation. If the event that occurred is considered significant, even though it affected a small area, it should be entered into the database (NWS, 2022b).

Previous studies have used various data records to examine the distribution of observed dust events across the USA and its dust-prone regions (Orgill and Sehmel, 1976; Tong et al., 2012; Rublee et al., 2020). Some focused on one site or a region (Nickling and Brazel, 1984: Lee and Tchakerian, 1995; Bach et al., 1996; Godon and Todhunter, 1998; Bernier et al., 1998; Novlan et al., 2007; Hahnenberger and Nicoll, 2012; Lei et al., 2016; Kelley and Ardon-Dryer, 2021), while others examine larger areas such as the Western USA as a whole (Lei and Wang, 2014; Eagar et al., 2017) or the entire nation (Orgill and Sehmel, 1976; Rublee et al., 2020). Two studies that examined dust events across the entire USA used different methods. The first one (Orgill and Sehmel, 1976) analyzed dust events from 1940 to 1970 based on measurements of visibility from 340 weather stations across the USA, but since this study was performed there have been changes in agricultural practices including the use of mitigation practices (Osmond and Line, 2017; U.S. EPA, 2021), that have possibly changed the distribution of dust events and may not reflect the current spatial or temporal changes of dust across the US. Orgill and Sehmel (1976)'s paper includes the term "dust storms" in the title but was based on hourly weather observations from stations recording dust, blowing dust, and blowing sand when visibility was 11.3 km (7 miles) or less, not consistent with current DS criteria. The second study by Rublee et al. (2020) presented the frequency of DS across the USA based on DS reported in SED from 1995 to 2017. They indicated that they found 967 DS events in the years 1996–2017 and 819 DS events in the years 2000–2015.

There appears to be a lack of consistent definitions and reporting of "dust storm" and of dust weather in general in the USA, and consistent definitions have not been used by those investigating the climatology of dust weather across the USA, potentially limiting the inter-comparability of these and other studies to each other and to analyses of dust occurrence in other nations. What is more, SED has been widely used by researchers in fields outside atmospheric science to investigate correlations between (SED-reported) "dust storms" in the USA and factors including mortality (Crooks et al., 2016), intensive care unit admissions (Rublee et al., 2020), the incidence of Valley fever (Comrie, 2021), violent crime (Jones, 2022), and as a GIS layer in modeling wind erodibility (Wagner and Casuccio, 2014).

Australian scientists (O'Loingsigh et al., 2010) have also detected inconsistent, incorrect, and incomplete reporting and coding of dust events of all kinds in their nation's weather reporting system, leading to limitations in the use of such data for research purposes, such as a 15.2% undercount of dust-storm days in the Lake Eyre Basin and discrepancies exceeding 30% at individual stations. In response to these discrepancies in recording of dust observations, O'Loingsigh et al. (2010) stated, "Questions arise as to how other WMO affiliated meteorological agencies around the world have handled their weather phenomena data…" and "Many studies both in Australia and worldwide make use of the WMO SYNOP weather codes but very few question the manner in which these codes are recorded, and therefore are unaware of how this might impact their research."

With these apparent discrepancies in dust reporting in mind, and particularly aware of how studies have used DS from SED to ascribe relationships between "dust storms" and sociological and health effects, we were motivated to make a preliminary examination of dust records in these widely-used databases to test their accuracy.

2 Materials and Methods

The SED, maintained by the NCEI, lists all reported severe or damaging meteorological events that occur across the USA including thunderstorms, tornadoes, hurricanes, derechos, winter storms, flash and river floods, hail, heavy rain, heat and cold waves, dust storms and many others. The database also included events that were associated with deaths, injuries, and material (properties and crops) losses. The SED data are gathered in several ways. One way is by using the NWS storm report logs. These reports are usually gathered during the event, but sometimes a few days late reports are received. SED data come from many sources including agency/official personnel including law enforcement and government officials, emergency management officials, departments of highways, NWS damage surveys or employees, trained spotters, and official meteorological station reports, as well as from the public including broadcast media, newspapers, and social media (NCEI, 2022). In this study, DS reports from the SED were downloaded as CSV files for all USA states (not including Alaska and Hawaii) from January 1, 2000, to December 31, 2020. All DS events were reported in local time.

To examine in-depth "dust storms" reported in the SED for selected locations (Lubbock Texas, several sites in Utah including Salt Lake City), records from the Meteorological Aerodrome Reports (METARs) that provide hourly meteorological measurements (e.g., visibility and present weather code) collected by the ASOS were used. Observations of dust events were based on the method used in Kelley and Ardon-Dryer (2021).

3 Results and discussion

3.1 Temporal variations of dust storms

A total of 1167 DS reports were identified from the SED from January 1, 2000, to December 31, 2020. The highest number of reports was for Arizona with a total of 480 DS reports while only one DS event was reported for the states of Delaware, Indiana, Missouri, and Wisconsin. In most cases, there was only a single report per day, but there were many with multiple reports of a single event (from multiple sources). As an example, the highest number of reports for one DS event was on February 24, 2001, in Oklahoma which had a total of 29 different reports from various sources and different counties. This creates an oversampling issue that becomes problematic if this dataset is used to derive long-term dust trends.

To make sure an event was not reported multiple times, DS reports, for each state (combining reports from multiple counties and sources per event), were combined to represent a single event per state (one day). In some cases, six days in total, two different DS were reported with several hours gap between them. In these cases, DS was counted as two separate events. The start and end times of each event per state were recorded and combined per event.

After removing multiple reports of the same event, a total of 647 DS events were reported in the SED from 2000 to 2020 across the USA. The number of annual DS reports ranged from 12 (in 2008) to 53 events (in 2018) (Figure 1a). No strong trend was found for the annual DS reports (R2 was 0.32) but an increase in the overall number of DS reported was observed (slope was 1.02). A bimodal distribution was observed for the monthly distribution (Figure 1b) with one peak in April, with 81 DS events, and another stronger peak in July and August with 112 and 98 DS reports, respectively. Most of the DS were reported between 12:00 to 18:00 local time, the highest number of reports (12%) was at 18:00 (Figure 1c). Most of the DS events (30%) reported lasted an hour or less (Figure 1d).

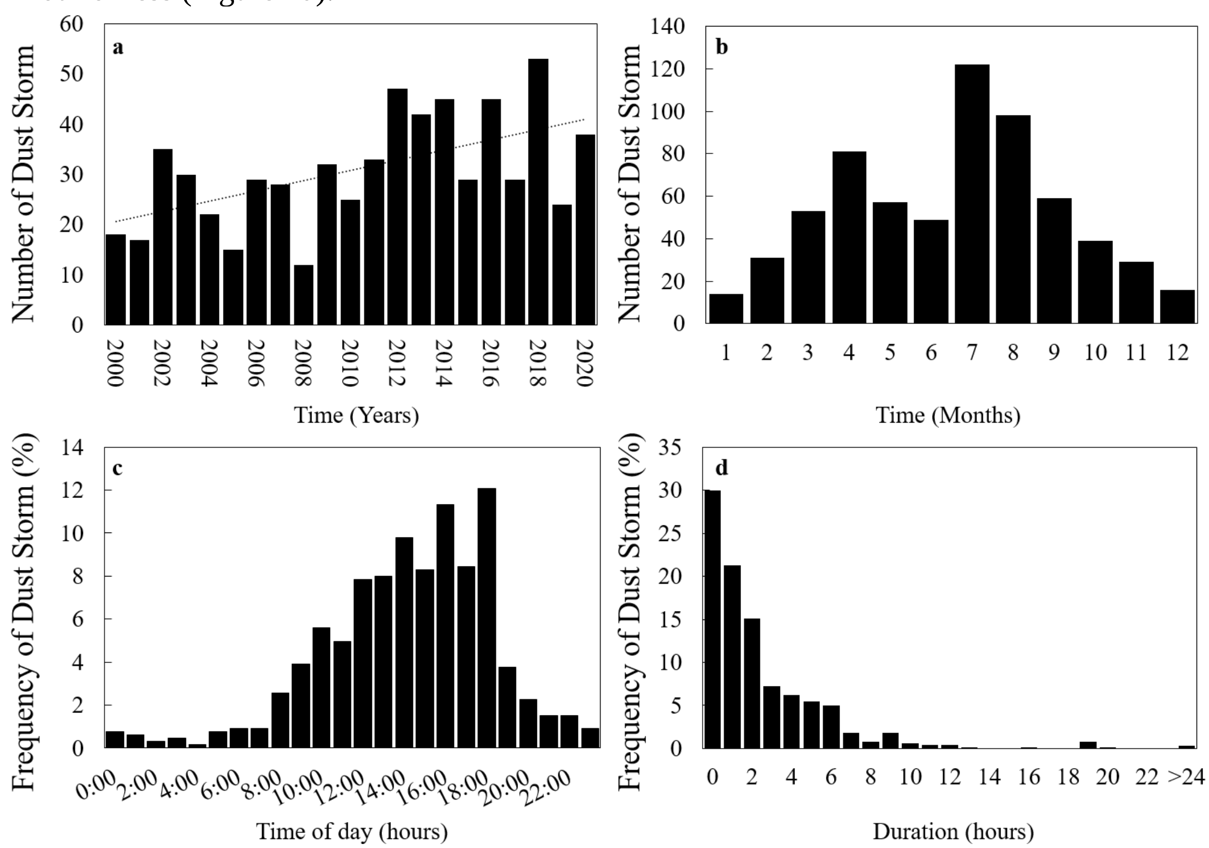

Figure 1. Temporal distribution and duration of dust storm events in the Contiguous United States: (a) yearly distribution; (b) monthly distribution; (c) time of day, and (d) duration, as reported in the Storm Events Database.

3.2 Spatial variations of dust storms

A total of 21 states had reports of DS in the SED (Figure 2a). Some states (11 in total) had less than 10 DS reports, while others (10 in total) had multiple reports ranging from 10 (Oregon) to 287 (Arizona) in total. While a majority of the reports are in the western part of the country, several states in the central (e.g., Wisconsin, Indiana, and Illinois) or eastern (e.g., Delaware) part of the USA had also reports of DS. Next, we looked at the monthly distribution of DS reports in states that had more than 20 DS reports in total (Figure 2b). Monthly distribution showed that different states had a higher frequency of DS in the summer while others were in the spring.

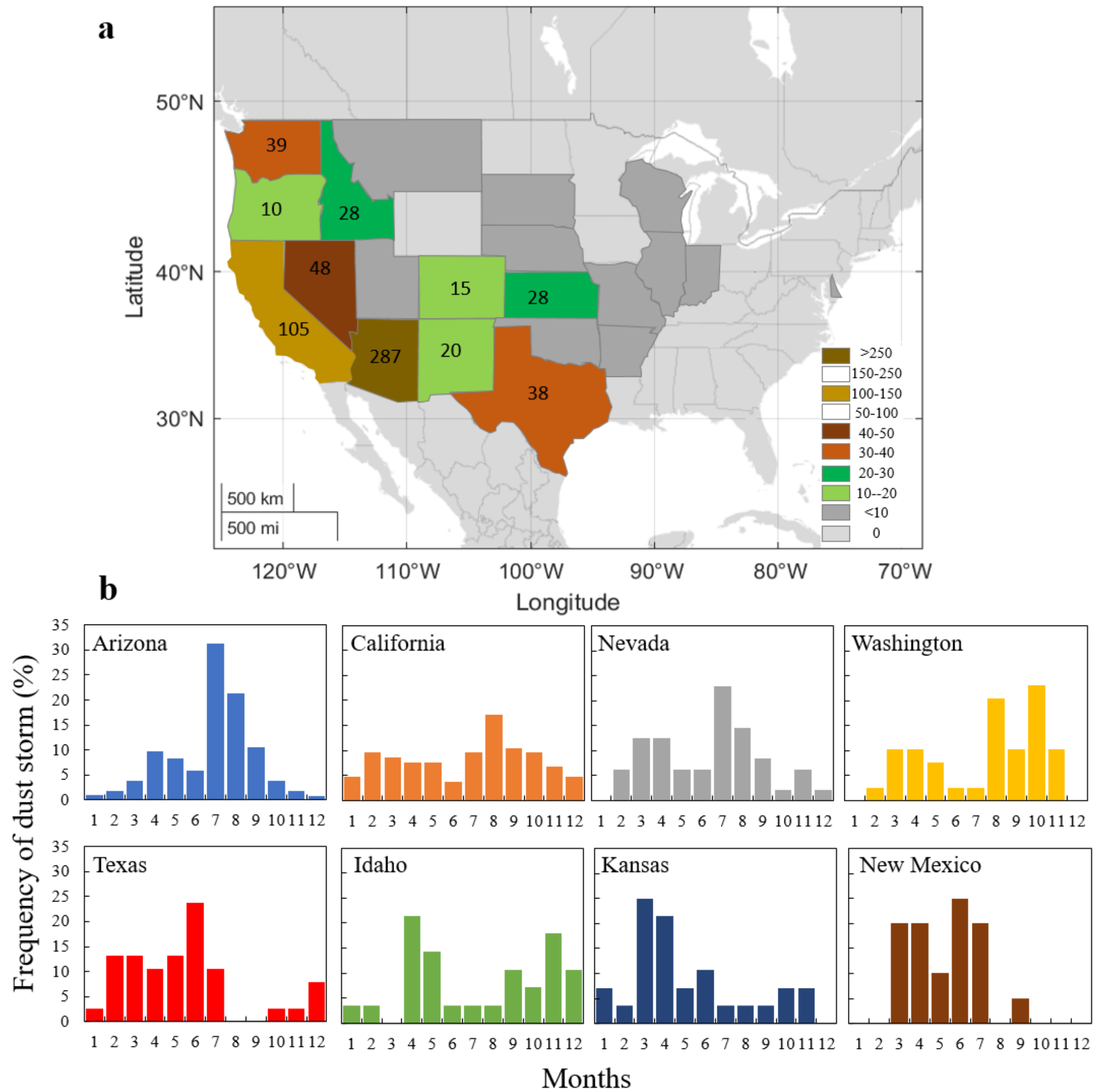

Figure 2: Distribution of dust storm events (after removing duplicated reports) per state, color indicates the number of DS reports (a). Monthly distribution of the dust storm events per state as reported in the SED, for states that had more than 20 DS reports in total (b).

3.3 Economic costs and Fatalities/Injuries reported from dust storms

The SED is known to be one of the most commonly used data sources that examine hazard losses (Black and Mote, 2015). According to the SED guidance (NWS, 2022b), Direct

Fatalities/Injuries resulting from DS would be people who were asphyxiated due to high dust/sand content in the air (rare), people who were hit by flying debris, fatalities, and injuries resulting from a vehicle being tipped/pushed over or blown off a road by the strong winds, resulting in an accident and associated fatalities/injuries. Indirect fatalities/injuries from DS would be caused by vehicular accidents caused by reduced visibility during a dust storm or by debris left on a road after a dust storm passed.

Since the SED provided information on DS events that were associated with deaths, injuries, and material losses (properties and crops), an examination of the reported number of deaths and injuries (direct and indirect), as well as property and crop losses, was performed (Table 1). The highest number of deaths (12) were reported in 2009, with 5 direct and 7 indirect deaths. The highest number of injuries (71 all direct) were reported in 2003. The property losses ranged from 0 in 2008, which had the lowest number of DS that year, to $2,290,000 in 2013 which had 42 DS reports (but not the year of greatest number of reports). No strong correlation (low R2 values) was found between the total number of DS per year to the number of death, injuries, or material losses, but an increase in slope was observed (data not shown). It should be noted that less than 7% of the DS events had reports of injuries, while less than 3% had reports of deaths. We also noticed that some DS events had in the episode narrative, which is part of the database, reports of injuries (e.g., "One motorist was injured in a weather related accident along U.S. Highway 84 in Garza County"), but no reports (counts) of injuries were provided in the database in the categories for direct or indirect injuries. The episode narrative also reports damages (e.g., "Damages were estimated to exceed $350,000 across the region") but no monetary valuation was provided for the material losses.

Table 1. Annual number of dust events, Death, and Injuries (direct and indirect) as well as Property Losses, and Crop Losses based on dust storm database.

Year	Number of events	Direct Injuries	Indirect Injuries	Direct Death	Indirect Death	Damage to Properties	Damage to Crops
2000	18	29		1		$190,000	
2001	18	5				$180,000	
2002	35	45		2		$427,000	
2003	30	71		2		$284,000	
2004	22	11				$80,000	
2005	15	32				$70,000	
2006	29	22		2		$690,000	$2,250,000
2007	28	4	3		2	$950,000	
2008	12						
2009	32		56	5	7	$760,000	$5,000,000
2010	25		7		1	$140,000	
2011	33	4	50		2	$848,000	
2012	47		35		1	$1,450,000	
2013	42		68		6	$2,290,000	
2014	45	16	14		3	$793,000	

2015	29	15		2	1	$25,000	
2016	45	1	17	3	1	$1,292,000	
2017	29		9		3	$345,000	
2018	53	5	3		3	$900,000	
2019	22					$100,000	
2020	38	6	18	1	2	$512,000	

3.4 Limitations of the Storm Events Database

An examination of the reporting source of the DS events in the SED (Figure S1) shows that the sources of the reports vary from professional and trained personnel to automated reports by an ASOS station to reports from the public. The greatest percentage of the DS events (34%) was reported by trained spotters and the next most frequent reports were from law enforcement (19%). Many DS events had multiple reports (up to 29) from different sources, creating an oversampling issue that becomes problematic if this dataset is used to derive long-term dust trends.

We decided to explore several locations to examine the accuracy of the reports. Two locations were selected: Utah and Lubbock, Texas. There were three DS events reports for Utah from 2000 to 2020 in the SED: the first one was on June 12, 2003, at Thompson Springs. This event was reported by law enforcement. Since the nearest ASOS unit was >30 km from Thompson Springs we could not examine this event. The next DS event was reported by an official NWS observer on June 7, 2006, at Hanksville. The ASOS unit 4HV located at Hanksville reported a DS event on the same day when the visibility was reduced to 0.8 km. We notice that the 4HV ASOS unit had another dust storm (reported as BLDU) on April 14, 2009, that had a visibility of 0.4 km (¼ mile), which was not reported in the SED. The third DS report in the SED for Utah was on August 7, 2006, at Provo. The visibility value from the nearest ASOS unit (PVU) at Provo was as low as 4 km (not meeting the DS criterion) and no weather code was reported. Next, we examine the SLC ASOS unit (Salt Lake City International Airport) that did not have any reports in the SED from 2000 to 2020. We found three DS dates (March 3, 2010, April 22, 2014, and April 14, 2015) that had visibility below 1 km (0.8 km). None of these days were reported in the SED. The April 14, 2015 event was notable as it had visibility below 0.4 km (¼ mile), caused a fatal accident on the highway and significant damage, and was widely reported both in the news media (Alberty and Mims, 2015) and the scientific literature (Nicoll et al., 2020). Another Utah DS event that was not reported in the SED, on April 15, 2002, was also reported in the literature (West and Steenburgh, 2010). Observation of all ASOS units from Utah during this DS event showed that six different ASOS units recorded visibility lower than 1 km, with three even recording visibility lower than 0.4 km (¼ mile), making it unclear why this observation was not reported in the SED.

In previous work we examined the dust events that occurred in Lubbock, Texas (Kelley and Ardon-Dryer, 2021); we, therefore, used this record to examine the ”dust storms” that were reported by the SED in this location. A total of 14 different DS were reported for Lubbock from 2000 to 2020 in the SED. One of the DS events did not have a record in the LUB ASOS unit. Observations of the lowest visibility values from each of the DS events showed that 46% of them had visibility >1 km (range 1.2 - 4.8 km). If visibility observations would have been made based on NWS, (2022a) criteria (< 0.4 km, ¼ mile) then 69% of the reported DS in the Storm Events Database for Lubbock should have not been characterized that way. One DS event that was reported in the SED for Midland but not for Lubbock, occurred on December 15, 2003. This event, which had visibility lower than 0.4 km (¼ mile) in LUB ASOS, was also reported in the literature (Lee et al., 2009) but not reported in the SED for Lubbock. The January 22, 2012 DS was also not reported in the SED and yet it had visibility lower than 1 km and was presented in the literature (Kandakji et al., 2020). Next, we explored all the LUB ASOS data (from 2000 to 2020) to examine if there were additional DS events that were missed from the SED. We identified a total of 26 DS events in Lubbock ASOS that had visibility <1 km, 10 of them had visibility < 0.4 km (¼ mile). A total of 20 (77%) of these DS events were not reported in the SED. This finding emphasizes the underrepresentation of DS events in the SED.

Previous studies have used data on different events from the SED to analyze the reporting of other various weather phenomena (Markowski et al., 1998; Bentley et al., 2002; Dixon et al., 2005; Ashley and Black, 2008). Many found the Storm Events Database to be an inconsistent and inaccurate record of severe weather (Downton et al., 2005; Trapp et al., 2006; Ashley and Black, 2008; Ashley and Gilson, 2009; Black and Ashley, 2010; Blair et al., 2011; Black and Mote, 2015; Miller et al., 2016). Others also found the reports on damage, injuries, and fatalities to be incomplete and inconsistent (López et al., 1993; Santos, 2016). Our analysis shows that there are also many issues with reporting dust storms in the Storm Events Database, with the inclusion of many dust events that do not meet the criteria for a Dust Storm (having visibility >1 km) along with an underrepresentation of events that fit the criteria needed for a DS but are not presented in the SED. Peterson and Zobeck (1996), who used the Storm Data publication to examine the record of DS events in the western US from 1972 to 1992 stated that some of the patterns found are plausible, some are puzzling, and some are perhaps dubious, finding an under-reporting of dust storms in the Lubbock area in comparison to their published analysis (Wigner and Peterson, 1987). Peterson and Zobeck (1996) stated that many of these events may not have been noted outside of the region. Furthermore, they stated that the occurrence of blowing dust in the Lubbock area may not have seemed sufficiently extraordinary to warrant reports to be submitted to the Storm Events Database. Rublee et al. (2020) stated that due to errors or biases in reporting DS events in the SED, the number of DS reported to the NWS may not represent the true number of dust storms that occurred in the USA.

We suggest that these issues could be caused by multiple factors. Edwards et al. (2018) stated that the SED contains no systematic information on experience levels within each stated estimation source. For example, it seems there is a confusion about the reports of dust storm events as the NWS (2022b) states that dust storms that occur in direct relation to convection should be entered as a thunderstorm wind event, including the appropriate wind magnitude, not as a DS entry; but when a DS moved away from the parent thunderstorm or convection and presents as its own hazard or threat, it should be classified as a DS event. These definitions seem confusing (especially to non-meteorologist contributors to the SED, such as law enforcement officers), as “a dust storm is a dust storm” and should be reported when it reduces the visibility below the threshold regardless of whether it was created with or without a thunderstorm. Similar rule-based under-reporting of dust storms associated with thunderstorms in Australia was lamented by O’Loingsigh et al. (2010). This cannot fully explain the under-reporting of dust storms in Lubbock noted in our analysis and by Peterson and Zobeck (1996), as most of the dust storms (>60%) were not caused by convective thunderstorms and should have otherwise been reported.

An additional factor could be attributed to the wide range of sources used to report DS events (Figure S1). Storm Events Database reports can originate from human sources such as law enforcement and the general public (Miller et al., 2016). Previous studies questioned the fact that some of the database population was gathered from media reports via newspaper and clipping services (Peterson and Zobeck, 1996; Ashley and Gilson, 2009). Miller et al. (2016) stated that the quality of the reports in the Storm Events Database is not guaranteed even though the NWS attempts to use the most accurate information available. The data gathered in the SED have significant impacts on policy, mitigation, and resource allocation and are widely used by scientific researchers in fields outside meteorology (e.g. Cutler, 2015; Jones, 2022) as well as in forensic investigations (Grimshaw and Ploger, 2018), public health assessments (Rublee et al., 2020), economic analyses (Griffin et al., 2021), finance (Bourdeau-Brien and Kryzanowski, 2019) emergency planning (Hays County Texas, 2017) and legal and political matters (Sisco, 2021). Therefore, the accuracy and precision of the database should be of great importance.

The Storm Events Database performs a valuable public service to many user and stakeholder communities in assembling data from across the USA on daily weather events of an impactful nature, and we appreciate the difficulty in assembling the database. We believe that because it is so widely used by professionals in diverse fields, accuracy should be the ultimate goal, therefore there should be greater emphasis on improving the methodological foundation of this database and there is a need for a more formal, efficient, precise and accurate way to collect the data, as well as to validate and verify the reports in the Storm Events Database. Investigators in many different fields need to know that the data in the Storm Events Database, while representative, may not be comprehensive: the data are useful, but not necessarily accurate or precise, and should not be used for quantitative studies of dust storms (or other impactful weather phenomena) and their effects. In addition, since the USA experiences far more events of BLDU (visibility >1km) than dust storms, we note the need for a database that will include dust events of all types including blowing dust and dust storms.

4 Conclusions

This study examines the long-term variations of reported dust storms from the Storm Events Database and its reliability and usefulness as well as limitations as a source for documenting the climatology of dust storms across the USA. While this database provides potentially useful information for understanding the frequency, distribution, and importance of dust storms across the USA, our analysis of events occurring from 2000 to 2020 shows that it is lacking many dust storms that occurred during that period, and also contains many events of blowing dust (with visibility > 1 km) that should not have been reported as dust storms. There are also multiple entries in the database from various sources for a single DS that could be problematic if the dataset is used to derive long-term dust trends. Some of the causes for the underrepresentation of DS events or confusion in reporting in the SED could be attributed to the diverse sources contributing to the reports or the lack of consistency and verification of the reports. Although it is one of the most widely used dust databases available for the entire USA, the issues found in this study raised questions on its efficiency, accuracy, and reliability as a dataset to study dust climatology and associated social effects.

Acknowledgments

TEG and DQT received partially supported by NASA Health and Air Quality Program, while KAD did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data Availability Statement

All the dust storm data used in this study were downloaded from the National Center for Environmental Information Storm Events Database (https://www.ncdc.noaa.gov/stormevents/)

References

Alberty, E., & Mims, B. (2015). Windstorm causes mayhem on Utah roads, leaves thousands without power. Salt Lake Tribune, April 14, 2015 6:09 pm. Retrieved from http://www.sltrib.com/news/2398392-155/utah-forecast-a-cold-windy-wintry.

Ashley, W. S., & Black, A. W. (2008). Fatalities associated with nonconvective high-wind events in the United States. *Journal of Applied Meteorology and Climatology*, 47, 717-725. https://doi.org/10.1175/2007JAMC1689.1.

Ashley, W. S., & Gilson, C. W. (2009). A reassessment of US lightning mortality. *Bulletin of the American Meteorological Society*, 90(10), 1501-1518. https://doi.org/10.1175/2009BAMS2765.1.

Ardon-Dryer, K., & Levin, Z. (2014). Ground-based measurements of immersion freezing in the eastern Mediterranean. *Atmospheric Chemistry and Physics*, 14, 5217–5231. https://doi.org/10.5194/acp-14-5217-2014.

Ardon-Dryer, K., Mock, C., Reyes, J., & Lahav, G. (2020). The effect of dust storm particles on single human lung cancer cells. *Environmental Research*, 181, 108891. https://doi.org/10.1016/j.envres.2019.108891.

Ardon-Dryer, K., Chmielewski, V., Burning E., & Xueting X. (2021). Changes of Electric Field, Aerosol, and Wind Covariance in Different Blowing Dust Days in West Texas, *Aeolian Research*, 100762, https://doi.org/10.1016/j.aeolia.2021.100762.

Bach, A. J., Brazel, A. J., & Lancaster, N. (1996). Temporal and spatial aspects of blowing dust in the Mojave and Colorado deserts of southern California, 1973–1994. *Physical Geography*, 17(4), 329-353. https://doi-org.lib-e2.lib.ttu.edu/10.1080/02723646.1996.10642589.

Bangert, M., Nenes, A., Vogel, B., Vogel, H., Barahona, D., Karydis, V.A., Kumar, P., Kottmeier, C., & Blahak, U. (2012). Saharan dust event impacts on cloud formation and radiation over western Europe. *Atmospheric Chemistry and Physics*, 12, 4045–4063. https://doi.org/ 10.5194/acp-12-4045-2012.

Bentley, M. L., Mote, T. L., & Thebpanya, P. (2002). Using Landsat to identify thunderstorm damage in agricultural regions. *Bulletin of the American Meteorological Society*, 83, 363-376. DOI: 10.1175/1520-0477-83.3.363.

Bernier, S.A. (1995). Climatology of blowing dust and triggering mechanisms across West Texas. M.S. Thesis (Atmospheric Science), Lubbock, TX: Texas Tech University.

Bernier, S.A., Gill, T. E., & Peterson, R. E. (1998). Climatology of dust in the Southern High Plains of Texas. In: Busacca, A. (Ed.), Proceedings of the International Conference on Dust Aerosols, Loess Soils and Global Change, Seattle, October 1998. Washington State University College of Agriculture and Home Economics Miscellaneous Publication, vol. 190, pp. 4–7.

Black, A.W., & Ashley, W.S. (2010). Nontornadic convective wind fatalities in the United States. *Natural Hazards*, 54(2), 355-366. DOI: 10.1007/s11069-009-9472-2.

Black, A. W., & Mote, T. L. (2015). Characteristics of winter-precipitation-related transportation fatalities in the United States. *Weather, Climate, and Society*, 7(2), 133-145.

Blair, S. F., Deroche D. R., Boustead J. M., Leighton J.W., Barjenbruch, B.L., & Gargan, W.P. (2011). A Radar-Based Assessment of the Detectability of Giant Hail. *Journal of Severe Storms Meteorology*, 6(7) 1-30.

Bourdeau-Brien, M., & Kryzanowski, L. (2019). Municipal financing costs following disasters. *Global Finance Journal*, 40, 48-64. https://doi.org/10.1016/j.gfj.2018.10.004.

Comrie, A. C. (2021). No consistent link between dust storms and Valley fever (coccidioidomycosis). *GeoHealth*, 5(12), e2021GH000504. https://doi.org/10.1029/2021GH000504.

Crooks, J. L., Cascio, W. E., Percy, M. S., Reyes, J., Neas, L. M., & Hilborn, E. D. (2016). The association between dust storms and daily non-accidental mortality in the United States, 1993-2005. *Environmental Health Perspectives*, 124(11), 1735–1743. https://doi.org/10.1289/EHP216.

Cutler, M. J. (2015). Seeing and believing: the emergent nature of extreme weather perceptions. *Environmental Sociology*, 1(4), 293-303. https://doi.org/10.1080/23251042.2015.1085117.

Dixon, P. G., Brommer, D. M., Hedquist, B. C., Kalkstein, A. J., Goodrich, G. B., Walter, J. C., Dickerson, C. C., IV, Penny, S. J., & Cerveny, R. S. (2005). Heat Mortality Versus Cold Mortality: A Study of Conflicting Databases in the United States, *Bulletin of the American Meteorological Society*, 86(7), 937-944. https://doi.org/10.1175/BAMS-86-7-937.

Downton, M. W., Barnard Miller, J. Z., & Pielke, R.A. (2005). Reanalysis of U.S. National Weather Service Flood Loss Database. *Natural Hazards Review*, 6 (1) 13-22. https://doi.org/10.1061/(ASCE)1527-6988(2005)6:1(13)

Edwards, R., Allen, J. T., & Carbin, G. W. (2018). Reliability and Climatological Impacts of Convective Wind Estimations, *Journal of Applied Meteorology and Climatology*, 57(8), 1825-1845. https://doi.org/10.1175/JAMC-D-17-0306.1

Eagar, J.D., Herckes, P., & Hartnett, H.E. (2017). The characterization of haboobs and the deposition of dust in Tempe, AZ from 2005 to 2014. *Aeolian Research*, 24, 81–91. http://dx.doi.org/10.1016/j.aeolia.2016.11.004.

FAA (Federal Aviation Administration). (2022). Air traffic organization policy JO 7900.5E. Retrieved from https://www.faa.gov/documentLibrary/media/Order/Order_JO_7900.5E.pdf.

Griffin, P.A., Guo, Z., & Sun, E.Y. (2021). Weathering the Weather: Does Extreme Weather Affect the Cost of an Audit? *Social Science Research Network*, http://dx.doi.org/10.2139/ssrn.3802059.

Grimshaw, R., & Ploger, D. (2018). Using Technology to Manage Engineering Companies Specializing in Forensic Investigations. Paper presented at 2018 American Society for Engineering Education Conferences - Conference for Industry and Education Collaboration / San Antonio proceedings, San Antonio. Retrieved from https://peer.asee.org/31359.

Godon, N. A., & Todhunter, P. E. (1998). A climatology of airborne dust for the Red River Valley of North Dakota. *Atmospheric Environment*, 32(9), 1587-1594. https://doi.org/10.1016/S1352-2310(97)00389-0.

Goudie, A.S. (2014). Desert dust and human health disorders. *Environment International*, 63, 101-113. https://doi.org/10.1016/j.envint.2013.10.011.

Hahnenberger, M., & Nicoll, K. (2012). Meteorological Characteristics of Dust Storm Events in the Eastern Great Basin of Utah, U.S.A. Atmospheric Environment, 60, 601–12, https://doi.org/10.1016/j.atmosenv.2012. 06.029.

Hays County, Texas. (2017). Hays County Draft Hazard Mitigation Plan Update 2017. Retrieved from https://hayscountytx.com/download/residents/hazard_mitigation_plan/Hays-County-Annex.pdf.

Haywood, J., Francis, P., Dubovik, O., Glew, M., & Holben, B. (2003). Comparison of aerosol size distributions, radiative properties, and optical depths determined by aircraft observations and sun photometers during SAFARI 2000. *Journal of Geophysical Research*: *Atmospheres,* 108, 8471. https://doi.org/10.1029/2002JD002250.

Jones, B. A. (2022). Dust storms and violent crime. *Journal of Environmental Economics and Management*, 111, 102590. https://doi.org/10.1016/j.jeem.2021.102590.

Kandakji, T., Gill, T. E., & Lee, J. A. (2020). Identifying and characterizing dust point sources in the southwestern United States using remote sensing and GIS. *Geomorphology*, 353, 107019. https://doi.org/10.1016/j.geomorph.2019.107019.

Kelley, M. C., & Ardon-Dryer, K. (2021). Analyzing Two Decades of Dust Events on the Southern Great Plains Region of West Texas, *Atmospheric Pollution Research*, 101091, https://doi.org/10.1016/j.apr.2021.101091.

Kelley, M. C., Brown, M. M., Fedler, C. B., & Ardon-Dryer, K. (2020). Long-term measurements of PM2.5 concentrations in Lubbock. Texas. *Aerosol and Air Quality Research*, 20, 1306-1318. https://doi.org/10.4209/aaqr.2019.09.0469.

Lee, J. A., & Tchakerian, V. P. (1995). Magnitude and frequency of blowing dust on the Southern High Plains of the United States, 1947–1989. *Annals of the Association of American Geographers*, 85(4), 684-693. https://doi-org.lib-e2.lib.ttu.edu/10.1111/j.1467-8306.1995.tb01820.x

Lee, J. A., Gill, T. E., Mulligan, K. R., Dominguez Acosta, M., & Perez, A. E. (2009). Land use/land cover and point sources of the 15 December 2003 dust storm in southwestern North America. *Geomorphology*, 105(1), 18-27. https://doi.org/10.1016/j.geomorph.2007.12.016

Lee, R. S., Craun, C., Robinson, M., & Phaneuf, M. (2012). Evaluating the impacts of haze on air traffic operations. Preprints of the 92nd Annual Meeting, American Meteorological Society, New

Orleans, LA, January 2012, https://ams.confex.com/ams/92Annual/webprogram/Handout/Paper201227/2011%20AMS%20Haze%20Paper%20v2.pdf

Lei H, & Wang J. X. L. (2014). Observed characteristics of dust storm events over the western United States using meteorological, satellite, and air quality measurements. *Atmospheric Chemistry and Physics*, 14:7847–7857. https:// doi.org/10.5194/acp-14-7847-2014.

Lei, H., Wang, J. X. L., Tong, D. Q., & Lee, P. (2016). Merged dust climatology in Phoenix, Arizona based on satellite and station data. *Climate Dynamics*, 47, 2785–2799. https:// doi.org/10.1007/s00382-016-2997-7.

López, R. E., Holle, R. L. Heitkamp, T. A. Boyson, M. Cherington, M. & Langford, K. (1993). The underreporting of lightning injuries and deaths in Colorado. *Bulletin of the American Meteorological Society*, 74, 2171-2178. https://doi.org/10.1175/1520-0477(1993)074<2171:TUOLIA>2.0.CO;2

Markowski, P. M., Rasmussen, E. N., & Straka, J. M. (1998). The Occurrence of Tornadoes in Supercells Interacting with Boundaries during VORTEX-95, *Weather and Forecasting*, 13(3), 852-859. https://doi.org/10.1175/1520-0434(1998)013<0852:TOOTIS>2.0.CO;2

Middleton, N.J. (2017). Desert dust hazards: a global review. *Aeolian Research*, 24, 53–63. https://doi.org/10.1016/j.aeolia.2016.12.001

Miller, P.W., Black, A.W., Williams, C.A., & Knox, J.A. (2016). Quantitative assessment of human wind speed overestimation. *Journal of Applied Meteorology and Climatology*, 55(4), 1009-1020. https://doi.org/10.1175/JAMC-D-15-0259.1.

NWS, National Weather Service (2022a). Watch/Warning/Advisory definitions. Retrieved from https://www.weather.gov/otx/Watch_Warning_Advisory_Definitions#Blowing%20Dust%20Advisory.

NWS, National Weather Service (2022b). National Weather Service Instruction 10-1605 July 26, 2021, NWSPD 10-16, Storm Data Preparation. Retrieved from https://www.nws.noaa.gov/directives/sym/pd01016005curr.pdf.

NCEI. (2022). Storm Events Database for dust storm. Retrieved from https://www.ncdc.noaa.gov/stormevents/.

Nickling, W. G., & Brazel, A. J. (1984). Temporal and spatial characteristics of Arizona dust storms (1965–1980). *Journal of Climatology*, 4(6), 645-660. https://doi.org/10.1002/joc.3370040608.

Nicoll, K., Hahnenberger, M., & Goldstein, H. L. (2020). Dust in the wind from source-to-sink: Analysis of the 14–15 April 2015 storm in Utah. *Aeolian Research*, 46, 100532.https://doi.org/10.1016/j.aeolia.2019.06.002

Novlan, D. J., Hardiman, M., & Gill, T. E. (2007). A synoptic climatology of blowing dust events in El Paso, Texas from 1932–2005. Preprints, 16th Conference on Applied Climatology, American Meteorological Society, J3.12.

OFCM (Office of the Federal Coordinator for Meteorological Services and Supporting Research) (1995). Surface Weather Observations and Reports. Retrieved from http://marrella.meteor.wisc.edu/aos452/fmh1.pdf.

O'Loingsigh, T., McTainsh, G. H., Tapper, N. J., & Shinkfield, P. (2010). Lost in code: A critical analysis of using meteorological data for wind erosion monitoring. *Aeolian Research*. 2(1), 49-57, https://doi.org/10.1016/j.aeolia.2010.03.002.

Orgill, M. M., & Sehmel, G. A. (1976). Frequency and diurnal variation of dust storms in the contiguous U.S.A. *Atmospheric Environment*, 10, 813–825. https://doi.org/10.1016/0004-6981(76)90136-0.

Osmond, D., & Line, D. (2017). Best Management Practices for Agriculture Nutrients. NC STATE EXTENSION, USA. Retrieved from https://content.ces.ncsu.edu/best-management-practices-for-agricultural-nutrients.

Peterson R., & Zobeck, T. M. (1996). Blowing dust and sand events across arid and semiarid regions of the United States from 1971 to 1992. Proceedings of the Fifth International Conference on Desert Development, Desert Development: The Endless Frontier, August 12-17, 1996, Lubbock Texas, Vol. II, pp. 683-699.

Rublee, C., Sorensen, C., Lemery, J., Wade, T., Sams, E., Hilborn, E., & Crooks, J. (2020). Associations between dust storms and intensive care unit admissions in the United States, 2000–2015. *GeoHealth* 4, e2020GH000260. https://doi.org/10.1029/2020GH000260.

Santos, R. P. (2016). Some comments on the reliability of NOAA's Storm Events Database. *Social Science Research Network*, 1606.06973. https://doi.org/10.2139/ssrn.2799273.

Shahsavani, A., Naddafi, K., Haghighifard, N.J., Mesdaghinia, A., Yunesian, M., Nabizadeh, R., Arahami, M., Sowlat, M.H., Yarahmadi, M., Saki, H., Alimohamadi, M., Nazmara, S., Motevalian, S.A., & Goudarzi, G., (2012). The evaluation of PM10, PM2.5, and PM1 concentrations during the middle eastern dust (MED) events in ahvaz, Iran, from April through September 2010. *Journal of Arid Environments*, 77(1), 72–83. https://doi.org/10.1016/j.jaridenv.2011.09.007.

Sisco, J. G. (2021). Puerto Rico's Debt: Still Foreign in a Domestic Sense. *Journal of Law and Policy*, 37, 53-98.

Tong, D. Q., Dan, M. Wang, T. & Lee, P. (2012). Long-term dust climatology in the western United States reconstructed from routine aerosol ground monitoring, *Atmospheric Chemistry and Physics*., 12(11), 5189–5205. https://doi.org/10.5194/acp-12-5189-2012.

Tozer, P., & Leys, J. (2013). Dust storms - what do they really cost? *The Rangeland Journal*, 35 (2), 131–142. https://doi.org/10.1071/RJ12085.

Trapp, R. J., Wheatley, D. M., Atkins, N. T., Przybylinski, R. W. & Wolf, R. (2006). Buyer beware: Some words of caution on the use of severe wind reports in postevent assessment and research. *Weather and Forecasting*, 21(3), 408-415. https://doi.org/10.1175/WAF925.1.

UNEP, WMO, UNCCD, 2016. Global Assessment of Sand and Dust Storms. United Nations Environment Programme, Nairobi. Retrieved from https://wesr.unep.org/redesign/media/docs/assessments/global_assessment_of_sand_and_dust_storms.pdf

U.S. EPA (Environmental Protection Agency). 2021. Agriculture and air quality. Retrieved from https://www.epa.gov/agricul ture/agriculture-and-air-quality#main-content.

Wagner, J. & Casuccio, G. (2014). Spectral imaging and passive sampling to investigate particle sources in urban desert regions. *Environmental Science: Processes & Impacts*, 16: 1745-53. DOI:10.1039/c4em00123k.

Wigner, K. A., Peterson, R. E. (1987). Synoptic climatology of blowing dust on the Texas South Plains, 1947-84. *Journal of Arid Environments,* 13, 199-209. https://doi.org/10.1016/S0140-1963(18)31108-X.

West, G. L., & Steenburgh, W. J. (2010). Life Cycle and Mesoscale Frontal Structure of an Intermountain Cyclone, *Monthly Weather Review*, *138*(7), 2528-2545. DOI: https://doi.org/10.1175/2010MWR3274.1.

WMO (World Meteorological Organization). (2019). WMO Technical Regulations Annex II Manual on Codes International Codes. I.1. Retrieved from https://library.wmo.int/index.php?lvl=notice_display&id=13617#.Yqux4nbMKUk