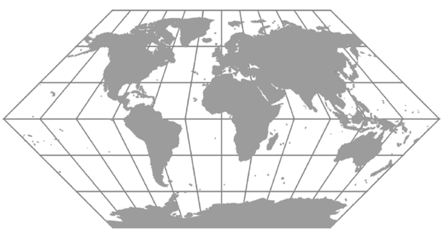
A Fog Climatology of the Delmarva Peninsula

Wesley R. Skeeter
Department of Geography
University of British Columbia
Vancouver, BC V6T 1Z2
E-mail: wesley.skeeter@alumni.ubc.ca

Darren B. Parnell
Department of Geography and Geosciences
Salisbury University
Salisbury, MD 21801
E-mail: dbparnell@salisbury.edu

Brent R. Skeeter
Department of Geography and Geosciences
Salisbury University
Salisbury, MD 21801
E-mail: brskeeter@salisbury.edu



ABSTRACT

The Delmarva Peninsula is a unique region with regards to the importance of fog. This study examines the spatial and temporal variability of fog characteristics across the Peninsula. In this paper, we use five stations with reliable records to create a regional fog climatology. Results indicate there is a high degree of temporal variability over relatively short distances, especially when comparing coastal to inland locations. The most inland location, Salisbury, receives by far the greatest annual frequency of fog. The seasonal distribution of fog events for the inland and coastal locations differ greatly, with Salisbury experiencing its maximum fog frequency during the summer while locations near the coast experience their maxima during the winter.

Numerous physiographic and meteorological factors combine in complex ways to create a unique fog climatology across the Peninsula. The results of this study can be useful to help understand and anticipate potentially dangerous transportation conditions due to fog.

Key Words: fog climatology, Delmarva Peninsula, school delays, transportation

INTRODUCTION

Across most of the United States, public school delays due to fog are rare. However, for parents and students residing on the Delmarva Peninsula school delays due to fog are commonplace. The Delmarva Peninsula consists of Delaware and the eastern portions of Maryland and Virginia (Fig. 1). The Peninsula is bordered to the east by the Atlantic Ocean and to the west by the Chesapeake Bay. Salisbury and Dover are the main population centers, resort towns line much of the Atlantic coast, and the rest of the Peninsula is predominantly rural. The Atlantic and Chesapeake both play a role in influencing the climate of the region including the vary-

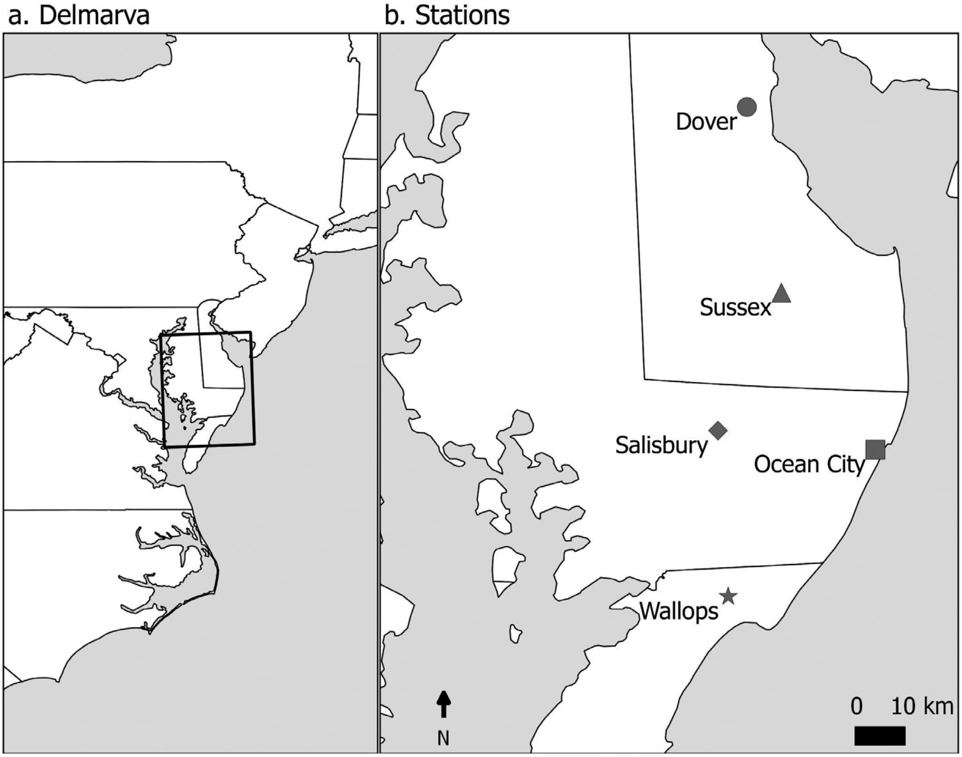


Figure 1. (a) Location of the Delmarva Peninsula. (b) The five weather stations across the Delmarva Peninsula which record hourly fog observations. Note: The station labeled as Sussex is in Sussex County, just outside of Georgetown, DE.

ing seasonality and characteristics of fog on a mesoscale. In Wicomico County, Maryland, over a recent five-year period (2011-2016) there was an average of five (one- or two-hour) school delays caused by fog per year (WCBOE 2016). Prior to 1997 Delmarva schools were rarely delayed for fog. However, a fatal school bus accident in Easton, Maryland during low visibility fog conditions on October 31, 1997 (The Daily Times 1997) changed the way that foggy conditions are treated in this region with regard to school safely. School delays due to fog are now issued whenever relatively dense fog conditions develop overnight and are expected to persist into the normal morning school bus route times. The preponderance of school delays along with the economic impact to coastal cities makes an examination of the climatology of fog conditions across the Delmarva region especially relevant.

Fog can form either by the cooling of near-surface air down to its dew point or by the addition of moisture to the air. The fog type (classification) depends upon the method of formation. There are five types of fog, three that result from cooling of the air and two that result from the addition of moisture to the air. The three types of fog that form from cooling are radiation fog, advection fog, and upslope fog. It is well known that radiation fog forms on calm and clear nights due to radiational cooling and is most common in the early morning hours surrounding sunrise (Westcott 2007). Advection fog forms when relatively warm, humid air moves over a colder surface such as cold water or snow. This fog type is common during the spring in coastal regions. Upslope fog forms due to the gentle uplift and cooling of air along a sloping surface. The two types of fog that result from the addition of moisture to the air are steam fog and frontal fog. Steam fog forms when cool air is present over a relatively warm water surface and is especially common during autumn. Frontal fog forms when light precipitation falls through a layer of cool air and typically is associated with a warm front (Ahrens 2013, Aguado and Burt 2013).

Fog occurrence is often a function of local, regional, and synoptic scale conditions and strongly varies with geographical location (Croft et al. 1995; Garcia-Garcia and Zarraluqui 2008). Forecasting fog is challenging due to the complex interplay of various atmospheric processes (Tardif and Rasmussen 2010). Despite advances in weather forecasting due to improvements of modelling techniques, accurate fog forecasting remains difficult (Bergot and Guedalia 1994).

Although fog is not often considered a newsworthy event, its impacts are often costly and can even be deadly (Croft et al. 1995, Haeffelin et al. 2010; Ashley et al. 2015). Delays in aviation, marine and surface transportation are the most well recognized (Garmon et al. 1996). It can also have less explicit, location-specific economic impacts; fog can make tourist destinations undesirable and drive away business. These effects have been studied for tourism in mountainous regions by Bürki et al. (2003) and more generally by Gómez Martín (2005). In spite of their importance, fog impacts have not been properly assessed throughout the world (Garcia-Garcia and Zarraluqui 2008). Fog has received relatively little attention compared to many other meteorological elements such as temperature, precipitation and wind.

Recent fog-related research has primarily focused on fog detection using satellite imagery (Ellrod 1995; Bendix 2002; Bendix et al. 2006; Cermak and Bendix 2008) and modelling techniques to predict the occurrence and characteristics of fog (Bergot and Guedalia 1994; Teixeira and Miranda 2001). The first major climatological study of fog in the United States was conducted in the 1930s (Stone 1936) and it was three decades before Court and Gerston (1966) and Peace (1969) expanded upon this work. Studies since then have examined fog occurrences across the United States in different regions, including the West Coast (Leipper, 1994; O'Hara, 2011), the Southeast (Croft et al. 1995; Croft et al. 1997), the Upper Midwest (Friedlein 2004; Westcott and Kristovich 2009) and the region surrounding New York City (Tardiff and Rasmussen 2007). Additionally, fog climatologies have been completed for numerous areas outside of the United States including Italy (Bendix 1994), Germany (Bendix 2001), Nova Scotia (Canavan and Sanford 2007), and Mexico (Garcia-Garcia and Zarraluqui 2008). Most of these studies primarily dealt with annual fog occurrence on a relatively large scale and did not go into great detail concerning seasonal and mesoscale differences in fog occurrence or type. To date, there have been no published studies specifically addressing the climatology of fog across the Delmarva Peninsula.

The fog climatology of the Delmarva Peninsula deserves attention because of the social and economic impacts it has on the region, including the high frequency of school delays compared to other regions. This study analyzes the spatial and monthly variations of fog events across the Peninsula and advances physical explanations to account for the observed variations.

DATA AND METHODS

The data for this study were obtained from the National Centers for Environmental Information (NCEI). Figure 1 shows the five weather stations across the Delmarva Peninsula that record hourly fog observations, and Table 1 shows the beginning date of each station's record, the completeness of their record, and their distance from the Chesapeake

Table 1. Beginning of record, completeness of record, and distance from the Chesapeake Bay and Atlantic Ocean for the five stations used in this study.

Station	Beginning of Record	Completeness of Record	Distance from Chesapeake Bay (km)	Distance from Atlantic Ocean (km)
Dover	January 1, 1980	99%	59.0	2.3
Ocean City	December 8, 1999	96%	67.5	1.7
Salisbury	January 1, 1980	97%	31.6	37.7
Sussex	February 2, 1987	73%	74.7	25.1
Wallops	March 1, 1991	81%	15.1	14.1

Bay and Atlantic Ocean. We obtained data for each station through the end of 2012. During fog events each station denotes fog with a present weather code of FG and indicates visibilities to the nearest one-tenth of a mile (NOAA 1998). We collected hourly surface observations to identify the occurrence and characteristics of fog events. At some point during the period of record, the observations for each station changed from manual to automated. We did not distinguish between manual and automated observations for this study because no obvious differences in fog frequencies were noted between the two reporting styles.

We classified a station as experiencing a fog event if it met two criteria. First, it had to report a weather code denoting fog for at least two consecutive hourly periods. Second, visibility needed to be less than one mile. To avoid double counting, if two identified events were separated by one missing hourly observation or one hour with a present weather code of FG indicating fog but visibility above the threshold, they were counted as one event. We then aggregated these event counts and averaged them by month. In order to directly compare the number of fog events between each station on a monthly basis, we used a weighting scheme to account for the varying degree of missing data among stations. Specifically, each monthly total was multiplied by the reciprocal of the completeness of record for that month. For example, if a station record was 80 percent complete the monthly total would be multiplied by 1.25 (1/0.8 = 1.25). In such a case, if the monthly total was 4.0 events per month it would be adjusted to 5.0 events. Histograms of average annual fog frequency and monthly fog frequency graphs were created to depict and help analyze the seasonality and spatial variability of the fog events.

RESULTS

Salisbury

Of the five weather stations analyzed, Salisbury has by far the greatest annual frequency of fog. Salisbury averages 56.0 fog events per year, well above any of the other stations (Fig. 2). An analysis of variance (ANOVA) test indicates that the frequency of Salisbury's fog events is significantly different than the other four locations ($F = 20.79$; $p < .0001$). Salisbury has the greatest total number of

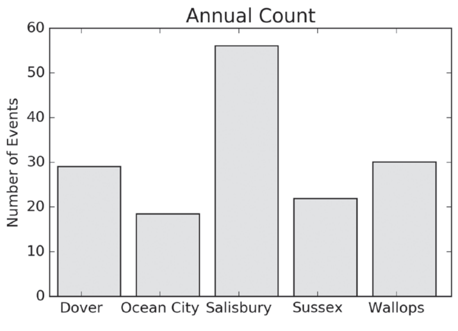


Figure 2. Average annual number of fog events.

fog events for every month, except January when Wallops experiences more (Figs. 3-7). This represents 47 out of 48 possible monthly station comparisons. There is a distinct peak in late summer and early fall, with the maximum of 6.4 events per month in August (Fig. 3). Fog is not quite as frequent in the cooler months as it is during the summer. Fog is least frequent in April, with an average of 3.3 events per month. The distribution is multimodal with less pronounced peaks in January and May. Fog is less frequent in late spring and late fall with a minimum of 3.3 events per month in April and less pronounced minima in June and December.

Coastal Locations (Dover, Ocean City, Wallops)

Dover, Ocean City and Wallops experience fog much less frequently than Salisbury. The annual number of fog events for these locations average 29.0, 18.4 and 30.0 respectively (Fig. 2). Each of these locations experience very different fog seasonality compared to Salisbury. Fog is more frequent in winter than the summer at these locations. More specifically, these locations have their maximum fog frequency from late fall through early spring and their minimum from late spring through early fall (compare Fig. 3 with Figs. 4-6). Dover typically experiences fog most frequently from November through April, with each month averaging at least 2.5 events per month and a peak of 4.0 events in February (Fig. 4). Dover's distribution is unimodal with a well-pronounced minimum in the summer. Ocean City experiences the fewest fog events of any of the five stations. Ocean City has its peak from November through May, interrupted by a local minimum in February. A longer minimum occurs in the summer and early fall with less than one event per month between June and September (Fig. 5). The maximum fog frequency for Wallops occurs during January, with 5.0 events per month, again, even exceeding Salisbury (compare Fig. 3 and Fig. 6). Wallops' distribution is unimodal aside from a slight decrease in February, with a distinct minimum of 0.5 events per month in July.

Sussex

Of the five weather stations analyzed, Sussex has the second lowest annual frequency of fog, averaging only 21.9 fog events per year (Fig. 2). Compared to the other four locations, Sussex has a smaller degree of variability with multiple maxima and minima of similar magnitude and essentially no seasonality. The difference between the maximum and minimum is only 1.3 events per month, with January averaging 2.5 events per month and 1.2 events per month in June (Fig. 7).

DISCUSSION

Salisbury

As noted above, Salisbury experiences a much higher frequency of fog events than the other four stations. Salisbury is located in the center of the Delmarva Peninsula, making it the farthest location from a water body. As a result, wind speeds are typically lower than most of the coastal stations, primarily due to Salisbury's lack of a sea breeze/land breeze circulation and increased friction (Fig. 8). On clear nights, this results in minimal mixing, creating ideal conditions for the formation of radiation fog (Westcott 2007). These conditions are especially common during the humid summer months when the area is typically situated under high pressure, creating a weak pressure gradient with light winds. Even though the nighttime cooling period is shortest during the summer, the high humidity and light winds make summer the most ideal time for fog formation in Salisbury. It is not surprising that August, the month with the highest fog frequency, is also the month with the lowest wind speeds. Furthermore, longer nights in late summer and early fall contribute to higher frequencies relative to early summer. Despite the longer nights during the cooler season, the higher

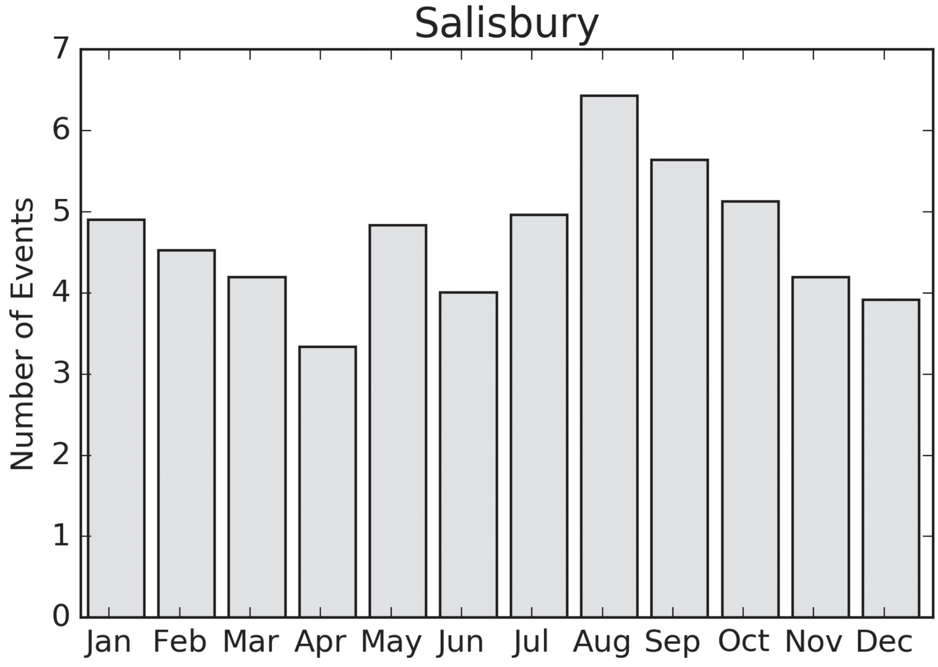


Figure 3. Average monthly number of fog events for Salisbury, MD.

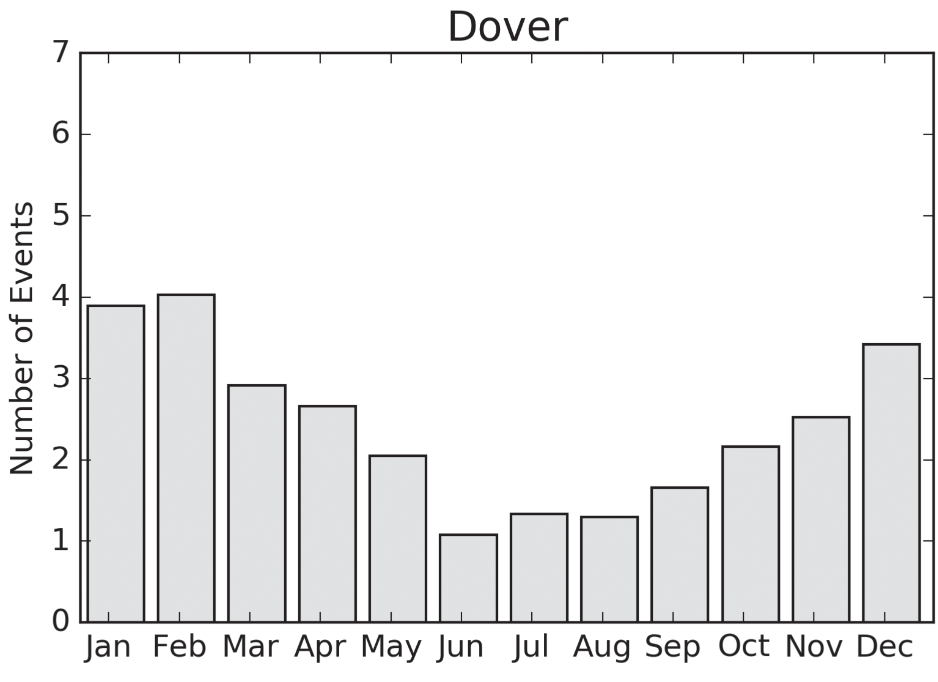


Figure 4. Average monthly number of fog events for Dover, DE.

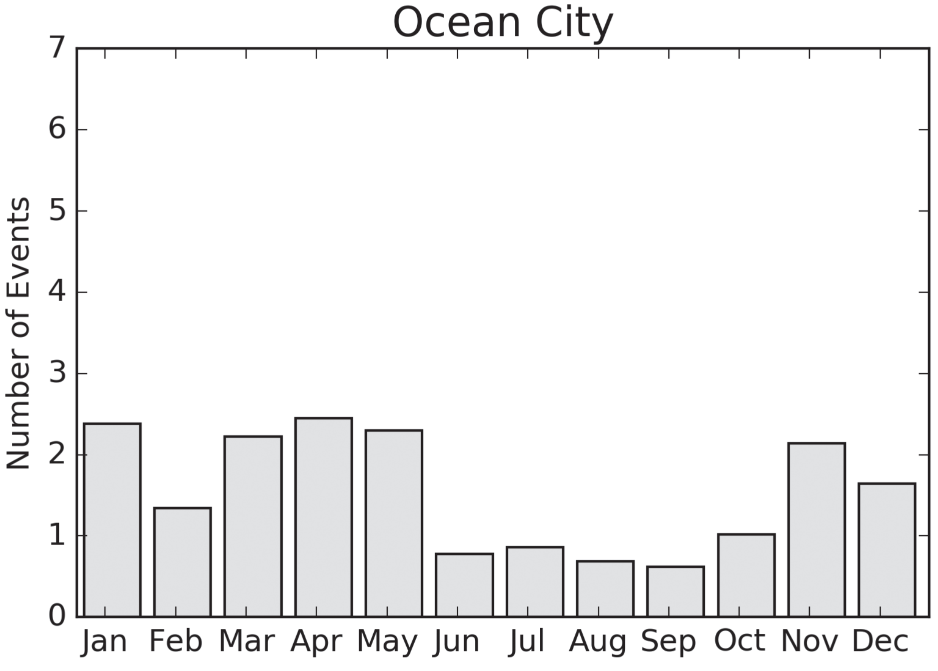


Figure 5. Average monthly number of fog events for Ocean City, MD.

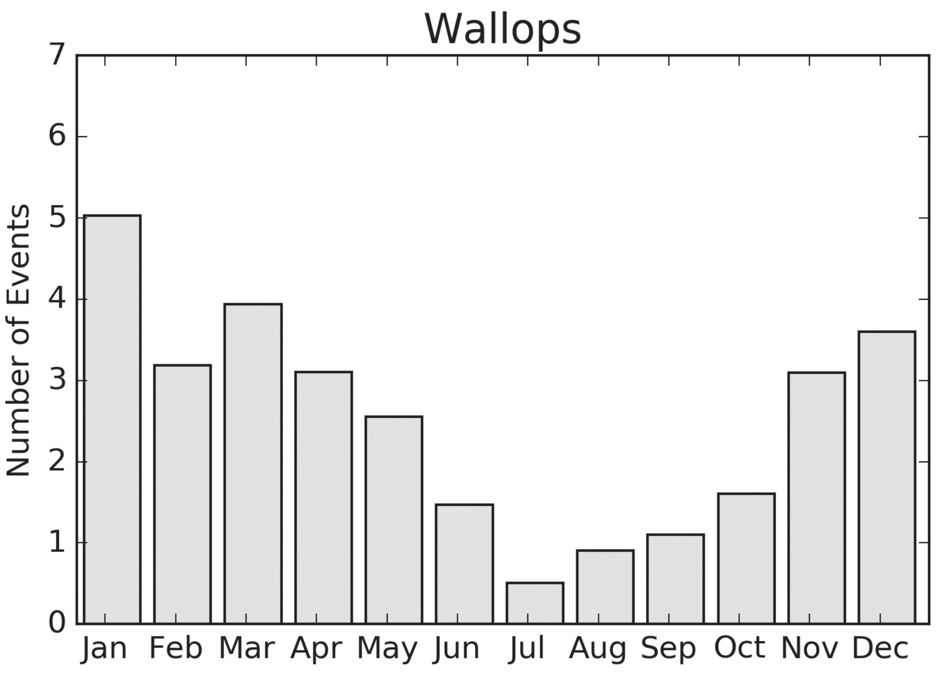


Figure 6. Average monthly number of fog events for Wallops, VA.

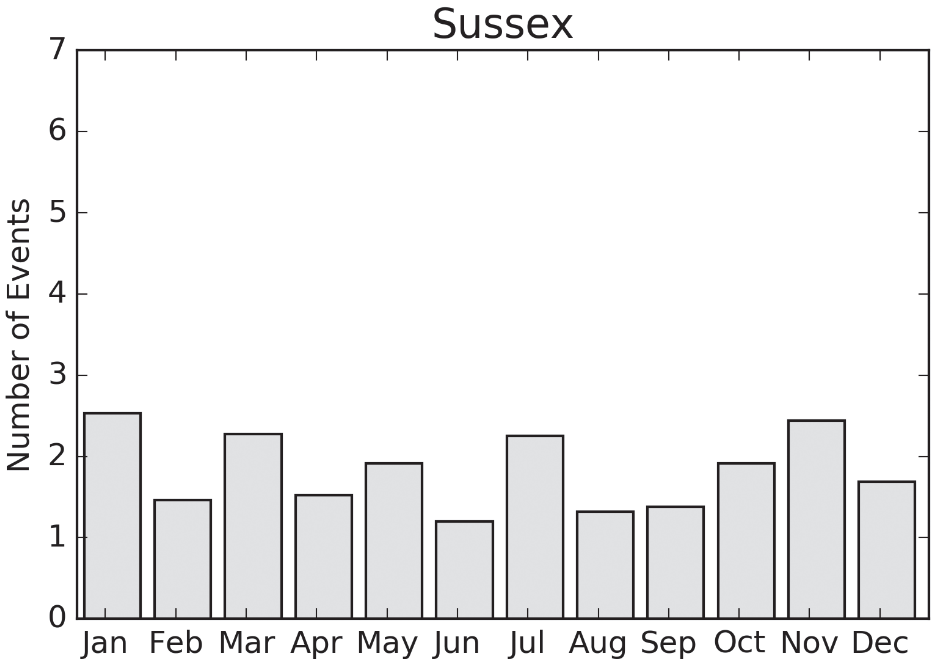


Figure 7. Average monthly number of fog events for Sussex, DE.

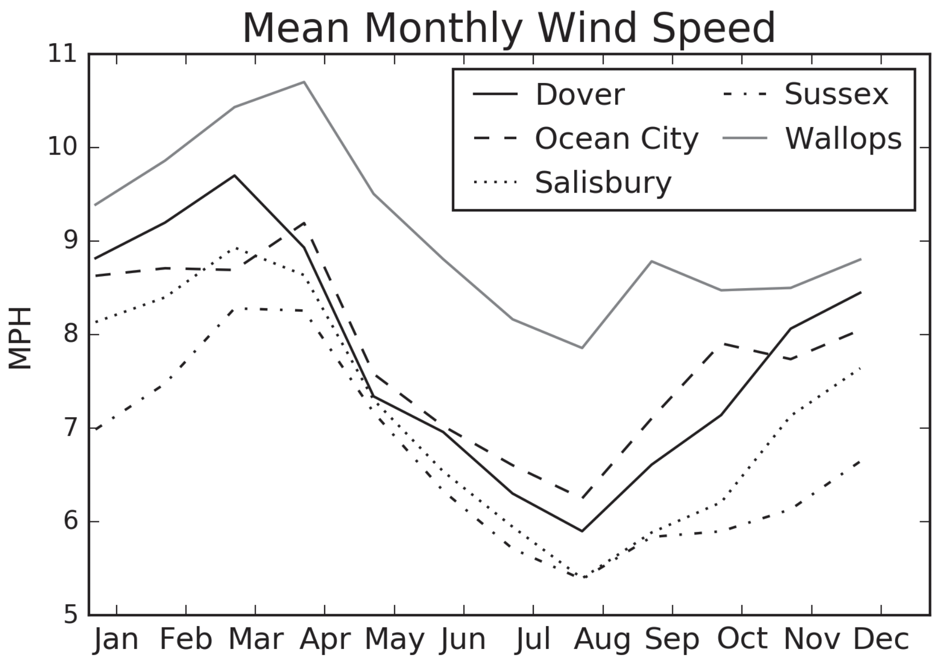


Figure 8. Mean monthly wind speeds for the five stations used in this study.

winds and lower humidity are less conducive to the formation of radiation fog. The ideal combination of lower humidity and elevated wind speeds, along with shorter nights helps explain why fog is least frequent in April.

Coastal Locations (Dover, Ocean City, Wallops)

It is noteworthy how different the timing of maximum and minimum monthly fog frequencies are between the inland Salisbury location and the coastal locations. The similarities in the seasonal pattern of fog occurrence for Dover, Ocean City and Wallops are due to their dependence on processes other than radiational cooling for most of their fog events. Unlike inland locations like Salisbury, where radiation fog is most common, coastal locations more commonly experience advection and steam fog. As a result, the conditions ideal for fog in Salisbury are not as common for locations closer to the coast. Advection fog is most common during the spring months and steam fog is most common during the fall due to strong contrasts between air and sea temperatures. The high frequencies during mid-winter, especially at Wallops and Dover, may be the result of the overlapping frequency distributions of advection and steam fog. The peak frequency in the spring for Ocean City may indicate advection fog is more prevalent at this location since it is closest to the ocean.

During the summer, coastal locations experience fog much less frequently than during cooler months, whereas Salisbury has its maxima (Figs. 3 and 5). Wind speeds are the lowest at all locations during the summer but still higher and more consistent along the coast due to well-defined sea breeze circulation cells which inhibit fog development. Furthermore, warm ocean and air temperatures along the coast in August are not conducive to the development of advection, steam or radiation fog. Temperature contrasts between air and sea surfaces are minimal and warm water surfaces do not cool as efficiently on clear nights as land surfaces. Therefore, fog development here is minimal in spite of the higher frequency farther inland.

Sussex

Of the five locations, Sussex is the only one that cannot be classified as a coastal or inland location. Rather, it is located in more of a transitional zone between the coast and inland areas. Therefore, conditions that lead to advection or steam fog along the coast do not necessarily produce fog at Sussex. In addition, it is not as ideally suited for the development of radiation fog as Salisbury since it is not as far inland. Sussex does receive some advection and possibly steam fog when the coastal areas are experiencing fog, but not to the same extent as Dover, Ocean City and Wallops. Sussex also receives some radiation fog but not as frequently as Salisbury. This explains the lack of any pronounced seasonality since no one fog type is dominant.

Of all of the findings, the most puzzling is Sussex's relative lack of fog compared to Salisbury. Sussex experiences lower wind speeds than the three coastal locations. Sussex's wind speeds are even slightly lower than Salisbury's during every month except August (Fig. 8). This would seem to favor Sussex experiencing frequent radiation fog like Salisbury. However, Sussex experiences less than half the number of fog events that Salisbury experiences (Fig. 2). The reasons described above may explain most of Sussex's lower annual frequency of fog. Although the reasons for these findings remain unclear, they could partially be a function of the location of Sussex's weather station at the micro scale which may influence the recorded wind speed and/or fog observations. While this is beyond the scope of our study, preliminary analysis indicates that the land cover characteristics surrounding the weather stations are similar. For example, the Salisbury and Sussex weather stations both are located just to the East of the urban areas and are surrounded by a nearly identical mix of forested land and open fields.

CONCLUSION

The frequency, timing and characteristics of fog events across the Delmarva Peninsula differ greatly, especially when comparing inland and coastal locations. Salisbury, the most inland location, experiences by far the greatest annual frequency of fog. Fog is prevalent at Salisbury throughout the year with the maximum occurrence during the summer months. Throughout most of the year fog is much less frequent for the coastal locations, with their maxima occurring during the winter or spring months and their minima occurring during the summer months. Clearly, the meteorological conditions that influence fog development differ for the inland and coastal locations. Numerous factors including: water temperature, air temperature, distance to the coast, wind speed and direction, and local topography combine in complex ways to create a unique fog climatology across the Peninsula.

These findings are especially important to the Delmarva region because fog is treated more seriously in this region than many other locations. Again, since the fatal bus accident of 1997 school delays due to fog are now commonplace across the Peninsula. The information obtained in this study can be used by local school and transportation officials to better anticipate and prepare for school delays and all other dangerous transportation conditions due to fog. Furthermore, the results can be used to help officials in coastal resort locations anticipate and possibly mediate some of the negative economic impacts of fog events during the early and late portions of the tourist season.

In addition to a more detailed examination of the location and characteristics of Sussex's weather station, future research could include an examination of the temporal and spatial variations in the duration and intensity of fog events across the Peninsula. The meteorological conditions during individual fog events at the various locations could be closely examined to provide more detailed information on the conditions most suitable for the different types of fog at each site. In addition similar studies could be conducted for numerous other areas that frequently experience fog. This region could be contrasted with similar locations such as Southern New Jersey or more inland locations on the other side of the Chesapeake Bay.

REFERENCES

Aguado, E., and Burt, J.E. 2013. *Understanding Weather and Climate*. Upper Saddle River, NJ: Prentice-Hall.

Ahrens, C.D. 2013. *Meteorology Today: An Introduction to Weather, Climate, and the Environment*. Belmont, CA: Brooks/Cole.

Ashley, W.S., Strader, S., Dziubla, D.C., and Haberlie, A. 2015. Driving Blind: Weather-Related Vision Hazards and Fatal Motor Vehicle Crashes. *Bulletin of the American Meteorological Society* 96(5):755-778.

Bendix, J. 1994. Fog Climatology of the Po Valley. *Rivista Di Meteorologia Aeronautica* 54(3-4): 25-36.

Bendix, J. 2001. A 10-Years Fog Climatology of Germany and the Alpine Region Based on Satellite Data – Preliminary Results. In *Proceedings of the Second International Conference on Fog and Fog Collection*: St. John's, Canada, July.

Bendix, J. 2002. A Satellite-Based Climatology of Fog and Low-Level Stratus in Germany and Adjacent Areas. *Atmospheric Research* 64:3-18.

Bendix, J., Thies, B., Naub, T., and Cermak, J. 2006. A Feasibility Study of Daytime Fog and Low Stratus Detection with TERRA/AQUA-MODIS over Land. *Meteorological Applications* 13:111-125.

Bergot, T., and Guedalia, D. 1994. Numerical Forecasting of Radiation Fog. Part I: Numerical Model and Sensitivity Tests. *Monthly Weather Review* 122:1218-1230.

Bürki, R., Elsässer, B., and Abegg, B. 2003. Climate Change Impacts on the Tourism Industry in Mountain Areas. Paper presented at the 1st International Conference on Climate Change and Tourism, Djerba, Tunisia, April 2003. [http://breiling.org/

snow/djerba.pdf]. Last accessed 26 January 2015.

Canavan, T., and Sanford, W. 2007. Fog Climatology Near the Atlantic Coast of Nova Scotia. Poster presented at the 16th Conference on Applied Climatology, San Antonio, TX, January 2007. [https://ams.confex.com/ams/pdfpapers/116589.pdf]. Last accessed 8 July 2014.

Cermak, J., and Bendix, J. 2008. A Novel Approach to Fog/Low Stratus Detection Using Meteosat 8 Data. *Atmospheric Research* 87:279-292.

Court, A., and Gerston, R.D. 1966. Fog Frequency in the United States. *The Geographical Review* 56(4):543-550.

Croft, P.J., Darbe, D.L., and Garmon, J.F. 1995. Forecasting Significant Fog in Southern Alabama. *National Weather Digest* 19:10-16.

Croft, P.J., Pfost, R.L., Medlin, J.M., and Johnson, G.A. 1997. Fog Forecasting for the Southern Region: A Conceptual Model Approach. *Weather and Forecasting* 12: 545-556.

Ellrod, G.P. 1995. Advances in the Detection and Analysis of Fog at Night Using GOES Multispectral Infrared Imagery. *Weather and Forecasting* 10:606-619.

Friedlein, M.T. 2004. Dense Fog Climatology. Chicago O'Hare International Airport, July 1996 – April 2002. *Bulletin of the American Meteorological Society* 85(4):515-517.

Garcia-Garcia, F., and Zarraluqui, V. 2008. A Fog Climatology for Mexico. *Die Erde* 139(1-2): 45-60.

Garmon, J.F., Darbe, D.L., and Croft, P.J. 1996. Forecasting Significant Fog on the Alabama Coast: Impact Climatology and Forecast Checklist Development. *NWS Tech. Memo. NWS SR-176*, 16 pp.

Gómez Martín, M.B. 2005. Weather, Climate and Tourism: A Geographical Perspective. *Annals of Tourism Research* 32(3):571-591.

Haeffelin, M., et al. 2010. PARISFOG: Shedding New Light on Fog Physical Processes. *Bulletin of the American Meteorological Society* 91(6):767-783.

Leipper, D.F. 1994. Fog on the U.S. West Coast: A Review. *Bulletin of the American Meteorological Society* 75(2):229-240.

NOAA [National Oceanic and Atmospheric Administration]. 1998. ASOS User's Guide. *Government Printing Office*. [www.nws.gov/asos/aum-toc.pdf]. Last accessed 4 October 2016.

O'Hara, B.F. 2011. Synoptic Climatology of Significant Fog Events at Trukee, California. *National Weather Digest* 35(1):83-90.

Peace, R.L. 1969. Heavy-Fog Regions in the Conterminous United States. *Monthly Weather Review* 97(2):116-123.

Stone, R.G. 1936. Fog in the United States and Adjacent Regions. *The Geographical Review* 26(1):111-134.

Tardif, R., and Rasmussen, R.M. 2007. Event-Based Climatology and Typology of Fog in the New York City Region. *Journal of Applied Meteorology and Climatology* 46:1141-1168.

Tardif, R., and Rasmussen, R.M. 2010. Evaporation of Nonequilibrium Raindrops as a Fog Formation Mechanism. *Journal of the Atmospheric Sciences* 67:345-364.

Teixeira, J., and Miranda, P. 2001. Fog prediction at Lisbon Airport using a one-dimensional boundary layer model. *Meteorological Applications* 8:497-505.

The Daily Times. 1997. Fog Blamed in Bus Crash. *The Daily Times*. Salisbury, Maryland. November 1, pp. 1-2.

Westcott, N.E. 2007. Some Aspects of Dense Fog in the Midwestern United States. *Weather and Forecasting* 22:457-465.

Westcott, N.E., and Kristovich, D.A.R. 2009. A Climatology and Case Study of Continental Cold Season Dense Fog Associated with Low Clouds. *Journal of Applied Meteorology and Climatology* 48:2201-2214.

Wicomico County Board of Education (WCBOE). 2016. Personal communication. May 24, 2016.