Comparing solar radiation trends over the Laurentian Great Lakes

Myles C Walimaa

Abstract

Human activities, such as burning fossil-fuels, have increased atmospheric aerosol concentrations worldwide since the industrial revolution. Aerosols are miniscule solid particles suspended in the atmosphere that absorb or reflect solar energy back into space. A consequence of this is a decrease in solar radiation reaching the Earth's surface, a phenomenon called "global dimming." The effects of global dimming may include lower gross primary production in plants, decreased evaporation rates, and lower surface temperatures. Due to the air quality regulations passed in the nineteen-eighties, many regions have experienced a reversal of the negative trend, conversely called "global brightening." The purpose of this study is to explore the dimming and brightening patterns over the Great Lakes region. Because the monitoring stations under analysis are all located in the Great Lakes region, I hypothesize that the solar radiation patterns will be similar to each other and will depict a tendency toward brightening. To test the hypothesis, I gathered the available longwave and shortwave radiation data from the Great Lakes Evaporation Network (GLEN) monitoring stations located in lakes Superior, Huron, Michigan, and Erie. This data was then compared to the long-term data collected by the Baseline Surface Radiation Network (BSRN) station in Bondeville, IL. A clear understanding of the surface radiation trends over the Great Lakes could give us insight on future evaporation rates and climate patterns, as well as how to conserve these large bodies of freshwater.

Introduction

The Great Lakes have fascinated people for eons: from stories of creation, to the graveyard of ships. Part of what makes ecosystems of the Midwest so unique is how the Great Lakes influence the region's climate. Because they hold the largest reservoir of fresh water in the world, Northern Michigan and Southern Ontario are prone to temperate summers and severe winters. Local weather patterns are highly influenced by the Lakes' patterns of evaporation and thermal cooling, which is dependent on the levels of solar radiation the region receives (Lenters 2004). Industrialization is associated with decreased radiation levels and increased aerosol concentrations (Cermak et al. 2010; Haywood et al. 2011; Wild et al. 2005). Because of this, it is possible that this phenomenon of decreasing solar radiation, coined "global dimming," began during the industrial revolution in the mid-1800s. Today, developing nation show signs of dimming and is likely linked to their development of industrial infrastructure (Wild et al. 2005; Cermak et al. 2010; Haywood et al. 2011). Climatological stations around the world have recorded an increase in solar radiation from 1985 to present, likely associated with the passing of air quality regulations (Wild et al. 2005; Stjern et al. 2009; Cermak et al. 2010; Haywood et al. 2011). This phenomenon opposite of global dimming is called "global brightening," which may affect evaporation patterns and ice cover on the Great Lakes.

Global dimming and brightening is attributed to the concentrations of aerosols, or solid particles suspended in the Earth's atmosphere (Wild et al. 2005; Stjern et al. 2009; Cermak et al. 2010; Haywood et al. 2011). Aerosols are extremely small particulates that can absorb radiation and prevent it from reaching the surface (Liepert 2002; Aguado and Burt 2015). Effects of this include aerosols scattering or reemitting radiation as heat in the upper troposphere, contributing to atmospheric warming, and preventing the very same radiation from reaching this surface of the earth (Liepert 2002; Cole-Dai 2010; Aguado and Burt 2015). Though the atmosphere warms, the surface cools due to reduced incoming radiation (Stjern et al. 2009; Cermack et al. 2010; Cole-Dai 2010). Atmospheric aerosols include volcanic ash, mineral dust, sea-salt, and anthropogenic emissions (Stjern et al. 2009; Cermack et al. 2010; Cole-Dai 2010; Haywood et al. 2010). Aerosols are the primary influence on the global dimming and brightening phenomenon.

Studies have shown that aerosols and greenhouse gasses work together to warm the troposphere (Liepert 2002; Wild et al. 2005). Interestingly enough, the crisis of global climate change did not become obvious until the monitoring stations on the surface began to notice a warming trend, coincidentally in the late 1990s after global brightening began (Wild et al. 2005). Though aerosol concentrations have been declining, higher temperatures introduce more water vapor into the atmosphere resulting in increased cloud formation (Haywood et al. 2011). Increased cloud formation is another factor in reducing surface temperatures because atmospheric water vapor (a greenhouse gas) scatters infrared wavelengths (Haywood et al. 2011). Due to the thermodynamic process of condensation, additional atmospheric warming occurs as the water vapor condenses to clouds and heat is released (Liepert 2002). Even though humans are working to remediate the air quality, feeling the full effect of climate change brings its own set of difficulties.

The trend in atmospheric warming is undeniable. Excessive aerosol emissions hid this trend from surface observations for nearly a century through global dimming. Now that air quality regulations are in effect, aerosol concentrations are thinning and solar radiation is increasing back to pre-industrial levels. However, increased atmospheric greenhouse gasses have been warming the atmosphere and surface temperatures are continuing to rise. This can have countless effects on the ecosystems of the world (Long et al. 2009).

The analyses in this study will focus on the Great Lakes. I will compare the incoming solar radiation data recorded from several Great Lakes Evaporation Network (GLEN) monitoring stations to examine brightening trends over the Great Lakes region in the Upper Midwest United States. The GLEN stations include Granite Island, Stannard Rock, White Shoal, Spectacle Reef, and Long Point lighthouses. In addition, it will be compared to radiation data collected from the nearest Baseline Surface Radiation Network (BSRN) station, which is located in Bondeville, IL. My hypothesis is that the stations solar radiation trends at each station will be following the same seasonal radiation patterns, including minor fluctuations, and have a trend toward brightening.

Methods

The instrumentation used to collect the radiation were pyrgeometers for longwave radiation and pyranometers for shortwave radiation (Granite Island 2018). The GLEN stations over the Great Lakes are built atop lighthouses located on islands or reefs in the Great Lakes. The ones used in this study are Stannard Rock (47.1835, - 87.2251), White Shoal (45.8422, - 85.1353), Spectacle Reef (45.7733, - 84.1367), and Long Point (42.5475, - 80.0592), located in Lakes Superior, Michigan, Huron, and Erie, respectively. The BSRN station in Bondville, IL, is located in a flat, rural, and grassy area (40.0667, - 88.3667). The geographic locations of these stations can be seen in Figure 1.

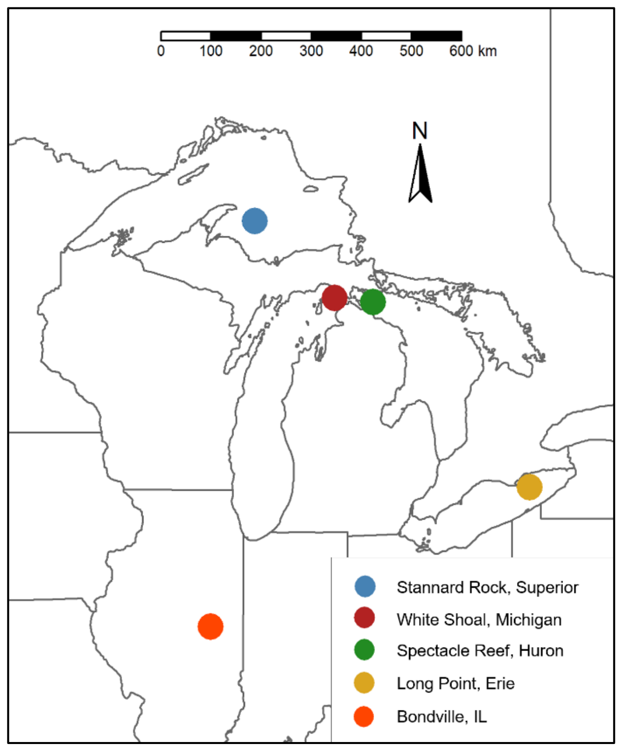

Figure 1. A map showing the locations of Stannard Rock and Bondville, as well as 3 of the other GLEN stations.

The Great Lakes Evaporation Network data was available on their website. The years available varied by station, with the largest range of 2009-2016 and a collection rate of 30 minutes. The ASCII text for each station was manually converted them to column-based comma delimited files using Microsoft Excel. The data was not checked for quality prior to uploading, so it was performed over the course of the study (Superior Watersheds n.d.).

Bondville radiation data were retrieved from the Baseline Surface Radiation Network from PANGAEA data portal. The years available were from 1995-2016 in monthly tab-delimited files, with a collection rate of 60 seconds. The data was reformatted in Microsoft Excel and exported as a comma-delimited file for use in R.

After organizing all the radiation data into manageable .csv files, R and RStudio were used for importing and analysis. The data was grouped into a single data frame by station. It was plotted for quality assurance, primarily to identify obvious outliers and missing data. Negative shortwave radiation values were changed to zero and missing data were converted to NAs. The GLEN stations White Shoal, Spectacle Reef, and Long Point were excluded from this study due to insufficient data or inaccurate data. For Bondville and Stannard Rock, total radiation was calculated by summing shortwave and longwave radiation. The data was summarized by monthly, seasonal, and yearly means, by station. The Mann-Kendall non-parametric statistical test was used for all of the monthly, seasonal, and yearly time-series analyses. This test is typically used by climatologists for analyzing a time series (Basarir et al. 2018). Kendall's Tao is used to show a positive or negative trend. In this study, p-values below 0.05 were considered significant and p-values below 0.1 were considered marginally significant.

The ratio of monthly means at Stannard Rock to Bondville were plotted over the years 2011-2016. A linear model was produced to test if there was a significant positive or negative trend to the ratios, which would determine if the ratio was changing over the course of the time-series. In addition, the monthly radiation means at both stations were plotted with each other for a visual inspection of their slopes over the annual climate variation.

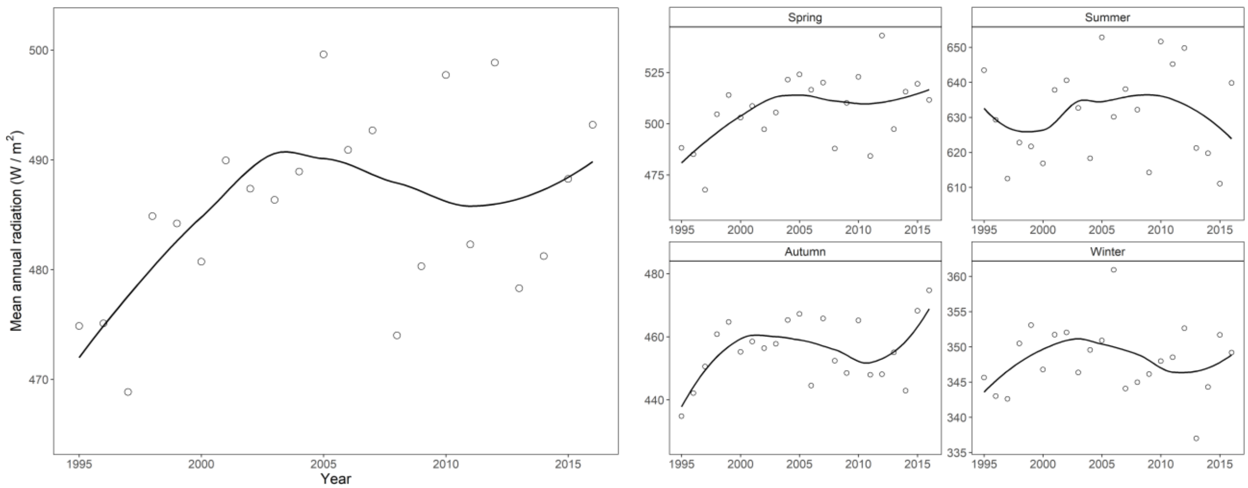

Figure 2. The solar radiation for Bondville, Illinois, as yearly and seasonal means for the years 1995-2016. The trendline is loess smoothing to help with visualization.

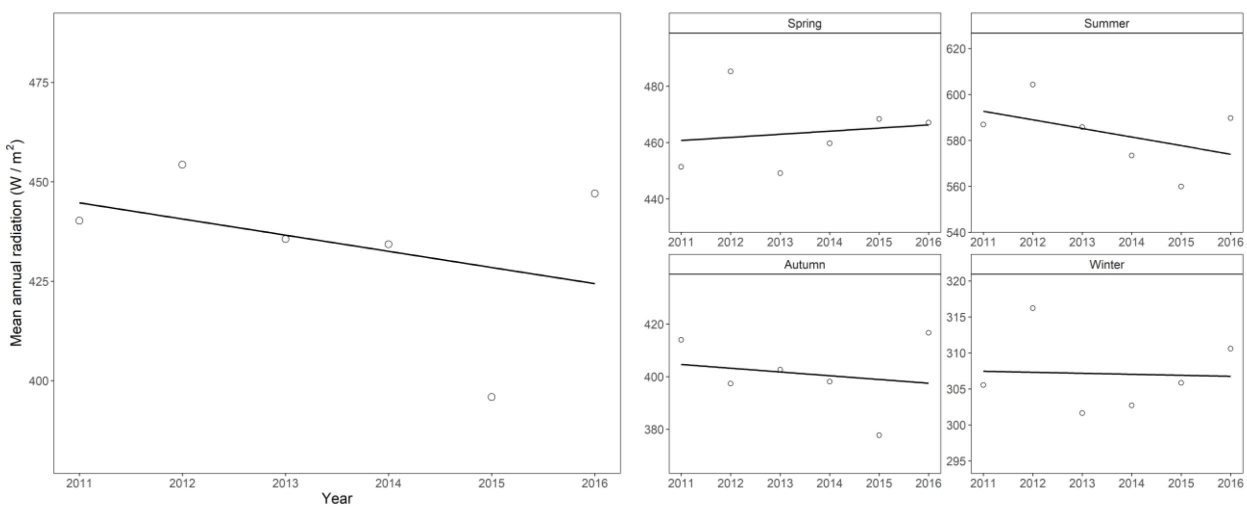

Figure 3. The solar radiation for Stannard Rock, Michigan, as yearly and seasonal means for the years 2011-2016. The trendline is la linear regression to help with visualization.

Results

The Mann-Kendall test at the Bondville station showed with marginal significance that solar radiation levels tended to be greater toward the end of the time series (tau = 0.30, p = 0.055) (Figure 2). In addition, the spring season showed the same pattern with significance (tau =

0.31, p = 0.048) (Figure 2). Stannard Rock showed no significant trends for either yearly or seasonal trends (Figure 3). The linear regression comparing the ratios of monthly solar radiation means between the Stannard Rock and Bondville stations was insignificant (p = 0.39), showing that the monthly means between the two stations are neither diverging nor converging (Figure 4).

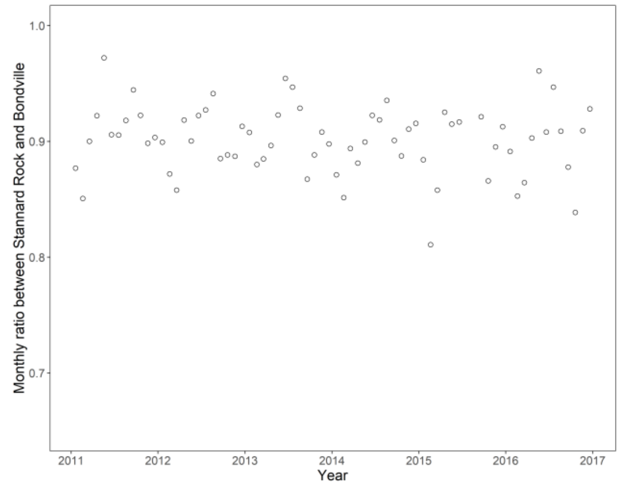

Figure 4. The ratio of monthly means of Stannard Rock to Bondville over the years 2011-2016.

Figure 5 shows the monthly means of solar radiation for Bondville and Stannard Rock. A visual inspection of the Figure 5 indicates that, though Stannard Rock values are lower, the slopes at each point are very similar with the exception of missing data in July 2015.

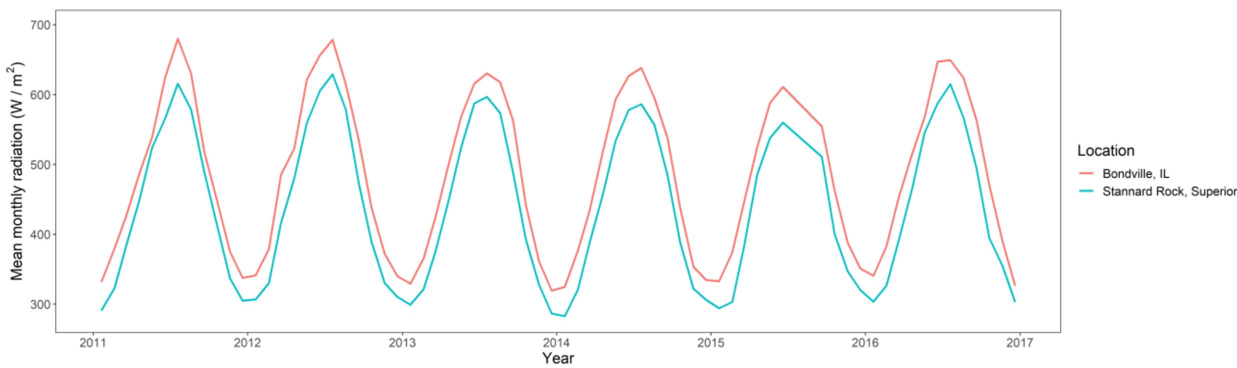

Figure 4. A sinusoidal graph of Bondville and Stannard Rock monthly means from the years 2011-2016.

Discussion

The results of this analysis show with marginal significance that the Bondville station is brighter now than it was 26 years ago. While each season is not necessarily experiencing an increase in solar radiation individually—though springs are statistically brighter at Bondville—the overall radiation values have been increasing. This coincides with the current literature revealing that there is a brightening trend across developed nations in the northern hemisphere (Wild et al. 2005; Stjern et al. 2009; Cermak et al. 2010; Haywood et al. 2011). There is an obvious dip in the brightening trend around 2014 as seen in Figure 4, which is likely due to increased cloud cover during those years (Cermack et al. 2010). A future study could investigate possible explanations for this. Evaporation rates have been increasing over Lake Superior and this idea could be worth exploring (Lenters 2004).

Because there is no significant trend between the ratios of average monthly radiation at Stannard Rock and Bondville, in addition to comparing the slopes at each point in Figure 3, both stations seem to be experiencing the same radiation patterns for the past six years. Even though Standard Rock experiences lower overall radiation, it is reasonable to believe that it is also brighter now than it was in 1995. The geographic locations of White Shoal and Spectacle Reef relative to both Bondville and Stannard Rock suggest that they have this same tendency (Figure 1).

The implications of increasing radiation over a boreal ecosystem could be dangerous. While carbon sequestration and growth rates will increase, a model by D'Orangeville et al. (2018) suggests that these benefits will be short lived. An extended growing season allows broadleaf deciduous species to transition further north. Additionally, more radiation and lower snow accumulation may not provide adequate water levels throughout the growing season, affecting forests and wetlands that rely on high water levels for homeostasis. Species such as balsam fir, white birch, and black spruce are sensitive to both warm temperatures and low water levels and are expected experience population declines, effectively altering the composition of the northern boreal ecosystems (D'Orangeville et al. 2018).

Conclusion

This study confirmed my hypothesis, with marginal significance, that the Great Lakes region is experiencing brightening along with the rest of the world. The greatest limitation in this analysis is the amount of data available from the GLEN stations. By definition, climatic trends occur over a course of 30 years and this analysis used less than a quarter of that. The Great Lakes Evaporation Network is still a recent initiative and the data collected by the Stannard Rock station seems to be following the same radiation patterns as the Bondville station—the closest long-term collector of solar radiation data. This study could be repeated in the future, yielding more significant results.

Literature Cited

Aguado E, Burt JE (2015) Understanding Weather and Climate, Seventh Edition. Pearson Education, Inc, Glenview, IL

Basarir A, Arman H, Hussein S, et al (2018) Trend detection in annual temperature and precipitation using Mann–Kendall test—A case study to assess climate change in Abu Dhabi, United Arab Emirates. Fırat S, Kinuthia J, Abu-Tair A (eds) Proceedings of 3rd International Sustainable Buildings Symposium (ISBS 2017). Springer International Publishing, pp 3–12.

Cermak J, Wild M, Knutti R, et al (2010) Consistency of global satellite-derived aerosol and cloud data sets with recent brightening observations. Geophysical Research Letters 37. doi: 10.1029/2010GL044632

Cole-Dai J (2010) Volcanoes and climate: Volcanoes and climate. WIREs Clim Change 1:824–839. doi: 10.1002/wcc.76

D'Orangeville L, Houle D, Duchesne L, et al (2018) Beneficial effects of climate warming on boreal tree growth may be transitory. Nat Commun 9. doi: 10.1038/s41467-018-05705-4

Great Lakes Evaporation Network – Home (n.d.). https://superiorwatersheds.org/GLEN/data.htm. Accessed 30 Apr 2019

Grolemund G, Wickham H (2011) Dates and Times Made Easy with lubridate. Journal of Statistical Software, 40(3), 1-25. URL http://www.jstatsoft.org/v40/i03/

Haywood JM, Bellouin N, Jones A, et al (2011) The roles of aerosol, water vapor and cloud in future global dimming/brightening. Journal of Geophysical Research Atmospheres; Washington 116. doi: http://dx.doi.org/10.1029/2011JD016000

Lenters JD (2004) Trends in the Lake Superior Water Budget Since 1948: A Weakening Seasonal Cycle. Journal of Great Lakes Research 30:20–40. doi: 10.1016/S0380-1330(04)70375-5

Liepert BG (2002) Observed reductions of surface solar radiation at sites in the United States and worldwide from 1961 to 1990. Geophysical Research Letters 29:61-1-61–4. doi: 10.1029/2002GL014910

Long CN, Dutton EG, Augustine JA, et al (2019) Significant decadal brightening of downwelling shortwave in the continental United States. Journal of Geophysical Research: Atmospheres. doi: 10.1029/2008JD011263@10.1002/(ISSN)2169-8996.DIMBRIGHT1

McLeod, AI (2011) Kendall: Kendall rank correlation and Mann-Kendall trend test. R package version 2.2. https://CRAN.R-project.org/package=Kendall

R Core Team (2019) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Stjern CW, Kristjánsson JE, Hansen AW Global dimming and global brightening—an analysis of surface radiation and cloud cover data in northern Europe. International Journal of Climatology 29:643–653. doi: 10.1002/joc.1735

RStudio Team (2015). RStudio: integrated development for R. RStudio, Inc., Boston, MA http://www.rstudio.com/

Wickham, H (2016) ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York.

Wickham H, François R, Henry L et al (2019) dplyr: A Grammar of Data Manipulation. R package version 0.8.0.1. https://CRAN.R-project.org/package=dplyr

Wild M, Gilgen H, Roesch A, et al (2005) From Dimming to Brightening: Decadal Changes in Solar Radiation at Earth’s Surface. Science 308:847–850

Photos of Granite Island Light Station - Lake Superior - Power Systems (2018). http://www.graniteisland.com/powerp.shtml#UofNstation. Accessed 30 Apr 2019.