High-Resolution Analysis of Cloud-Radiation Feedback Systems During Hurricanes

Abstract

Earth's solar reflectance, or albedo, is one of the most significant influences on climate change. Over the past decade we've observed an alarming decrease in albedo, which effectively means that Earth is absorbing more solar energy. However, one consequence of this is an increase in the intensity and frequency of hurricanes -- and since the low-lying clouds associated with hurricanes are especially reflective, we expect to observe a cloud-radiation feedback system that "self regulates" global warming to some degree. Although previous analyses have identified a strong positive correlation between cloud cover and albedo, no work has been done to understand these trends during severe spikes in cloud cover during hurricanes. So we used high-resolution cloud data from the GOES satellite and solar flux data from the CERES instruments to identify trends in the northern Atlantic, a hotbed of tropical storm activity. After correcting the data and deriving the desired values, we performed a superposed epoch analysis to filter out extraneous signals and isolate the relationship between cloud cover and albedo. Our results strongly support previous conclusions on the positive correlation between cloud cover and albedo. However, we also identified interesting patterns in the timing and rate of albedo variations surrounding cloud cover spikes, for which we were unable to identify any underlying physical phenomena and warrant further study. This analysis will soon be repeated with data from BBSO's Earthshine project, which will help us understand the evolution of Earth's climate in light of extreme global warming.

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1. Introduction

1.1. Earth's Albedo

Earth's albedo, or solar reflectance, is the proportion of incoming solar energy (shortwave radiation) that is scattered back into space. This reflected energy significantly effects Earth's energy balance, as change in our climate can be broadly attributed to the interplay of solar intensity, terrestrial albedo, and greenhouse gas insulation (Goode et al., 2021). Since the late-1990's, albedo variations and their impact on Earth's climate were (and probably still are) the least understood of those three parameters and has been fiercely debated over centuries (Gray et al., 2010; Intergovernmental Panel on Climate Change, 2009).

The launch of NASA's CERES (Clouds and Earth's Radiant Energy System) instruments aboard various low-Earth orbit satellites in 2000 marked the beginning of an era of high-quality terrestrial reflectance data. Specifically, they measure top-of-atmosphere (TOA) shortwave (SW) and longwave (LW) radiative fluxes in order to extend previous climate data records with two to three times less error (Wielicki et al., 1996).

At the same time, the Earthshine Project began in Big Bear Solar Observatory (BBSO) in the mid-1990's to measure the Earth's albedo by observing the Moon with a technique pioneered nearly a century ago (Danjon, 1928). Earthshine can be understood as the sunlight reflected off of the dayside Earth to the dark side of the Moon as seen from Earth, depicted in Figure 1.

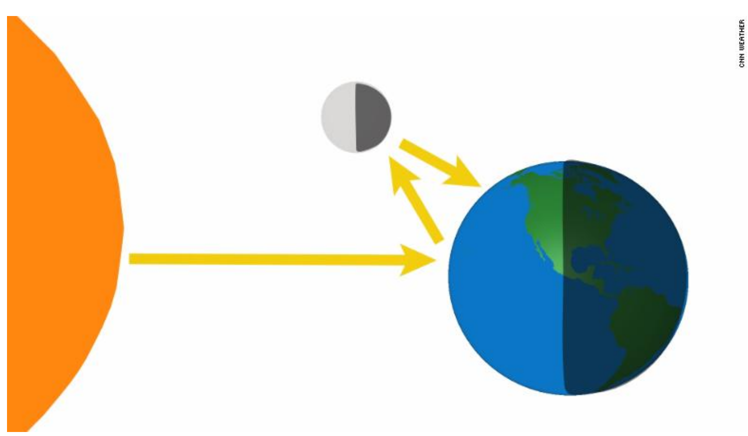

Figure 1: Diagram of earthshine

The CERES and Earthsine measurements compliment each other nicely. This is because CERES uses bi-directional reflectance models to infer the "Bond" albedo, or light reflected more perpendicular to Earth, whereas earthshine measures light reflected at wide angles (Loeb et al., 2012).

A recent landmark paper by Goode et al. provided the first comprehensive summary report of Earthshine Project findings over the past two decades. They found striking agreement between inter-annual earthshine and CERES albedo measurements, clearing up previous criticisms of strong anti-correlation between the two time series. The CERES team has also discarded the possibility of long-term calibration issues causing a dirft in the data, further increasing our confidence in current albedo trends. But more importantly, the earthshine albedo showed a gradual but climatologically significant ~$0.5\ W/m^2$ decline in the global albedo over the past two decades (Goode et al., 2021). In plain language, this means that the earth is absorbing more sunlight than it was before — a significant concern for global warming.

1.2. Cloud/Radiation Feedback Systems

As the Earth gets warmer, we observe a rise in atmosphere/water surface temperatures which intensifies evaporation of the oceans, transferring more energy from oceans to air (Loeb et al., 2018). We expect this to provide more "fuel" to tropical storms (especially on the east coast), increasing the frequency of hurricane formation and overall intensity/size. More importantly, the associated increase in low-lying cloud cover would serve to increase Earth's albedo. This is because low-lying clouds are highly reflective and there's no cancellation between changes in short-wave (SW) and long-wave (LW) fluxes, compared to other cloud types for which SW and LW effects are similar in magnitude but opposite in sign (Goode et al., 2021). Effectively, this would result in a cloud/radiation feedback mechanism wherein global warming would "self-regulate" to some small extent.

Taking all of this into account, our research seeks to hone in on the association between the large spikes in cloud cover we observe during north Atlantic hurricanes and variations in Earth's albedo in order to better understand cloud/radiation feedback systems.

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2. Methodology

2.1. GOES Cloud Cover

Although the CERES instruments also measure cloud cover, we opted to use the Geostationary Operational Environmental Satellite (GOES) operated by the United States' National Oceanic and Atmospheric Administration (NOAA). Specifically, we used data from the GOES Sounder instruments ("GVAR_SND"), which was downloaded from NOAA's CLASS ordering system (avl.class.noaa.gov) over the "Northern Atlantic" region. We downloaded data for multiple north Atlantic hurricanes between 2000 and 2015, spanning the period from seven days before the hurricane formed to seven days after the hurricane dissipated.

The GOES sounder cloud products have three main advantages over the CERES products. First, over the same region captured by GOES's "North Atlantic scanner" ($21° \rightarrow 44°$ longitude to $-71° \rightarrow -28°$ latitude), the CERES instruments measures 968 pixels while the GOES satellite measures $45,657$ pixels — more than a 47 times increase in resolution. Second, the GOES sounder collects four measurements per day, while the CERES instruments only measure once per day. Finally, the sounder measures emitted radiation in 18 thermal infrared bands that are sensitive to temperature, moisture, and ozone, and reflected solar radiation. The advantage of sounder over imager instruments are their ability to measure vertical profiles of the atmosphere, which helps us isolate the low-lying clouds created by hurricanes.

Following from the last advantage, we chose to use band 13 measurements from the GOES sounder which which captures light at a $10.3\ \mu m$ wavelength. This is less sensitive than other infrared window bands to water vapor absorption, and therefore improves atmospheric moisture corrections and aids in identifying/classifying cloud particles and other atomspheric features. It also allows for accurate measurements at nighttime. As such, band 13 is primarily used for measuring the intensity of convective severe weather signatures in hurricanes (Schmit et al., 2005). Regardless of which band we use, later experimentation showed that all 18 bands are in general agreement during adverse events such as hurricanes.

2.1.1. Data Corrections

Although the GOES sounder offers great spatial, temporal, and wavelength resolution, that accuracy makes the data sensitive to many sources of variability and corruption.

The data were downloaded in netCDF format for processing and analysis. The cloud variables came as a set of "data frames", or 2D integer arrays corresponding to each measurement. Intuitively, this could be thought of as a series of 6-hourly "snapshots" or "frames" of the north Atlantic, with each "pixel" representing the raw satellite counts at that location. To visualize these, we wrote a Python script that uses NASA's Panoply tool to plot, project, and color-code individual data frames, as can be seen in Figure 2.

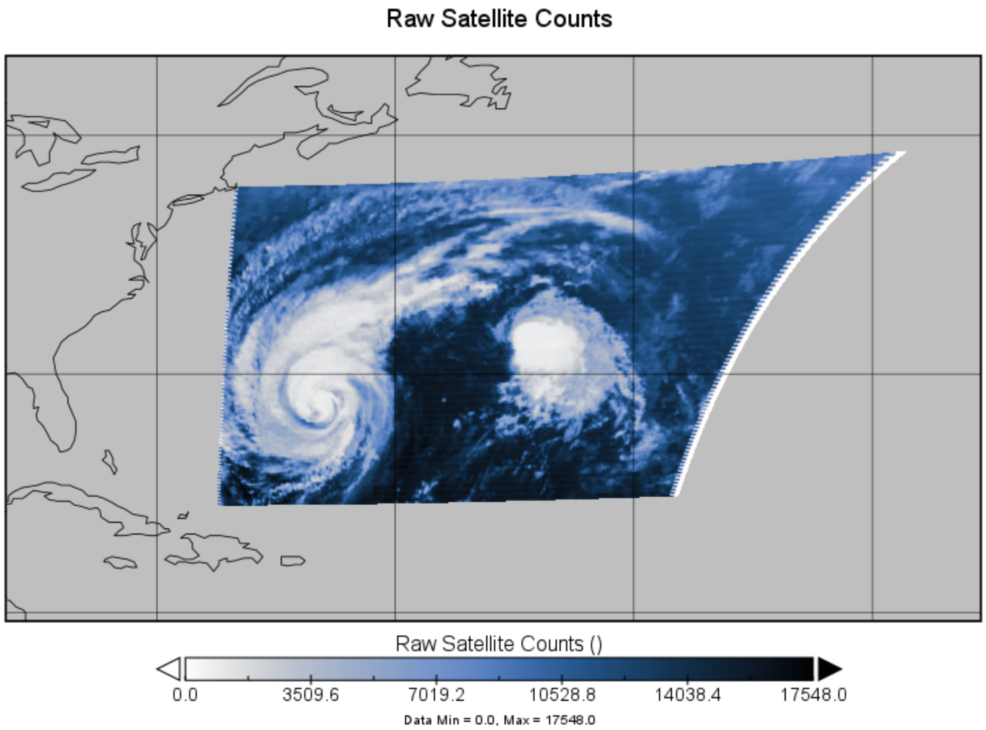

Figure 2: Visualization of low-lying cloud cover (~10.3 μm wavelength) over the north Atlantic on September 19, 2010 captured by GOES-12. The cloud group the left is Hurricane Igor, and the cloud group on the right is tropical storm Earl.

Since each time measurement came as a separate file, we began by using Python's Xarray library to concatenate the files into a single data frame, which was optimized for Numpy calculations and enabled us to make full use of Python's indexing capabilities and other searching algorithms. When visualized in series, we noticed that a portion of the daytime measurements had "hot pixels", or individual values that were absurdly large as seen in Figure 3. Our suspicion is that this is caused by cosmic rays flipping bits in the data — for fun, we noticed that after converting some of the "hot pixel" values to binary, they were sometimes one bit away from a number much closer to the surrounding pixel values. Regardless, this skewed the data so we corrected it by applying a median filter to regions with abnormally high values, which effectively "smoothed out" the values.

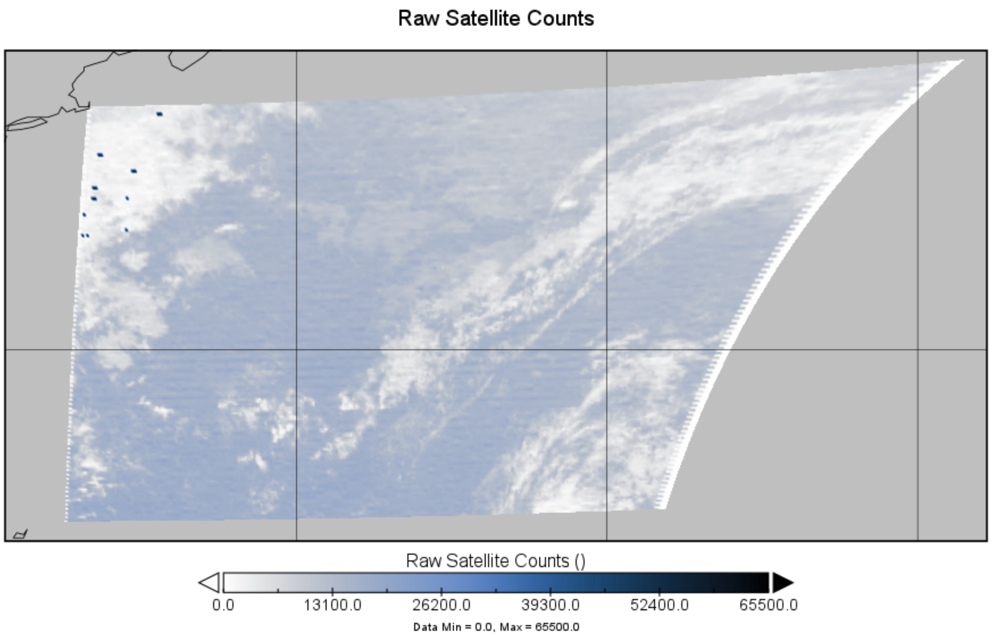

Figure 3: "Hot pixels" can be seen as dark spots in the top left, which skew the coloring of the entire plot. Notice how the maximum value here (~$65K$) is significantly larger than in Figure 2 (~$17K$).

2.1.2. Quantifying Cloud "Cover"

Having pre-processed the data, we were left a single file containing a series of 2D arrays/"snapshots" over the course of the hurricane. In order to quantify the "cloud cover" for a single instance in time, we used a nested for loop to calculate the percent of pixel values less than or equal to a certain threshold value, which we chose to be 10,000 satellite counts. This threshold was arbitrarily chosen based on Panoply visualizations, but we found that $\pm 25\%$ changes to the threshold value has little effect on the trends of the graph. Additionally, we will later perform a superposed epoch analysis which will correct for upwards/downwards shifts caused by threshold variability. Finally, we plotted the percent cloud cover versus time over the course of various hurricanes.

2.2. CERES Albedo Averages

Although we could order albedo quantities directly from CERES-EBAF-TOA-Ed4.1, we weren't satisfied with the regional and temporal resolutions. So we opted to derive the albedo ourselves, which required accessing the latest raw solar flux data sets from the CERES instruments (CERES-SYN1deg-Ed4A) downloaded from the NASA LARC ordering tool (ceres.larc.nasa.gov). These data comprise the period from March 2003 to present. For earlier dates, the all-sky fluxes used here were derived from CERES Terra between 03/2000 to

06/2002 and CERES Terra + Aqua from 07/2002 onwards. We downloaded hourly values of the TOA Shortwave Flux and the TOA Solar Flux variables, in the spatial range of $21° \rightarrow 44°$ longitude to $-71° \rightarrow -28°$ latitude (chosen to match the GOES "north Atlantic scanner" spatial range) with $1° \times 1°$ resolution.

The CERES data was in netCDF format as well. The albedo is derived by dividing the shortwave flux by the solar flux value (intuitively understood as the percent of all incoming sunlight reflected back into space), meaning all albedo values are between 0 and 1. To clean up the data and improve continuity, we first had to filter out nighttime measurements (as albedo is obviously zero at night) and average the remaining albedo measurements over the course of the daytime to remove extreme noise/variability. This leaves us with series of daily albedo dataframes or "snapshots", each of which can be visualized with a Python script and NASA's Panoply tool such as in Figure 4.

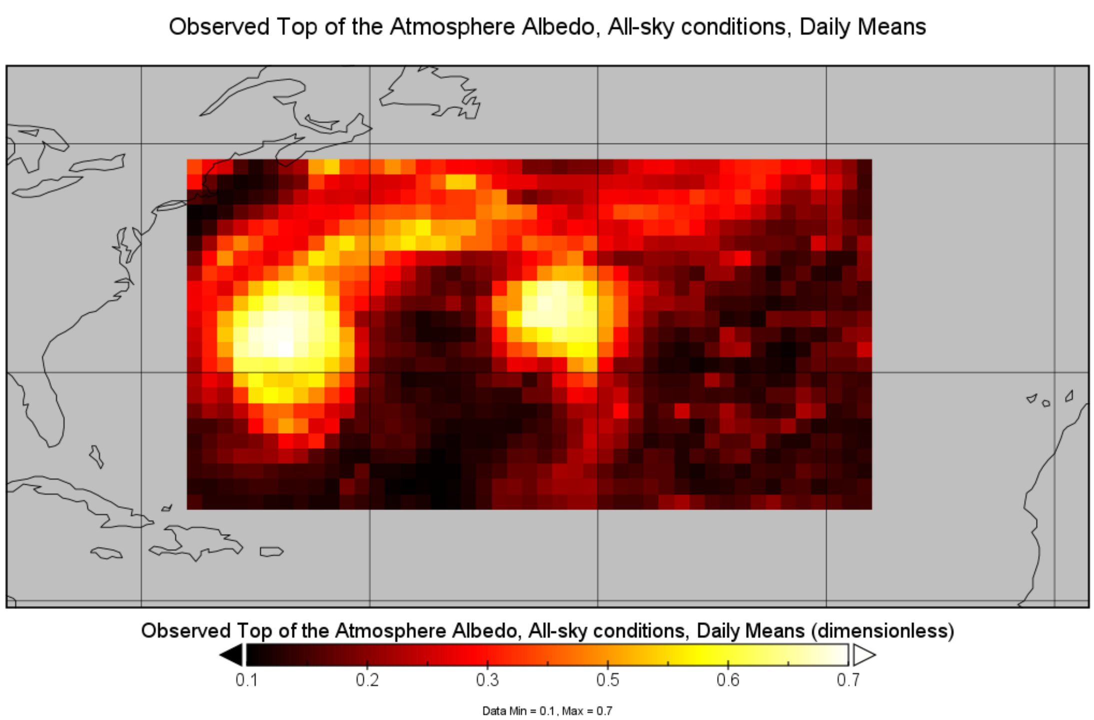

Figure 4: Albedo measurements from CERES instruments on September 19, 2010, plotted and colored with NASA's Panoply software. The bright spot on the left is Hurricane Igor, and the bright spot on the right is tropical storm Earl. Note the striking resemblance to Figure 2.

Having pre-processed the data, we used a nested for loop to find the average albedo value for each day. This was plotted against time over the course of various hurricanes.

2.3. Superposed Epoch Analysis

The "percent cloud cover" and "average albedo" measurements over time are mostly dimensionless, so naively plotting them on the same graph does not allow for trends/correlations to be recognized. So we used a technique called superposed epoch analysis, also known as Chree analysis after a paper by Charles Chree ("III. Some Phenomena of Sunspots and of Terrestrial Magnetism at Kew Observatory," 1913). This method of analysis is used in several geophysical disciplines either for testing the relationship between two diverse phenomena or to search for periodicities in the data. The general idea is that if we average the data in some meaningful way in relation to some event, then that event signal will remain and all other influences will tend to average out.

Since our analysis focuses on the effect of cloud cover on albedo, we manually selected for hurricanes which produced distinct "spikes" in cloud cover as they passed through our viewing window.We ended up choosing five out of the fifteen hurricanes we originally collected data on: Hurricanes Karl (2004), Bill (2009), Igor (2010), Sean (2011), and Sandy (2012).

To perform the analysis, we manually defined the peak cloud cover in each hurricane as "key times" and averaged together the cloud cover plots. We took the average albedo measurements over the corresponding time periods of each hurricane, averaged them together with the same "key time" signature, and then superposed, or plotted it against, the average cloud cover. Finally, we vertically scaled the graphs to minimize the square distance between datasets while preserving relative changes. From this, we could isolate periodicity/correlations between variations in cloud cover and albedo during hurricanes.

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3. Results

After processing the GOES cloud data and CERES solar flux measurements and averaging/superposing five hurricane events, we plotted cloud cover versus albedo over the north Atlantic in Figure 5:

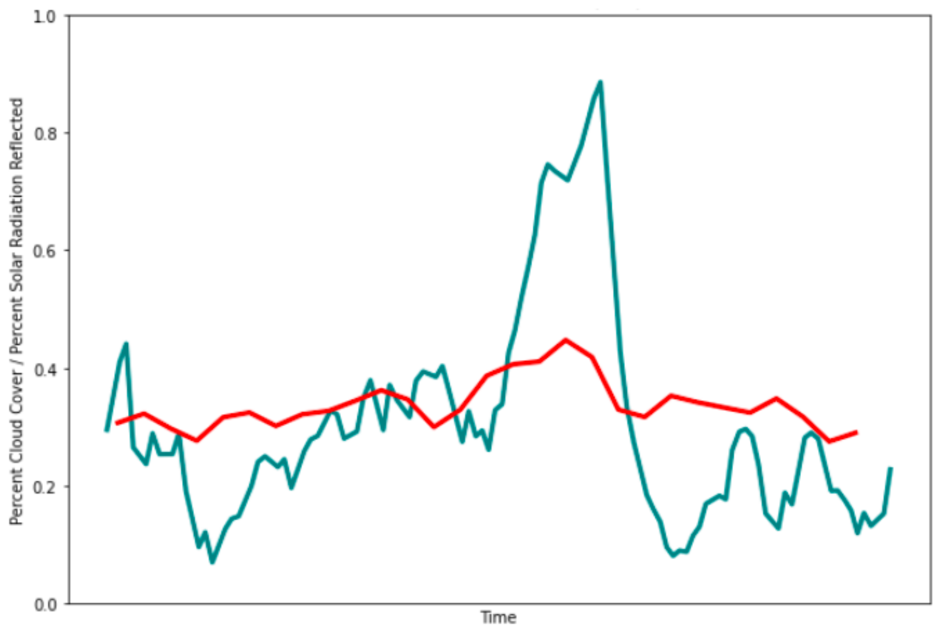

Figure 5: Superposed epoch of cloud cover (blue) versus average albedo (red) averaged over five northern Atlantic hurricanes.

However, the incomporable/dimensionless y-axes make this a poor way to gauge correlation. So we scaled the graphs to minimize the square distances between points to create Figure 6:

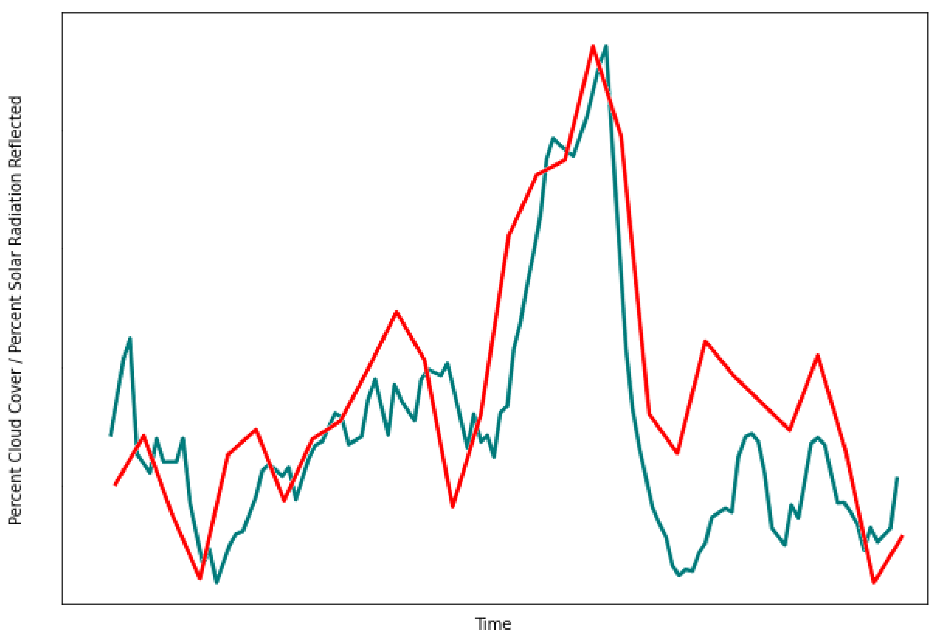

Figure 6: Superposed epoch of cloud cover (blue) versus average albedo (red) averaged over five northern Atlantic hurricanes — scaled to minimize square distance between points.

4. Discussion

As expected, our results in show remarkably strong correlation between cloud cover and albedo during hurricanes. This supports the idea that low-lying clouds are highly reflective and there's no cancellation between changes in short-wave (SW) and long-wave (LW) fluxes, compared to other cloud types for which SW and LW effects are similar in magnitude but opposite in sign.

Previous research has shown general correlation between cloud cover and albedo, but we looked at extreme "spike" events during hurricanes with high-resolution and corruption-corrected GOES data to gain a new perspective on this correlation. We noticed that in Figure 6, although the peaks of the cloud cover and albedo tend to line up, the periods before and after the main event have relatively higher albedo values than cloud cover, which is not typically present in time periods outside of hurricanes. Although this could just be an artifact of our scaling the graphs to line them up, this could also be a physical phenomena that warrants further study. In addition, both the averaged and individual superposed plots show the albedo peak to be "wider" than the cloud cover peak — that is, albedo begins to increase before cloud cover increaes, and albedo begins to decrease after cloud cover decreases. We coudn't find any literature to explain the underlying physical phenomena that causes this, so investigations could start by repeating this hurricane analysis but isolating more variables in the GOES cloud data such as other wavelengths, temperatures, and different layers of cloud cover (low/mid/upper atmosphere).

5. Conclusions

We sought to investigate the correlations between cloud cover and albedo over the north Atlantic region. Where our analysis differs from others is how we look at dramatic spikes in low-lying cloud cover during hurricanes and our processing/derivation of high-resolution GOES cloud data and CERES solar flux data. The original scope of this project was a comparison of cloud cover with the BBSO's new earthshine data, but unfortunately we were unable to obtain the data since December.

We identified five hurricanes that passed through our spatial window (Karl (2004), Bill (2009), Igor (2010), Sean (2011), and Sandy (2012)) and performing a superposed epoch analysis to average out extraneous signals and isolate the relationship between cloud cover and albedo. We found remarkable agreement between cloud cover and albedo trends as expected, but qualitatively noticed some strange phenomena in Figure 6 such as the main albedo peak being "wider" than the main cloud cover peak, and albedo increasing more dramatically than cloud cover in the periods right before and after the main spike. Further work should stratify the GOES data to isolate any physical causes of these phenomena, and also repeat this analysis with earthshine data to compare trends.

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6. Acknowledgements

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7. References

Danjon, A. (1928). Revue des Travaux Astronomiques. *L'Astronomie*, *42*, 572–581.

Goode, P. R., Pallé, E., Shoumko, A., Shoumko, S., Montañes-Rodriguez, P., & Koonin, S. E. (2021). Earth's Albedo 1998–2017 as Measured From Earthshine. *Geophysical Research Letters*, *48*(17). https://doi.org/10.1029/2021gl094888

Gray, L. J., Beer, J., Geller, M., Haigh, J. D., Lockwood, M., Matthes, K., Cubasch, U., Fleitmann, D., Harrison, G., Hood, L., Luterbacher, J., Meehl, G. A., Shindell, D., van Geel, B., & White, W. (2010). SOLAR INFLUENCES ON CLIMATE. *Reviews of Geophysics*, *48*(4). https://doi.org/10.1029/2009rg000282

III. Some phenomena of sunspots and of terrestrial magnetism at Kew Observatory. (1913). *Philosophical Transactions of the Royal Society of London. Series A, Containing Papers of a Mathematical or Physical Character*, *212*(484–496), 75–116. https://doi.org/10.1098/rsta.1913.0003

Intergovernmental Panel on Climate Change (Ed.). (2009). *Climate Change 2013 - The Physical Science Basis*. Cambridge University Press. https://doi.org/10.1017/cbo9781107415324

Loeb, N. G., Kato, S., Su, W., Wong, T., Rose, F. G., Doelling, D. R., Norris, J. R., & Huang, X. (2012). Advances in Understanding Top-of-Atmosphere Radiation Variability from Satellite Observations. *Surveys in Geophysics*, *33*(3–4), 359–385. https://doi.org/10.1007/s10712-012-9175-1

Loeb, N., Thorsen, T., Norris, J., Wang, H., & Su, W. (2018). Changes in Earth's Energy Budget during and after the "Pause" in Global Warming: An Observational Perspective. *Climate*, *6*(3), 62. https://doi.org/10.3390/cli6030062

Schmit, T. J., Gunshor, M. M., Menzel, W. P., Gurka, J. J., Li, J., & Bachmeier, A. S. (2005). INTRODUCING THE NEXT-GENERATION ADVANCED BASELINE IMAGER ON GOES-R. *Bulletin of the American Meteorological Society*, *86*(8), 1079–1096. https://doi.org/10.1175/bams-86-8-1079

Stephens, G. L., O'Brien, D., Webster, P. J., Pilewski, P., Kato, S., & Li, J. (2015). The albedo of Earth. *Reviews of Geophysics*, *53*(1), 141–163. https://doi.org/10.1002/2014rg000449

Wielicki, B. A., Barkstrom, B. R., Harrison, E. F., Lee, R. B., Smith, G. L., & Cooper, J. E. (1996). Clouds and the Earth's Radiant Energy System (CERES): An Earth Observing System Experiment. *Bulletin of the American Meteorological Society*, *77*(5), 853–868.

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8. Authors

Sophie Dengler is a junior at Rumson-Fair Haven Regional High School.

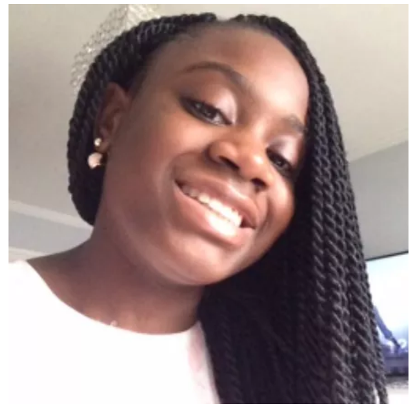
Aleksander Garbuz is a sophomore at Biotechnology High School.

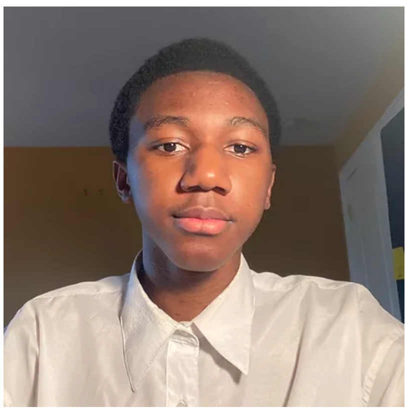
Moho Goswami is a senior at John F. Kennedy Memorial High School.

Andric Lu is a senior at the Academy for Biotechnology in the Morris County Vocational School District, which is located at Mountain Lakes High School.

Elaina Mann is a senior at Livingston High School. Her primary interest lies in computer science and applied physics.

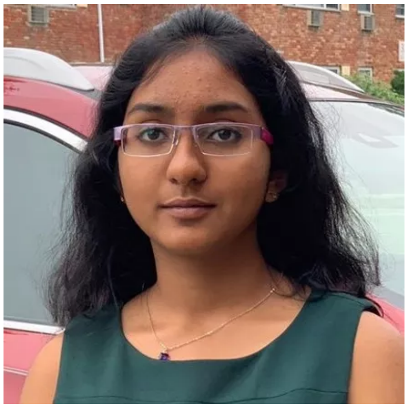
Deborah McDougall is a junior at East Orange STEM Academy High School.





Achunike Okafor is a junior at Science Park Magnet High School.

Chris Sebastian is a senior at Randolph High School.



Ananya Shrivastava is a junior at Parsippany Hills High School.

Shivam Syal is a senior in the electrical and computer engineering program at the Middlesex County Academy for Science, Mathematics and Engineering Technologies.

Zain Kamal is a freshman at Rutgers University studying computational physics and education. (Team Lead)