Title
Prototyping a Global Lightning Monitoring Array

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Publication Date
2018-06-01

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June 18, 2018

Acknowledgements:

I would like to express gratitude to all those involved in the conception, execution and completion of this project. Most importantly to my Capstone Advisory Committee (CAC): To Dr. Steven Constable Professor of Geophysics at the Institute of Geophysics and Planetary Physics at Scripps Institution of Oceanography for his expert instruction, guidance and assistance in scoping this research, funding and support in the installation of three recording stations, and for his code development and patience in direction. He was the mastermind behind the processing and managed to impart a few handy lessons on me while he was at it. Also, to Dr. Catherine Constable, Dr. Corey Gabriel, Cheryl Peach and Sam Shen, all of Scripps Institution of Oceanography, for their contributions by way of motivation and expertise with regard to the science, understanding and climate studies aspects of this endeavour.

A great deal of thanks is also owed to my Climate Science and Policy cohort for their continuous support, encouragement, prowess and friendship throughout this challenging year.

Additionally, a very sincere thank you to the consistently impressive and incredibly hardworking folk in the Marine EM Lab at the Institute of Geophysics and Planetary Physics: Jacques Lemire, John Souders, Jake Perez and Christopher Armerding.

Finally, a very special thank you to those that made the establishment of remote sites possible in a hurry: Oliver Ritter and Tobias Reise at Potsdam, Germany and to Goran Boren and Dr. Graham Heinson of the Geophysics department of The University of Adelaide (plus a shout out to Matt Blanchard and co. of XLI), without whom my adventure in Australian field installation and data acquisition could not have been a success.

The completion of this project would not be possible without the continued support from each of these individuals, my family and friends.

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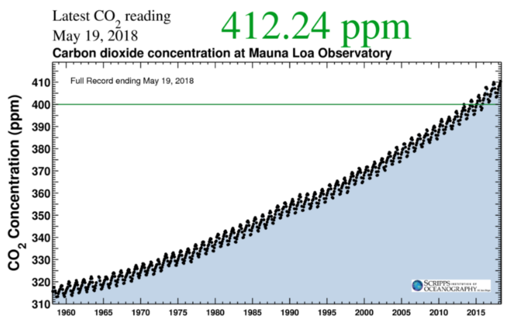

Figure 1: Keeling Curve

In 1988 the United Nations Environment Programme and the World Meteorological Organization established the Intergovernmental Panel on Climate Change (IPCC). This organization of more than 1,300 international scientists is tasked with evaluating the scientific, technical and socioeconomic information that can advance our understanding of climate change and it's effects as well as potential mitigation and adaptation strategies. Since its inception, the panel has not conducted new research nor monitored climate-related data. Rather, it tackles the challenge of informing international policy and negotiations on climate-related issues through a comprehensive assessment of published and peer-reviewed scientific, technical literature. Additionally, it aims to convey to the general public that the threat of climate change is no longer a distant one.

In the most recently released report, the IPCC announced that results obtained from multiple independently produced studies indicate that "the atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen." The combined land and ocean surface temperatures, averaged globally from 1880–2012, have increased 0.85 (0.65 to 1.06)°C.[1] The report also states that anthropogenic emissions of greenhouse gases are the highest in history and the human influence on the environment is clear.

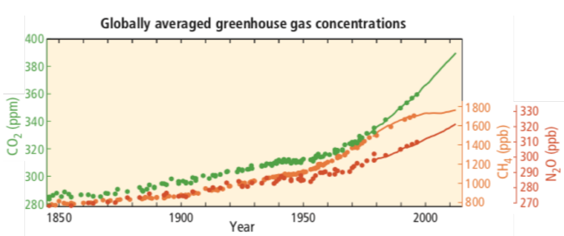

Figure 2: Atmospheric concentrations of the greenhouse gases determined from ice core data (dots) and direct atmospheric measurements (lines). Carbon dioxide (CO_2, green), methane (CH_4, orange) and nitrous oxide (N_2O, red).[1]

Continuous daily measurements made at the Mauna Loa Observatory since 1958 depict the rising curve of carbon dioxide (CO_2) concentrations (Figure 1). The trend of this, as well as other greenhouse gases, correlate with the global anthropogenic CO_2 emissions from the burning of fossil fuels, land use, such as forestry, as well as cement production and flaring (Figure 2).

The integrated work of the IPCC's three working groups concludes that "It is extremely likely that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together."[1] Furthermore, as global mean surface temperature increases, hot temperature extremes over most land areas will become more frequent, while cold temperatures extremes will diminish on daily and seasonal timescales (Figure 3).

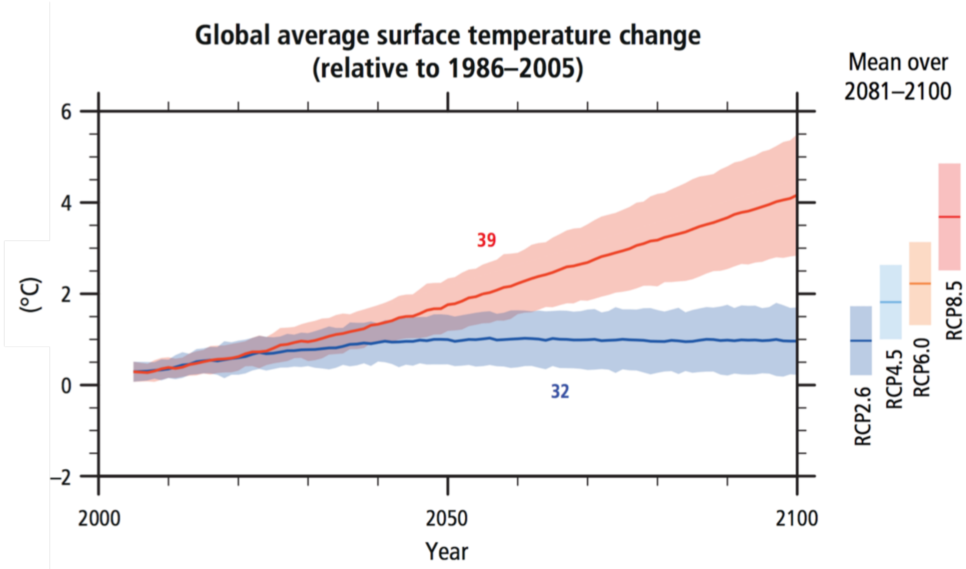

Figure 3: Multi-model simulations determine global average surface temperature change from 2006 to 2100, relative to 1986–2005. The time series of projections with a measure of uncertainty (shading) are shown for scenarios RCP2.6 (blue) and RCP8.5 (red). At the right, the mean and associated uncertainties averaged over 2081–2100 are given for all RCP scenarios.

To aid in the development of international awareness and policies that aim to ameliorate this trend, scientists strive to create models intended to predict future patterns. These models are constantly evolving as more scientific data becomes available. Modelers find ways to better incorporate and assimilate this additional data, taking full advantage of today's advancing computer resources. Developing accurate climate models remains difficult, however, as there is still much to know about the dynamic Earth system.

It is widely understood that our atmosphere allows shortwave solar radiation to pass through. This visible light is absorbed at and near the surface, converted to longwave radiation and re-radiated back to space. These infrared wavelengths are absorbed by the atmosphere, warming the near surface air. Greenhouse gases play a pivotal role in the extent of absorption and, therefore, warming. Water vapour is one such greenhouse gas but, due to its variability in the upper troposphere, concentrations are difficult to measure. Measuring atmospheric variables such as magnetic field disturbances has been proposed as a means of studying this complexity.[2]

The global lightning monitoring array proposed in this study would record lightning induced electromagnetic waves that could provide an independent source of data about global temperature, as well as the response of the entire troposphere to surface warming. This could help constrain uncertainty in observations and lead to more robust climate models. An array would also capture more information about the relationship between lightning and climate change while aiding in severe weather prediction, wildfire mitigation and furthering understanding of the extreme energy of lightning.

In this report, we will discuss the current techniques for measuring lightning and emphasize the advantage of magnetic measurements. Section 1 will also examine lightning's link to climate change and the relevance and application of magnetic measurements. Section 2 will describe the data acquisition followed by the processing and results of this pilot study in section 3. In the final section, we will briefly discuss possible follow up work to further the contribution of this method to climate and lightning hazard studies.

1.1 Lightning monitoring: Past, present and future

Historically, there has always been much interest in observing and monitoring lightning. It is a hazard for anyone who works outdoors or enjoys outdoor activities, for aviation, and for fire safety, which includes the associated effects of fire on infrastructure and the economy. It is also closely linked with severe weather, making it a meteorological focus. Given its importance to a broad range of stakeholders, it is not surprising that there exist worldwide, networks of ground-based detectors observing frequencies and electricity in the atmosphere. In addition, mobile detectors locate lightning using attenuation techniques - calculating distances of flashes using measured signal intensity.

NASA developed one such lightning detection and ranging system that ran from 1997 until 2008 near Kennedy Space Center. To examine the intricacies of regional cloud-to-ground lightning, the six detection antennas and central station were located in a hexagonal pattern and measured very high-frequency pulses. A small network of ground-based detectors based on this is still maintained in the Washington DC area as well as a few other US cities. The Lightning Mapping Array (LMA) is another network of ten ground instruments located in Washington, DC region and used to determine lightning activity in storms.

Monitoring efforts extending beyond the US include Vaisala, a private, commercial company originated by NASA, also uses ground-based detectors. Networks of hundreds of these detectors worldwide supply data to a central hub where it is aggregated to create what is advertised as a global dataset. In Europe, a non-commercial, ground-based lightning detection network exists. Blitzortung.org operates similar to a citizen science project, supplying very low-frequency lightning receivers to volunteers. These receivers transmit short periods of data over the Internet to a central processing server. The data transferred contains the geographic location of the receiver site and the precise time of arrival of the lightning strike impulse received at the site. The system is low cost but for now only in Europe, significantly limiting its scope. This is a notable disadvantage of most of these systems.

While real-time, localized measurements are useful for monitoring ground-based hazards, they are very local, regional or at most cover a large part of Europe with accuracy. Tropical areas, like Central Africa, are lightning prone areas too difficult to monitor due to a lack of infrastructure (roads, supplies, safety support.) The Southern hemisphere is largely unaccounted for. In addition, the traditional techniques are not infallible. Calculating the lightning location with reasonable error requires at least three stations to detect the lightning, so cloud to cloud lightning can easily be overlooked. Attenuation systems have the potential to mistake a closer, less intense flash as one that is more distant.

The satellite era has assisted with these limitations, advancing lightning datasets and understanding. Data the satellites furnish are a crucial part of scientific observation and model development. The International Satellite Cloud Climatology Project, for example, provides observations that have improved understanding of clouds. The hydrological cycle, as well as tropical cloud cover and supersaturation, is becoming more understood.[3] Other satellites aimed at detecting lightning and Schumann resonance have led to the discovery of the varying size of the ionosphere and the implication of this geometry on wave propagation.[4]

The Tropical Rainfall Measuring Mission (TRMM) was a research satellite that for more than seventeen years collected data to attain information on precipitation in the tropics and the heat release associated with it. The data was used in conjunction with other NASA Earth Observing System satellites to better understand the interaction and role of water vapour, clouds and precipitation in regulating the climate. The intention was to improve our knowledge of the distribution and variability of precipitation within the tropics. This furthered our grasp of weather and climate through a better understanding of the movement of major air masses around the planet. Mounted on TRMM was the Lightning Imaging Sensor (LIS). This instrument recorded the time and location of any lightning event it observed, as well as measured the energy radiating from the event. Although TRMM was decommissioned there is still an LIS onboard the International Space Station. The data is considered provisional, however, as the algorithm used to process observations is still in beta testing.

A compact set of optical and electrical devices known as the Optical Transient Detector

(OTD) also continues to observe global lightning activity. The OTD has a relatively small field of view, however; visibility can be limited by lighting conditions as well.[5] It also lacks the ability to capture inter-annual variability in lightning activity.[6] More recently, the Geostationary Operational Environmental Satellite series (GOES-16), a joint NASA-NOAA project launched in November 2016, integrated the Geostationary Lightning Mapper (GLM). The GLM boasts continuous detection of all forms of lightning between 52 degrees North and 52 degrees South with high resolution and efficiency, though the instrumentation is still in the experimental phase.

All of these satellites provide helpful information for studying long-term lightning characteristics and statistics more than the finer details. These systems also have inherent flaws and uncertainty associated with them. For instance, their ability to 'see' the lightning events require the lightning to be within their scope of vision. Also, the data collected can have gaps and interference that makes assembling and interpreting the information challenging.

With these limitations in mind, scientific research based on data from these lightning monitoring methods indicates that for every 1^{o}C rise in air temperature there is an increase in ionosphere potential, the potential difference between the Earth and the conductive upper atmosphere, of about 7%[7]. From this, scientists deduce an increase in global lightning activity that is well correlated with variations in global temperatures. A truly. global, real-time remote sensing array offers an alternative to the standard methods. Detecting small-scale changes in lightning will give better insight into the relationship between global lightning and global mean temperature. The ability to constrain the temperature dependence on lightning strikes will also reduce the uncertainties associated with the rise in the dangers of lightning to human populations as the planet warms.

1.2 Lightning's known link to Climate Change

In the broadest sense, climate is the condition of the environment based on the interaction of the Earth's atmosphere, oceans, land masses, cryosphere and biota. Solar radiation is the primary source of energy input into this system (refer to Figure 4). Due to our planet's spherical shape, the sun heats the Earth more in equatorial regions than polar regions leaving the oceans and atmosphere endlessly working to redistribute the heat energy. Ocean waters are constantly blending together, altering their physical properties, such as temperature and density. They also intermingle and exchange heat with the air above, a crucial process of the climate system. The air above expands and contracts, shifting its variable properties and entraining water molecules.

The concentration of water vapour in a saturated atmosphere is a function of temperature. In the troposphere, from the earth's surface to about 6–10 km, this water vapour

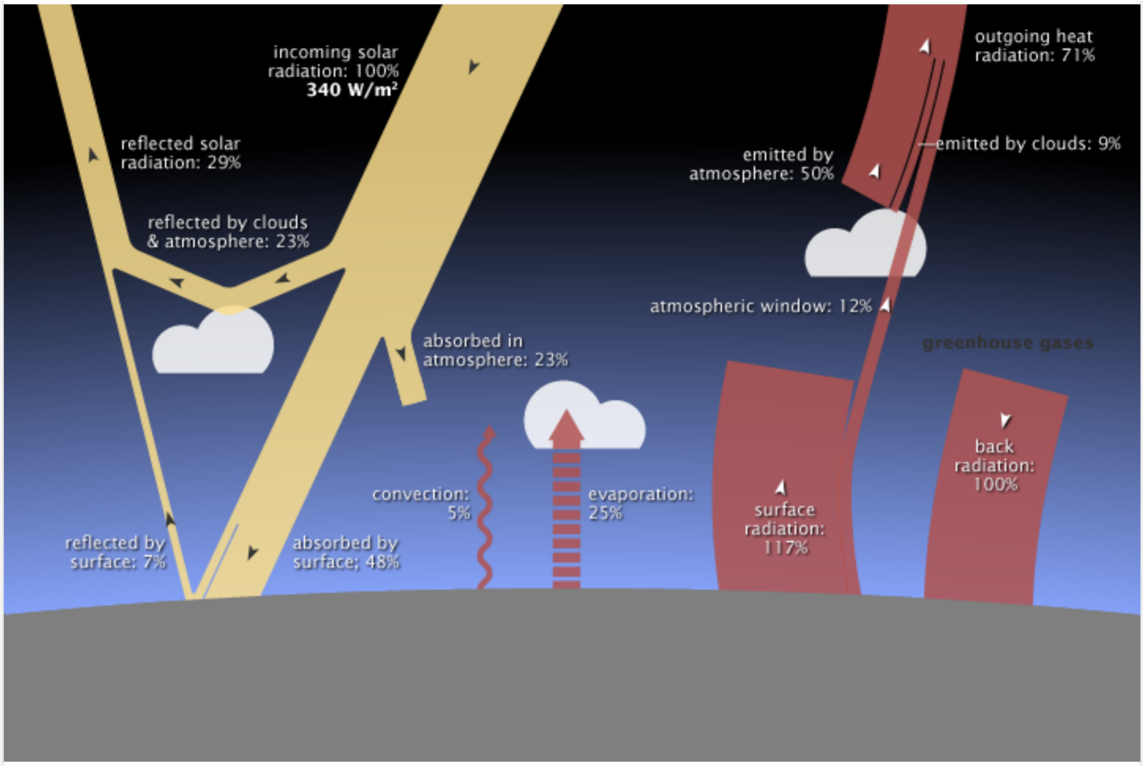

Figure 4: Clouds reflect incoming sunlight, impede radiation of heat from the Earth's surface to space and release heat to the atmosphere as they produce precipitation. More information is needed about clouds and their response to changes in climate in order to resolve their net effect on the energy budget. http://earthobservatory.nasa.gov/Features/EnergyBalance/page6.php

becomes a driving force of deep convection. Heating at the surface causes intense rising motion in this part of the lower atmosphere. As water molecules are lofted turbulently their charges separate, setting conditions needed for lightning to occur. With increasing temperatures lightning strikes will increase by about 12% per 1°C [8], predominantly over land[9]. This means a rise in the dangers of lightning to human populations as the planet warms. Along with an increase in lightning related deaths and injuries[10], lightning is a hazard to infrastructure through direct strikes and wildfires.

Moreover, the amount of water vapour in the troposphere, as well as the process of deep convection, are essential in the formation of clouds, where lightning is initiated. Understanding water vapour and clouds is crucial in climate modeling. As a key infrared absorber, water vapour is a primary greenhouse gas and plays a vital role in climate regulation.

Quantifying water vapour in the atmosphere, along with evaluating the associated clouds, is challenging due to the significant uncertainties associated with these elements. The disparate effect of different cloud properties influence the solar radiation budget, and yet most studies to date tend to be indirectly related to clouds and deep convection clouds but, contribute to their estimation in models.[11] A method of monitoring the global lightning activity associated with these clouds could enable integration of lightning into climate models that would further aid comprehension of the impact of water vapour and clouds.

In 1998 Martin Füllekrug suggested a remote, ground-based lightning detection system that could do this. His study surveyed the magnetic spectrum and distinct ionospheric and magnetospheric signals for frequencies above 1 Hz in order to observe the planet's lightning activity.[12]

1.3 Lightning and Earth's Electric Circuit

Measuring magnetic field variations to monitor lighting is made possible by the knowledge of the link between lightning and electricity. This has been studied since at least 18th century, when Benjamin Franklin performed his famous kite and key experiment. Since that time scientific experts have built on contributions like that made by C.T.R. Wilson in the early 1920's. Wilson studied the effect of the electric fields of thunderclouds on excited galactic particles that enter Earth's atmosphere.[13] The flux of incoming cosmic rays and solar energy play a large role in our atmosphere and therefore its electric conductivity.[14] This knowledge led to the development of the idea of a Global Electric Circuit, or GEC (Figure 5).

Thunderstorms in the troposphere are a primary source of power for this circuit.[14] Lightning generated by storm conditions can take several forms that range in frequency and altitude distribution through the atmosphere (transient luminous events, sprites, etc.) but, at any time there is lightning occurring somewhere on Earth. There is an average of 46 flashes a second[15] and this lightning contains enormous amounts of energy.
The strikes produce extremely low-frequency (3 Hz–3 kHz) and very low frequency (3–30 kHz) electromagnetic signals.[14] These waves propagate through the Earth's ionosphere, a region of the atmosphere where small packets of incoming electromagnetic radiation - short-wave energy - eject electrons when they engage with atmospheric gases. The low pressure at these altitudes allows the resulting charged particles to transport energy further[16], fostering this conductive section of the atmosphere.[17] The spherical corridor between Earth and the ionosphere acts as a waveguide for the lightning initiated electromagnetic signals. Minimal attenuation results in what is known as the Schumann resonance, at around 8 Hz and its harmonics (14 Hz, 20 Hz, 26 Hz, etc.).[14] . Schumann resonances have long been suggested as useful in tracking global lightning rates.[18]

Observations made by recording stations in the tropics reveal lightning's dependence on

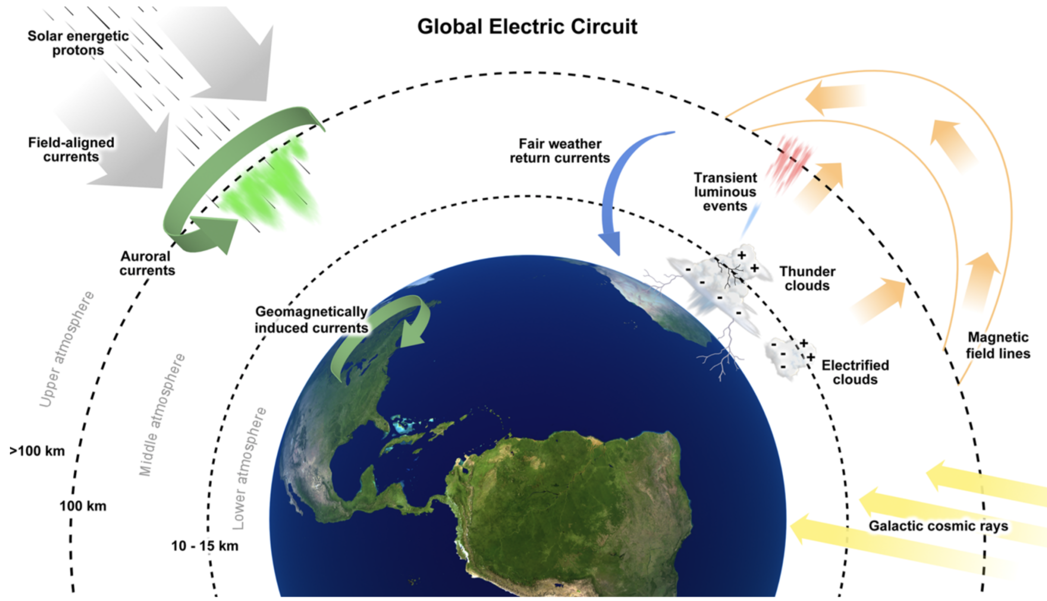

Figure 5: Due mostly to targeted NASA satellite missions we know an increasing amount about Earth's Global Electric Circuit. The figure depicts forces that alter the magnetosphere and ionosphere driving the circuit. (credit: Jeffrey Forbes, University of Colorado at Boulder, http://sisko.colorado.edu/FESD)

temperature. From this, scientists theorize that the temperature controls the convective available potential energy (CAPE) and CAPE, in turn, constrains the number of ice-particles, which are believed to be accountable for lightning formation. The GEC also appears sensitive to temperature as Schumann resonances amplitude fluctuations can be correlated to changes in temperature on a timescale of several years.[19] Accurate global observations that allow mapping of lightning distribution and intensity would provide information on the amount of energy that is driving the GEC and be a beneficial way to monitor and furthering our understanding of weather and climate. The installation of an array capable of such measurements, along with initial observations, are described in the sections that follow.

2 Data Acquisition and Methods

A global monitoring system of magnetotelluric systems to measure Extremely Low-Frequency (ELF) and Very Low-Frequency (VLF) radio waves would need to be operating consistently and provide reliable high quality data to further any real knowledge of the system that could be used toward models and predictions. A primary goal of this project was to take

Füllekrug's experiment an incremental step forward in this effort. Here we demonstrate how a small number of ground based measurements could be implemented swiftly and, using a consistent sample rate of 500 Hz across all three stations as well as improved timing accuracy, could enhance results.

2.1 Equipment and Site set-up

Our prototype array consists of three receivers deployed in three sites around the world: Borrego, California, USA, Wittstock/Dosse,Germany and Ngarkat State Reserve, Adelaide, Australia. These sites were selected based on several criteria including accessibility, long term ground support and, crucially, as little anthropogenic signal interference as possible. At each location we measure time and the magnetic field in North (B_N) and East (B_E) directions.

Each setup consisted of two orthogonal magnetic induction sensors and a computer logger. The magnetic induction sensors are metal coils wound in a specific way to ensure robust and highly sensitive detection of variations in the Earth's magnetic field. This field is oriented horizontally due to the vertical electric field of the radio waves emitted by a lightning discharge. The coils are sensitive to 0.3V/nT with a noise floor of about $10^{-14}T^2/Hz$ in the range of frequencies concerned here. The housing of these coil windings measures 56 inches in length and 2.4 inches in diameter and is made from a lightweight, high pressure fiberglass laminate. It is corrosion-resistant and very strong, but unlike steel or aluminum cylinders, will not induce a current. This is important because these sensors are shallowly buried underground, where they are sheltered from motional noise caused by weather and animal interference. As seen in Figure 6, each coil within its casing is place horizontally in a small trench at the site. The coil and the cables connecting it to the logger box are buried approximate six inches below the surface. One coil is precisely measured to be oriented North, B_N, while the second, East, B_E.

Figure 6: The logger and magnetic coil antennas are shallowly buried

The data acquisition unit (Figure 7) is repurposed from marine electromagnetic operations. The system assembly is made up of three boards. The main CPU an analog-to-digital daughter assembly and a 32-bit digitizing Seascan oscillator which includes a clock with timing accuracy of approximately 1 millisecond. The signal recorded from the coils is sent directly into the analog to digital converter and there is a ram buffer ensuring that the data is written to the memory card, an SD disk, only a minimum number of times. This not only saves power but insures less noise is generated on the data. The unit is powered by batteries and generates 7 volts with +/-5 analog which feeds the analog to digital converter in the amplifier boards. Rechargable batteries power the CPU, the oscillator, the analog to digital converter as well as the amplifiers inside the coils.

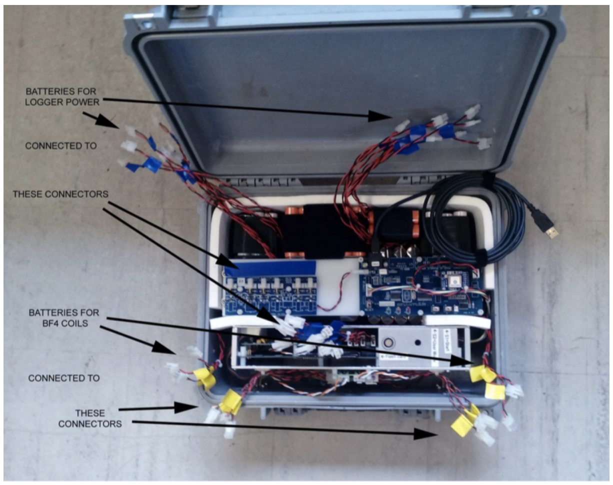

Figure 7: The data acquisition unit.
Credit: Jonathan Souders

The unit is slightly customized for this project. Whereas regular operation is manual, here an extra circuit board has been added in order to automate the process. With a press of a button it automatically synchronizes the clock to GPS. The CPU is keeping time as it would on the seabed, where GPS is not available, but the advantage to our land operation is the ability to align the data to GPS controlled pulse per second (PPS) before it is digitized. This PPS signal can be verified on channel 3 of the raw data recording. (Figure 8)

2.2 Data Processing and Analysis

The accurate GPS signal allows simultaneous recording of the raw data to be stored on the memory card in the time domain. Data is then manually downloaded from the memory card so it can be analyzed in Matlab. The initial dataset considered in this report is a simultaneous nineteen hour record from each of the three sites.

One challenge common to geophysical measurements such as this is noise contamination. A fast Fourier algorithm converts the time series to the frequency domain. We are then able to identify the primary source of interference in our ground-based measurements of atmospheric frequencies, electromagnetic fields created by power lines. The presence of human-made noise such as power lines can reduce our ability to hone in on the signals caused by lightning strikes. Care must be taken when subtracting noise from any dataset as it is possible to distort the signal if the wrong noise estimate is removed.[20] An initial examination of our dataset reveals varying noise characteristics over time. Using spectral

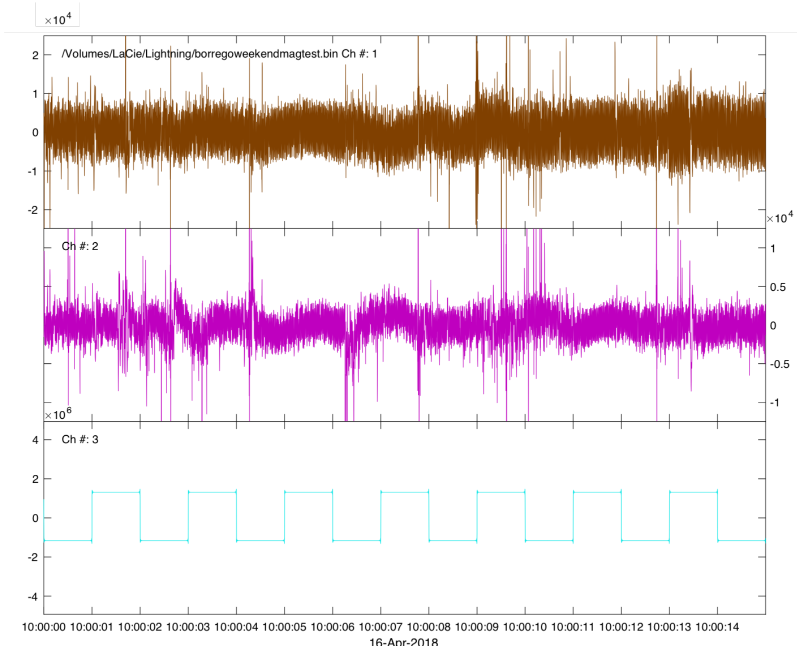

Figure 8: The raw time series: Channel 1 is the North component, Channel 2 the East and channel 3 the PPS

analysis, we identify the region dependent noise frequencies. (See Table 1 and Figure 9)

The frequencies are fixed, but as the amplitudes and phase of the noise can vary in time, we take an adaptive approach to removing it. We consecutively analyze two-second sections of the time series, carrying out a least-squares fit to the power line harmonics. The coefficients from this fitting are then used to generate a model of the power line noise for that two-second segment, which can then be subtracted from the data.

Borrego	**Wittstock**	**Ngarkat**
60.00	16.67	50.00
120.00	38.26	100.00
160.00	49.98	200.00
180.00	150.00	

Table 1: Spectral analysis is used to determine the different noise frequencies (Hz) resulting from the different power grids around the world. The table shows frequencies of power line noise that we removed

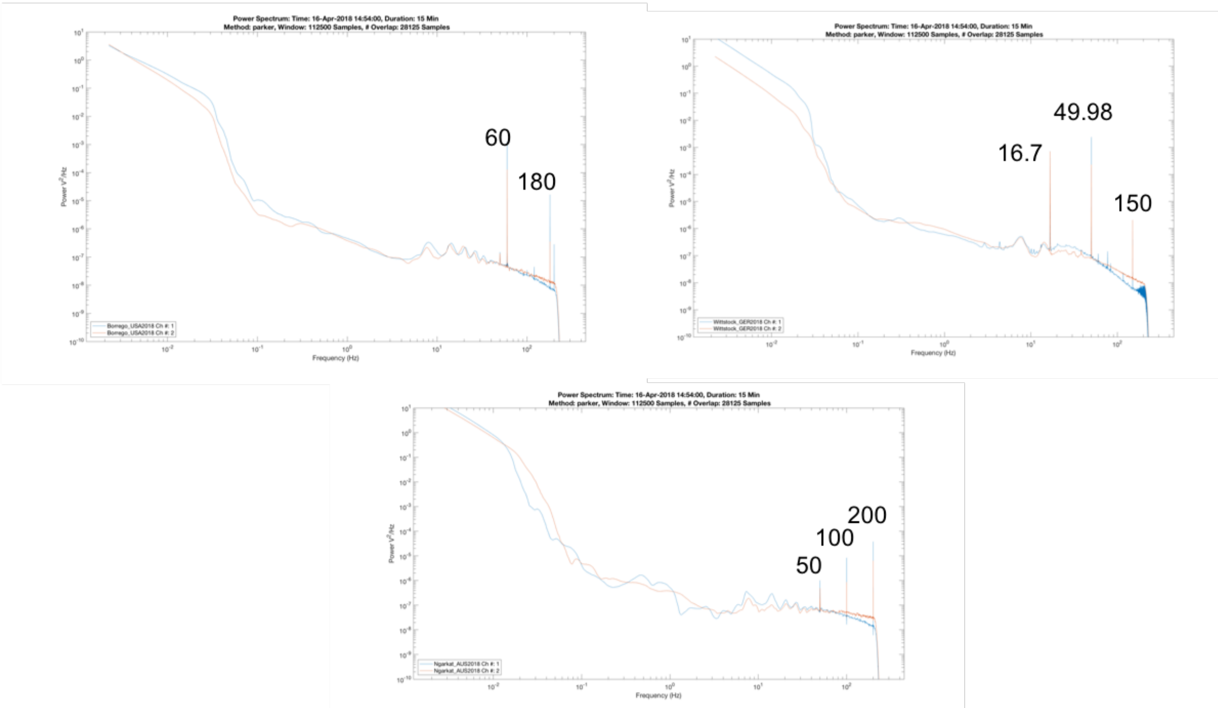

Figure 9: The power spectrum of each of the three sites pinpoints noise frequencies.

3 Locating the Lightning Strikes

Once we have removed the anthropogenic noise from the raw time series, we next convert cartesian coordinates to polar coordinates and perform a peak evaluation.

3.1 Geometry

Conversion to polar coordinates is possible given the waves are traveling at near light speed, $3\text{x}10^8$ m/s. The diagram in Figure 10 shows the geometry used in our triangulation of the lightning locations. S is the magnetometer site and L is the lightning strike. θ_s, Ψ_s, θ_l, Ψ_l are the colatitudes and longitudes (positive east) of the two sites, and ϕ is the incident angle of the strike at the side, positive East from North.

The angle $\Delta\theta$ is the travel time converted to an angle from the time of the strike t_l and the time of arrival at the observing site t_s:

$$\Delta\theta = \frac{2\pi(t_s - t_l)}{t_c}$$

where t_c is the time it takes for light to travel the Earth circumference computed from lights peed c and Earth radius r_e:

$$t_c = \frac{2\pi r_e}{c}$$

Next a peak analysis tool, available in most signal processing software such as MATLAB, allowed auto-selection of lightning strike peaks by setting parameters that determine only the amplitudes that exceed the median amplitude by a user-defined threshold (Figure 11). Threshold values are selected for each site individually once the data is examined and amplitude ranges confirmed. The algorithm is also set up to ignore smaller peaks that occur in the too close proximity of a large local peak. The result of the speak analysis is 18000 possible strikes each of the three locations.

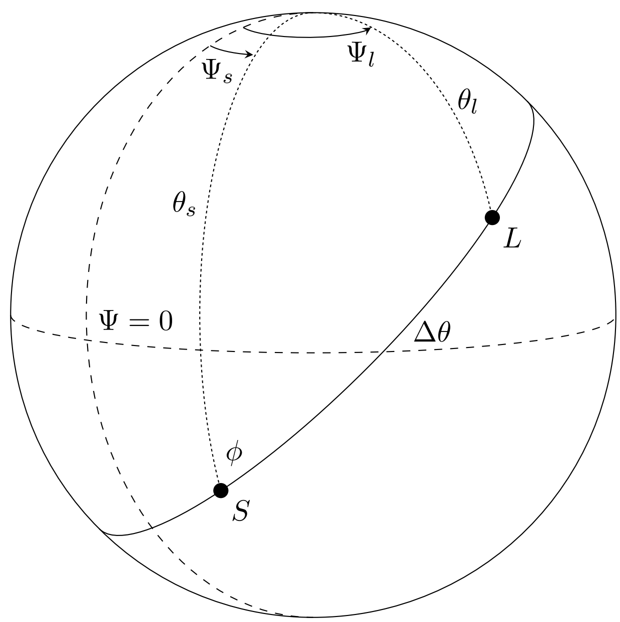

Figure 10: Calculating location of a lightning strike or flash.

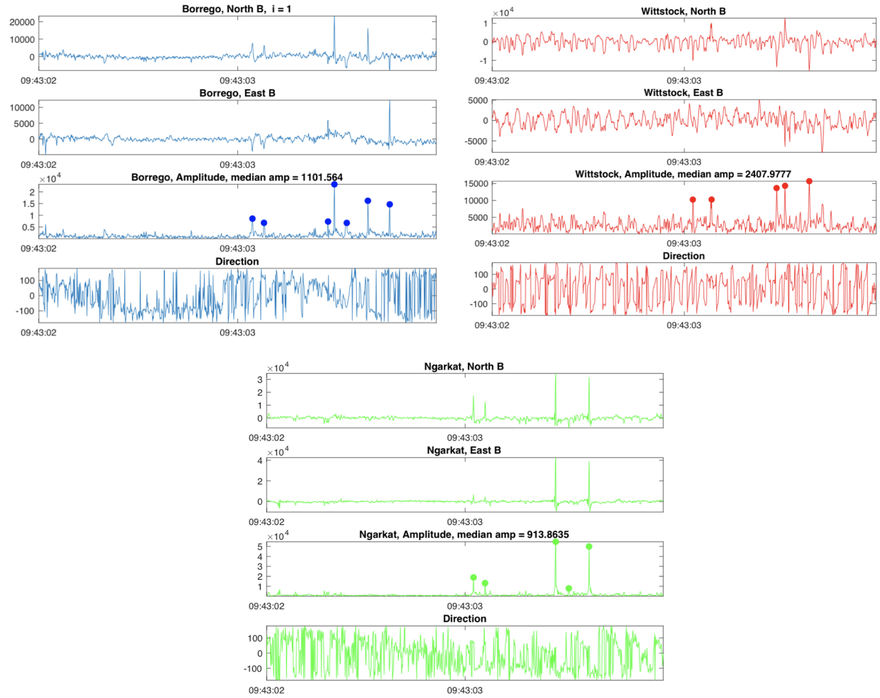

Figure 11: Automated peak selection in the time series.

Given the time and place a strike is observed we can recover the location of each strike that results in a peak. If we cast this as an inverse problem, expressions for the forward problem that predict the observations ϕ and t_s from known locations of S and L. The t_s is easy from cosine rule:

$$\begin{aligned}\cos\Delta\theta &= \cos\theta_l\cos\theta_s + \sin\theta_l\sin\theta_s\cos(\Psi_l - \Psi_s)\\ \Delta\theta &= \cos^{-1}(\cos\theta_l\cos\theta_s + \sin\theta_l\sin\theta_s\cos(\Psi_l - \Psi_s))\end{aligned}$$

or

$$t_s = t_l + \frac{t_c}{2\pi}\cos^{-1}(\cos\theta_l\cos\theta_s + \sin\theta_l\sin\theta_s\cos(\Psi_l - \Psi_s))$$

3.2 Results

Each peak is analyzed using a time and location triangulation methods and those that agree are retained for the final dataset. The result of this analysis are 8,000 located lightning strikes with θ_l, Ψ_l. Figure 12 illustrates the locations and concentration of these strikes.

Using the Blitzortung and other local and regional networks in the northern hemisphere

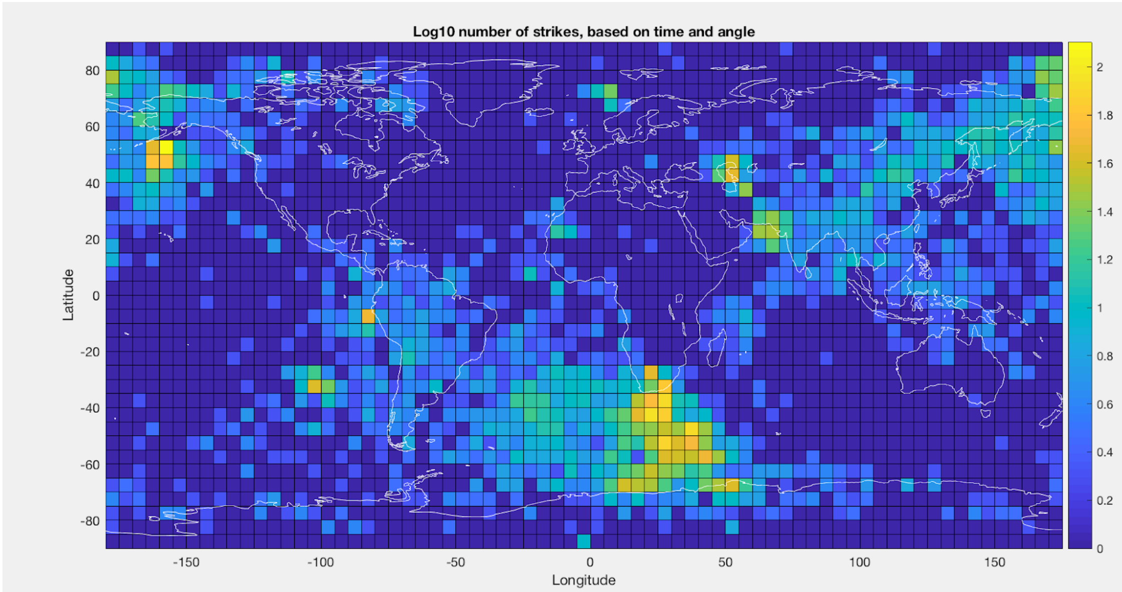

Figure 12: Final data map of lightning locations and concentrations.

we are able to evaluate accuracy to a small degree. However, in the Southern hemisphere, there does not exist a comparable observation system.

4 Future Work

We have completed here a pilot study with improved sampling rate and timing accuracy. We also developed the basic processing code for analyses of the collected data. Along with analyzing the larger dataset collected in this field campaign, there is great potential for future work with this study.

On the field acquisition side, sites could be installed in more locations, especially in remote areas. The equipment exists to establish stations that provide near real-time telemetry of the sensor data, utilizing solar power. Implementation of a global, continuously recording, high-precision magnetometer network could then swiftly and relatively inexpensively become a reality.

Concerning the data, there is room to improve processing techniques and the triangulation. Correlation with other lightning and meteorological datasets would bolster confidence in the observations. Further work can also be looking at the charge moments of lightning, which could lend insight into how the height of the tropopause in the tropics affects the charge distribution of lightning. If this reveals more ground-ward charge, it could help corroborate studies indicating a poleward spreading of cloud-to-ground lightning as the higher latitudes continue to warm.[21]

Overall understanding of lighting, its generation and effects could also benefit from this data acquisition. The analyzed data could also be used for research on the impact of increasing lightning on the greenhouse gas nitrous oxide which is added to the atmosphere by lightning. Moreover, questions could be answered about the effect of increasing global temperatures on lightning as well as the associated atmospheric properties. Where will the most significant amount of lightning increase occur? Can we glean knowledge about the effects on the vertical structure of temperature and stability in the atmosphere in order to improve severe weather predictions? A consistent global dataset collected by the proposed array could fill a considerable scope of prospects in atmospheric and climate science.

5 Conclusion

Lightning is a global phenomenon with lightning flash rates increasing non-linearly with atmospheric temperature. Utilizing Schumann Resonances to measure lightning activity is a thermometer that can gauge even subtle changes in temperatures. One decade ago, Füllekrug aimed to observe lightning and these electromagnetic field perturbations on a planetary scale by simultaneously recording ELF magnetic field disturbances at three stations. He used the data collected at these sites to triangulate lightning flash locations. His results reported about 2000 strikes a day. In our latest dataset, we select approximately 8000 strikes using separate time and location triangulation methods. The elevated number of lightning flashes located is attributed to our improved sampling rate, consistent across all three sites. The addition of a GPS time synchronization, unavailable during the earlier experiment, makes possible a travel time-based triangulation. While the results here are not conclusive, they appear to be meaningful. Satellite images as well reanalysis data from the National Centers for Environmental Prediction (NCEP) of the days leading up to our record period substantiate the forward model created here.

The data in this study reveals a monitoring system that could aid in understanding the global dynamics of lightning. Bolstering our knowledge of the processes involved in its formation would further discern the climate system as a whole. Using a remote, ground-based array to more accurately monitor lightning activity worldwide will be useful in current monitoring and warning efforts, as well as provide a crucial data point in climate change research. Climate change has many known ramifications. Overall lightning could be one of the most overlooked of the hazardous repercussions. Given that the majority of lightning activity increase will be over land, an impact on human populations is inevitable. A greater prevalence of lightning strikes will directly impact human health, infrastructure, communications and even air travel. Already an increase in wildfires ignited by lightning is taking their toll on populations, land and infrastructure. The Insurance Information Institute reports that in 2016 more than $825 million in lightning claims were paid out in the United States. And according to the National Interagency Fire Center between 2001 and 2012 15% of wildfires were ignited by lightning and these destroyed 60% of the total acres burned. A recent NASA study reports that there has already been a 2–5% rise in lightning-ignited fires since 1975. The researchers also explain that rising temperatures lead to more thunderstorms supplying more lightning.[21] Lightning related deaths could be particularly devastating in monsoon prone regions, where little warning or shelter are available.

With an expected general increase in lightning in a warming climate[22], a remote global monitoring system could prove advantageous to understanding and predicting severe weather and forecasting the effects of climate change in order to help prepare for and mitigate catastrophes.

References

[1] R. K. Pachauri, M. R. Allen, V. R. Barros, J. Broome, W. Cramer, R. Christ, J. A. Church, L. Clarke, Q. Dahe, P. Dasgupta, *et al.*, *Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change.* IPCC, 2014.

[2] N. Kobayashi and K. Nishida, "Continuous excitation of planetary free oscillations by atmospheric disturbances," *Nature*, vol. 395, no. 6700, p. 357, 1998.

[3] A. M. Tompkins, K. Gierens, and G. Rädel, "Ice supersaturation in the ecmwf integrated forecast system," *Quarterly Journal of the Royal Meteorological Society*, vol. 133, no. 622, pp. 53–63, 2007.

[4] F. Simões, M. Rycroft, N. Renno, Y. Yair, K. Aplin, and Y. Takahashi, "Schumann resonances as a means of investigating the electromagnetic environment in the solar system," in *Planetary Atmospheric Electricity*, pp. 455–471, Springer, 2008.

[5] A. Nickolaenko, A. Koloskov, M. Hayakawa, Y. M. Yampolski, O. Budanov, and V. Korepanov, "11-year solar cycle in Schumann resonance data as observed in antarctica," *Sun and Geosphere*, vol. 10, no. 1, pp. 39–49, 2015.

[6] B. I. Magi, "Global lightning parameterization from cmip5 climate model output," *Journal of Atmospheric and Oceanic Technology*, vol. 32, no. 3, pp. 434–452, 2015.

[7] M. Ma, S. Tao, B. Zhu, W. Lü, and Y. Tan, "Response of global lightning activity to air temperature variation," *Chinese Science Bulletin*, vol. 50, no. 22, pp. 2640–2644, 2005.

[8] D. M. Romps, J. T. Seeley, D. Vollaro, and J. Molinari, "Projected increase in lightning strikes in the United States due to global warming," *Science*, vol. 346, no. 6211, pp. 851–854, 2014.

[9] D. J. Allen and K. E. Pickering, "Evaluation of lightning flash rate parameterizations for use in a global chemical transport model," *Journal of Geophysical Research: Atmospheres*, vol. 107, no. D23, 2002.

[10] J. S. Jensenius Jr, "A detailed analysis of lightning deaths in the United States from 2006 through 2013," *National Weather Service NOAA*, 2015.

[11] D. Finney, R. Doherty, O. Wild, H. Huntrieser, H. Pumphrey, and A. Blyth, "Using cloud ice flux to parametrise large-scale lightning," *Atmospheric Chemistry and Physics*, vol. 14, no. 23, pp. 12665–12682, 2014.

[12] M. Füllekrug and S. Constable, "Global triangulation of intense lightning discharges," *Geophysical Research Letters*, vol. 27, no. 3, pp. 333–336, 2000.

[13] C. T. Wilson, "The acceleration of β-particles in strong electric fields such as those of thunderclouds," in *Mathematical Proceedings of the Cambridge Philosophical Society*, vol. 22, pp. 534–538, Cambridge University Press, 1925.

[14] C. Constable, "Earth's electromagnetic environment," *Surveys in Geophysics*, vol. 37, no. 1, pp. 27–45, 2016.

[15] D. J. Cecil, D. E. Buechler, and R. J. Blakeslee, "Gridded lightning climatology from TRMM-LIS and OTD: Dataset description," *Atmospheric Research*, vol. 135, pp. 404–414, 2014.

[16] L. Adams and R. Hall, "The effect of pressure on the electrical conductivity of solutions of sodium chloride and of other electrolytes," *The Journal of Physical Chemistry*, vol. 35, no. 8, pp. 2145–2163, 1931.

[17] P. L. Bhatnagar, E. P. Gross, and M. Krook, "A model for collision processes in gases. i. small amplitude processes in charged and neutral one-component systems," *Physical review*, vol. 94, no. 3, p. 511, 1954.

[18] C. Price, "Elf electromagnetic waves from lightning: the Schumann resonances," *Atmosphere*, vol. 7, no. 9, p. 116, 2016.

[19] E. R. Williams, "Global circuit response to seasonal variations in global surface air temperature," *Monthly Weather Review*, vol. 122, no. 8, pp. 1917–1929, 1994.

[20] M. Hattingh, "A new data adaptive filtering program to remove noise from geophysical time-or space-series data," *Computers & Geosciences*, vol. 14, no. 4, pp. 467–480, 1988.

[21] S. Veraverbeke, B. M. Rogers, M. L. Goulden, R. R. Jandt, C. E. Miller, E. B. Wiggins, and J. T. Randerson, "Lightning as a major driver of recent large fire years in north american boreal forests," *Nature Climate Change*, vol. 7, no. 7, p. 529, 2017.

[22] S. Menon, K. L. Denman, G. Brasseur, A. Chidthaisong, P. Ciais, P. M. Cox, R. E. Dickinson, D. Hauglustaine, C. Heinze, E. Holland, *et al.*, "Couplings between changes in the climate system and biogeochemistry," tech. rep., Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA (US), 2007.

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