Curriculum Units by Fellows of the National Initiative
2022 Volume V: Floods and Fires, How a Changing Climate Is Impacting the U.S.

Energy Dynamics of Tropical Cyclones: The impacts of climate change

Curriculum Unit 22.05.02, published September 2022
by Zachary Meyers

"Climate change is the Everest of all problems, the thorniest challenge facing humankind"

-- Lewis Gordon Pugh

Introduction and Rationale

Humanity faces an unprecedented global climate crisis within the next turn of the century. A myriad of climate data (i.e., increased sea surface temperatures, rate of CO_2 emissions, decline in arctic sea ice cover) suggests a climatic shift towards warmer global average temperatures coupled with a greater propensity for extreme weather events. The potential economic and humanitarian consequences threaten our global infrastructure and our children's future, with the most adverse consequences affecting vulnerable populations. It is imperative that students are educated on the complex dynamics of the ongoing current climate shift and the potential socioeconomic outfalls that could arise. One area of concern is the damage and hazard associated with future tropical cyclones. Between 1980 and 2021 tropical cyclones caused over 1.1 trillion dollars in damages in the United States alone. [1] The economic impact of extreme weather events and the displacement of communities from those events is becoming far too common and costly. Along the east coast of the United States, cities are being impacted by tidal surges and rainfall from large weather systems that have historically remained in the southern states. Since 1842 only 18 hurricanes have impacted the DMV (DC, Maryland, Virginia) however this frequency could change with the onset of a warmer environment. [2] This unit seeks to unravel the physics associated with these changing phenomena by examining the development of tropical cyclones using thermodynamic principles. Students will (1) investigate correlations between surface sea-level temperatures and hurricane intensity, or frequency; (2) analyze the conditions required for cyclogenesis to take place through the lens of the first and second law of thermodynamics and (3) predict future outcomes of tropical cyclone intensity and frequency under climate change in the Atlantic basin give historical data, projected models, and fundamental mechanisms grounded in thermodynamics. The goal of this unit is to provide an application of thermodynamic principles associated with energy transfer that may have consequential impacts on my students' future. Understanding the mechanism associated with heat-exchange coupled with weather development may allow them to grasp additional nuances associated with climate change which will better prepare them for a tumultuous future.

Demographics

I serve as the 11th-grade academy lead Physics science teacher at Jackson Reed High School. Jackson Reed High School is a relatively high-performing school in Washington, DC that consists of approximately 2,400 students. The diverse student body presents challenges for instructional delivery because of persistent achievement gaps within the school. Students have historically tested below grade level in mathematics with only 22% of students meeting academic expectations. [3] The socioeconomic issues associated with urban schools are still present (i.e., in-seat attendance, assignment completion rate, etc.). The student body is often segregated due to the number of advanced placements classes offered coupled with minimal opportunities for remediation throughout the year. The primary feeder school for Jackson Reed High School is Deal Middle School which represents a range of socioeconomic populations in DC and is currently overpopulated like Jackson Reed. The physics department is currently in the process of redesigning its curriculum to reflect more project-based learning and analysis of phenomena to cultivate critical-thinking in a collaborative forum. Last year presented several challenges for students, as it was the first year back from the COVID-19 pandemic. Students struggled to complete assignments outside of the classroom and due to COVID-19 policies many students remained absent for more than ten days once testing positive. After seven years of teaching in the District of Columbia Public School (DCPS), I have learned that one must adapt to the present circumstances and develop units to the changing environment. In my experience students respond best to positive, dynamic classrooms, with hands-on activities that require unique authentic answers to complex problems. The development of this unit is intended to be implemented for in-class person instruction in the hopes to cultivate vigorous inquiry opportunities that center around thermodynamics and energy transformations as they pertain to tropical cyclone and hurricane development. Students will be provided context into recent climatic changes as it pertains to the pre-civilization and modern common era. The more the student understands the content's relevance to climate change and their current and future lives, the more likely they are to gain a greater depth of knowledge and appreciation of the content.

Content Objectives

This two-to-three-week unit attempts to enhance students' content mastery (HS-PS3-1 & HS-PS3-2) and analytical skills by examining the thermodynamic principles in tropical cyclones for juniors in high school. In addition, students will investigate the relationships associated with warmer sea surface average temperatures and the likelihood of oceanographic weather events, such as tropical cyclones located in the Atlantic basin. This unit is primarily targeted to high school students that have the necessary analytical skills to decipher complex patterns associated with climate data. Students will require a rudimentary understanding in topics associated with the greenhouse effects, convection, adiabatic cooling, and the specific heat of water to master the heat exchange involved in hurricane systems. A close examination of sea surface temperatures in the Atlantic Ocean will allow students to determine if a significant correlation exists about storm intensity and/or frequency. This unit is meant to be a project that elicits individual exploration as well as cultivates a depth of thinking that goes beyond the standards of NGSS. It is my hope that students will gain a deeper understanding of energy dynamics and their implication with climate change.

Unit Content

The Historical Context and Implications of Climate Change in the Modern Era

Our ancestors thrived in numerous climatic conditions from warm savannas to frigid Arctic environments. Throughout this time, we managed to successfully navigate interglacial and glacial events that expanded and contracted our populations around the globe. Today we are faced with another climatic event that our technocentric society must adapt to. However, there are key differences in the events of the past and what we face before us. Modern society lives in a globalized world with goods and services that span oceans and continents. We live with conveniences that are dependent on an aging electrical grid, monoculture crops, and communication services. Our ancestors were not sedentary as we are today and thus adapted to the onset of climatic shifts. In addition, the climate shift proposed by the Intergovernmental Panel on Climate Change (IPCC) suggests a much more rapid warming event than has previously been observed over the last 300,000 years. [4] For us to successfully navigate humanity from this disaster, it is imperative that generations fully understand the complexities that will materialize in the next 50 to 100 years. This unit seeks to tackle the potential impacts of extreme weather events, specifically with regards to tropical cyclone development. As oceans warm, coastal cities may increasingly experience flooding and storm damage in the wake of sweeping intense tropical cyclones. Areas within the DMV are prone to flooding and may experience challenges with flash floods and runoff especially as incidences of tropical cyclones begin to migrate northward (Figure 1). It is vital that students understand the physics that underpin the dynamics associated with tropic cyclones and successfully navigate data to better prepare for their future.

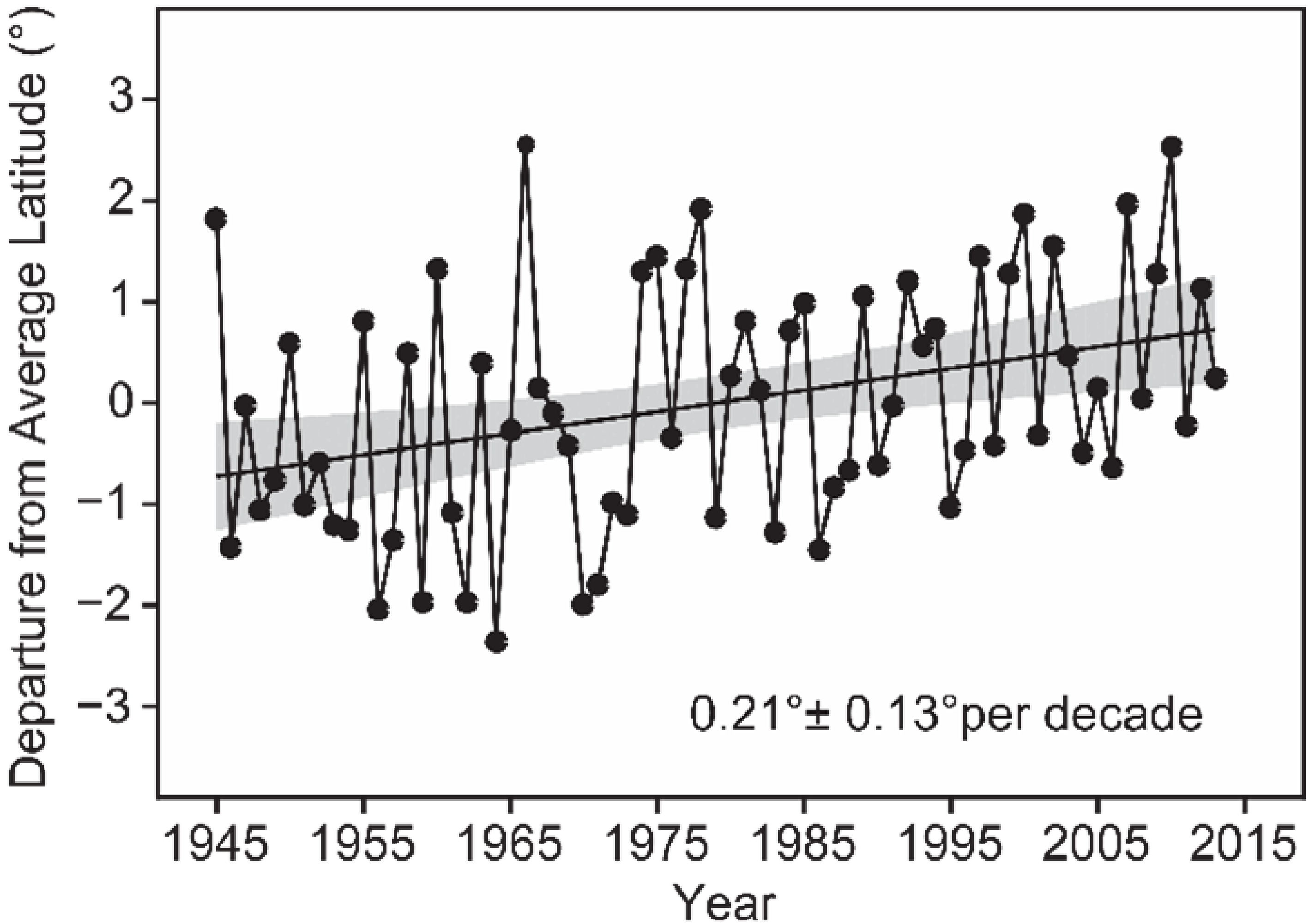

Figure 1. A line graph depicting tropical cyclone departures from average latitude by year

Energy Balance and Climate Change

To fundamentally understand the potential impacts that climate change poses on our way of life, it is imperative to grasp the importance of the energy balance that occurs between the sun, the Earth, and the Earth's atmosphere. Life on Earth is intrinsically linked to the energy being emitted from the sun. The Earth is approximately 150 million km from the sun and receives 10^{34} Joules of energy every year. [5] This may appear to be an extraordinary amount of energy, and it is, but not all the energy is readily absorbed by earth. Interactions with the Earth's atmosphere and magnetosphere reflect or divert incoming energy outwards. Approximately 30% of incoming solar radiation is reflected by clouds or other surfaces with high albedo. [6] The remaining energy that penetrates our atmosphere is absorbed by Earth's surfaces (i.e., oceans, cities, forests) which radiate thermal energy (infrared radiation) back through the atmosphere. Some of the outbound thermal energy from Earth's surface is absorbed by atmospheric gases, most notably water vapor, carbon dioxide, methane, nitrous oxide, and ozone. [7] Once absorbed, the long wavelengths of the thermal energy are redirected towards Earth, providing additional warming of Earth's surface. This phenomenon is known as the greenhouse effect and provides the necessary mechanism that allows Earth's surface temperature to be 13.9 degrees Celsius rather than the -18 degrees Celsius it would otherwise be without the greenhouse effect. [8] Earth's atmospheric composition is directly linked to the amount of energy retained, which contributes to the distribution of energy around the world as well as the global climate regimes and dynamic weather patterns.

Today the concentration of carbon dioxide exceeds 410 ppm which is the highest in more than 3 million years, when global surface temperatures were 2.5 to 4 degrees Celsius warmer than today. [9] As we continue to release CO_2 into our atmosphere, we are fundamentally changing our planet's energy balance, thus altering climate/weather stability, including the frequency and intensity of tropical cyclones around the tropics.

Tropical Cyclone's Impact on Civilization

Only recently, have we been able to track tropical cyclones with remote sensing satellites and instrumentation. Historical written records have documented the destructive potential of tropical cyclones around the tropics. One of the most famous examples occurred in 1274 when Kublai Khan attempted to invade imperial Japan. As Khan's naval forces sailed from Korea to Japan, they were met with a violent tempest which many believed to be a tropical cyclone (typhoon) that decimated Khans fleet. In central America, the Mayan's worshipped the wind god, Huracan, who was one of the most powerful deities believed to be responsible for the creation of Earth.[10] On a clifftop in Tulum, Mexico is a temple that served as a Mayan early warning system for inbound tropical cyclones. The temple contains an intricate web of holes that produces an extremely loud whistle which scientist believed warned residents from 1200 to 1450 AD. [11] Tropical cyclones have left a legacy on civilizations that have had the misfortune of settling in high-risk regions around the tropics. Even in the modern era, coastal communities still experience devastation as was documented in 1900 near Galveston, Texas. Between 1980 and 2021 tropical cyclones have caused over $1 trillion dollars of damage. [12] The costliest tropical cyclone in the United States occurred in 2005 when Hurricane Katrina struck New Orleans which inundated the city with flood water leaving behind $186.3 billion dollars in damages. [13] Of the five costliest Atlantic tropical cyclones, three have occurred within the past five years. Washington, DC has not traditionally been in the maw of the tropical cyclones but have been impacted, nonetheless. In 2020 tropical storm Isaias hit parts of Maryland and DC with strong winds and heavy rains leaving behind 4.73 billion dollars in damages. [14]

What, When and Where do Tropical Cyclones Occur?

Approximately 726 million people around the globe were impacted by tropical cyclones between 1998 and 2017. [15] Understanding these storm systems has been of paramount importance. A tropical cyclone is defined as a "warm-core, non-frontal, low pressure system that develop[s] over the ocean and has a definite organized surface circulation". [16] The term cyclone was first used in 1848 to describe a rotating storm system; it originates from the Greek word *kuklôn* meaning cycle or wheel. [17] Tropical cyclones are more commonly known as hurricanes, typhoons, or simply cyclones. Figure 2 shows a typical Atlantic hurricane (tropical cyclone) season, beginning on June 1st and lasting until November 30th . The peak Atlantic hurricane months are between September 1st and October 1st . [18] A typical hurricane season has 15 named storms, 8 hurricanes, and 4 major hurricanes with winds up 165-224 kph. [19] Hurricanes develop in the tropics and occur all around the world from the Indian Ocean to the North and South Pacific.

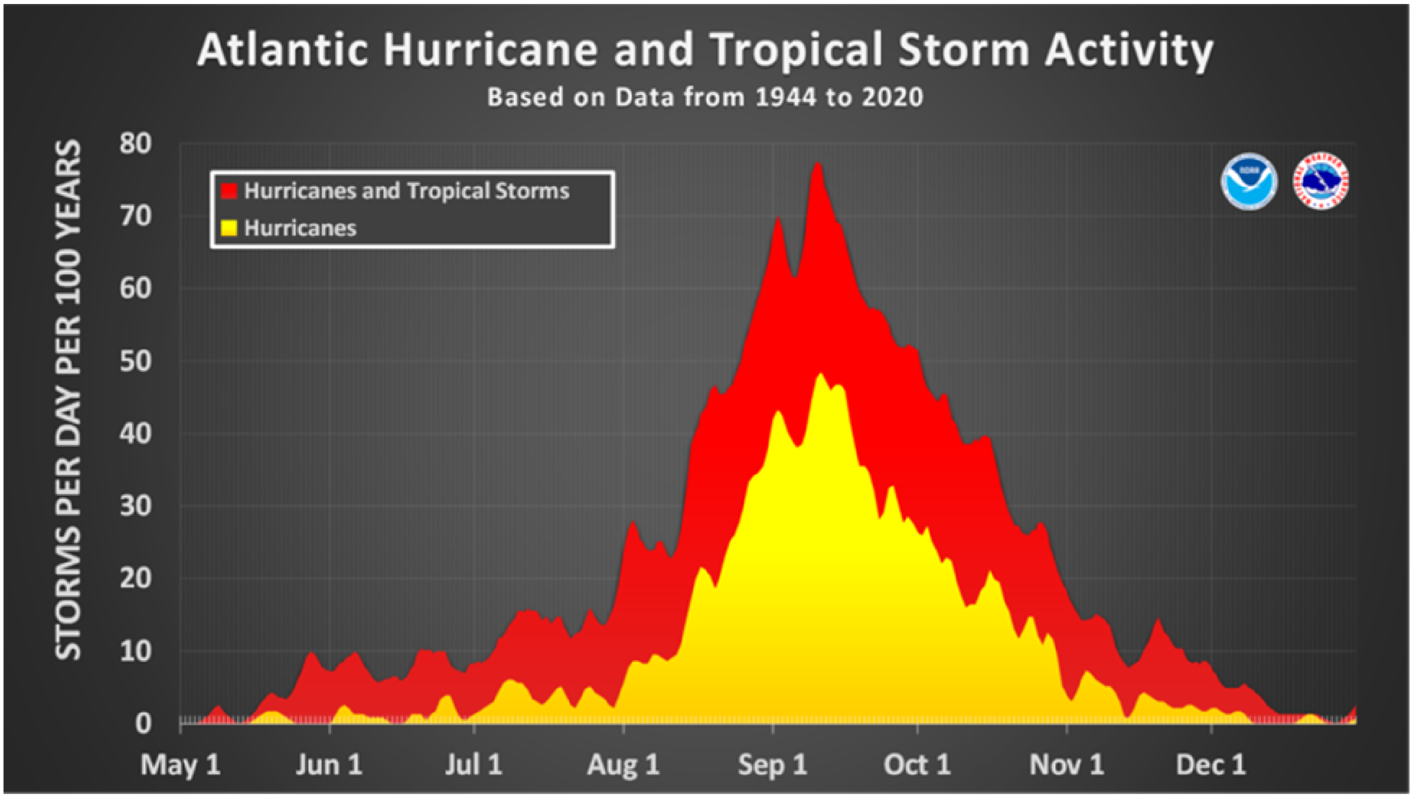

Figure 2. Depicts the frequency of tropical storms and hurricane in the Atlantic Ocean from NOAA.

Tropical Cyclone Monitoring

As these phenomena regularly occur throughout the world, a global monitoring network was established to provide accurate data and projections for tracking named systems. Currently, there are six tropical cyclone Regional Specialized Meteorological Centers (RSMSc) and five Tropical Cyclone Warning Centers (TCWCs) around the world. [20] These agencies provide advisories and updates to government agencies about the projected track and intensity of the storm. Each region has various classification systems to designate potential damage of a tropical system. The Atlantic tropical systems utilize the Saffir-Simpson Scale which consists of five categories of expected damage (i.e., minimal (category 1), moderate (category 2), extensive (category 3), extreme (category 4), catastrophic (category 5). Tropical systems in this region are called hurricanes are named once maximum sustained wind speed reaches 119 kph. [21] The Australian region tropical cyclone utilizes a similar five category schema for determining potential damage of tropical systems. [22] Lastly, the Western North Pacific and Indian Ocean designate tropical systems into two or three categories based on the maximum sustained surface wind speed. These categories range regionally but use similar criteria for classification. To mitigate the loss of life, it is paramount to continue having a robust monitoring and research network to warn communities of tropical cyclones. This units seeks to investigate tropical cyclones that originate within the South Atlantic Basin.

Tropical Cyclogenesis

Solar Radiation and Earth's Orientation

On the global scale, we know that the tilt of the Earth as well as the orientation of continents determine the likelihood of tropical cyclones developing in a particular region. Tropical cyclogenesis is initiated by the unequal heating of the Earth that gives rise to atmospheric convection. Incoming solar radiation, emitted from the sun, enters Earth's atmosphere at varying degrees due to an axial tilt of 23.5 degrees of our planet. [23] This positional difference results in more oblique angles of sunlight at higher latitudes and more direct angles towards equatorial regions. This is precisely why polar ice caps are located at the North and South poles and the tropics host some of the warmest climates on earth. Once the incoming solar radiation enters Earth's atmosphere, the energy is readily absorbed and reflected from varying surfaces. The vast majority of Earth's surface is composed of water, ice, rock, sand, and vegetation each of which stores thermal energy at various amounts due to their material properties. The heat capacity, albedo, and state of matter of surfaces all interplay to determine how much thermal energy is stored in a particular area. [24] The differences in stored thermal energy and a material ability to facilitate heat exchange produce the necessary mechanism for convection to occur both within Earth's oceans and atmosphere.

Atmospheric Convection and Regional Convection Cells

Convection is the process by which heat is transferred within fluids and gasses due to a temperature differential which govern movement. Warmer masses rise and expand which releases heat thus cooling the mass resulting in its descent. The greater the differential, the greater the rate of heat transfer and thus the masses motion. As molecules of air or water heat up (become more energetic) they begin to expand, become less dense, and rise. As the molecules move away from the source of energy, they release heat, subsequently becoming denser and sink back to the energy source. The expansion of rising warm air occurs near the sea surface and contracts in the upper troposphere with the condensation of water vapor. This circulation pattern converts a portion of the thermal energy into the system as mechanical work which typically manifests as fierce wind or rainbands. Convection can occur locally or at a global scale, both of which contribute to the patterns of tropical cyclogenesis that are currently observed. Atmospheric convection currents, which include the Hadley Cell, Polar Cell, and Ferrell Cell can be found at varying latitudes across the globe. [25] These large-scale currents circulate energy and facilitate heat exchange around the world as shown in Figure 2. The primary driver of tropical cyclones involves the Hadley Cell, which occurs 30 degrees north and south of the equator. [26] The heat exchange at the equator causes warm air to rise and descend near 30 degrees latitude.

Environmental Conditions that Promote Cyclogenesis

The conversion of moist static energy from the tropics to kinetic energy through convection provides the mechanism, termed cyclogenesis, for tropical cyclones to intensify. Initially, a disturbance must be present to promote a convective system. The stability and longevity of this convective system depends on vorticity, stability, and depth. [27] Many disturbances travel across the tropical ocean and yet only a small percent develop into tropical cyclones. Warm ocean waters of at least 26 degrees Celsius with a depth of 50 m are needed to provide the sustained energy for continued development. [28] Warmer waters promote the convective processes needed to form large volumes of moist air to rise. In addition, an atmosphere which cools fast enough to establish thunderstorm activity is required to release the heat from the rising moist air of the oceanic waters. A moist mid-troposphere (~5 km in altitude) further promotes thunderstorm development. The location of the initial disturbance with respect to its relative position above or below the equator will promote rotation force. Low vertical wind shear approximately 40 km/h or less from the surface offers favorable conditions for the organization of the eye wall to be established along with subsequent rainbands.[29]

Tropical Cyclone Formation and Anatomy

Once systems become organized, a mature tropical cyclone will consist of a boundary inflow layer, clear central eye, eyewall, cirrus cloud shield, rainbands, and upper tropospheric outflow. [30] In a tropical cyclone, warm air flows inward toward the central eye becoming more energetic as it approaches the eye wall. The rainbands and central eyewall act as convective zones that allow warm air to rise, cooling as it reaches higher altitudes creating an outflow of energy and moisture. This multi-directionality of air mass movement creates rapid atmospheric disturbance which allows tropical cyclones to develop and become large hazardous storms. The warmer the ocean water is, the greater the influx of energy and moisture which promotes further system organization and structure.

In summary, these dynamic systems require two conditions in order to form: (1) favorable warm oceanic waters that are positioned north or south of the equator and (2) limited shear winds so that tropical systems can properly organize and develop. A deeper understanding of cyclogenesis must start with the fundamental physics The development of tropical cyclones is limited by the available thermal energy supplied by the ocean water which is principally determined by the first law of thermodynamics. The mechanism by which tropical cyclones transfer heat utilizes the process of convection. In addition, the spiraling rotational motion of tropical cyclones which circulate mechanical energy manifests in the forms of rainbands and wind speeds.

Tropical Cyclone Physics

Thermodynamic Principles

The formation of tropical cyclones adheres to the law of conservation of energy which states that energy is neither created nor destroyed, energy can only be transferred from one form to another. Thus, the energy entering the system must equate to the energy exiting the system. The first law of thermodynamics is an adaptation of this principle and states that in a closed system (no transfer of matter into or out of a system) the energy within the system (U) is equal to the difference between the heat supplied to the system (Q) and the work (W) done by the system (Equation 1). Work is defined as the process of transferring energy from one system to another. [31] The flow of heat or heat exchange in an example of energy transfer which is dynamically observed during tropical cyclogenesis.

$$\Delta U = Q - W \quad \text{Eqn. 1}$$

The direction of heat exchange observed in the convective currents within tropical cyclones can be explained by the second law of the thermodynamics. This principle introduces the concept of entropy or a measure of unusable energy or disorder within a closed or isolated system. The second law of thermodynamics as it pertains to heat transfer states that heat exchanges occur irreversibly from higher to lower temperature bodies. This provides the underlying mechanism of convective atmospheric cells and how heat exchange occurs within tropical systems. The greater the heat applied to the system (i.e., increase sea surface temperatures) the greater the amount of work (i.e., increased intensity of tropical cyclones) performed by the system. Conceptually the thermodynamic principles support scenarios of increased tropical cyclone activity.

The Carnot Cycle

In 1824, Nicolas Leonard Sadi Carnot observed the fundamental thermodynamic principles associated with heat engines and eventually developed the Carnot Cycle. [32] His work was pivotal in understanding the limitations of energy efficiency in heat engines. The first law of thermodynamics assumes that energy entering a system is perfectly conserved however Carnot was unable to construct a “perfect” heat engine where all absorbed heat turned into work. The heat in natural systems likewise do not perfectly absorb heat and convert it into work, other processes and transformation restrict the efficiency of the system. [33] Tropical cyclones like heat engines operate based on temperature differentials that perform work and operate under the confines of the second law of thermodynamics. The isothermal and adiabatic processes that Carnot described cycle heat through a system to perform work. Tropical cyclones similarly function in the same way as a heat engine but occur on much larger scales with devasting consequence as the work produce in the low-pressure systems can come in the form of intense rainbands and wind gusts of 200 kph. [34] Figure 3 shows a cross-section of a thermodynamic cycle of a tropical cyclone which serves as an analog to the Carnot cycle. The evaporation of seawater drives the transfer of energy from sea to air which acts as the fuel source for the tropical system to further develop. The changes that take places within the tropical system are largely governed by alteration in atmospheric pressure and volume (i.e., expansion or compression) of air mass that ultimately drive wind speeds. High pressure atmospheric systems flow to low pressure atmospheric systems, this movement of air mass ultimately generates work in the form of wind speed. The greater the pressure differentials the greater the amount of work or wind speed.

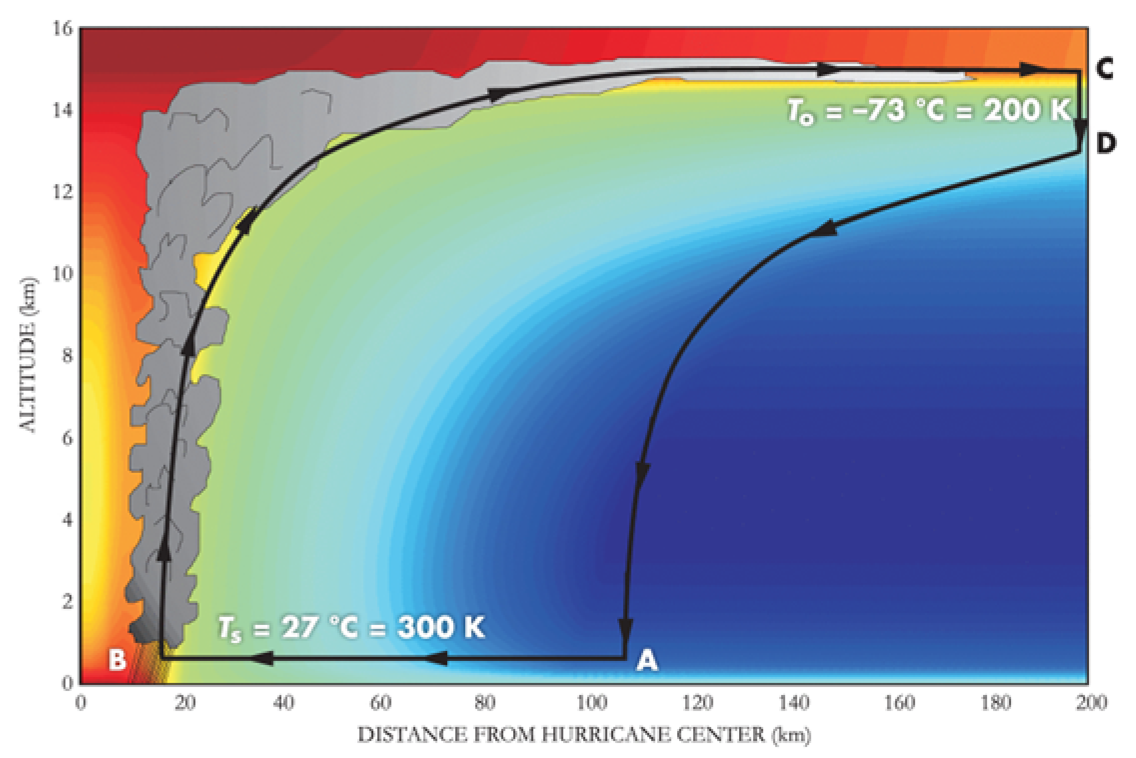

Figure 3. Provides a cross section of a tropical cyclone with regards to the distance from the center of the storm, height of air mass and temperature differential at sea surface level and at the tropopause. The color schema is meant to reference hot and cold regions that are analogous to the Carnot Cycle.

Phase I – Isothermal Expansion (A to B)

First, air is directed into the eye wall of the tropical cyclone through a pressure gradient. The water vapor absorbs the heat from the tropical oceans which acts as a heat reservoir. Based on ideal gas laws, air will begin to expand once introduced to a low-pressure environment. The air mass thus undergoes isothermal (temperature remains constant) expansion along the sea surface moving towards the inner eyewall of the tropical cyclone. [35] Because of the internal energy of an ideal gas, in this case water vapor, nitrogen, oxygen, is a function of temperature change, the internal energy is zero during isothermal expansion (“The Carnot Cycle – University Physics Volume 2” n.d.). Work (W1) is being carried out through this process as the water vapor moves towards the center of the low-pressure system.

Phase II – Adiabatic Expansion (B to C)

The air ascends along large columns of cumulonimbus clouds through adiabatic expansion. The extremely low-pressure of the inner eye wall facilitates the rapid movement of the expanding air where work occurs (W2). The air mass is thermally isolated (adiabatic), resulting no change in heat which results in a decrease in temperature during the expansion (work) process. [36]

Phase III – Isothermal Compression (C to D)

Next the air mass undergoes isothermal (temperature is constant) compression. The air mass is placed in contact with a cold reservoir and compressed. In the case of the air mass circulating within the tropical cyclone the air is propelled to the tropopause where temperatures can get as low as -73 degrees Celsius. Work (W3) is done on the gas whereby the air mass gives up heat to the surrounding cold reservoir. Again, no temperature or energy change occurs rather the air mass cools which causes the denser air mass to increase in pressure.

Phase IV – Adiabatic Compression (D to A)

The final step is adiabatic compression which results in no change in heat but an increase in temperature as well as an increase in energy. [37] Work (W4) is done on the gas where it returns to its initial state.

These four fundamental phases explain how tropical cyclones transfer heat through their dynamic systems to maintain or even further develop around the worlds oceans. The total work done within the system can be determine by Equation 2. Work is equal to the area of the enclosed loop (AàBàCàD). [38] Thus, the greater the temperature differential within the system the greater the area or work achieve by the system. As mean ocean temperature rise there is greater potential for tropical cyclones to achieve greater windspeeds, as the amount of wind generated is directly related to the work generated by the low-pressure system.

$$W = W1 + W2 - W3 - W4 \quad \text{Eqn. 2}$$

Rotational Motion and the Coriolis Effect

The Coriolis effect describes a pattern in deflection that occurs when objects or systems travel along a rotating body such as the Earth. The Earth is a spheroid body with equatorial regions having the largest diameter and pole regions the smallest. Our planet rotates eastward around a tilted axis of approximately 23.5 degrees. [39] This rotating reference frame with respect to other moving bodies generates what is known as a Coriolis force. The magnitude of this force is proportional to the rotation rate of the reference frame. The Earth completes one rotation every 23 hours, 56 minutes, 4 seconds and since the circumference of the Earth is approximately 40,000 kilometers that means that the surface of the equator moves at roughly 460 meters per second. [40] This rotation rate is reduced the farther away from the equatorial regions of the earth since the circumference is smaller closer towards the poles. This differential in rotational rates causes objects that are traveling at fixed or relatively fixed rates to become deflected through the Coriolis force. For example, a plane taking off from the equator, traveling north will deflect eastward, while one traveling towards the equator from the northern hemisphere will deflect westward. The Coriolis effect is fundamentally important in generating sufficient rotational force to provide the feedback mechanism for heat exchange to efficiently transfer throughout the tropical cyclone.

Climate Change Projections and the Implications of Tropical Cyclones

Increase in Sea Surface Temperature

Since the 1800s, the IPCC asserts that the anthropogenic contribution to global mean temperature increased an average of 1 degree Celsius. [41] Due to a greater thermal capacity, a less pronounced warming trend has also been observed with respect to sea surface temperatures around the world. As shown in Figure 4, from 1901 through 2020, sea surface temperatures rose an average of 0.07 degrees Celsius per decade. [42] Sea surface temperatures have consistently been higher over the past 30 years than any other time in recorded history. Although on average sea-surface temperatures have increased worldwide, regionally some waters have cooled. These observations are mainly attributed to water's high specific heat capacity and ocean currents facilitating the transport of thermal energy within water columns. The surface temperature of the world's oceans is predominantly warmest towards the equator and progressively cools towards higher latitudes and similar to air temperatures, the degree of warming has been most pronounced towards the arctic region with annual sea ice vanishing. Since the oceans are intrinsically linked with atmospheric changes, increased sea surface temperatures promote greater evaporation and increase the amount of atmospheric water vapor.

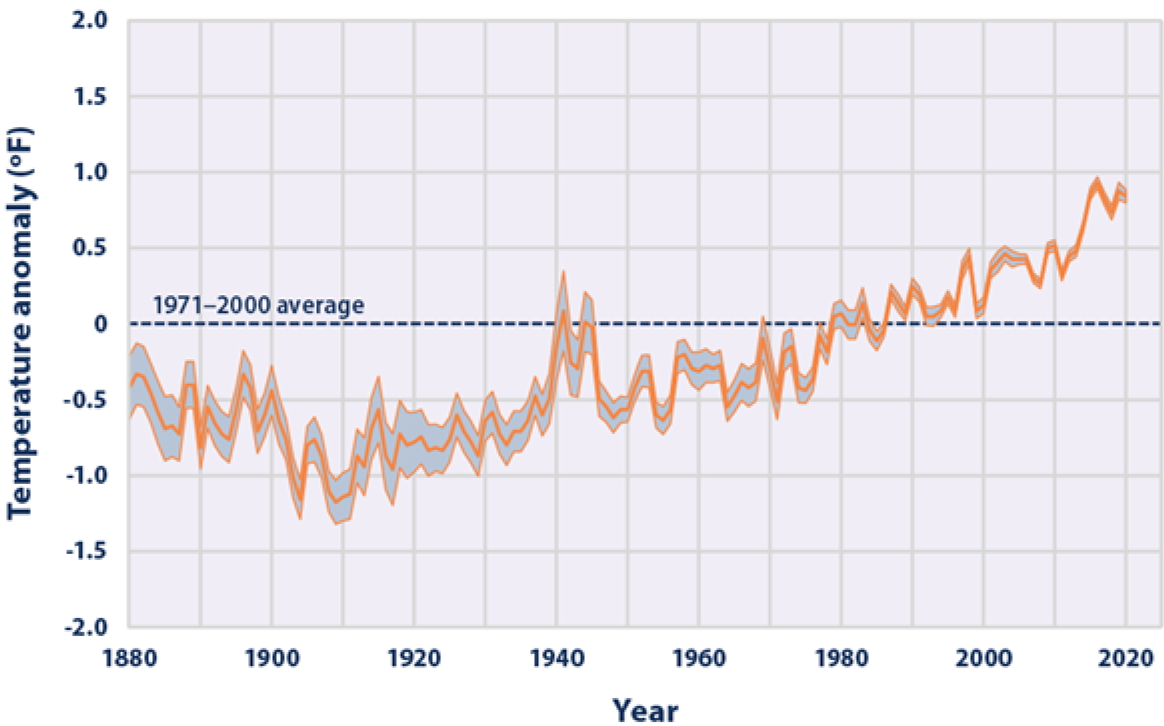

Figure 4. A line graph illustrating the increase in sea surface temperature from 1880 to 2020 using the mean temperatures from 1971-2000 as a baseline.

Tropical Cyclone Frequency and Intensity

These temperature changes have major implications for tropical cyclone frequency and intensity, purely from a thermodynamic perspective. The projected climatic effects on global tropical cyclone activity include sea level rise, increased tropical cyclone rainfall rates, and increased tropical cyclone intensity. [43] However, due to the dynamic and complex nature of these low-pressure systems (tropical cyclones) the IPCC has not definitively correlated anthropogenic warming with increased Atlantic basin hurricane activity.

Vecchi et al. 2021 compared multiple datasets to determine any long-term trends in sea-surface temperatures with respect to increased frequency in landfall of hurricanes and number of higher category storms. Adjusting for limited observation data from the 1800s and current trends they that the frequency of tropical cyclones in the Atlantic has not increased significantly over the last 100 years (Figure 5). [44] In addition to increased sea surface temperatures, models project rapid upper tropospheric temperature warming coupled with increasing levels of vertical wind shears over the western portion of the Atlantic Ocean. [45] Tropical cyclone frequency will likely be suppressed because of increased upper tropospheric temperature and greater vertical wind shear, however storms will likely be stronger with greater average rainfall when they do develop. [46]

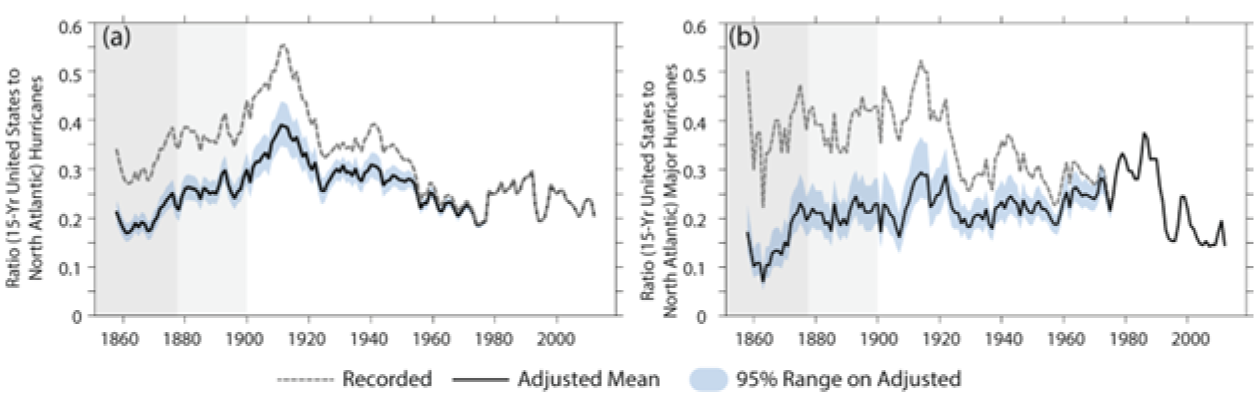

Figure 5. Compares the recorded and adjusted occurrences of North Atlantic Hurricanes from 1860 to 2020

To understand the nuances of these projections in frequency we must reconcile the quality of the data prior to the development of satellite and digital instrumentation. However, thoughtful transparent normalization will help aid our understanding of tropical cyclones as we continue to develop our models to understand these complex and dynamic systems.

In summary, coastal city along the east coast, including the District of Colombia, should prepare for large intense tropical cyclones with heavy precipitation. As the Atlantic Basin continues to experience increased sea surface temperature there remains an increased likelihood of large low-pressure systems to develop into category 4 and 5 hurricanes that could wreak havoc to local infrastructure. We have demonstrated the thermodynamic principles that underpin the development of tropical cyclones and now understand how heat exchange occurs within these systems. With continued monitoring and data available perhaps soon we will be better suited to better predict the frequency and trajectory of these storms.

Teaching Strategies

Extended Constructed Response (ECR)

Extended constructed response questions provide an opportunity for students to demonstrate the extent of mastery within a given content area while building capacity for sustained critical thinking. Students will be provided an essential question (i.e., How do the laws of thermodynamics influence tropical cyclone development? Use data to support your claims.), every two weeks, that complements an observable phenomenon or data-driven inquiry lab. The Next Generation Science Standards (NGSS) heavily emphasize students' ability to rationalize phenomena. Last year, students dramatically improved literacy skills and produced higher quality responses. To encourage a growth mindset, multiple drafts are required prior to final submission. The iterative process provides numerous opportunities for students to refine their rationale and improve the mechanics of their responses. The process must be done with fidelity and with opportunities for students to peer-review.

Station Rotation with Heterogenous Groups

Station rotation facilitates the engagements of students through several concurrent activities throughout the class period or week, depending on the model. This instructional strategy allows students multiple opportunities to refine conceptual understanding and mastery by participating in activities that target various modes of learning (e.g., kinetic, auditory, visual). Students will spend approximately 20 minutes working independently or in groups on activities. As a class, students will share findings, observations, and misconceptions that persist, once every student has rotated through each station.

The unit will concentrate heavily on deconstructing energy transformations from a myriad of observable phenomenon. Thus, it is imperative that students take detailed notes and effectively communicate their thoughts to peers. Students will be expected to take Cornell Notes, a system of notetaking that actively engages the students to ask questions, organize information, and summarize key ideas. Student groups will be compiled from pre-assessment data, attendance, and behaviors from the first 2-3 weeks of the year. At the conclusion of every semester, student groups will be reassessed and reassembled. The number of stations may vary based on the number of students and classroom dynamics. Station rotations have been shown to be an effective strategy for students to maximize their learning and to develop skills of independent problem solving.

Inquiry Activities

As a science, physics offers opportunities for students to apply a multitude of mathematical concepts and arithmetic skills when describing physical phenomena. This unit will seek to strengthen students' content mastery of energy transformation while simultaneously refining laboratory skills and engaging in discussion. From my experience at Jackson Reed High School, kinesthetic activities, with a summary discussion at the end of class, have often led to the most successful lessons. This unit will utilize inquiry as an access point for student ingenuity and provide the context for students to revise their ideas about the concepts being introduced. The activity will vary in duration and rigor, requiring students to work in collaborative groups.

Activities

Energy Transformation Demonstrations –Heat Engine (Stirling)

Students will observe a series of phenomena to better understand the intricacies associated with heat exchange and work. A heavy emphasis will be placed on comparing various models of Stirling engines with regards to their energy pathways and work output. Students will individually identify and record in their science notebooks all forms of energy observed in the initial demonstration. After three to five minutes, students will collaborate in small groups to determine the energy pathway for the whole group demonstration. Students will be given ten minutes to illustrate the energy pathway starting with the chemical potential energy. Each group will present on their initial observations to prepare for the independent work. In groups of four, students will identify the types of energy present within each system (i.e., model of Stirling engine). Each group will construct an energy pathway diagram and identify forms of energy and locations of energy transformation. Individually students will be asked to explain why Stirling engines will never achieve perfect efficiency using supportive evidence from their observations as well as content from their science notebooks. This activity can be scaffolded to accommodate middle and elementary students by simplifying the observed energy transformations.

Lava Lamp Demonstration – Modelling Convection

Students will be tasked to deconstruct the fundamental processes associated with convection by observing the motion within a lava lamp. The small-scale demonstration will serve as an entry activity to allow students to visualize how tropical cyclones exchange heat within their organized system during cyclogenesis. Students will individually analyze the lava lamp and develop an explanation(s) based upon their prior knowledge of thermodynamic principles. As a whole group, we will discuss the process of convection formally and relate it to natural phenomena just as the ocean currents, earth's mantle, and lastly tropical cyclones. Students will get into groups of four or five to discuss what would happen to the motion of the "lava" if the base temperature was increased and justify their predictions using thermodynamics. Another heat lamp will be added to the base of the lava lamp to determine if motion has increased. As a whole group we will discuss how these same principles could be applied to the formation and intensity of tropical cyclones.

Research Writing – Summative Data Analysis of Climate

The summative project will task students to examine and analyze a curated dataset looking at mean sea surface temperatures in the Atlantic. Students will work in small groups to determine if significant correlations exist between tropical cyclone frequency and intensity with yearly mean sea surface temperatures. Next students will use the projected climate data from the IPCC for the Atlantic and make prediction about the intensity and frequency in the next fifty years. They will use their previous calculations to justify their prediction and discuss the strength of their predictions. Students will be asked to develop a presentation in groups of two or three. They will present their findings to a scientific panel consisting of science teachers and local experts (i.e., EPA, NOAA, University faculty) to judge the strength of their findings and arguments. Students will be given a rubric with several checkpoints over a two-week period. This project will provide an opportunity for students to gain a deeper understanding and appreciation for the complexities associated with climate change. Tropical cyclones are extremely complex and still not fully understood but students will develop a sufficient understanding to develop predictions of the future with regards to tropical cyclones and the thermodynamic principles that govern cyclogenesis.

Bibliography

Biology Libre Texts. 2022. *8.2: Earth's Energy Balance*. [online] Available at: https://bio.libretexts.org/Courses/University_of_Pittsburgh/Environmental_Science_(Whittinghill)/08%3A_Atmosphere_and_Air_Pollution/8.02%3A_Earth's_Energy_Balance [Accessed 18 July 2022].

Choi, Charles Q. “Earth's Sun: Facts about the Sun's Age, Size and History.” Space.com. Space, June 9, 2021. https://www.space.com/58-the-sun-formation-facts-and-characteristics.html.

Dr. Jenni Evans, Dr. Arlene Laing. “Introduction to Tropical Meteorology 2nd Edition.” Introduction to Tropical Meteorology, Ch. 8: Tropical Cyclones. Accessed July 19, 2022. https://ftp.comet.ucar.edu/memory-stick/tropical/textbook_2nd_edition/print_8.htm.

Emanuel K. 2006. Hurricanes: Tempests in a greenhouse *Physics Today*. 59: 74-75. DOI: 10.1063/1.2349743

Emanuel K. 1999. “Thermodynamic control of hurricane intensity” *Nature.* 401: 665-669

Gray, William M. "Tropical cyclone genesis." PhD diss., Colorado State University. Libraries, 1975.

Hoegh-Guldberg, O., D. Jacob, M. Taylor, M. Bindi, S. Brown, I. Camilloni, A. Diedhiou, R. Djalante, K.L. Ebi, F. Engelbrecht, J. Guiot, Y. Hijioka, S. Mehrotra, A. Payne, S.I. Seneviratne, A. Thomas, R. Warren, and G. Zhou, 2018: Impacts of 1.5ºC Global Warming on Natural and Human Systems. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 175-312, doi:10.1017/9781009157940.005.

IPCC (Intergovernmental Panel on Climate Change). 2013. Climate change 2013: The physical science basis. Working Group I contribution to the IPCC Fifth Assessment Report. Cambridge, United Kingdom: Cambridge University Press. www.ipcc.ch/report/ar5/wg1

Lampkin, Chester. “Here Is Every Hurricane to Ever Hit the DMV.” wusa9.com, May 20, 2020. https://www.wusa9.com/article/weather/every-hurricane-to-ever-hit-dc-maryland-virginia/65-14f8191d-9eb6-4e30-9d6a-f45307f44df4.

MySchoolDC. “Jackson-Reed | My School DC,” 2020. https://www.myschooldc.org/schools/profile/125.

School Profiles Home https://profiles.dcps.dc.gov/Jackson-Reed+High+School Accessed: 2022-07-18

NOAA National Centers for Environmental Information (NCEI) “U.S. Billion-Dollar Weather and Climate Disasters” (2022). https://www.ncei.noaa.gov/access/billions/, DOI: 10.25921/stkw-7w73

NOAA. “Hurricane Costs.” NOAA Office for Coastal Management. Accessed July 19, 2022. https://coast.noaa.gov/states/fast-facts/hurricane-costs.html#:~:text=Of%20the%20310%20billion%2Ddollar,6%2C697%20between%201980%20and%202021

NOAA. “Glossary of NHC Terms.” Accessed July 19, 2022. https://www.nhc.noaa.gov/aboutgloss.shtml.

NOAA. “Seasonal Tropical Cyclone Activity.” Tropical cyclone climatology. Accessed July 19, 2022. https://www.nhc.noaa.gov/climo/.

Persson, Anders (1 July 1998). "How Do We Understand the Coriolis Force?". *Bulletin of the American*

Meteorological Society. **79** (7): 1373–1386.

Pradeep Thakur. Mar 5, 2017. “Un Studies Ancient Maya Structure for Hurricane Prediction - Times of India.” The Times of India. Accessed July 19, 2022. https://timesofindia.indiatimes.com/home/science/un-studies-ancient-maya-structure-for-hurricane-prediction/articleshow/57479329.cms.

"Research on the Gale and Hurricane in the Bay of Bengal on the 3rd, 4th, and 5th of June, 1839". *Journal of the Asiatic Society of Bengal*. 8: 631–650. 1839

Samuel J. Ling, William Moebs, Jeff Sanny. University Physics Volume 2. OpenStax. 2016. https://openstax.org/books/university-physics-volume-2/pages/3-3-first-law-of-thermodynamics

Samuel J. Ling, William Moebs, Jeff Sanny. University Physics Volume 2. OpenStax. 2016. https://openstax.org/books/university-physics-volume-2/pages/4-5-the-carnot-cycle

US Department of Commerce, NOAA. “Tropical Storm Isaias Impacts: August 4th, 2020.” Tropical Storm Isaias Impacts: August 4th, 2020. NOAA's National Weather Service, December 9, 2020. https://www.weather.gov/lwx/TropicalStormIsaias.

Vecchi, G.A., Landsea, C., Zhang, W. *et al.* Changes in Atlantic major hurricane frequency since the late-19th century. *Nat Commun* **12,** 4054 (2021). https://doi.org/10.1038/s41467-021-24268-5

World Health Organization. “Tropical Cyclones.” World Health Organization Accessed July 19, 2022. https://www.who.int/health-topics/tropical-cyclones#tab=tab_1.

Teacher Resources

For supplemental information that will be utilized at varying degrees throughout the unit please review the following. A deactivated link is provided along with a summary of the resource. In addition, several referenced materials are recommended for review that further supplement the content in this unit.

Khan Academy

Khan Academy is a non-profit educational organization that provides free lectures in the form of YouTube videos. There are practice exercises along with a personalized dashboard if students register on the website. This resource is helpful for students that require supplemental learning or need to make up work due to absences. (https://www.khanacademy.org)

Physics classroom

Physics classroom is a free online resource for beginning students and teachers. There are several animations, problem sets, and tutorials that supplement classroom content. The website provides guidance to targeted misunderstandings and strengthens students’ critical thinking skills with multi-tiered word problems. Students who require additional support should be guided to this website. (http://www.physicsclassroom.com)

PHET simulations

PhET simulations offer free virtual labs from several topics in physics, chemistry, biology, and earth science. Each simulation comes with teacher instructions but can be modified depending on the scope of your investigations. There is browser (i.e., Chrome and Safari) and software compatibility constraints (i.e., HTML5, Java, and Flash) that should be checked prior to each virtual lab. If students are using district computers, ensure they have the necessary software your chose PhET simulation. Overall, this is a great resource to bridge the gap during hybrid instruction.

Appendix on Implementing District Standards

NGSS Standard Integration

The unit will incorporate standards from the Next Generation Science Standards (NGSS) in Unit III. The focus will be primarily on the nature of electromagnetic energy and their associated wave interactions with matter.

Disciplinary Core Ideas

Energy is a quantitative property of a system that depends on the motion and interactions of matter and radiation within that system. (HS-PS3-1)

Conservation of energy means that the total change of energy in any system is always equal to the total energy transferred into or out of the system. (HS-PS3-1) (HS-PS3-2)

When two objects interacting through a field relative position, the energy stored in the field is changed. (HS-PS3-5)

Crosscutting Concepts

When investigating or describing a system, the boundaries and initial conditions of the system need to be defined, their inputs and outputs analyzed and described using models. (HS-PS3-4)

Science & Engineering Practices

Use mathematical representation of phenomena to describe explanations. (HS-PS2-2)

References

1 NOAA National Centers for Environmental Information (NCEI) “U.S. Billion-Dollar Weather and Climate Disasters” (2022). https://www.ncei.noaa.gov/access/billions/, DOI: 10.25921/stkw-7w73

2 Lampkin, Chester. “Here Is Every Hurricane to Ever Hit the DMV.” wusa9.com, May 20, 2020.

https://www.wusa9.com/article/weather/every-hurricane-to-ever-hit-dc-maryland-virginia/65-14f8191d-9eb6-4e30-9d6a-f45307f44df4.

[3] MySchoolDC. "Jackson-Reed | My School DC," 2020. https://www.myschooldc.org/schools/profile/125.

School Profiles Home https://profiles.dcps.dc.gov/Jackson-Reed+High+School Accessed: 2022-07-18

[4] Hoegh-Guldberg, O., D. Jacob, M. Taylor, M. Bindi, S. Brown, I. Camilloni, A. Diedhiou, R. Djalante, K.L. Ebi, F. Engelbrecht, J. Guiot, Y. Hijioka, S. Mehrotra, A. Payne, S.I. Seneviratne, A. Thomas, R. Warren, and G. Zhou, 2018: Impacts of 1.5ºC Global Warming on Natural and Human Systems. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 175-312, doi:10.1017/9781009157940.005.

[5] Choi, Charles Q. "Earth's Sun: Facts about the Sun's Age, Size and History." Space.com. Space, June 9, 2021. https://www.space.com/58-the-sun-formation-facts-and-characteristics.html.

[6] Biology LibreTexts. 2022. *8.2: Earth's Energy Balance*. [online] Available at: https://bio.libretexts.org/Courses/University_of_Pittsburgh/Environmental_Science_(Whittinghill)/08%3A_Atmosphere_and_Air_Pollution/8.02%3A_Earth's_Energy_Balance [Accessed 18 July 2022].

[7] Biology LibreTexts. 2022. *8.2: Earth's Energy Balance*.

[8] Biology LibreTexts. 2022. *8.2: Earth's Energy Balance*.

[9] Biology LibreTexts. 2022. *8.2: Earth's Energy Balance*.

[10] Pradeep Thakur. Mar 5, 2017. "Un Studies Ancient Maya Structure for Hurricane Prediction - Times of India." The Times of India. Accessed July 19, 2022. https://timesofindia.indiatimes.com/home/science/un-studies-ancient-maya-structure-for-hurricane-prediction/articleshow/57479329.cms.

[11] Pradeep Thakur.

[12] NOAA. "Hurricane Costs." NOAA Office for Coastal Management. Accessed July 19, 2022. https://coast.noaa.gov/states/fast-facts/hurricane-costs.html#:~:text=Of%20the%20310%20billion%2Ddollar,6%2C697%20between%201980%20and%202021.

[13] NOAA

[14] US Department of Commerce, NOAA. "Tropical Storm Isaias Impacts: August 4th, 2020." Tropical Storm Isaias Impacts: August 4th, 2020. NOAA's National Weather Service, December 9, 2020. https://www.weather.gov/lwx/TropicalStormIsaias.

[15] World Health Organization. “Tropical Cyclones.” World Health Organization Accessed July 19, 2022. https://www.who.int/health-topics/tropical-cyclones#tab=tab_1.

[16] NOAA. “Glossary of NHC Terms.” Accessed July 19, 2022. https://www.nhc.noaa.gov/aboutgloss.shtml.

[17] "Research on the Gale and Hurricane in the Bay of Bengal on the 3rd, 4th, and 5th of June, 1839". *Journal of the Asiatic Society of Bengal*. 8: 631–650. 1839

[18] NOAA. “Seasonal Tropical Cyclone Activity.” Tropical cyclone climatology. Accessed July 19, 2022. https://www.nhc.noaa.gov/climo/.

[19] NOAA.

[20] Dr. Jenni Evans, Dr. Arlene Laing. “Introduction to Tropical Meteorology 2nd Edition.” Introduction to Tropical Meteorology, Ch. 8: Tropical Cyclones. Accessed July 19, 2022. https://ftp.comet.ucar.edu/memory-stick/tropical/textbook_2nd_edition/print_8.htm.

[21] Dr. Jenni Evans and Dr. Arlene Laing.

[22] Dr. Jenni Evans and Dr. Arlene Laing.

[23] Biology LibreTexts. 2022. *8.2: Earth’s Energy Balance*.

[24] Biology LibreTexts. 2022. *8.2: Earth’s Energy Balance*.

[25] Emanuel K. 2006. Hurricanes: Tempests in a greenhouse *Physics Today*. 59: 74-75. DOI: 10.1063/1.2349743

[26] Emanuel K. 2006.

[27] Emanuel K. 1999. “Thermodynamic control of hurricane intensity” *Nature.* 401: 665-669

[28] Emanuel K. 1999.

[29] Emanuel K. 1999.

[30] Dr. Jenni Evans and Dr. Arlene Laing.

[31] Samuel J. Ling, William Moebs, Jeff Sanny. University Physics Volume 2. OpenStax. 2016. https://openstax.org/books/university-physics-volume-2/pages/3-3-first-law-of-thermodynamics

[32] Samuel J. Ling, William Moebs, Jeff Sanny. University Physics Volume 2. OpenStax. 2016. https://openstax.org/books/university-physics-volume-2/pages/4-5-the-carnot-cycle

[33] Samuel J. Ling, William Moebs, Jeff Sanny. OpenStax. 2016.

[34] Samuel J. Ling, William Moebs, Jeff Sanny. OpenStax. 2016.

[35] Samuel J. Ling, William Moebs, Jeff Sanny. OpenStax. 2016.

[36] Samuel J. Ling, William Moebs, Jeff Sanny. OpenStax. 2016.

[37] Samuel J. Ling, William Moebs, Jeff Sanny. OpenStax. 2016.

[38] Samuel J. Ling, William Moebs, Jeff Sanny. OpenStax. 2016.

[39] Gray, William M. "Tropical cyclone genesis." PhD diss., Colorado State University. Libraries, 1975.

[40] Persson, Anders (1 July 1998). "How Do We Understand the Coriolis Force?". *Bulletin of the American Meteorological Society*. **79** (7): 1373–1386.

[41] IPCC (Intergovernmental Panel on Climate Change). 2013. Climate change 2013: The physical science basis. Working Group I contribution to the IPCC Fifth Assessment Report. Cambridge, United Kingdom: Cambridge University Press. www.ipcc.ch/report/ar5/wg1

[42] NOAA (National Oceanic and Atmospheric Administration). 2021. Extended reconstructed sea surface temperature (ERSST.v5). National Centers for Environmental Information. Accessed July 2022. https://www.ncei.noaa.gov/products/extended-reconstructed-sst

[43] Vecchi, G.A., Landsea, C., Zhang, W. *et al.* Changes in Atlantic major hurricane frequency since the late-19th century. *Nat Commun* **12,** 4054 (2021). https://doi.org/10.1038/s41467-021-24268-5

[44] Vecchi, *et al.* 2021.

[45] Vecchi, *et al.* 2021.

[46] Vecchi, *et al.* 2021.