Paleotempestology: Exploring methods to develop tropical storm records in response to theoretical interactions between changing climates and hurricane intensity

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ABSTRACT

With improved research efforts and heightened awareness, it has become increasingly obvious that the impacts of climate change will underlie many of the environmental hazards that human populations will face in the future. These hazards will be diverse and have a broad range of outcomes. Several intriguing consequences of climate change exist, including the associated impact on tropical storms and hurricanes. These events can have serious impacts on human lives and infrastructure, especially as a result of flooding caused by storm surges. A better understanding of how projected climate change will affect these tropical storms is necessary in order to prepare coastal populations for future events. In this essay, a basic greenhouse gas model is described that correlates the effects of anthropogenic carbon emissions to climate change. The basic theory that links climate change to tropical storm development is then presented based on published models in the Atlantic Ocean basin. In order to justify the predicted results of these models, it becomes pertinent to understand the development and magnitude of past storms in relation to their intensities. Several methods are outlined that have been developed to create a record of storm events utilizing various environmental evidence and quantitative models. Beyond published work, a method attempted to investigate a new proxy is described. This method was not successful due to sampling errors, but does suggest sites for future research.

INTRODUCTION

As research is continually focused toward the topic, it has become apparent that the effects of global climate change will be broad and far-reaching. One of the more popular topics related to the subject in news and media is the role that warming temperatures will play in intense hurricane frequency. Because of their direct effect on human population centers and property, predicting the strength and dynamics of these storms will be of utmost importance in the near future. Theories exist explaining the connection between climate change and tropical storm formation, but not enough evidence currently exists to predict the future of the two with high accuracy. The need for this evidence has produced the field of paleotempestology, which attempts to record the history of past storm events. Several methods exist in the field, but work is still necessary to determine their relative accuracies. Additionally, room exists to explore new, novel methods.

In order to gain a holistic perspective on the topic, this essay is divided into four parts. The first part is a climate change review that cites the most recent predictions of future climate and outlines the theories which predictions are based. The second part outlines hurricane development, kinetics, and energetics so that the relation between climate change and storm intensity becomes clear. The third section describes the circumstances that drove the development of the field of paleotempestology and several of its diverse methods. The final portion describes an attempt to investigate a potential new method in the field.

CLIMATE CHANGE REVIEW

GREENHOUSE GAS MODEL

Climate is defined by averages of several meteorological principles including temperature, wind, pressure, humidity, and precipitation. While many of these principles were once perceived to be natural processes outside the scope of human control, research overwhelmingly suggests that anthropogenic sources do in fact play an important role. Specifically, the release of carbon dioxide from fossil fuel combustion enhances the atmosphere's heat retention, thereby increasing surface temperatures. This system is described by the Greenhouse Gas model, a basic energy balance with principal behaviors that were first proposed by Fourier (1824), but has since been expanded on. This section will outline the governing ideals of the model so that the role of human actions in climate change become clear.

Firstly, it is important to understand that in the 4.5 billion year history of earth, climatic factors have changed significantly. The Greenhouse Model is of importance in these changes, but on a time period of this scale, other factors also make significant contributions to temperature changes. Temperature is a measure of energy, and the source of most of the surface energy on earth is the sun. The sun, though, has not provided a constant flux of energy. This is a result of the relative position of the sun and earth in space, which follow periodic cycles on thousand year timescales. These astrophysical cycles, including axial tilt, eccentricity, and precession, were proposed to be climate change factors long ago because of their effect on solar insolation (Croll, 1875), but were more formally calculated by Milankovitch (1941) and named after him. These calculations closely match observed planetary motion trends (Bretagnon, 1982). Existing climate models show the relationship between insolation fluctuation and resulting weather and climate (Kukla, 1975), while climatic variation observed in deep sea cores match several of the periods of the fluctuations (Hays, Imbri, Shackleton, 1976). These fluctuations, however, occur over periods of time much longer than the existence of modern civilization. Thus, although the interaction between Milankovitch Cycle fluctuations and the Greenhouse Gas Model is important on a geologic time scale, they will not be explicitly considered in this review and solar insolation will be assumed to be a constant.

In this discussion, carbon dioxide will be the most closely examined greenhouse gas, but other greenhouse gases do exist. Most notably, water vapor is very important in climate discussions. However water vapor concentration, or humidity, is primarily a function of temperature, as described by the Clausius-Clapeyron relation (Clapeyron 1834, Clausius, 1850). Therefore, the concentration of water vapor in the atmosphere is not a primary contributor to greenhouse warming such as CO_2, but rather acts as a positive feedback loop. This implies that increased temperatures will increase the water vapor concentration, which in turn affects temperature with changes in outgoing radiation heights and convective effects (Manabe and Wetherald, 1967).

Additionally, methane (CH_4) is a greenhouse gas that actually absorbs and emits heat radiation with a higher efficiency than carbon dioxide, in effect making it more potent on a per molecule basis. However, when considered on a global scale, the net effect of CH_4 is much smaller because its overall concentration is less and residence time much shorter than CO_2 (Lelieveld, Crutzen, Dentener, 1998). For this reason and the sake of simplicity, methane will not explicitly be mentioned in the model, though the physics outlined do often pertain to it.

The reason that some molecules behave as greenhouse gases and others do not is a result of radiation transfer and quantum mechanics principles. These are described by Chandrasekhar (1960). In a very simplified analogy, atoms that make up molecules can be thought of as masses connected by springs. As if connected by a spring, atoms can exhibit three types of motion: vibration, rotation, and translation. Because of electron orbits, different types of atoms have unique vibrations and rotations. The three combined movements result in internal kinetic energy in the molecule. Molecules can absorb and emit electromagnetic radiation, but only at discrete energy levels. This means that the energy of the radiation must correlate to the internal energy of the molecules as described.

According to Maxwell's Equations (1865), radiation moves at the speed of light, but has different wave lengths (and frequencies). Different types of radiation in the electromagnetic spectrum are identified by these different wavelengths. As described by Planck (1901), the energy associated with electromagnetic radiation is directly proportional to its frequency. This means that shortwave radiation, such as x-rays, has higher energy values than long-wave radiation, like radio waves. This concept defines the interactions between molecules and radiation, and it becomes apparent that certain relationships exist. For example, orbital transitions are associated with ultraviolet and visible light absorption, vibrational transitions are associated with infrared wavelengths, and rotational is correlated to microwaves. Additionally, electron dipoles play an important role in photochemical effects (Rabinowitch, 1942). Thus, different molecules will interact with different kinds of radiation based on atomic components.

With this idea in mind, it becomes necessary to determine why different types of electromagnetic radiation are formed. Kirchhoff (1860) first proposed several important ideas necessary to frame the problem. According to his law of thermal radiation, material bodies in thermodynamic equilibrium emit and absorb radiation at specific wavelength values. Furthermore, if a body absorbs energy, it will emit the same energy. He then went on to define a blackbody, which is an object that absorbs radiation at every wavelength. Many objects in the universe, such as the earth and sun, can be approximated as blackbodies.

Based on this theory, Stefan (1879) was able to empirically derive the famous Stefan-Boltzmann Law, which was later shown to be an integral over all wavelengths of Planck's (1901) law of blackbody radiation. The law is a simple correlation, which states that the peak radiation wavelength of a blackbody is proportional to its temperature to the fourth power. Though a simple relation, a blackbody's strong dependence on temperature has very important effects.

Using all of these physical ideas, a basic greenhouse gas model takes shape. Obviously, the sun is much hotter than the earth, and emits radiation at about 6000 degrees kelvin. By the Stefan-Boltzmann law, this radiation will exist in the ultraviolet and visible wavelengths. According to radiation theory, greenhouse gas molecules do not have corresponding energies to these waves. Therefore, the waves will pass through the earth's atmosphere and reach the surface. By Kirchhoff's Law, the earth will absorb this radiation and then emit it. However the earth, around 300 degrees kelvin, emits at a much cooler temperature than the sun. Observing the Stefan-Boltzmann law again, the earth will emit infrared radiation toward the atmosphere. As a result of energies due to rotation and electric dipoles in greenhouse gases, molecules will absorb IR radiation. Once again observing Kirchhoff's Law, this radiation will be emitted. Some of it will be emitted up out of the atmosphere back toward the sun, but some will also be emitted back down toward the earth. Thus, the earth receives radiation not only from the sun, but also ‘recycled’ radiation from the atmosphere. This extra energy is the cause of warming effects.

With this model in mind, it makes sense that by increasing the concentration of carbon dioxide in the atmosphere, its effects would become more profound. This is exactly what has happened in the past century, as atmospheric carbon dioxide concentrations have grown exponentially and are estimated to increase 0.5-3 ppm annually (Keeling and Whorf, 2001). This growth is caused by anthropogenic emissions from fossil fuel combustion and deforestation, as determined by stable carbon isotope measurements (Quay et al. 1992). From a geologic perspective, this time period is the blink of an eye. According to ice core analysis, the modern atmospheric concentration of carbon dioxide exceeds that over any other concentration in a 420,000 year time period (Petit et al. 1999). Therefore, the exact effects of these concentrations on climate remain unknown, but global climate models predict increasingly more accurate outcomes.

CLIMATE MODEL PARAMETERS

Climate models utilizing the principles of the greenhouse gas model try to quantify the effects of these increased concentrations. The first modern models were created around the 1970s and estimated that the average surface temperature of earth will increase by several degrees Celsius per doubling of CO_2 concentration (Manabe and Wetherald, 1967 and 1975). With advancements in computer programming power, the models have become more accurate. In order to calculate temperature relationships, these climate models must take into account more factors than CO_2 concentrations. A variety of forcing and feedback systems plays intricate roles in the climate and must be quantified in models. The principal ideas behind the major parameters will be described.

Climate models must use accurate values of atmospheric carbon dioxide concentration. However, not all of the emitted CO_2 remains in the atmosphere. Instead, some of it is removed to carbon sinks by reactions with several environmental systems. These sinks decrease the atmospheric carbon dioxide concentration and can play important roles in other environmental aspects. These interactions are broadly called the carbon cycle, and it is important that they are quantified.

Carbon dioxide has existed naturally in the atmosphere, ocean, biosphere, and sediment system throughout the history of the earth. Atmospheric concentrations initially existed as a result of volcanic emissions that derived their source of carbon from the huge reservoirs that are stored in sedimentary rocks (Rubey, 1951). CO_2 was later returned to the sediment system at varying rates by way of silicate weathering (Siever, 1968; Walker et al. 1981). These processes are very slow and only considered at geologic time scales. On shorter time scales, carbon is removed from the atmosphere by two important sinks: the biosphere and the ocean.

In a broad scale, the biosphere involves all biology that surrounds various types of vegetation, soil (heterotrophic) respiration, and the impact that humans have on them (Schimel, 1995). From the most basic standpoint, the biosphere is a sink for carbon dioxide because plants use CO_2 in photosynthesis. It is thought that increased emissions will encourage plant growth and ecosystem production, essentially acting as a type of fertilizer. This implies that the carbon dioxide flux into the terrestrial biosphere sink would increase with increasing emissions, thereby minimizing some of the impact. However, many locally independent factors such as regional precipitation, land use patterns, pollution, and nitrogen deposition play important roles in organic systems and make models exceedingly difficult to quantify (Cramer et al. 2001).

Furthermore, while the fertilization hypothesis may hold merit, the relation between the atmospheric carbon dioxide concentration and biosphere growth is not linear. The biology controlling carbon interactions with plant growth and stimulation is complex (Amthor, 1995) and other variables play a large role. Taking this into account, calculations (Cao and Woodward, 1998) predicting net ecosystem consumption show future growth, but decline as CO_2 concentration reaches a certain saturation point. More complex models (Cramer et al. 2001) indicate similar results, with ecosystem production showing a sort of diminishing returns around the year 2050. A large reason for this may be from soil respiration, as described by Cox et al. (2000). Soil respiration, which measures the release of carbon dioxide from organisms in the soil, increases with temperature. This effect therefore counteracts the increased sink from enhanced ecosystem production and overtakes net carbon uptake. Additionally deforestation, which clears significant carbon sinks and releases CO_2 if harvested wood is burned, may serve as another significant source of carbon dioxide (Bolin, 1977).

The second carbon dioxide sink is the ocean. Atmospheric carbon dioxide diffuses into the ocean until equilibrium is reached. As described by Henry's law, $P_{CO2} = k \cdot C_{CO2}$. This implies that a greater concentration of atmospheric CO_2 (partial pressure or P_{CO2}) will result in a correlating, linear increase in aqueous CO_2 (C_{CO2}) in the ocean by the constant factor k. This relation is based on chemical equilibrium and does not provide a rate of transfer.

To further complicate, the equilibrium concentrations between the atmosphere and ocean are also controlled by a more complex process called the bicarbonate system. The bicarbonate system is a natural buffer in ocean water. It includes H_2CO_3, HCO_3^-, CO_3^{2-}, and H^+ ions. When CO_2 is dissolved in water, it does not maintain its same form. Instead, it interacts with the bicarbonate system to form carbonic acid. A complex equilibrium occurs in which carbonic acid decreases the pH of the system (Caldeira and Wickett, 2003). Essentially, the system is controlled by Le Chatlier's Principle, meaning that the concentration of a reactant is increased as a result of a reaction. The net effect of this is that a 1% change in oceanic CO_2 concentration correlates to a 12.5% change in atmospheric CO_2 concentration (Bolin an Eriksson, 1958).

In addition to the buffer system, the temperature stratification of the ocean also affects carbon dioxide uptake. The ocean is divided into the shallow mixed layer and deep interior by the thermocline, a steep temperature gradient. The shallow mixed layer has a much smaller volume than the ocean as a whole, meaning that CO_2 concentrations reach equilibrium relatively quickly, and the mixed ocean layer becomes saturated on short time periods.

Therefore, the rate of carbon dioxide uptake by the ocean is controlled primarily by the interaction between the mixed layer and deep interior. Carbon dioxide transfer between the two layers occurs as a result of pumps (Volk, 2013). The first type of pump is controlled by biological processes. In the mixed layer, tiny organisms such as plankton exist (Falkowski, 1992). These organisms ingest carbon and transfer it to the bottom of the interior ocean when they die and sink. There, they decay and the carbon is returned to the sediment. The life of these organisms depends on sunlight, nitrogen, and phosphorus, implying that this transfer rate is independent of atmospheric concentrations (Siegenthaler, 2013).

The second pump results from the thermocline itself. Disturbances in the interior ocean will cause buoyant upwellings in which parcels of cold, deep water rise into the warm, mixed layer. Because carbon dioxide has a higher solubility in cold water than it does warm (Volk, 2013), the cold upwellings will absorb CO_2. Then, they experience negative buoyancy and sink to normal depth, thereby decreasing the carbon dioxide concentration in the mixed layer and allowing for further atmospheric uptake. The biological and thermocline pumps are relatively slow, but provide a consistent carbon dioxide sink.

Taking into account these processes and more complicated systems, the most recent IPCC (Intergovernmental Panel on Climate Change) report (Ciais et al. 2013) quantifies global carbon fluxes between anthropogenic emissions and atmospheric, biosphere, and ocean concentrations. Accordingly, annual emissions from fossil fuel combustion over the past decade were calculated to be on the order of 8.3 petagrams of carbon equivalents per year. Of these 8.3 petagrams, 2.4 were transported to the ocean sink, and 1.6 to the biosphere. This resulted in a net increase of 4.3 petagrams of carbon dioxide in the atmosphere per year. Ultimately, it is this net concentration of atmospheric carbon dioxide that climate models must account for now and in the future. It is a challenge to calculate because it is a function of not only anthropogenic emission rates, but also natural responses that vary over time.

As described, the carbon cycle creates significant changes to the greenhouse gas model and subsequent warming effects because of its interaction with atmospheric carbon dioxide concentration. This altercation is called a forcing because it directly affects the global radiation budget (Boucher, 2013). In addition to the carbon cycle, other factors play important roles as forcings in climate models. One of these factors is aerosols.

Atmospheric aerosols are small liquid or solid particles suspended in the atmosphere (Boucher et al. 2013). Aerosols do occur naturally, but the most significant source results from anthropogenic sulfur emissions. Unlike greenhouse gases, which allow shortwave radiation to pass through them and absorb longwave radiation, aerosols scatter shortwave radiation (Charlson et al. 1992). This means that aerosols increase albedo, or the reflectivity of the earth. They have the opposite effect of greenhouse gases in that they may actually account for cooling, essentially counteracting warming effects (Mitchell, 1995). Models that take into account this cooling effect more accurately describe climate over the past century than those that don't (Mitchell, 1995). Interestingly, predictions of future aerosol concentrations may be more tied to politics than physics. Due to stricter pollution control, sulfur related pollution has significantly decreased in developed countries, leading to smaller concentrations. This decreases the cooling effect, which in turn may enhance the net greenhouse warming in future years (Boucher et al. 2013).

Aerosols are also quite important because of their effect in cloud formation. Clouds form when water vapor condenses into liquid droplets. Due to microphysical processes involving vapor pressure and surface tension, this process is more likely to occur when heterogeneous CCN (Cloud Condensation Nuclei) are available for the vapor to condense onto. Aerosols act as this CCN, thereby increasing the rate of cloud formation (Andreae and Rosenfeld, 2008).

Clouds play a significant role in the global radiation budget, but have a very broad array of properties that make them difficult to model. Consequently, clouds represent one of the biggest challenges in climate models (Randall et al. 2003). Clouds increase albedo by reflecting shortwave radiation back toward the atmosphere, but they also act as a greenhouse gas by absorbing longwave radiation and reemitting it back toward earth. The dominant feature and overall net effect of a cloud depends on cloud cover, height, convection, temperature, optical depth, microphysical properties, lapse rates, and latitudes. Generally high, cold clouds tend to warm the earth while low clouds enhance cooling (Stephens, 2004). Because of the number of variables, trends are model dependent and much work is left to be done, especially with low clouds (Sherwood, 2014).

Clouds get even more complicated because they not only play important roles in radiative forcing, but also in the feedback system (Stephens and Webster, 1981). As mentioned before, atmospheric water vapor capacity is a function of temperature. Temperature decreases with height through the troposphere to the Tropopause (division between troposphere and stratosphere), where a temperature inversion exists and temperatures increase with height. Clouds exist in the troposphere and are made of liquid water droplets. These water droplets deplete the magnitude of radiation reaching the ground by scattering waves. This depletion is measured in a quantity called optical depth. It is this optical depth that determines emissivity, absorption of radiation, and subsequently the albedo and greenhouse effects of clouds (Stephens, 2003). Because it is dependent on water vapor concentration, it is a function of temperature.

OBSERVATIONS AND PREDICTIONS

Based on the greenhouse gas model and evidence of increased CO_2 concentrations since the industrial revolution, it should be expected that temperatures on earth would have warmed over the past century. Several measurement systems, using independent data sets and research groups, consistently reach the same conclusion that this is in fact happening. These results are most clearly compared and displayed in the IPCC report (Hartmann et al. 2013). LSAT (Land

Surface Air Temperature) and SST (Sea Surface Temperature) have risen since 1880, with even faster rates since the 1970s. Other evidence, including increasing specific humidity measurements, smaller spring snow cover, decreasing Arctic ice concentrations in glaciers, and subsequent sea level rising all point to warming temperatures. These data, compiled by independent researchers from several sources, clearly signal the warming trends of the past decades (Hartmann et al. 2013).

Climate models match these observed values and quantify external and internal factors by combining them with the general circulation models that define earth's weather and climate. As described, future climate will be heavily influenced by man-made forcings such as carbon dioxide and aerosol emissions. These types of forcings are considered external to the system. The exact outcome will then be modified by the environment's response to these forcings, which is considered internal (Kirtman et al. 2013). Essential internal processes include the carbon cycle and water vapor feedback cycle (Collins et al. 2013) as described. Some processes cannot be represented explicitly because they are either too complex, such as biogeochemical processes, or occur on a very short time scale, such as clouds. These processes are parameterized, or statistically changed so that that they may be represented in the same model grid (Flato et al. 2013). From these, two types of models arise. AOGCM (Atmosphere-Ocean General Circulation Models) describe the physical components of climate and their relation to increased CO_2 emissions. ESM (Earth System Models) use similar principles as AOGCMs, but include more complex internal aspects relating to the carbon cycle and the relation of aerosols to the sulfur cycle (Flato, 2011).

Climate is predicted using the AOGCMs or ESMs by implementing numerical values onto a grid. This grid describes the earth's surface and is usually defined by latitude and longitudinal lines. A higher number of grid squares over a given surface area, called resolution, will usually lead to more accurate results. Advances in computing power allow models to reach higher and higher resolutions (Flato et al. 2013).

Currently, the most recent climate predictions come from the CMIP5 (Climate Model Intercomparison Project) (Taylor, 2012). The CMIP5 integrates several sets of experiments and multiple models that include ESMs and AOGCMs. Modeling groups use it worldwide with varying inputs of parameters and predictions. It can provide results for both short term and long term periods and is used extensively in the IPCC report (Collins et al. 2013). One of the most commonly cited results of the CMIP5 is the ECR (Equilibrium Climate Sensitivity). This metric is defined as the annual mean global surface temperature change following a doubling of CO_2 atmospheric concentration. The IPCC report rates ECR as most likely to be between 1.5 and 4.5 degrees Celsius for future climate (Collins et al. 2013). Based on fossil fuel combustion estimation, the CMIP5 estimates that relative to the reference period from 1986-2005, the global mean surface air land temperature will be 0.47 to 1 degree Celsius higher in 2016-2035 (Kirtman et al. 2013).

More important to this essay than air temperature changes are sea surface temperature changes. Models predict that SSTs will change in a similar manner as surface land air temperatures, but at a smaller magnitude because of the increased heat capacity of water. Temperature changes in the ocean are more complicated because of the previously described depth-temperature gradient and circulations, so model results are more variable than for land air temperatures. However, nearly all results do agree that the sea surface temperature will be warmer in the time period from 2016-2035 than the period from 1986-2005 (Kirtman et al. 2013). This increased temperature will lead to a variety of effects, some of which are unknown at this time and others that are quite difficult to predict. These future effects are currently being analyzed and studied. One of them is the effect that increased SST will have on hurricane intensity. In order to correlate these two factors, a basic understanding of hurricane physics is required.

HURRICANES

Tropical cyclones are rapidly-rotating storm systems centered on a low pressure area that produce high winds and heavy rains (American Meteorology Glossary, 2012). Hurricanes are a type of tropical cyclone with wind speeds that exceed 32 meters per second (American Meteorology Glossary, 2012). When these storms make contact with land and human population centers, they can have a tremendous impact. As will be described in this section, the intensity of these storms is expected to increase as a result of global warming effects. The Eastern and Northeast coasts of the United States are especially at risk. One of the more recent tropical cyclones to affect the northeast United States, Hurricane Sandy, caused $50 billion in damage and accounted for 147 direct deaths (Blake et al. 2013). Part of the reason why these storms create such an important impact is the high population density on the coasts. Currently, 39% of the U.S. population lives in Coastal Shoreline Counties. Interestingly, this number is expected to grow by 8% this decade (Crossett et al. 2013). The risk that this population faces with respect to tropical storm impacts is great, but is only expected to increase with enhanced population density and storm intensity. However, the risk is not borne by the coastal population alone. Flood insurance programs are governed by the federal government. In order to encourage participation, these national programs provide coverage below fair market cost (Browne and Hoyt, 2000). Given current policies then, the government will subsidize the risky behavior taken by some to live in coastal areas. Thus, the issues related to increasing tropical storm intensities are relevant to all taxpayers living in the United States.

GENESIS

In order for hurricane formation to occur, several factors must be in place. Some main points will be mentioned here, as described by Gray (1979). Hurricanes draw their energy from the ocean. The ocean provides this energy from temperature and a high relative humidity from the surface through the mid-troposphere region. From a physical point of view, hurricanes virtually always form at least 300 miles from the equator. This is a result of the Coriolis force and development from gradient wind to cyclostrophic balance, as will also be described in more detail below. Also, only a small horizontal wind gradient may exist from the sea surface to the top of the troposphere. Finally, an environmental flow perturbation must exist that combines water vapor, enthalpy, and momentum distributions around a low pressure area. There are a diverse number of factors that can cause this perturbation. With respect to hurricanes affecting the East Coast of the United States, easterly waves over West Africa are especially important. These can be understood in conjunction with the dynamics of Trade Winds.

Trade Winds

Trade Winds, also referred to as easterlies, are consistent air motions that define global wind circulation. In the northern hemisphere, easterlies occur mostly in the lower troposphere in the tropics near the equator. Westerlies occur at latitudes further north and blow from the west to the east. Hadley (1735) first proposed the origin of these winds. Hadley's ideas were quite advanced for his time and later shown to be accurate from a mathematical basis (Gill, 1980). His proposed circulation model came to be called Hadley Circulation. The very basics relative to the Atlantic Ocean in the northern hemisphere are described as follows.

The earth rotates around the sun on a tilted axis. This means that the planet does not receive an even distribution of heat. A temperature gradient exists from the equator to the poles, which results in the warm weather in the tropics and cold weather in the Arctic. Warm air in the Tropics expands and rises, while cold air in the Arctic sinks. These opposing motions create a pressure gradient pointed from the equator northward. After air rises in the Tropics, it follows this pressure gradient to the Arctic, where cold temperatures cause it to sink. These low-lying air masses then move south back toward the Tropics to replace the rising air, thereby completing the loop. This circulation, however, is complicated by the Coriolis force. This force results from the rotation of the earth and always acts to the right of moving fluids in the northern hemisphere. It will be seen again in the General Equation of Motion. So, when air moves north in the northern hemisphere, it gains an eastward component. Southward moving air receives a force in the opposite direction, resulting in a westward component. The Coriolis force does not exist on the equator, which results in a convergence zone at 0° latitude. The general flow is represented in the following figure. Take special note of the flow straight west over Africa, the following northeast components near the coast of the U.S., and the counterclockwise circulation in the Atlantic:

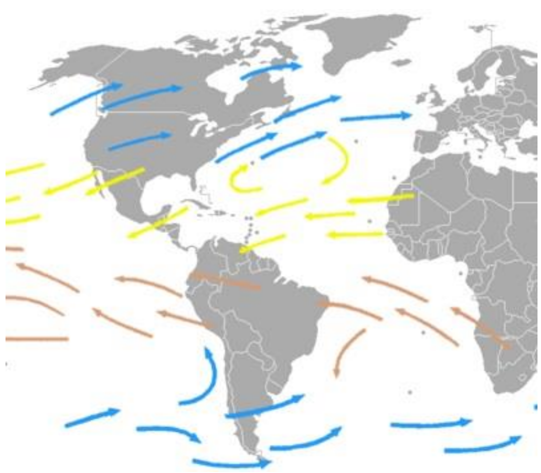


Fig. 1
http://en.wikipedia.org/wiki/File:Map_prevailing_winds_on_earth.png

African Easterly Waves

Air moves westward over West Africa into the Atlantic Ocean. As it does so, it experiences a unique temperature gradient between the cool waters of the Gulf of Guinea and much hotter Sahara Desert. This gradient generates low pressure instabilities in the easterly jet. This low pressure point travels along the jet, creating a wave along the fluid flow (Burpee, 1972). As the centers of low pressure move over the ocean, they interact with the general circulation model and may result in storm formation, as further described in the next sections. The complete dynamics of African Easterly Waves are still being studied, but it is thought that they account for the creation of up to 85% of major hurricanes in the Atlantic Ocean (Landsea, 1993), including Hurricane Sandy.

Hurricane Paths

To a general approximation, hurricanes move with the general circulation flow. However, their exact path is much more difficult to predict. Hurricanes are not simply embedded into the airflow environment, but actually interact with it and change it (Montgomery and Kallenbach, 1997). The following figure shows storm paths from 1992-2001 (Neumann, 2003). These paths bare some semblance to the previous figure depicting trade winds. By observing the paths, it becomes clear that many of the storms that affect the East Coast of the U.S. originate near Africa, as predicted by the African Easterly Wave theory.

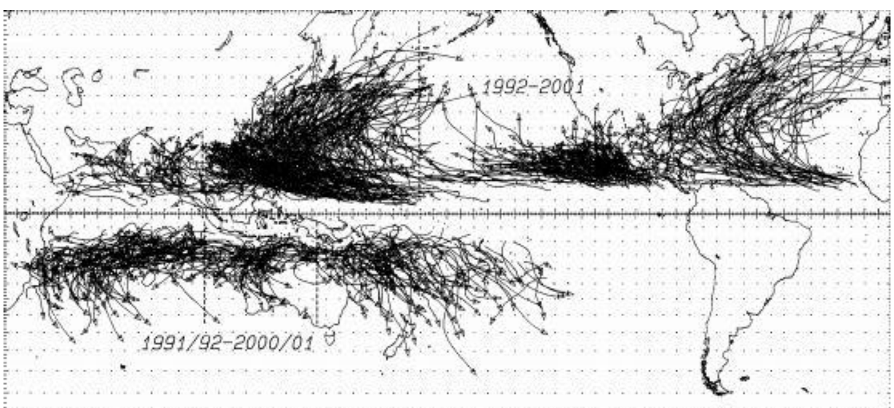


Fig. 2
(Neumann, 2003)

HURRICANE ROTATION

In order to model hurricane rotation, two perspectives will be taken: one from a kinetics standpoint and one from an energetics standpoint. As commonly understood from radar images, a counterclockwise circulation of clouds defines a hurricane in the northern hemisphere. This type of motion is called cyclonic flow, which is a specification of the gradient wind balance (Willoughby, 1990). The gradient wind balance is derived from the basic equation of motion that defines atmospheric fluids. This equation is similar to the governing Navier-Stokes equations, which apply Newton's second law to fluids, but adjusted to account for rotation in the system. The derivations assume parcel theory, implying that one parcel of air is observed with forces acting on it defined. The equations will be briefly mentioned here, as derived by Houze (1993).

General Equation of Motion

The atmospheric equation of motion for fluids is:

$$\frac{D\mathbf{v}}{Dt} = -\frac{1}{\rho}\nabla p - f\mathbf{k}\times\mathbf{v} - g\mathbf{k} + \mathbf{F}$$

Recall that Newton's Second Law states that F=ma. Rearranged, it is equivalent to a=1/m * F. The general equation of motion is an analog to Newton's Second Law, where the left side represents acceleration of a parcel and the right side represents the forces acting on it. Each of these terms is defined as follows:

$\frac{D\mathbf{v}}{Dt}$: $\mathbf{v}$ is the three dimensional velocity of a parcel of air. $\frac{D}{Dt}$ is the material derivative, which accounts for changes in the parcel with respect to time and space. Overall then, this term defines how velocity changes with respect to space and time, similar to acceleration. This is a different application of Newtonian acceleration, which typically only describes a derivative with respect to time. This distinction is necessary to describe fluids because the volume of fluids can change even though they maintain their mass.

$-\frac{1}{\rho}\nabla p$: ρ is the density of air. ∇ is the three dimensional gradient operator. p refers to pressure. The term overall quantifies the pressure gradient. In the case of a hurricane with a low pressure center, the pressure gradient will be a force that points inward toward the center.

$-f\mathbf{k}\times\mathbf{v}$: f is the Coriolis force. The Coriolis force is an 'imaginary' force. It results from the rotation of the earth and helps describe observed motion of fluids from the point of view of the rotating system. By making an f-plane approximation, f can be calculated as f = 2Ωsin(φ), where φ is the latitude of a parcel. This means that the Coriolis force is a function of latitude. **k** is the unit vector in the z (vertical) direction. $\times$ identifies a cross product. The net result of this term is that a Coriolis force will always exist on a moving parcel of air. In the northern hemisphere, this force will always act to the right of motion (except at the equator, where φ = 0).

$-g\mathbf{k}$: g is acceleration due to gravity. As described by the unit vector in this notation, it only affects vertical motion.

$\mathbf{F}$: $\mathbf{F}$ is the friction force.

Gradient Wind Balance

Now, with the general equation of motion in mind, a few assumptions and approximations can be made to simplify it. First, only horizontal motion will be considered. This negates the gravitational term. Second, only motion above the boundary layer will be considered (for now). In atmospheric flows, when assuming a homogenous fluid, friction forces occur between the boundary interface and the fluid flow. The boundary layer describes the vertical height at which frictional forces are relevant. By assuming flow above the boundary layer, the frictional flow can be negated. Third, it will be assumed that flow becomes highly circular-a good approximation when considering hurricanes. This introduces the centrifugal force, which should be familiar from Newtonian mechanics and is represented by the term $\frac{\mathrm{v}^2}{r}$.

The Gradient Wind Balance equation thus looks like:

$$\frac{D\mathrm{u}}{Dt} = -\frac{1}{\rho}\frac{\partial p}{\partial r} + f\mathrm{v} + \frac{\mathrm{v}^2}{r}$$

Because only horizontal flow is considered and because circular flow is assumed, this equation is represented in cylindrical coordinates for the sake of simplicity. In this notation, u represents horizontal radial velocity, v represents horizontal tangential velocity, and *r* is the radical coordinate.

Cyclostrophic Balance

Next, two more assumptions can be made based on the gradient wind balance to define cyclostrophic balance. First, steady state motion is assumed. This means that velocity doesn’t change over time or space, so the material derivative term can be negated. Second, we assume that hurricane formation occurs in the tropics. This assumption is based on genesis requirements and matches observations quite well. The tropics are near the equator at low latitudes. Recall that the Coriolis force is a function of latitude. After hurricane genesis has occurred and steady state achieved, hurricanes exhibit strong pressure gradient and centrifugal forces. Then, the Coriolis force term can be negated because of its small value relative to the pressure and centrifugal terms. Thus, the simple relation that remains is:

$$\frac{\mathrm{v}^2}{r} = \frac{1}{\rho}\frac{\partial p}{\partial r}$$

So, the centrifugal force acts in an equal and opposite direction as the pressure gradient. This results in flow that occurs at a right angle to both forces. Because the pressure gradient always points toward the low pressure point, the balance results in circular flow around a low pressure center that will be counterclockwise in the northern hemisphere.

Flow in the Boundary Layer

Now, flow in the boundary layer must be considered. By the definition of boundary layer, this is flow that occurs very close to a fluid boundary interface. In the case of hurricanes, boundary layer flow is wind over the ocean or land, depending on the location of a hurricane. When considering the boundary layer, it is important to remember the scales of distances that are being discussed. In the case of hurricanes, the vertical height of the boundary layer where friction is significant is on the order of one kilometer. The total height of the hurricane and vertical distance to which cyclostrophic flow is significant extends to the top of the troposphere, or about ten kilometers. The radial distance at which a cyclostrophic flow is significant varies, but is on the order of 100 kilometers (Smith, 1968). In order to represent this relatively thin boundary layer, the frictional term must be reincorporated back into the cyclostrophic motion equation, giving:

$$\frac{\mathrm{v}^2}{r} + \mathbf{F} = \frac{1}{\rho}\frac{\partial p}{\partial r}$$

Now, the pressure gradient is balanced by both the centrifugal and friction forces. While the addition may seem simple, it has very important implications when considering the vectors of these forces. Resulting flows of this balance will no longer be at right angles as they are in the cyclostrophic flow, but will skew inward toward the center of rotation at an angle dependent on the magnitude of the friction force.

The following figure provides a visual for the previously described flows. Three important terms should be noticed in it. First, the low pressure center of a hurricane is called the ‘eye’, and this is represented in the center of the figure. Second, the gradient wind represents the air flow above the boundary layer. Note the right angle between it and centrifugal, pressure, and Coriolis forces. Third, the near-surface wind represents flow in the boundary layer, or close to the surface. It becomes obvious that this vector is not at a tangential angle but rather skewed inward toward the eye.

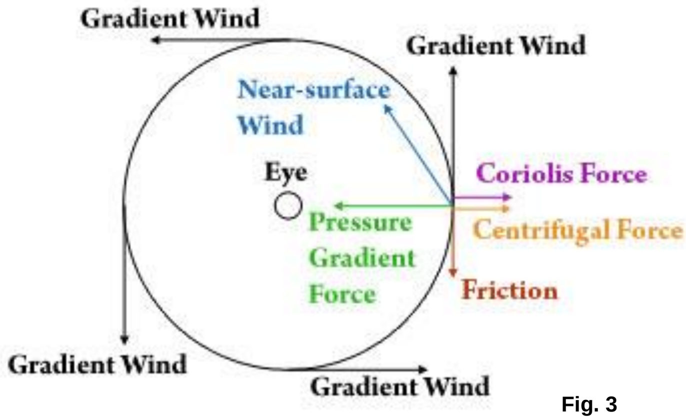


Fig. 3
http://www.hurricanescience.org/science/science/primarycirculation/

EKMAN PUMPING

The near surface interaction of atmospheric fluid with the bottom boundary layer plays another important role (Smith, 1968). According to Ekman transport theory (Ekman, 1902), the friction forces experienced by air flowing across the boundary creates a shear force on fluid velocity. Ekman integrated this shear force vertically and solved the resulting differential equations. This demonstrated that cyclonic flow and friction produces a vertical component to flow so that fluid in the boundary layer will be transported upward in a swirling motion from the surface. This system of equations can be solved and applied to a variety of natural science problems. It accounts for vertical mixing in the oceans and the formation of weather systems such as tornadoes. With respect to hurricanes, Ekman transport plays the critical role of pumping air near the land/ocean interface vertically upward into the atmosphere.

Recall the Clausius-Clapeyron relation previously discussed. This stated that the capacity for air parcels to contain water vapor decreases with temperature. Temperature decreases with height in the troposphere, so saturation water vapor capacity of an air parcel will also decrease with height. When a hurricane is moving over an ocean interface, an air parcel will have high water vapor content (humidity) at the surface because of its proximity to the huge liquid water reservoir in the ocean. As it rises, its capacity decreases, so the saturation humidity must decrease as well. This means that the water vapor must condense into liquid water. As discussed previously, this condensation leads to cloud formation and then precipitation. Additionally, condensation releases latent heat to the air parcel. This gives the parcel more buoyant energy, causing it to rise faster and higher. Rising air in the area immediately surrounding the eye causes even lower pressure. The area of rising air, cloud formation, precipitation, and high rotational velocities is referred to as the eyewall. It exists on the outside radius of the low pressure eye and accounts for many of the damaging effects of hurricane.

When the rising air from Ekman pumping reaches the top of a hurricane, it experiences the temperature inversion of the troposphere-stratosphere boundary. This causes the now relatively cool air to spread out. Then, because of radiative cooling, the air will achieve negative buoyancy and fall back down to the sea surface far from the eye wall. Air in the stratosphere is dryer than the troposphere and therefore denser. This higher density results in a small negative buoyant force that will cause downdrafts in the radius of the hurricane eye where updrafts don't exist.

The paths traced out by vertical Ekman transport are presented in the following figure:

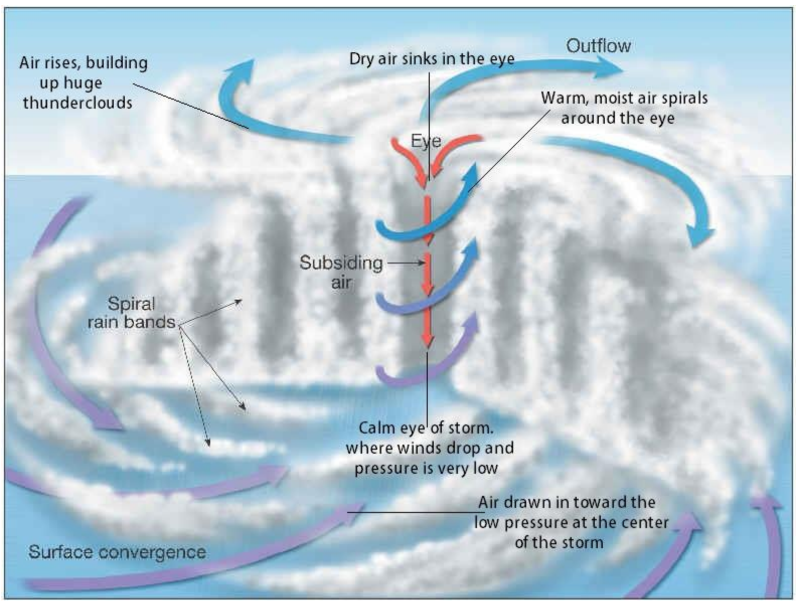


Fig. 4
http://www.ccvawx.net/wp-content/uploads/x-sec_hurricane.jpg

HURRICANE ENERGETICS

The previous section described hurricane mechanics strictly from a motion point of view. In order to understand hurricane intensities, it is necessary to consider the system from an energetics point of view. Interestingly, on a basic level, a hurricane essentially describes a Carnot Cycle (Emanuel, 1986). In order to understand this, a simple Carnot Cycle will be outlined, followed by its relation to hurricane dynamics.

Carnot Cycle

Sadi Carnot (1824) first suggested the Carnot Cycle, along with several other fundamental thermodynamic principles. In a basic sense, the Carnot Cycle describes the method in which heat energy is transformed into useable work via a closed cycle. The most common example of a Carnot Cycle is a steam engine, in which the thermal expansion of air is used to create work. This example is shown in the next figure with a pressure-volume diagram. This figure will be referenced in the Carnot Cycle description.

In these descriptions, it is important to remember the equation of state (Clapeyron, 1834). It describes properties of fluids by the following:

$$P * V = n * R * T$$

Where *P* refers to pressure, *V* refers to volume, *n* refers to mass, *R* is the ideal gas constant, and *T* refers to temperature.

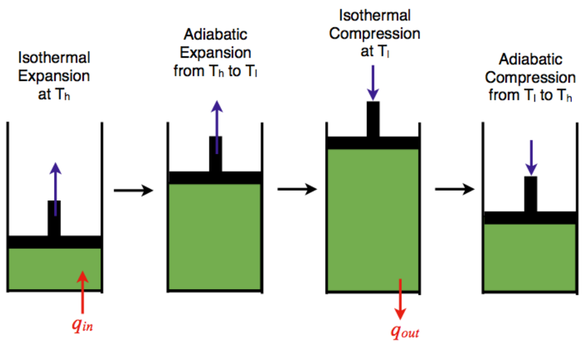


Fig. 5
http://chemwiki.ucdavis.edu/@api/deki/files/10064/Screen_shot_2010-12-16 at 12.39.24 PM.png

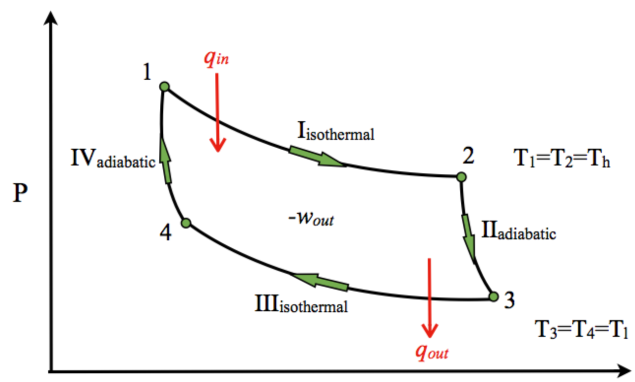


Fig. 6
http://chemwiki.ucdavis.edu/@api/deki/files/10056/Screen_shot_2010-10-30_at_8.56.41_PM.png?revision=1

Step 1: The fluid is heated. This causes the volume of the fluid to increase. This expansion pushes the piston upward, thereby lowering pressure. The rate of heating and rate of decreased pressure are exactly balanced so that temperature does not change. Steps in which temperatures remain constant are called isothermal.

Step 2: The heat input is stopped. However, the piston continues to rise, decreasing pressure on the fluid. This results in a decrease of temperature. There is no heat input or output, which refers to an adiabatic step.

Step 3: A cold source is added, so that the fluid releases heat. The piston falls, putting more pressure on the fluid. However, the volume of the fluid shrinks at the same rate. This means that the temperature of the fluid does not change.

Step 4: The cold source is removed. The piston falls, increasing pressure until the temperature of the fluid warms to its original temperature.

As implied by these steps, in order for a Carnot Cycle to function, a heat reservoir must exist that is at a higher temperature than a corresponding cool heat sink. Based on this fact, Carnot was able to calculate the efficiency of this cycle, which he defined as work done divided by the heat input. This was shown to be the difference in temperatures of the heat source and sink. Stated mathematically:

$$\eta = \frac{W}{q_{in}} = 1 - \frac{T_{cold}}{T_{hot}}$$

Where η refers to efficiency, W refers to work, q_{in} refers to the heat input, T_{cold} is the temperature of the heat sink, and T_{hot} is the temperature of the heat reservoir. Rearranging this equation leads to an important relation that will be used later:

$$W = Q(\frac{T_{hot} - T_{cold}}{T_{hot}})$$

Hurricane Carnot Cycle

The relation of a hurricane to a Carnot Cycle was first proposed by Emanuel (1986). Hurricane motion can be viewed from a different angle:

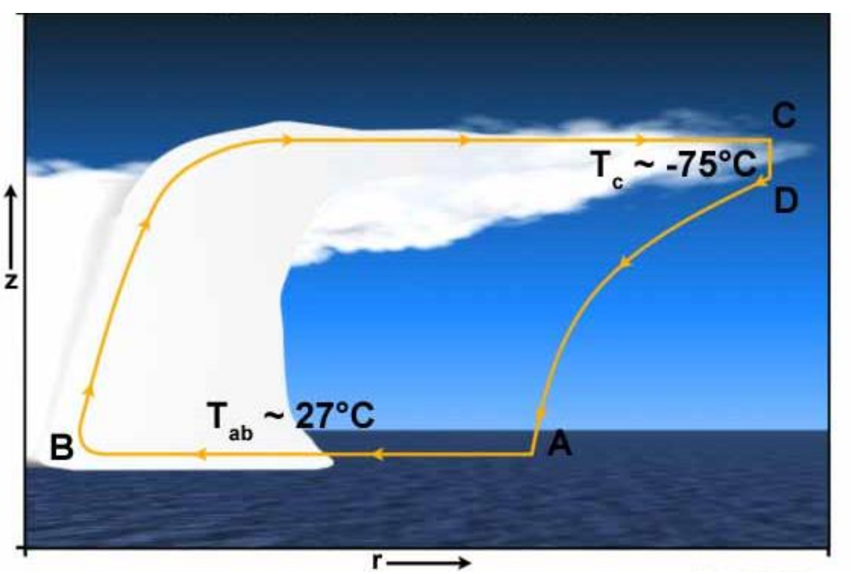


Fig. 7 https://www.meted.ucar.edu/tropical/textbook_2nd_edition/media/graphics/carnot1.jpg

This diagram shows motion as described in the previous section, but at the perspective of a cutaway side view. The eye is located at the bottom left side of the graph, and moving out on the x-axis represents movement away from the eye on the radial axis. The z-axis represents vertical movement in the atmosphere. Labels are not explicitly placed on the graph, but from the parameters discussed earlier, the x-axis scale is on the order of 200 km and the z-axis on the order of 15 km.

From a kinetics standpoint, it becomes apparent that movement from point A to point B indicates the aforementioned near-surface wind flow that is skewed inward toward the eye. Flow from B to C represents rising air that results from Ekman pumping and moves outward as a result of temperature inversion at the stratosphere. The rising air composes the eyewall and cloud formation. Movement from C to A indicates the sinking of the air back to the surface. Note that because of the perspective offered by this image, cyclonic motion is moving in and out of the page and is therefore not visible on the graph.

From an energetics standpoint, the relation of these dynamics to a Carnot Cycle can be observed. Recall that as near-surface wind moves from point A to point B (toward the eye), it experiences a gradient from high pressure to low pressure. According to the equation of state, this decreased pressure should result in a decreased temperature of the air. However, the air remains the same temperature from A to B. This fact is quite important. Near the surface, air can maintain its temperature along a pressure gradient because of its interaction with the ocean. The ocean receives heat from solar radiation. This heat energy is transferred to near-surface winds by evaporation. Thus, when air parcels arrive at point B from point A, they will be the same temperature but have a higher humidity. This first leg of the trip should seem familiar, as it correlates well to the first step of the Carnot Cycle: an isothermal movement with input from a heat reservoir.

Then, as described earlier, the air rises in the eyewall from point B to C. Water vapor collected from the ocean condenses to form clouds. Liquid water is at a lower energy state than water vapor. So, condensation releases energy in the form of latent heat. As another important point, this latent heat is not released to the environment, but maintained within given air parcels. Therefore, the rising and subsequent horizontal movement (as a result of the temperature inversion) from point B to C conserves heat and is adiabatic. As air rises in the atmosphere, pressure decreases, volume increases, and temperature cools. This correlates to the second step of the Carnot Cycle.

At point C, the parcel loses heat in the form of electromagnetic radiation. This radiation is emitted to the stratosphere. The air sinks to point D, experiencing increased pressure but decreasing its volume at the same rate. This results in an isothermal movement, which correlates to step three of the Carnot Cycle. Also note that the upper atmosphere acts as a heat sink for the hurricane.

Finally, air sinks from point D to A. As it does so, it continues to lose heat by radiation. However, the heat lost is equivalent to the amount of heat lost if liquid water in the air, had it not fallen out as rain in the eyewall, had been evaporated to vapor. This movement is an analog to the rising air from point B to C. It implies adiabatic motion, which in turn correlates to step four of the Carnot Cycle.

Now that the complete cycle has been outlined, a few things should be noted. Similar to an engine, it is assumed that certain efficiencies are necessary for hurricane formation to take place. These efficiencies are dependent on the temperature difference between the heat reservoir and sink. Greater differences will result in greater efficiencies. In the time scale of the near future, the temperature of the heat reservoir (ocean) changes faster than the temperature sink (stratosphere). Therefore, higher ocean temperatures will correlate to higher efficiencies, increasing the likelihood of intense storm formation.

Also, the final step in the hurricane Carnot Cycle (C to D) is an approximation. Because the radial scale is much bigger than the height scale, it is unlikely that the same air is cycled, but the approximation is necessary for calculations. Experiments show this approximation to be accurate (Emanuel, 1986).

WORK

When considering an engine that utilizes the Carnot Cycle, work is done by the crankshaft attached to the pistons. The work capacity is easily calculated from the heat flux and temperatures of the heat reservoir and sink, as shown earlier. Work done by a hurricane can be computed similarly, assuming that it is equivalent to energy dissipated from the ocean surface to the atmosphere. This relation can be manipulated, as shown below, to produce the maximum wind speed. The following relations are proven rigorously by Bister and Emanuel (1997). Only the key points will be expressed here, as simplified by Emanuel (2003). This way, the connection between hurricane intensity and sea surface temperatures will later be seen explicitly.

Energy Dissipation and Heat Transfer

As air flows over the ocean, it will produce a shear stress. This shear stress then results in energy dissipation from the ocean to the atmosphere as well as heat transfer. Kinetic energy dissipation can be calculated using the following formula (Bunker, 1976):

$$D = C_D \rho V^3$$

Where *D* represents energy dissipated, C_D is the drag coefficient, which measures the roughness of a surface, and *V* is the wind velocity. This equation represents the total energy available to a hurricane.

As implied earlier, a major heat influx from the ocean to the atmosphere is provided by the latent heat of evaporation. However, another heat influx exists: the frictional heating from air movement over the ocean. This factor makes hurricanes very efficient heat engines, as most frictional energy is lost to the environment in man-made Carnot engines. This factor is described by the same equation used for kinetic energy transfer. Thus, the heat input into a hurricane looks like (Fairall et al. 1996):

$$Q = C_k \rho V (k_0^* - k) + C_D \rho V^3$$

Where C_k represents the enthalpy exchange coefficient, k_0^* represents the enthalpy of air in contact with the ocean, and *k* represents the specific enthalpy or air near the surface. The first term on the right side represents the heat flux from evaporation overall. The term can be considered analogous to heat conduction in solids as described by the one-dimensional Fourier's Law, but in terms of enthalpy instead of temperature. In this case, enthalpy is a measure of the latent and sensible heat values of moist air, so the gradient given by the equation can be calculated by measuring humidity.

Hurricane Intensity

Recall the equation used to calculate work done by a Carnot Cycle. The new value for *Q* can be substituted into this to correlate to hurricanes:

$$W = Q\left(\frac{T_{hot} - T_{cold}}{T_{hot}}\right) \Rightarrow W = [C_k \rho V (k_0^* - k) + C_D \rho V^3] \times \left(\frac{T_{hot} - T_{cold}}{T_{hot}}\right)$$

This relation gives the maximum work potential of a hurricane. The next assumption made is that the only source of energy a hurricane has to do work is from the energy dissipated from the ocean. So, energy dissipation and work will be set equal to each other:

$$C_D \rho V^3 = [C_k \rho V (k_0^* - k) + C_D \rho V^3] \times (\frac{T_{hot} - T_{cold}}{T_{hot}})$$

Then, rearrangement with simple algebra yields the following relationship:

$$V_{\max} = \sqrt{\frac{C_K}{C_D} \frac{T_{hot} - T_{cold}}{T_{cold}} (k_0^* - k)}$$

This relationship is incredibly useful because it allows the maximum potential wind velocity of hurricanes to be calculated from constants and measureable variables. This maximum potential wind velocity is often referred to as the potential intensity of a hurricane (Emanuel, 1999). Keeping this in mind, the positive correlation between hurricane intensity and sea surface temperature (T_{hot}) is explicit. Based on these principles, Emanuel (2003) proposed that maximum potential wind speed increases by 3.5 ms^{-1} for every 1 degree Celsius increase in SST.

STORM SURGE

The greatest impact of a hurricane felt by human populations is the storm surge. The number of disasters due to storm surge floods surpasses all other natural disasters throughout the world (Shah, 1983). Hurricanes cause storm surges as a result of the low pressure eye and friction between the air-sea interfaces (Murty et al. 1986). The pressure of the eye pulls the water above its mean height, much like sucking on a straw lifts fluid out of a glass. The lifting effect of the low pressure center, though, is small. A much greater effect results from the wind, as shown below:

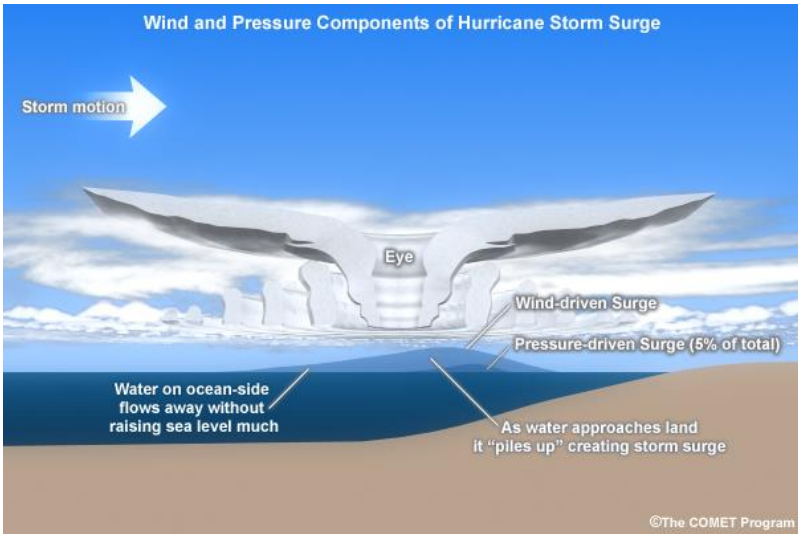


Fig. 8
http://www.nhc.noaa.gov/surge/

As air flows over water, a frictional force acts between the two fluids, producing a shear. This shear is a force that pulls the water forward, causing water to 'pile up'. Mathematically, this shear can be represented by (Murty et al. 1986):

$$\tau_s = C_D \rho_a V^2$$

By manipulating the general equation of motion (Murty et al. 1986), a relation between the shear force and storm surge rise can be calculated. This relation can be rearranged and integrated on each side. Then, the known value of the shear stress can be substituted in:

$$\frac{\partial \eta}{\partial L} = \frac{\tau_s}{\rho_w g h} \Rightarrow \eta = \frac{\tau_s}{\rho_w g h} L \Rightarrow \eta = \frac{C_D \rho_a V^2}{\rho_w g h} L$$

Where η is defined as the surge above the mean sea level, h is the mean sea level, and L is the distance over which the wind blows. The next figure gives a clearer picture of the difference between mean sea level and the heightened surge:

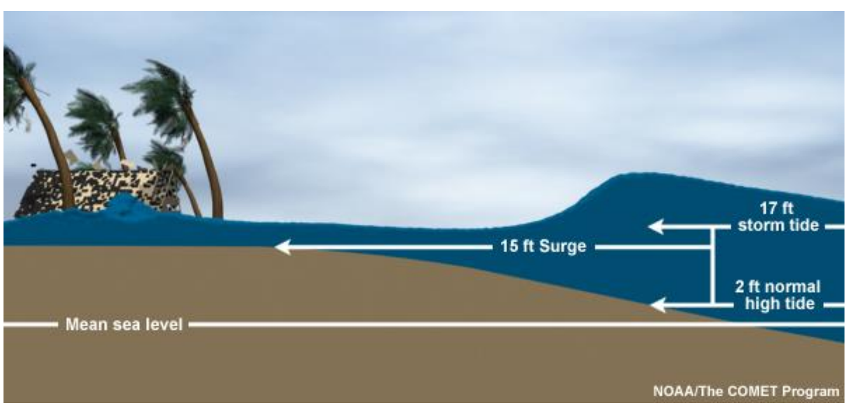


Fig. 9
http://www.nhc.noaa.gov/surge/

From these equations, the quadratic relationship that storm surge height has to wind speed becomes visible. Wind speed is a function of SST, which is enhanced by greenhouse gas warming. As mentioned earlier, greenhouse gas warming is also expected to raise the mean sea level as a result of ice melt and thermal expansion (Lin et al. 2012). These effects will make storm surges higher and more dangerous. Thus the intensity of storm surges, a natural disaster that already has stunning effects on human population centers, is expected to increase in the future.

PALEOTEMPESTOLOGY

The relations between tropical storm intensity and climate change are based on sound theory. However, when understanding natural processes and the physics that control them, an incredible number of factors can alter results and many necessary simplifications must be made. Therefore, it is essential to provide observational evidence to support theoretical claims.

These kinds of observations can be made accurately thanks to technological advances in radar systems in the past forty years. Satellites can accurately measure paths, wind speeds, and precipitation rates of storms. These observations are kept on record, providing useful databases for researchers. Based on the warming SST values in this time period, there should be a correlation to more intense storm events.

In fact, this correlation was made evident by Emanuel (2005). Emanuel established a power dissipation index (PDI) as a statistical value to measure hurricane intensity with respect to coastline area damages. In the PDI, maximum wind is the defining variable while other factors, such as wind shear forces and ocean energy flux, enhance its characteristics (Emanuel, 2007). When the PDI of storm events in the past 60 years is compared to SST values in the same time period, the correlation is significant at the 99% level. Especially important are the markedly increasing trends of the two values over the past 20 years. This is a result of an increase in the number of intense hurricanes, defined as storms with wind speeds higher than 50 meters per second lasting longer than one minute (Emanuel, 2007). The striking semblance of the two curves can be seen below (Emanuel, 2007):

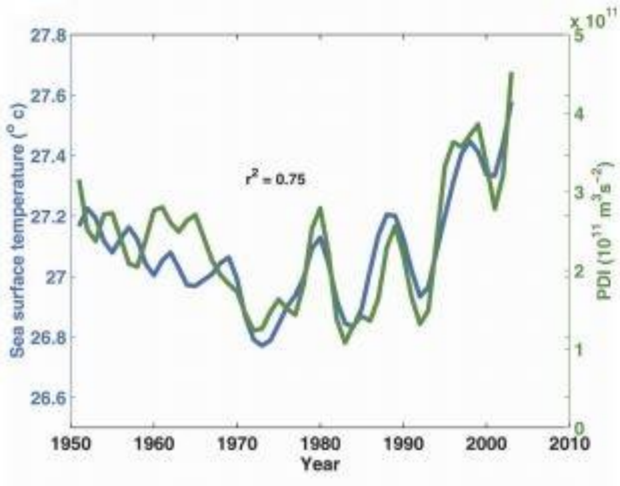


Fig. 10
(Emanuel, 2007)

In itself, this correlation seems to offer proof of the proposed significance of SST as a factor of hurricane intensity. Unfortunately, the correlated global SST values as described cannot currently be proven to be the causation of the more frequent intense storm events because other variables also show a strong correlation.

Vecchi et al. (2008) follow a similar procedure as Emanuel and calculate similar results. However, Vecchi et al. also plot another value that they define as 'relative SST'. In recent years, the Atlantic Ocean basin has experienced warmer SST values relative to the global mean. These enhanced relative temperatures, defined as the relative SST, are thought to be an anomaly, and not necessarily a norm that will continue into the future. Specifically, they may be a result of the Atlantic Multi-decadal Oscillation (AMO) (Kushnir, 1994). The exact cause of the AMO is currently unknown, but it is thought to be a consequence of changes in north-south atmospheric circulation and ocean heat overturning. That being said, the results of the AMO are recorded in paleo-climate proxies. They show that the relative Atlantic SST varies cyclically, as described by Knight et al. (2005) in the figure below:

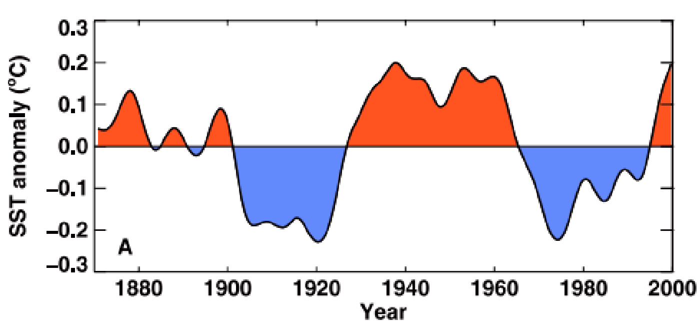


Fig. 11
(Knight et al. 2005)

When plotted against PDI, relative SST displays as much statistical correlation as Emanuel's global SST. This is important because relative SST values in the Atlantic are expected to diminish in the near future according to the cyclical trend of AMO. Global SST values, though, are expected to rise indefinitely as a result of global warming. Therefore, if PDI is assumed to be a function of SST, the hypothesized values are expected to increase in the future. However, if PDI is assumed to be a function of relative SST, future values are expected to stabilize, as shown below (Vecchi, 2008):

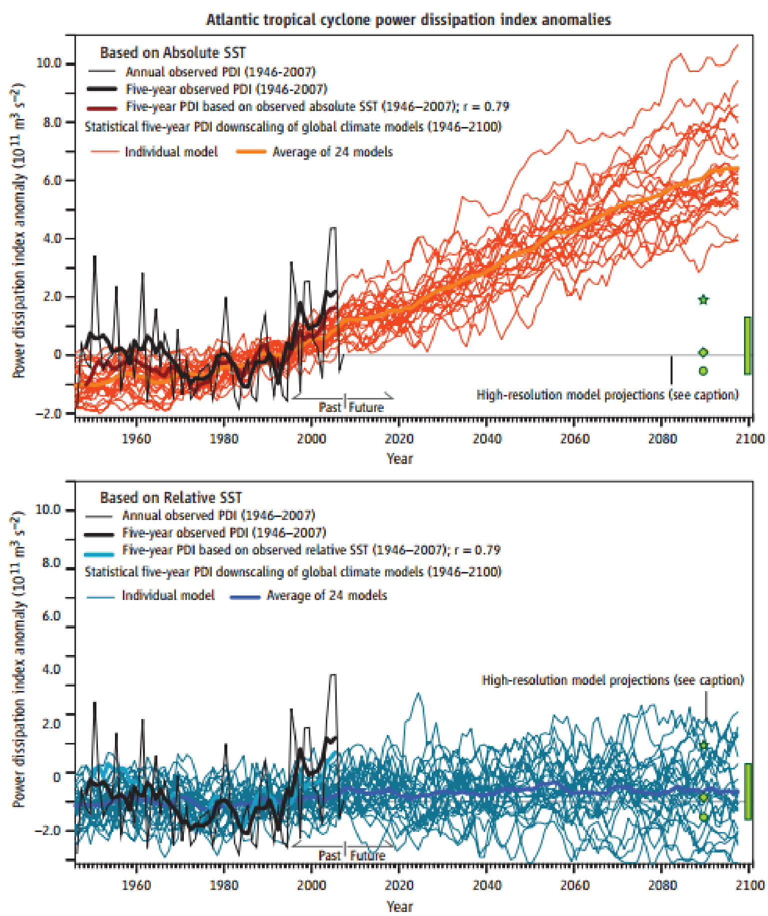


Fig. 12
(Vecchi, 2008)

The legitimacy of the AMO theory is still debated. The interaction of AMO with climate change is unknown, and its exact effect on tropical storms is still being discussed. When forecasting the intensity of future hurricanes, this is a problem because of the discrepancies of predicted values in the two models. This problem could be solved, or at least mitigated, by establishing a record of hurricane events over a time period longer than the past few decades. If hurricane activity is cyclical, it could help validate the AMO theory and future activity may be expected to decrease in the future. If not, it could substantiate hurricane intensity as a function of global SST, and intense storm frequency may be expected to increase in the future according to global warming estimates. However, these correlations are much more difficult to establish because the necessary information predates the satellite era.

Relations can be established on a time scale of a few hundred years using observations taken from ship measurements, as proposed by Vecchi and Knutson (2008). Based on this information, the authors determined that the intensity of storm events has increased markedly since the mid 1800's. Unfortunately, the results of studies such as these are disputable. The problem is that this type of data is relatively arbitrary. It relies on ship tracking information taken by people up to 150 years ago when scientific measuring methods were less established. Also, over a century-scale time period, measurement capabilities have become increasingly advanced and observations are easier to record. This means that small storm events, previously considered to be of negligible importance, are now recorded in great detail. Therefore, it is difficult to determine if, in the past century, the positive correlation between storm intensity and time is a result of increased SST measurements or simply a consequence of more accurate techniques.

Thus, there exists a need to find reliable and objective recordings of storm events in the pre-satellite era. From this need, the field of paleotempestology developed. The field is relatively new, but diverse enough to foster several different attempts to develop a proxy for historical storm measurement (Wallace et al. 2014). The rest of this section will explore and outline some of these published paleotempestology methods. The methods are quite diverse, and have been initiated over various regions of the world, including New England, the Gulf of Mexico, the Caribbean, and Australia (Australia is located in the southern hemisphere, so hurricanes are referred to as cyclones. Other than direction of rotation, the two terms describe the same event). Most of the authors have calculated rough trends in storm events over periods of a few hundred to a few thousand years. The authors also validate their efforts by correlating their method results to recorded data from recent storm events, but each one only serves as an exploratory attempt. Until more studies are completed exhausting more techniques in more areas in each region, no definitive statements about past hurricane intensity, frequency, or activity can be made.

METHODS

Tree Rings

In a method related to the measurement of past global ice volumes, past tropical storms can be recorded by utilizing oxygen isotope concentration anomalies in tree rings. Isotopes refer to atoms of the same element with varying values of neutrons. Oxygen has three stable isotopes: O-16, O-17, and O-18. The numeric values refer to the atomic weight of the atom. Each proton and neutron has an atomic weight of 1. Oxygen has 8 protons, which account for an atomic weight of 8. This implies that O-16 has 8 neutrons, O-17 has 9, and O-18 has 10 neutrons. These isotopes exist in natural systems and can be measured in oxygen atoms in water molecules. Based on numerous measuring techniques, a natural abundance has been calculated that describes the concentration of each isotope in natural systems. O-16 dominates this natural abundance.

Certain events can alter these natural concentrations. An important example of this is rainfall. As previously described, clouds in storm events and hurricanes contain liquid water molecules. These water molecules fall as rain, but due to energetic properties, water molecules containing the more massive oxygen isotopes condense and subsequently fall as rain first. Thus, rain is comprised of water molecules that have a heavier, and measureable, mass distribution anomaly relative to natural abundances. This phenomenon is called fractionation. Mathematically, isotope compositions are defined as follows (Krauskopf, 1995):

$$\delta^{18}O = \frac{({}^{18}O/{}^{16}O)_{sample} - ({}^{18}O/{}^{16}O)_{SMOW}}{({}^{18}O/{}^{16}O)_{SMOW}} \times 1000‰$$

In this notation, superscripts refer to isotope values. The subscript SMOW refers to Standard Mean Ocean Water. It represents the standard isotopic composition of a sample of seawater. From this relation, it is easily seen that stable isotope concentrations are measured on a relative, per mil basis.

Rain from hurricanes has a unique $\delta^{18}O$ value relative to thunderstorms because of the intense fractionation that the molecules must undergo in a short period of time from ocean water, to vapor, to rainwater. This process gives it a very negative $\delta^{18}O$ value (Lawrence and Gedzelman, 1996). After the hurricane rain hits the ground, it absorbs into the topsoil. There, it travels through plant roots and is stored in the cellulose of plant cells. Once the water is stored, the isotopic composition anomaly of the rainwater is conserved and can be measured, even hundreds of years later.

For this purpose, trees are especially useful. As commonly known, trees grow outward from the center of their trunk. Each year, a ring is added, and the age of the tree can be found by counting the rings. For more objective measurements, the exact age of each ring can be found by radiocarbon isotope measurements.

The previously described relationship between oxygen isotopes exists because the atoms are considered to be stable. Not all atoms, however, are stable. Some are radioactive, meaning that they spontaneously eject a subatomic particle from their nucleus. This rate of ejection is constant, and can serve as a paleontological clock. In methods involving biological components, radiocarbon dating is commonly used. In this system, the Carbon-14 isotope decays to a stable Nitrogen-14 isotope by ejecting an electron. By comparing the relative mass concentrations of C-14 isotopes in samples, ages can be calculated. In the case of trees, samples near the center of the trunk will have lower concentrations of Carbon-14 atoms because that part of the tree is older. Moving outward from the center will result in younger samples that have higher C-14 concentrations. Because of the rate of decay of Carbon-14, radiocarbon dating is accurate for periods up to 70,000 years (Krauskopf, 1995).

With these tools, radiocarbon and stable oxygen isotope concentrations can be correlated. This technique was utilized by Miller et al. (2006) to cite past hurricane events. They used trees from a site in southern Georgia and leftover stumps from trees that had been harvested in the past. For a given trunk, oxygen isotope samples were measured from the very center moving outward along the radius. From this, a record of anomalies was recorded from approximately 600 years ago to the present. Interesting relationships can be found, such as the following (Miller et al. 2006):

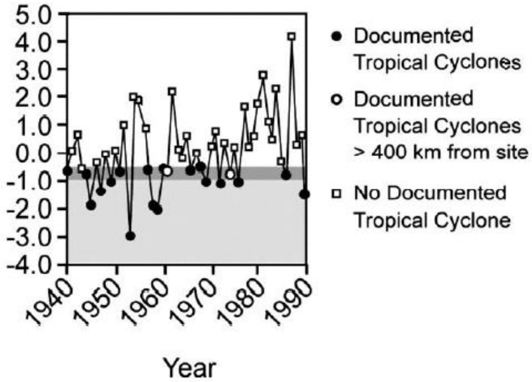


Fig. 13
(Miller et al. 2006)

On this graph, the y-axis and plotted line represent measured $\delta^{18}O$ values in the tree trunk. These values were correlated to radiocarbon age dates. The x-axis was limited to a time period in which relatively accurate records of hurricanes exist. Then, dates of hurricanes were plotted as points along the $\delta^{18}O$ line. Notice how well these dates correlate to measured $\delta^{18}O$ anomalies (low points). This correlation validates the method, at least somewhat, and its proposed record of even older hurricane events. However, on a broad scale, the method may be somewhat limited. It is important to remember that a variety of other biological factors besides rainfall may play a role in water absorption by trees. These factors could affect measured stable isotope anomalies. Also, the method may serve well to measure frequency of events, but not necessarily intensity.

Speleothems

When hurricanes and other intense storm events deposit rain, not all of it is absorbed by plant roots. Some water drops seep down through the soil and bedrock underneath. As they do so, minerals such as calcium dissolve into the water. In specific areas, once through the bedrock, the water droplets end up on the ceilings of caves. Here, they collect together and fall to the cave floor. Depending on pH levels and other factors, the droplets may deposit absorbed minerals on the cave ceiling before falling. Also, minerals collect on the cave bottom where the drops collect. Over periods of long time, these mineral deposits get bigger and bigger, eventually forming speleothems, or cave formations. The most common speleothems are stalactites (on the ceiling) and stalagmites (on the ground). These speleothems are typically made of limestone (calcium-carbonate) and water (Allison, 1923).

The water molecules in speleothems maintain their isotopic concentrations. Therefore, if the source of the water is from a hurricane event, the same $\delta^{18}O$ anomaly as previously described may be detected in a formation. In a process that is, broadly speaking, quite similar to the tree ring method, isotopic oxygen concentrations of water molecules can be measured from speleothems. Instead of using rings in tree trunks to date these values, the growth rate of the cave formations can be used. Like tree rings, $\delta^{18}O$ values can be plotted against age, with anomalies representing past hurricane events.

This method was used to create a hurricane record in the Caribbean by Frappier (2007) from stalagmites in caves in Belize. Nott et al. (2006) were also able to utilize the technique to recreate a hurricane history in Australia. However, the exact methodology is fairly complex, and probably limits its applicability to other situations. Firstly, the technique only works in regions where both tropical storms and cave formation are relatively common. Secondly, many factors can affect speleothem formation and are difficult to quantify, including soil depth and porosity, water infiltration extent, exact growth rates, cave entrance effects, and flooding. Thirdly, due to cave conservation efforts, speleothem collection can be difficult. Furthermore, determining which formations represent accurate samples is problematic while collection is taking place on site. As a result, paleotempestology from speleothems is a promising field, but currently challenging.

Porites Boulders

Stable oxygen isotope concentrations are useful in a variety of paleo-climate situations. For example, SST can be correlated to $\delta^{18}O$ values based on the fractionation argument. Because O-16 is less massive, less energy is required to evaporate it in water molecules out of the ocean. This means that, in equilibrium processes between the atmosphere and ocean, energy from the ocean will be spent converting O-16 atoms into gaseous form before O-18 isotopes will be converted. When warmer climates prevail, more energy is available to evaporate water. Therefore, extra energy exists to evaporate more O-18 isotopes, causing $\delta^{18}O$ values to fall in the ocean.

These $\delta^{18}O$ variations are recorded very well in porites, a type of stony coral reef. During skeletal growth and generation, corals use oxygen atoms contained in water molecules. Similar to the tree ring and speleothem methods, historical SST values can be determined from coral samples by plotting $\delta^{18}O$ records against dates obtained from radiogenic isotope dating and coral growth rates (Cobb et al. 2003). On a yearly basis, this correlation has a sinusoidal cycle. Conceptually, this makes sense because SST temperatures vary from high values in the summer to low temperatures in the winter.

Suzuki et al. (2008) utilized this correlation when dating a tsunami event in Japan. Tsunamis are defined by giant waves that disrupt the vertical profile of the ocean. Sometimes, during this disruption, pieces of coral are broken off and transported to shore. Once coral is broken off from the main body, it dies. This disrupts its Carbon-14 isotope concentration. Because of this, Suzuki et al. hypothesized that the date that these coral pieces were brought to shore could be calculated and that this age would represent the date of the storm event. To be even more specific, the sinusoidal $\delta^{18}O$ function described above was utilized to find the season in which the coral broke off.

Suzuki et al. were able to use this method to successfully correlate a porite sample to a tsunami event in 1771. Storm events cause similar ocean disruptions, so it is hypothesized that hurricanes could be dated in a similar fashion. However, this method has only been used to date a few singular events. It seems unlikely that it will be used to create a comprehensive record.

Storm Ridges

Utilizing a similar idea, Nott and Hayne (2001) developed a more inclusive method to identify previous storm events and utilized mathematical models to obtain hurricane (or cyclone, because the study was based in Australia) intensity values. The method begins with tide observations. Tides are variations of sea level height on a shoreline. They are a result of planetary motion, and therefore occur in a cyclical fashion. When the ocean level rises at high tide, it carries with it coral and shell sediments. These sediments are then deposited along the shore. The depositions collect at the peak height of the water level and create slopes called ridges. At low tides, these ridges are easy to observe and can be used to find sea height variations.

As described in the hurricane section, wind stress forces from storm events cause storm surges. These surges force the sea surface level to rise higher than the typical tidal levels. This higher level leaves similar depositions at much higher points than the typical high tide. These depositions are recorded in the beach landscape and can be observed many years later. The storm surge events can then be dated by using radiogenic carbon dating of the biologic sediment in the ridge.

Nott (2011) used this method to develop a storm record in Hamelin Pool, Shark Bay, Western Australia. This was a unique case because ridges were formed by a single species of cockle shells. These ridges formed terraces, whose geometry was formed by ‘still’ water level and wave ‘run-up’. Still water is sea level height as a function of storm surge, tide, and wave set-up, with set-up referring to the rise in water level as a result of breaking waves. Wave run-up refers to the rush of water up against the beach itself (Nott and Hayne, 2001). Through analysis of the terraces, Nott recreated the described still water levels and wave run-up that formed the ridges.

Using this evidence, the tropical storm surge and wind model GCOM2D was used to determine water depth, currents, topography, and bathymetry. The SWAN shallow wave model was also used to determine wave heights, periods, set-up, and travel direction. Based on the calculated storm surge heights and correlated storm intensity relations, Nott determined wind speeds and eye pressures of the associated storm events. By using this method for each ridge, he was able to recreate a storm history (Nott, 2011).

This method is useful, but requires a relatively high number of quantitative calculations. In order for the calculations to work, several simplifying assumptions must be made. For example, it must be assumed that storm ridges are only caused by storm events and not some other natural phenomenon. Additionally, these ridges must remain undisturbed. Also, assumptions must be made in wave inundation methods based on available evidence. And, in the case of Shark Bay, a single species of shell existed in every ridge, making age calculation methods homogenous. This may not always be the case in more ecologically diverse environments, making age calculations more difficult.

Fresh Water Plumes/Coral

In the Great Barrier Reef (GBR) in Australia, much work has been done examining the interactions of coral reefs with fresh water resulting from river plumes. Australia experiences a wet summer season and a dry winter season. During the summer season, the continent receives about 70% of its annual rainfall. This large amount of rain in a short period of time results in excessive water runoff into rivers. This excess water is not stable and results in large surges of freshwater that are sent into the ocean. The higher volume extends further into the sea than typical rates and is called a fresh water plume (Lough et al. 2002). Hurricanes and storm events deposit large amounts of rainwater into river systems during a short period of time. This results in a sudden surge, creating a relatively large plume (Lough, 2007).

Like tree rings and speleothems, coral grows at a measureable rate. So, by taking a core sample from the reef, a scale can be developed to assign an age to small segments in the sample. Some of these segments, when exposed to ultraviolet light, tend to emit luminescent light (Isdale, 1984). Plotting these luminescent bands relative to age shows a strong correlation to freshwater plume events. By taking a series of coral samples extending from near the shore into deeper ocean areas, Lough (2007) was able to use the correlated surge extent to calculate the volume of fresh water leaving the river systems and entering the ocean. Subsequently, this volume was used to calculate rainfall in certain areas of Australia throughout the past 400 years. Based on the relative extent of the plumes, the intensity of the storm events that caused the rainfall could be calculated.

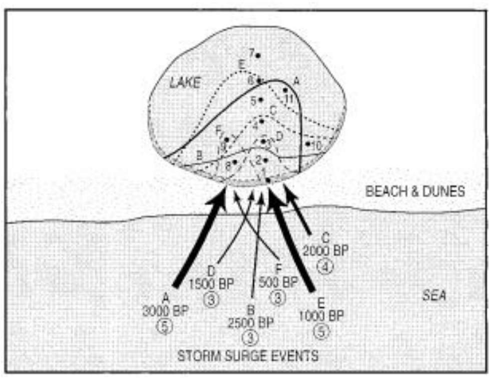
This method seems accurate, but some holes exist in the methodology. Specifically, the reason why fresh water causes luminescence in coral reefs is still unknown. Fresh water plumes transport nutrients, sediments, and pollutants into the ocean. These factors, and the lower salinity densities, can stress coral structures. Accordingly, it has been hypothesized that the luminescent lines indicate growth responses from the decreased salinity densities or are a direct result from humic acidity caused by the plumes. However, some evidence supports a third hypothesis that decreased skeletal density in coral reefs causes luminescence. This third hypothesis is a problem because skeletal density is not just a function of freshwater plumes, but includes a variety of other factors (Lough, 2011). Until this discrepancy is resolved, the exact legitimacy of this indicator will remain unknown.

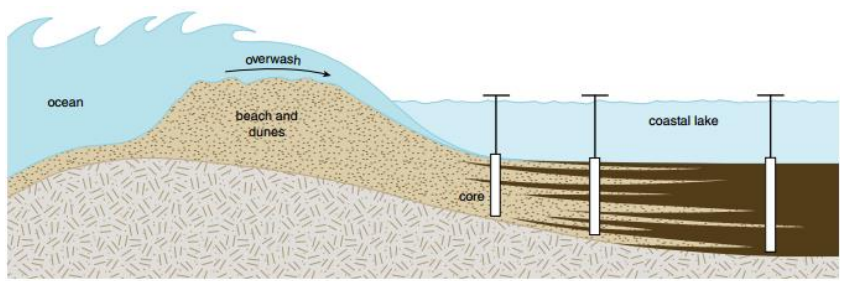
Sedimentary Analysis

Sediment analysis was first attempted by Emery (1969) and may be the first described method of paleotempestology. The first thorough attempt, though, of recreating an historical record of hurricane landfall from the results was made by Liu and Fearn at Lake Shelby, Alabama (1993). Their method involved analysis of overwash deposits in core samples taken in the lake. Using this same method at a dozen sites, Liu and Fearn recorded a rough storm history for the shore of the Gulf of Mexico (Liu and Fearn, 2000). This method is described in more detail below.

Liu and Fearn chose lakes and marsh areas as their sites. These areas contained bodies of water that were isolated from the Gulf, but only by a very narrow strip of land. This strip is referred to as the barrier beach. As described in the hurricane section, past intense storm events caused shear from high winds to create storm surges that rose above the height of the typical sea level. Because the barrier beach is so narrow, the surge caused ocean water to flow over it directly into the observed body of water. While doing so, the ocean water collected sediment material from the barrier and carried it into the lake. Once in the lake, the sediment was deposited on the bottom. Erosion in the lake caused the deposited coarse beach sediment to be covered and buried by organic and finer-grained sediments. The two types of sediment are quite distinct, causing observable layers in the lake bottom. The layers of coarse beach sediment are referred to as overwash layers.

The distribution of overwash layers are representative of relative storm intensity. As described, more intense storms result in higher storm surges. These stronger surges cause ocean water to penetrate further into the body of water, closer to the center, while weaker surges remain closer to the shore. This results in a ‘fanning’ distribution of coarse sediment grain at the bottom of the observed lake or marsh. The necessary location of a body of water relative to the ocean and results of storm surges are visualized in the following figures from Liu and Fearn (2000, 2007):





Figs. 14 & 15
(Liu and Fern, 2000, 2007)

Notice the vertical rectangles in the coastal lake in the second figure. These represent core samples. Core samples allow vertical profiles of the sediment layer to be observed in the lab. These samples are taken in a line extending from the beach toward the center of the lake, as indicated in figure 15. As a result of natural sedimentation, deeper overwash layers correlate to older events. By utilizing radiogenic isotope dating techniques, these events can be quantitatively defined with a relatively high level of accuracy. Then, with these accurate dates, overwash layers can be connected across samples, as indicated in the figure below (Liu, 2007):

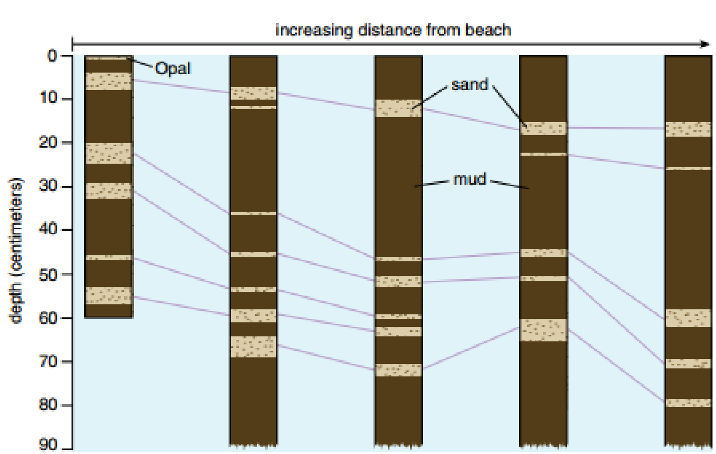


Fig. 16
(Liu, 2007)

These cores were collected in Western Lake Florida (Liu and Fearn, 2000). Notice the 'Opal' label. The overwash layer is assumed to represent this relatively recent storm event because of the correlating date. The storm took place in 1995, so satellites existed to accurately record its path and effect. Based on these results, Opal was named a category 3 hurricane.

Next, notice that the Opal overwash layer does not extend very far away from the beach. Other overwash layers that are deeper in the cores, or older, extend further out. This indicates that stronger storms did take place in the past and that these storms were more intense than a category 3 hurricane. These are relatively qualitative statements, but represent the type of evidence that can be provided by analyzing core samples. With this type of methodology, Liu and Fearn performed more quantitative calculations and were able to create an historical hurricane record dating back 3,800 years. With potentially deeper cores (older dates), this type of a history could be correlated to known historical climates.

This method has been used to explore regions beyond the Gulf of Mexico and into the Caribbean Sea and Atlantic Ocean. In the Northeast United States, paleohurricane records have been measured in several areas, including: Succotash Marsh in Rhode Island (Donnelly et al. 2001), Whale Beach in New Jersey (Donnelly et al. 2001b), Brigantine, New Jersey (Donnelly et al. 2004), and Long Island (Scileppi and Donnelly, 2007). Not enough sites currently exist to provide an exact history of the coast, but correlating values between the studies are encouraging.

Though promising, this type of paleostorm reconstruction has come under some criticism. Specifically, it was argued that the origin of sediments comprising the observed overwash layers could not be verified to have necessarily come from the barrier beach during storm events. Rather, they may have been deposited from other sources due to other natural events (Otvos, 1999). As described, sediment analysis does not provide a method to solve this discrepancy, but several techniques have been developed to test the overall accuracy of the method.

Mathematical models developed by Brandon et al. (2013) have established a power-law relationship between maximum sediment grain sizes observed in deposits and correlating hurricane intensities in Florida. These models are very useful in quantifying results, creating constraints for storm intensity, and showing that all layers could be deposited by hurricane events. Using recorded data of the storm track, pressure, and other meteorological indicators from the 1991 storm Hurricane Bob, Cheung et al. (2007) created a numerical model that simulated coastal waves and surf zone processes. The results match observed land fall evidence quite well, and add further legitimacy to the coarse grain redistribution results observed from core samples taken in the area. Utilizing a less computationally intense method, Boldt et al. (2010) used the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model to estimate past storm surges by utilizing historic records in Mattapoisett Marsh in New England. Their results also support coarse grain deposition by past hurricanes measured by sedimentary paleotempestology methods.

From a statistics standpoint, it is important to establish that measured trends in core samples are statistically relevant and not a result of probability or background noise. Woodruff et al. (2008) combine an atmospheric circulation model with a Monte Carlo storm probability technique to generate simulated overwash layers. Lane et al. (2011) conducted a similar statistical model in Florida. Results from studies like these statistically support the recorded trends and positive correlations and strengthen the reliability of the method.

Foraminifera

Hippensteel and Martin (2000) and Scott (2003) collected core samples on the coast of South Carolina in a similar method to the one described in the sediment section. However, instead of testing grain size, they were interested in the use of foraminifera (microscopic protozoa) as a proxy and storm indicator. Storm surges created by hurricane events deposit sandy overwash layers into water bodies from barrier beaches. In addition, they also transport tiny organisms from the sea. These organisms are mixed into the overwash layer and their concentrations can be measured. Stronger storms deposit more protozoa, so previous storm event intensities can be determined by concentrations of foraminifera in overwash layers.

This proxy is a good addition to the sediment analysis because it helps solve the coarse sediment origin problem. Different species of foraminifera live in the sea and in freshwater. Therefore, when ocean species of foraminifera are discovered in overwash deposits, they must have been transported from the sea. The only probable way this could happen is in the storm surge of a hurricane event. Furthermore, because of sedimentation rates, the sediment in which they are mixed in must also have been deposited at the same time by the same hurricane event.

However, several discrepancies exist in this method as well (Hippensteel, 2010). For example, thousands of species of foraminifera exist. Accordingly, there is disagreement over which species of foraminifera should be observed and recorded. Additionally, bioturbation effects may alter the samples. In the case of South Carolina, the fiddler crab tends to burrow into sandy coastal regions, disrupting the sediment record. This disruption could modify the corresponding overwash records, thereby changing their calculated dates.

Wind Shear Relation

Until this point, sea surface temperature has been the only time-dependent variable considered to affect intense hurricane formation. In reality, though, there are a number of other thermodynamic and physical factors that determine storm development. One of the most important of these factors is local wind shear, defined here not as a force but as the gradient of wind speed measured over the depth of the troposphere that results from frictional interactions with the sea surface. In fact, it has been shown that on shorter, inter-annual time periods, observed wind shears show an even stronger correlation to observed storm intensity than SST (Goldenberg et al. 2001).

From a physical standpoint, wind shear affects storm formation in the Atlantic because of its interaction with the aforementioned Easterly African Waves. Because they are caused by a constant temperature gradient between the ocean and Sahara, these atmospheric waves occur on a regular basis. Hurricane formation, however, is quite irregular over long time periods. Therefore, other irregular factors, such as wind shear, must interact with the pressure anomalies in order to prevent them from developing into much more intense storms (Goldenberg and Shapiro, 1996).

Based on recorded measurements, a strong wind shear generally exists over the Atlantic Ocean that serves to disrupt this development. This is because the vertically integrated wind velocity gradient creates asymmetric properties throughout the depth of a potential storm forming around a low pressure center. Additionally, because winds are stronger in the upper troposphere, circulation at high elevations is disrupted. This allows heat to escape at the top, which affects the pressure of the storm and overall intensity. Basically, the storm weakens from the top down until a less intense steady state is reached (Frank and Ritchie, 2001). Thus, an inverse relationship exists between wind shear and intense hurricane frequency. Statistically speaking, a relationship does exist between SST and wind shear as well, implying some interconnection between the three properties (Goldenberg and Shapiro, 1996).

Nyberg et al. (2007) used this wind shear correlation to develop a model to determine past intense hurricane activity in the Atlantic. Interestingly, Nyberg et al. utilized luminescence bands from coral samples in the Caribbean and foraminifera records as evidence for their calculations, similar to other studies mentioned. However, instead of calculating precipitation rates and storm surge intensities and linking them to local hurricane events, Nyberg et al. instead calculated past wind shear values and their effects in Atlantic storm formation.

Their logic was that coral luminescent bands in the Caribbean signify freshwater runoff, which is controlled by precipitation rates. Periods of decreased precipitation in the Caribbean are caused by increased trade-wind speeds, which correspond to higher sea-level pressures, enhanced sinking motion, and a more stable atmosphere. These factors cause lower precipitation and high wind shear to appear in the Atlantic. Additionally, Nyberg et al. cite increased concentrations of foraminifera in collected samples to indicate enhanced upwelling in the Caribbean that is caused by stronger trade-wind speeds. These wind speeds are closely linked to Atlantic SST, and therefore could be used to indicate SST anomalies in the Atlantic Ocean.

By using these correlations, Nyberg et al. recreate a 270 year storm history in the Atlantic from evidence collected in the Caribbean. They use their results to support the theory of the Atlantic Multi-decadal Oscillation. Their exact methodology has been questioned (Neu, 2008), but in this case the Nyberg et al. study brings up important points regarding paleotempestology. While a fair amount of evidence exists to assess past hurricane activity, the most accurate techniques and correct methods of interpreting results are quite debatable. This presents a major challenge in a field that needs to be developed in order to answer pressing questions about the earth's future climate. In an attempt to aid in this development, the following exploratory study method was proposed by Lisa Weber (Yale School of Forestry, '12 graduate) and funded by the Yale Climate and Energy Institute.

PROPOSED XRF SCANNING METHOD

BACKGROUND

The goal of the project was to contribute to the hurricane record in the Northeast United States and investigate a new method of measuring past tropical storm events by collecting core samples of sediment in Connecticut marshes and observing them with an ITRAX scanner available at the University of Massachusetts at Amherst. ITRAX is a multi-function core scanning instrument. Three different components exist on the machine that allow for in-depth core analysis. These include a digital camera, X-ray, and X-ray fluorescent (XRF) scanner.

The machine is relatively simple to use. Once cores are collected they can be split, placed on the motor drive of the scanner, and advanced under the instruments at an incremental speed. This slow speed and method allows the instruments to take very detailed images without disturbing or destroying the sample. The digital camera creates a digital image of the split core that can be archived and used to determine obvious physical attributions. The X-ray creates a radiographic image that is useful in sediment density distribution analysis. However, the most valuable component of ITRAX is the XRF scanner. The scanner provides data files of nearly all relevant elemental compositions in the core on a micrometer step size. Associated ReadyCore software can easily be used to create detailed elemental distribution profiles of the core (Croudace et al. 2006). The following is a personal picture intended to serve as an example of the ITRAX capabilities. It was developed from the ITRAX scanner and ReadyCore software analyzing potassium distribution in a core sample taken from Jordan Cove, Connecticut:

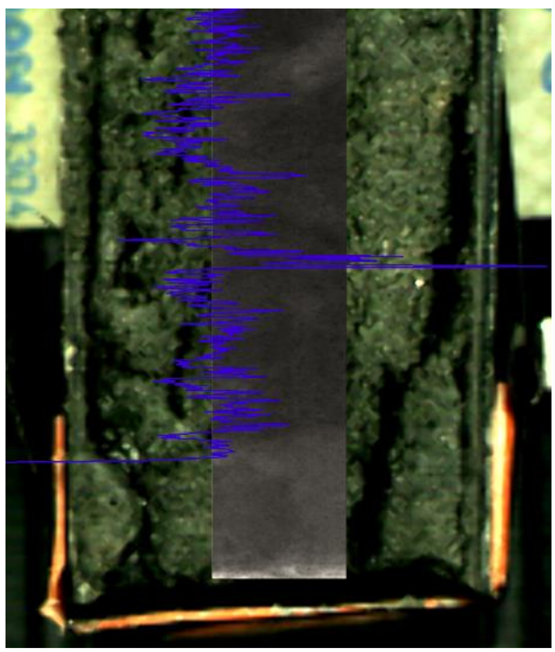


Fig. 17
Personal Photo

There are three important components to this picture. The first is the background photo of the core itself. This was taken with the digital camera on the ITRAX scanner. The narrow gray band inlaid in the center of the core is a radiographic image. It was taken by the X-ray on the ITRAX scanner and represents sediment density. Finally, the blue line represents the relative potassium mass distribution measured throughout the depth of the core by the XRF scanner. The ReadyCore software automatically aligned the three images so that proper length scales were developed, meaning that the three images correlate to the same positions in the core. Potassium was chosen as a completely arbitrary element to serve as an example. The software program allows for any element to be displayed as such, including combinations of elements in the same image. More importantly, the scanner provides correlating data tables that can be transferred to any numerical computing program.

This was intended to be an exploratory study to investigate the potential of a new method of measuring previous storm events, meaning that any exact elemental distribution correlations to hurricanes are unknown. However, elemental distributions from XRF scans of core samples have been suggested to study other paleoenivronment topics. For example, silicon, zirconium, and titanium distributions may be representative of relative grain size. This distribution could be used to determine flood layer correlation in ancient environments. Additionally, some work shows that titanium and iron data are inversely related to sediment organic content. These distributions could be used to derive past lake levels (Tierney et al. 2005). These types of related environmental measurements suggest that more work could be done to establish stronger proxies with a broader range of natural events.

METHOD

When choosing sites and collecting core samples, the method outlined in the sedimentary analysis section was roughly followed. Sites were chosen based on their proximity to the Atlantic Ocean and availability of barrier beaches to provide necessary overwash layers. Two sites were chosen for core sample selection in Connecticut: Jordan Cove, near the city of Waterford, and South Cove, near the city of Old Saybrook. Exact locations are displayed in the following pictures taken from Google Earth.

Two core samples were collected from Jordan Cove at approximately 41° 18’ 41” N and 72° 08’ 52” W. The collection location is marked by the yellow pinpoint. The sandbar to the left of the pin was intended to serve as the barrier beach, separating the small water inlet from the oceanic cove.

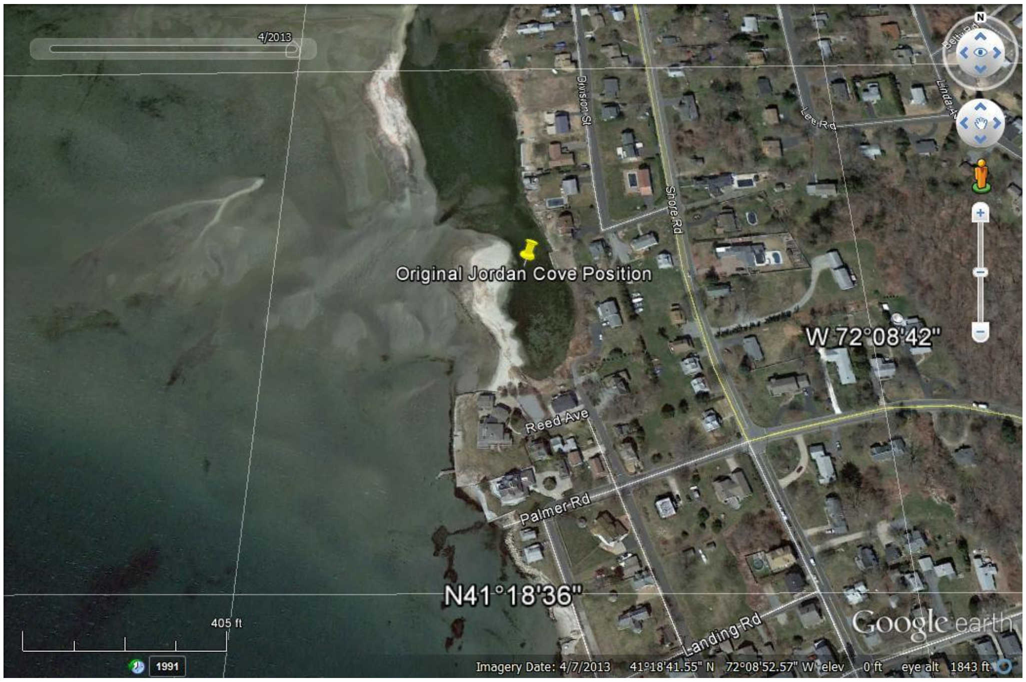


Fig. 18
GoogleEarth

Two additional core samples were collected from South Cove at 41° 16’ 21” N and 72° 22’ 04”. Again, the location is represented by the yellow pinpoint, and the land formation to the south was meant to act as a barrier beach for storm events.

Fig. 19
GoogleEarth

Cores were taken on October 24, 2013 and November 5, 2013. They were taken by hand by wading into the coves, pushing a liner into the sediment layer, and pulling it out while maintaining a vacuum under the water surface. Cores were approximately 18 inches in length. Core liners were capped and sealed and stored in the Yale Kline Geology Laboratory freezer until January 17, 2014. Then, they were transported to University of Massachusetts at Amherst. There, one core from South Cove and one core from Jordan Cove were split and advanced through the available ITRAX scanner.

RESULTS

The ITRAX machine successfully scanned each core so that sediment density and elemental distributions were analyzed and correlating data points were collected. The original plan was then to bring the cores back to Kline Geology Laboratory where Cesium and Lead radiogenic dating methods would be used to date the observed elemental distribution in the cores. However, after a personal conversation with Jonathan Woodruff, Assistant Professor of Sedimentology and Coastal Processes at University of Massachusetts at Amherst, further analysis of these particular cores was stopped. Professor Woodruff had extensive experience in sediment analysis and suggested that, because of the locations where the sample cores were taken, they would not provide significant results of storm records.

In the case of Jordan Cove, the landmass that was intended to serve as a barrier beach is actually a very dynamic feature. Its location relative to the shore fluctuates regularly, especially after high wind events. Therefore, the cores selected from this area would likely only provide data on the geomorphology of the singular region. These movements can be tracked by using the time lapse feature of Google Earth as follows:

Fig. 20-22
GoogleEarth

Figure 20 is a satellite image taken in 1991, the figure 21 from 2011, and figure 22 from 2013. The absolute position of the yellow pinpoint remains the same in each photo. Thus it can be seen that, as recently as twenty years ago, the proposed barrier beach very nearly did not exist. And, once it was formed, it has been moving east. The initial movement in 1991 may have been a result of dredging or some other kind of manmade interference. The recent movement in 2011 was most likely a result of Hurricane Irene. Regardless, this type of a location is too dynamic to yield accurate core results (Woodruff, personal communication).

The South Cove location was also identified as a poor location for analysis. The sampling location was not completely isolated from the ocean. This meant that most of the sediment record was dominated by very fine grained organic material, making it difficult to collect and very compressible within the core liner.

PROPOSED SAMPLING SITES

Although the original sampling locations were deemed poor choices, two locations near the same coves were chosen for future study in collaboration with Professor Woodruff. A new position was chosen for Jordan Cove on the other side of the inlet. This new location seems to be more isolated and is next to a much less dynamic barrier beach. Its only drawback is that it appears to be on private property. It can be observed relative to the original location in the Google Earth image below:

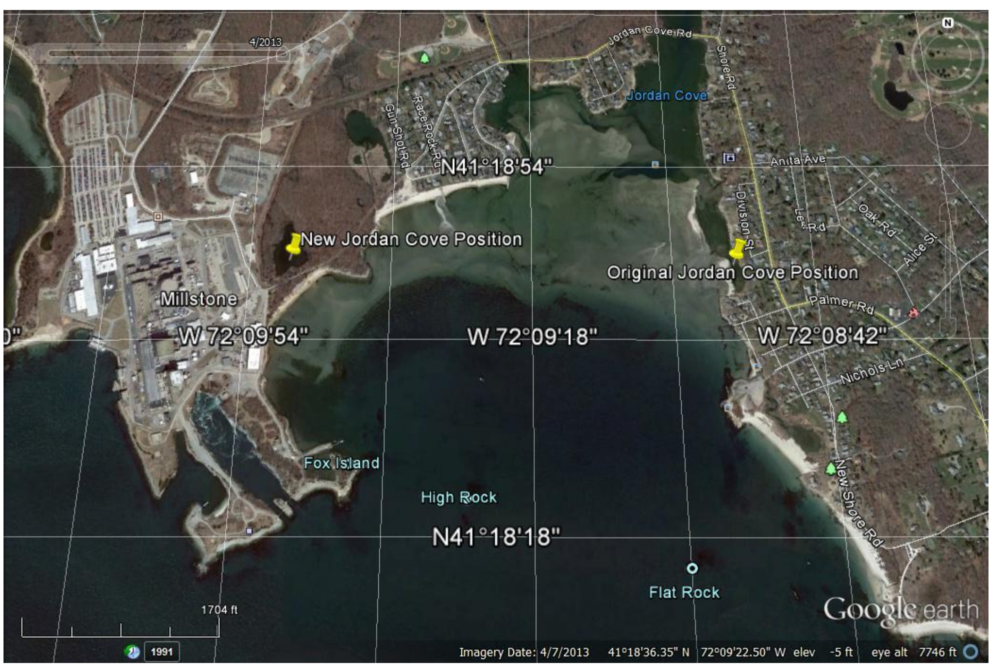


Fig. 23
GoogleEarth

Similarly, a more appropriate location was chosen for South Cove as well. It is believed that the property belongs to the Old Beach Lyme Club. It can be seen in the following Google Earth image:

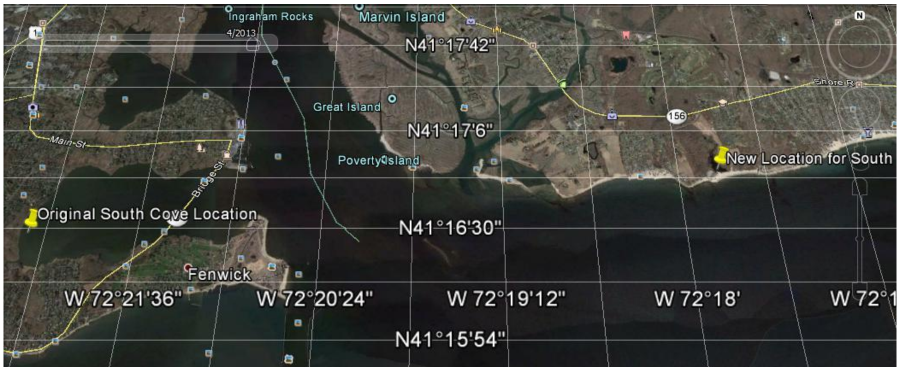


Fig. 24
GoogleEarth

Unfortunately, suggestions for these new locations were given in January, during the winter in Connecticut. This meant that the ground was frozen and lake areas icy. Accordingly, samples would have been nearly impossible to collect by hand. Due to time constraints, more samples could not be taken in the spring, leaving the research project open-ended. However, the experience can assist future work by suggesting future sampling sites.

CONCLUSION

The scientific principles explaining how anthropogenic sources of carbon dioxide are contributing to the warming of the earth have been readily established. Furthermore, natural systems that interact with these emissions are better understood as more research is focused toward them. As these ideas are better quantified, the evidence of warming temperatures on the earth's surface has become obvious. The entire spectrum of effects caused by these warmer temperatures is unknown, but strong theory supports the idea that they will produce more intense hurricane events. To support this theory, evaluation of past hurricane records would be ideal in order to observe historic trends. Unfortunately, it is quite difficult to obtain these records. A variety of methods do currently exist, but much more work needs to be done in sampling more locations and determining the most accurate methods. One novel proxy was suggested here, but data could not be obtained to validate its potential.

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