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EXECUTIVE SUMMARY

OVERVIEW
Hurricane Sandy hit the northeastern United States on October 29th, 2012 and with it came record-breaking storm surges and floods due to its landfall location and massive spatial extent. The storm followed an unusual trajectory which was accurately predicted by the European forecasting model, but was missed by the American model; instead of veering into the Atlantic Ocean, Sandy made landfall in New Jersey, which saw some of the most destructive impacts of the storm, along with New York City. Sandy’s devastation led many to question if the storm was a result of climate change, and whether or not human activities contributed to its severity. This summary will analyze Sandy’s unique development and storm track, discuss attribution of the storm to climate change, make predictions for North Atlantic tropical cyclones in the future, and mention the limitations and post-Sandy improvements to the US forecasting model.

ANALYSIS AND IMPACTS OF HURRICANE SANDY
Hurricane Sandy was an uncommon storm due to its large extent, sudden shift in trajectory toward the East Coast, and landfall position in New Jersey. While at its height Sandy was only a Category 3 storm, it reached over 1000 miles in diameter, making it one of the largest Atlantic hurricanes to date. Additionally, the full-moon tide amplified the storm surge, causing increased flooding. Sandy caused $65 billion in damages, mostly associated with inundation due to the storm surge, which broke historical records for New Jersey and New York City. Because it hit a densely populated area and caused massive devastation to infrastructure, Hurricane Sandy is considered undoubtedly to be an extreme weather event.

FUTURE TROPICAL CYCLONE PREDICTIONS
While there may be robust predictive responses to anthropogenic forcing for variables that contribute to individual tropical cyclone formation, how these perturbed variables will combine to alter tropical cyclone activity is poorly understood. Despite these shortcomings, there is some model agreement for the future behavior of tropical cyclones. There will be an increase in the most intense hurricanes (Category 4 & 5 storms), but there will also be an overall reduction in tropical cyclone frequency. Additionally, the Atlantic tropical cyclone storm track is predicted to shift northward, leading to a decrease in storm count in the Gulf of Mexico and increase in storm count along the East Coast. Probably the most consistent prediction for future tropical cyclone activity is that continued sea level rise will exacerbate the impacts of storm surge and flooding in the future, making severe inundation events more frequent and more destructive.

ATTRIBUTION TO CLIMATE CHANGE
Because they are rare and extreme events, no individual tropical cyclone can be attributed to climate change, which includes Hurricane Sandy. Tropical cyclones are highly dependent on mechanisms of internal variability and at this point, any anthropogenic signal cannot be discerned from the noise. However, it is important to note that climate and weather are not separate entities. Instead, it is more appropriate to say that climate change influences weather but does not cause specific events.
Nevertheless, at this time the fraction of anthropogenic signal in tropical cyclone activity cannot be accurately quantified.

**FORCAST MODEL DISCUSSION**

The European forecast model accurately anticipated Hurricane Sandy’s trajectory shift toward the East Coast, while the US model predicted it would turn into the Atlantic basin and bypass landfall. This model output difference was attributed to the European model having more computing power than its American counterpart. After Hurricane Sandy, the US spent $23.7 million to upgrade their forecasting model and increase its computing power to rival the European model. However, since extreme events are inherently rare, there has been little opportunity to compare the two since the US upgrade. While the US model outperformed the European model for the Northeastern blizzard in January, 2015, it is too early to make a judgement as to whether these costly improvements to the US model were advantageous and justifiable.

**CONCLUSIONS**

Hurricane Sandy was an extreme and unique event due to its extent, landfall position, trajectory, and impact on infrastructure and society. Even so, it is impossible to explicitly state that Hurricane Sandy or any tropical cyclone was caused by anthropogenic climate change. This lack of attribution is not a deficiency, but rather it reflects the fact that anthropogenic climate forcing does not cause weather events, but instead acts to shape them. Nevertheless, the North Atlantic states are expected to see an increase in the number of intense tropical cyclones in the future and sea level rise will aggravate storm surge and flooding events. Because predictions for sea level rise and corresponding flood risk are robust, the Northeastern US should adequately prepare for this increasing threat to coastal cities. Additionally, it is important for forecasting models to accurately diagnose tropical cyclone development and storm track, and after Hurricane Sandy the US allocated millions of dollars to improving their forecasting model. However, at this point it is unknown whether those upgrades resolved any of the forecasting issues associated with Hurricane Sandy and if they were worth the cost.
INTRODUCTION

Hurricane Sandy was a late-season Atlantic hurricane, and later extratropical storm, that formed in October of 2012. Its extreme size, unique path, and impacts on the eastern coast of the United States made “Superstorm” Sandy one of the most discussed news stories of that year. A particularly popular topic of discussion involved Sandy’s relation to climate change: was Hurricane Sandy a direct result of climate change? If not, was it an example of the type of storms we can expect with our changing climate? Another point of discussion involved the National Weather Service’s use of forecast models. The model produced by the European Centre for Medium-Range Weather Forecasting predicted the westward turn into the coast two days before the model created by National Centers for Environmental Prediction here in the United States. This may have impacted how forecasts were issued and therefore how preparations along the coast were handled.

We begin with an analysis of Hurricane Sandy’s meteorological history, characteristics, and impacts. Next, we examine the feasibility and challenges of attributing Sandy or similar storms to climate change. Finally, we discuss the disagreement between the weather forecasting models and the implications this had.

ANALYSIS OF HURRICANE SANDY

TIMELINE OF STORM

Hurricane Sandy started as a tropical wave that moved off the coast of Western Africa on October 11th, 2012. Upper-level convergence and wind shear prevented the wave from developing further, but by October 18th, the wave had reached the Caribbean Sea where conditions were more favorable for cyclogenesis. Convection started to develop around the low pressure center and by October 22nd the system had been classified as Tropical Depression 18 while it was positioned south of Jamaica. Six hours later, data from Hurricane Hunter aircraft prompted another upgrade in classification, to Tropical Storm Sandy. Still strengthening, Sandy was classified a hurricane on October 24th as it headed north and later passed over Jamaica.

By October 25th, Sandy was a major hurricane with estimated winds of 115 mph and made landfall in eastern Cuba. After passing over Cuba, Sandy began to interact with a drier air mass, increased shear, and an upper level trough. These factors weakened the storm as it moved northwestward over the Bahamas and eventually Sandy was downgraded to a Tropical Storm on October 27th. However, the wind radius had nearly doubled compared to when it passed over Cuba.

After passing the Bahamas, Sandy turned to the northeast and strengthened back to hurricane status. A unique and spatially extensive hurricane, Sandy exhibited some frontal structure which was indicative of an extratropical transition. Over the Gulf Stream, Sandy strengthened to a secondary peak and gained more tropical characteristics including an eye. On October 29th, Sandy began to turn more north and northwest toward the east coast. This was due to a blocking high pressure system centered over the North Atlantic that prevented the storm from moving out to sea like most tropical systems in the region do.

As Sandy approached the coast of New Jersey, it encountered much cooler water and a cold air mass positioned over the region. These conditions led to its weakening and full transition to extratropical, which
means that it no longer received its energy from warm ocean waters and convective latent heat release; energy was instead derived from the baroclinic instability of large scale horizontal temperature variation.

Post-tropical Cyclone Sandy made landfall during the evening of October 29th in Brigantine, New Jersey, with winds of 80 mph and a central minimum pressure of 945 mb. Sandy moved slowly over the region, gradually heading west and north. By October 31st, the center had become ill defined over Ohio and the system began to head northeast to Canada where it eventually merged with another low pressure system (Blake et al., 2013). Figure 1 shows the path and intensity of Sandy over time.

**RECORDS AND SIGNIFICANCE**

At maximum intensity, Hurricane Sandy was a Category 3 on the Saffir-Simpson Hurricane Wind Scale with sustained winds estimated at 115 mph on October 25th as it made landfall in Cuba. Its overall lowest pressure of 940 mb was reached a few hours before making landfall in New Jersey (Blake et al., 2013). The records for wind speed and low pressure in the Atlantic were set by Hurricane Allen (1980) with winds of 190 mph and Hurricane Wilma (2005) with a minimum pressure of 882 mb (National Hurricane Center). Hurricane Sandy was not the most intense Atlantic hurricane on record, in terms of high wind speed or low pressure. However, the size, storm surge, locality, and amount of destruction were particularly noteworthy with Sandy.

Sandy’s unique structure made it the largest hurricane in the Atlantic basin since records began in 1988. At its widest, tropical storm force winds extended 1000 miles across (Figure 2 shows the scale near the secondary peak in intensity). This extreme size was a result of several factors including its transition from tropical to extra- (or post-) tropical and interaction with troughs nearby. After passing over Cuba, Sandy moved into a modified continental air mass. This new environment prompted the beginnings of a transition to extratropical and fronts began to form several hundred miles away from the center. This weakened the storm to tropical storm status, but allowed the wind and pressure fields to grow in area. Sandy later moved into more favorable conditions for tropical development and regained hurricane classification, but retained the large wind radius it gained from the partial extratropical transition (Blake et al., 2013).

As with most landfalling tropical systems, Sandy’s storm surge was the most impactful of its effects. Storm surge is the abnormal rise of water due to a storm’s winds and low pressure (National Hurricane Center). Because of Sandy’s vast areal extent, water levels from Florida to Maine rose (Figure 3). The greatest impact of the surge was felt at the coasts of New Jersey, New York, and Connecticut. The maximum surge was 12.65’ at King’s Point, New York at the west end of Long Island Sound. The highest storm tide (storm surge rise paired with high tide rise) was 14.58’ in Bergen Point, New Jersey. The storm tide of 14.06’ at Battery Park in Manhattan was over four feet higher than the previous record set in 1992 (Blake et al., 2013).

Sandy brought the lowest pressure ever measured in the United States at a location north of Cape Hatteras, North Carolina with a landfalling pressure of 945 mb, beating a record set by the 1938 Long Island hurricane (Blake et al., 2013). Because of the prevailing westerlies in the area, the United States’ northeastern coast does not often see direct landfalls from tropical or extratropical storms. Sandy’s unique path was directed by both an anomalous high pressure center over the North Atlantic that blocked it from moving out to sea and a negatively tilted trough over the Eastern United States that pulled Sandy westward. Both of these phenomena were influenced by an especially wavy pattern in the jet stream that may be a result of melting Arctic ice (Masters, 2012).
Because Sandy struck a heavily populated area of the United States coast with strong winds and particularly high storm surge, damage and effects were catastrophic. 159 deaths in the United States were attributed to Sandy, 71 direct and 87 indirect. Indirect deaths were mainly due to prolonged and widespread power outages that lead to hypothermia, falls in the dark by senior citizens, and carbon monoxide poisoning due to poor generator placement. 650,000 homes were damaged in 24 states and 8.5 million customers lost power during the event. Damage in the United States was estimated at $50 billion, which ranks Sandy behind only Hurricane Katrina (2005) in terms of damage (Blake et al., 2013).

**ATTRIBUTION TO CLIMATE CHANGE**

Prior to examining the details of attributing Hurricane Sandy to climate change, the question must be appropriately framed. The discussion cannot center around a simple yes-or-no question, mainly; was Hurricane Sandy caused by climate change? This question is misleading for several reasons. First, it is not possible to attribute any single event to climate change. However, claiming that extreme weather is not representative of climate change is also false. There will inevitably be weather events that occur which could have been realized by historical conditions before anthropogenic (human-induced) climate change, but this is because climate change is simply a shift in average weather patterns, as illustrated in Figure 4. It is important to recognize that climate and weather are different descriptions of the same phenomena; long-term and short-term respectively. Thus, just because an extreme event could have been caused by historical climate conditions does not mean it is atypical of a changed climate. The event in question could fall under the behavior of both climatic conditions, which can be envisioned as falling under both curves in Figure 4. Approaching attribution as a yes-or-no question means attempting to separate climate and weather as isolated entities, which is an inappropriate way of looking at the issue (Shearer and Rood, 2011).

Framing the discussion around a yes-or-no question is also misleading because it suggests that there are two realities; one in which anthropogenic climate change is real and an alternate reality in which climate change does not exist and “natural” pre-industrial greenhouse gas levels exist. Simply because an event could have occurred in the conditions of the alternate reality does not mean that climate change is not occurring, as explained in the previous paragraph. A more accurate way to examine the issue is to ask if anthropogenic emissions have changed climate conditions in a way that makes extreme events more likely to occur. For instance, can we quantify the contribution of anthropogenic warming to the likelihood of a particular event occurring (Shearer and Rood, 2011)? Attributing Hurricane Sandy to climate change in this format is much more realistic than a binary framework.

**INTRODUCTION TO ATTRIBUTION**

The process of attributing a specific weather or climate phenomenon to anthropogenic climate change is extremely complex. Thus, before diving into the details of such an investigation, it is important to explain the fundamental procedures that go into climate attribution while defining core concepts along the way. This will be done here before the attribution of Hurricane Sandy to climate change is investigated explicitly.

First, it should be explained what is meant by climate attribution. Climate attribution is a process for identifying the causes of observed weather or climate patterns (Hoerling, 2013). This process involves analyzing observations and climate relationships while experimenting with climate models for
comparison. Climate models are necessary because they provide a needed control experiment that cannot be obtained in reality. This process can be understood as separating a signal from noise; climate attribution ensures that natural variability (the noise) is not misunderstood to indicate that climate change (the signal) is responsible for observed behavior (Rood, 2015).

Climate attribution is extremely important to mankind’s continued existence in the face of climate change. Without knowledge of the climate system, policy and decision makers cannot make informed decisions concerning how society should invest in critical infrastructure (Hoerling, 2013). It is therefore very important that it be carried out thoroughly and dutifully.

In order to perform climate attribution, there are several well-established procedures. The most well-known include fingerprinting, joint attribution, and event attribution. Fingerprinting considers how each influence has a different type of effect on the climate. It is done by searching through computer model predicted patterns of climate change in observed climate records with the assumption that each factor that influences the climate has a different characteristic signature (i.e. fingerprint). If changes characteristic of the fingerprint of a certain type of influence are found, then that influence can be assumed to be responsible for the observed behavior (Hegerl et al., 1996). Joint attribution is similar, but is done by comparing an understanding of climate processes to observed behavior. Climate models are used with process-based statistical models to simulate changes caused by different influences and then compared with observational data. If the observations converge with the models then the influence used in the model can be considered responsible for the the observed behavior (Rosenzweig et al., 2008). Finally, event attribution, as its name suggests, involves attribution of a single weather or climate event to climate change. Event attribution is the most difficult but is what must be undertaken in order to link Hurricane Sandy to climate change.

Before proceeding, it is important to define what an extreme event is in regards to weather and climate. An extreme weather or climate event is the occurrence of a weather or climate variable near the limits of the range in which that variable is typically observed. This definition is quite sensible, but it is important to note that an event can be considered extreme either because of its meteorological character or because of its resulting impact. For instance, an event that is not strong meteorologically can have an extreme impact, either because it occurs with other events simultaneously, or because it crosses a critical threshold in a sensitive sociological or ecological system. On the other hand, an event that is strong meteorologically may not have an extreme impact if it hits an uninhabited area or dissipates over the ocean (Seneviratne et al., 2012). In regards to Hurricane Sandy in particular, it can be considered an extreme event because of its damaging impact on the east coast of the United States. Although it was indeed a powerful tropical cyclone, there have been observed cyclones of greater intensity that have not had such devastating effects.

Attributing extreme events to climate change is complex and often not straightforward. Since natural variability and regional weather conditions have such a large impact on single extreme events, fingerprinting and joint attribution cannot be employed; instead, probabilistic event attribution must be used. In this method of event attribution, the risk of the event at question is simulated using a model with and without anthropogenic forcings. By doing this, one can obtain an event recurrence interval, which describes how many times an extreme event of a given magnitude should have been observed under certain conditions. From this, the fraction of risk introduced by anthropogenic drivers to the event happening may be found (Bindoff et al., 2013).
TROPICAL CYCLONE ATTRIBUTION

With attribution and extreme events explicitly defined, the attribution of tropical cyclones to climate change may be investigated. A tropical cyclone is a rotating, organized system of clouds and thunderstorms that originates over tropical waters. These include systems referred to as tropical storms, hurricanes, and typhoons, the latter names specifically referring to strong tropical cyclones (National Weather Service, 2014). Historical data has found a doubling in the number of tropical cyclones over the past 100 years, as well as a positive correlation between sea surface temperature (SST) and tropical cyclone frequency, particularly in the Atlantic basin. However, these observations assume that all tropical cyclones were correctly accounted for in the historical data, which has recently been found to be a false presumption (Vecchi and Knutson, 2007).

Improved monitoring in recent years is what is responsible for most, if not all, of the observed trend in increasing cyclone frequency. The advents of satellite imagery and airplane reconnaissance have enhanced data collection capabilities tremendously, as well as better measurement techniques and larger coastal populations. It has been discovered that the recent reporting of an increase in tropical cyclone frequency has only added cyclones that did not reach landfall. If the number of landfall cyclones has not increased with new technology but the number that remain over the ocean has, this suggests that there was underreporting in the past. Moreover, many cyclones in the past that did hit landfall may not have been recorded as cyclones because the impact of the storm alone is not enough to determine if it can be labeled as such; only satellite imagery can prove this definitively (Landsea, 2007).

All of this has led to a low confidence in the observed increase in tropical cyclone activity, as illustrated in Figure 5, which shows trends in tropical cyclone frequency from 1878-2006 in the Atlantic basin. In the figure, the yellow linear trendline shows the increase in cyclone frequency predicted by historical data while the green trendline shows the increase if the historical data is corrected for underreporting. Clearly the yellow line, which predicts an additional 4.39 cyclones per century, is more steep than the green line, which only predicts an additional 1.60 cyclones per century, which is a much less significant trend (Vecchi and Knutson, 2007).

In addition to poor historical data, there are other factors that complicate the attribution of tropical cyclones to climate change. The largest complication is the tremendous fluctuation in frequency and intensity of tropical cyclones; despite our now advanced data collecting capabilities, there have not been enough cyclones measured with new technology to observe any definitive trends. Moreover, we have an incomplete understanding of the physical mechanisms linking tropical cyclones to climate change. We do have a good understanding of how the individual factors that go into forming cyclones, such as SST, will change with anthropogenic climate change. However, we do not know how the changes in these factors will converge to change the behavior of tropical cyclones because there are countless variables to consider in such a complex system. All of these facts make the attribution of tropical cyclones to climate change even more problematic (Knutson et al., 2010).

With these difficulties in mind, a community of tropical cyclone researchers and forecasters at an international workshop for the World Meteorological Organization (WMO) released a consensus statement on the links between anthropogenic climate change and tropical cyclones. Among their most important claims, they assert that no clear anthropogenic signal in the tropical cyclone climate records has yet emerged. They also claim that no individual cyclone can be directly attributed to climate change, which is especially pertinent to Hurricane Sandy (McBride, 2006).
FUTURE PREDICTIONS FOR ATLANTIC TROPICAL CYCLONES

Yet, despite the fact that no firm conclusions can currently be made, there are some predictions that can be asserted with moderate confidence from theory and modelling. Due to the rise in SSTs from greenhouse gas warming, the globally average intensity of tropical cyclones is expected to increase because the cyclones will be able to absorb more energy in their genesis. However, because the cyclones will absorb so much energy at once, the average tropical cyclone frequency is actually expected to decrease. Thus, there is an expected competition between the influences of increasing cyclone intensity and decreasing frequency. In keeping with this trend though, there is an expected increase in the frequency of the most intense cyclones, as well as expected increase in maximum wind speed and precipitation rates (Knutson et al., 2010).

One of the most important variables that constrains the impact and destructive power of a tropical cyclone is its storm track. For instance, a Category 5 hurricane could have a relatively minor influence if its storm track pushes it into the middle of the Atlantic basin. Conversely, if that same tropical cyclone made landfall in New York City, it would be catastrophic. Future shifts in storm tracks could have considerable consequences for coastal cities, but these changes are challenging to model. Nevertheless, it is expected that the number of tropical cyclones making landfall in the Gulf of Mexico will decrease, whereas slightly more tropical cyclones will move through the Atlantic basin and make landfall on the East Coast (Murakami and Wang, 2010; Roeckner, 2006; Bender et al., 2010) (Figure 6). While the northeastern storm count is expected to increase by only one additional tropical cyclone per decade (Colbert, 2013), the effect of this extra cyclone could be minimal or disastrous depending on its strength and exact location. Also, tropical cyclones are reaching their peak intensity at more northern latitudes as the tropical belt expands poleward (Kossin et al., 2014), and there has been an observable eastward shift of the storm track in the last century (Vecchi and Knutson, 2007). As tropical cyclones reach their apogee further north and their landfall frequency along the East Coast increases, chances are that the New York metropolis will see more tropical storms in the future.

In addition to these trends predicted for the behavior of tropical cyclones in response to climate change, the projected rise in sea level will affect the impact of tropical cyclones upon landfall. According to the Intergovernmental Panel on Climate Change’s (IPCC’s) Fifth Assessment Report, it is very likely that there is a substantial contribution from anthropogenic forcings to the global mean sea level rise (Bindoff et al., 2013). This sea level rise is expected to contribute to extreme coastal high water levels in the future, and in turn, increased storm surges with tropical cyclones, which are in fact the most damaging aspect of tropical cyclones (Seneviratne et al., 2012).

While the current literature has some consensus prognoses for changes in tropical cyclone features and storm track, it is unclear at what point these shifts will be dominated by anthropogenic climate forcing over internal variability. The genesis of tropical cyclones and their resulting storm tracks are both highly dependent on internal variability (Done et al., 2014). The major sources of Atlantic variability are the El Niño Southern Oscillation (ENSO), the Atlantic Meridional Mode (AMM) and the associated Atlantic Multidecadal Oscillation (AMO). During El Niño events, there are usually fewer landfalling tropical cyclones along the East Coast, whereas that number is higher during La Niña events (Wang and Wu, 2013). During a positive AMO, represented by warmer sea surface temperatures, there is increased tropical cyclone activity (Wang and Wu, 2013). In fact, tropical cyclone frequency during a positive AMO phase could be up to 68% higher than in its corresponding negative phase (LaRow et al., 2014). While there is significantly more tropical cyclone activity in a positive AMO phase, the probability for East Coast landfall is actually higher during a negative AMO phase (LaRow et al., 2014). Currently, internal variability has a
much larger impact on tropical cyclone frequency, track, and strength than anthropogenic forcing. However, these internal modes can act in concert or discord to alter tropical cyclone activity and are poorly understood overall, making insightful predictions impossible at this point.

All of these predictions, particularly the increase in storm surge, highlight the importance of attributing tropical cyclones to climate change. Recent decades have seen a large increase in the economic damage caused by cyclones due to rising coastal populations and increasing infrastructure in coastal areas. It is thus likely that climate change will affect the future evolution of damage from cyclones, despite the fact that predicted changes in cyclone behavior from climate change are uncertain. With higher sea levels, coastal regions are becoming increasingly vulnerable to storm surge flooding, even if tropical cyclones remain unaffected by future climate change (Knutson et al., 2010). Coastal regions should therefore prepare for climate change accordingly.

**HURRICANE SANDY IMPACT ATTRIBUTION**

As previously stated, it is currently impossible to attribute a single tropical cyclone event to climate change because tropical cyclones are extreme weather events, which are not caused by climate change but are molded by its influence. As such, attempting to attribute Hurricane Sandy as an overall event to climate change is a futile effort. Nevertheless, portions of Sandy’s impact, especially storm surge, has been modeled through event attribution to find recurrence intervals for the storm’s effects, but not for the storm itself. According the American Meteorological Society, since the large increase in anthropogenic carbon dioxide emissions in the 1950’s, the recurrence interval for Hurricane Sandy’s storm surge and floods in New York City and New Jersey has reduced by half (Sweet et al., 2013). Because storm surge is a result of sea level, most model predictions for inundation recurrence are based on forecasts of future sea level rise. By the year 2100, the mean recurrence interval for a Sandy-like flood will be every once every 373 years, which is 2.5 times more likely relative to the early 21st century (Shrestha et al., 2014) (Figure 7, Figure 8). Future predictions for more frequent flooding in the New York City region are robust, and it follows that as sea levels rise, so will the storm surge impacts.

**ATTRIBUTION CONCLUSIONS**

Extreme weather events can be can be labeled as such based on sheer meteorological strength, impact on society, or both. Because of its destruction to the Northeastern US, Hurricane Sandy was undoubtedly an extreme event. Extreme events are difficult to attribute to climate change because they are inherently rare. As a result, using attribution techniques such as the fingerprint method or joint attribution are not feasible, leaving only the event attribution approach. Tropical cyclones in particular are notoriously difficult to attribute to anthropogenic greenhouse gas forcing. This is due to their large dependence on internal variability, mediocre historical tropical cyclone reporting and scarcity of measurements for validation, and a poor overall understanding of how combined anthropogenic perturbations to meteorological variables will affect tropical cyclones. Despite these challenges, there is some agreement on predictions for Atlantic tropical cyclones in the next century, including a decrease in overall frequency but increase in Category 4 & 5 hurricane storm counts, as well as fewer tropical cyclones in the Gulf of Mexico and more along the East Coast. Population increase in risk-prone areas and rising sea levels will increase the chances for destructive impacts, and the recurrence interval for a Sandy-magnitude flood will decrease into the 21st century.

To reiterate, it is impossible to attribute a single extreme event to climate change, which includes attribution of Hurricane Sandy. This is not due to a lack of statistical methodology or anthropogenic signal,
but because the interpretation behind such an endeavor is fundamentally flawed. Climate change on its own does not generate extreme events, rather it contributes to them. Any extreme event could have materialized by chance in a non-anthropogenic climate, but the natural frequency, intensity, duration, and extent of those events will be altered through anthropogenic perturbations to the climate system. In reality, weather is an expression of climate and it is impractical to separate the two. Human activities have altered the earth’s climate, and because weather and climate are inextricably linked, all weather events will materialize anthropogenic influence in some manner.

MODEL PERFORMANCE

In the aftermath of Hurricane Sandy, much was made of the performance of the different numerical weather prediction models, mainly the European Centre for Medium-Range Weather Forecasting (ECMWF or Euro) and the American model, the Global Forecast System (GFS). This section will briefly discuss some characteristics of the two models, analyze the performance of both models during Hurricane Sandy, and end with an examination of possible reasons for a better performance by the Euro and a discussion of improvements that have been made since the event.

CHARACTERISTICS

Some similarities between the Euro and the GFS are that they are both spectral models and have a global domain. This means that they produce numerical forecasts for the entire globe and are not confined to a specific region of the world, unlike the North American Model (NAM), which only produces weather forecasts for the North American region. However, the two models use different microphysical schemes. The GFS uses a simple cloud scheme while the Euro uses a predicted cloud liquid and ice, rain, snow, and cloud fraction scheme. This shows that the two models use different parametrizations and techniques in their processes to resolve what makes a cloud or a thunderstorm and how these phenomena evolve (Marsik, 2014).

PERFORMANCE DURING HURRICANE SANDY

Figure 9 shows model forecast tracks from the evenings of October 22-25. The white track is the actual path that Sandy took, the light blue track is the GFS, and the coral track is the Euro. The figure shows that on the evening of October 22nd, all forecasts predicted that Sandy would turn out to the open ocean. However, the next evening on October 23rd, the Euro predicted a turn to the coast while the GFS still predicted the storm to go out into the open ocean. It wasn’t until two days after the Euro that the GFS predicted a turn to the coast. By this time, Sandy was already in the Bahamas and not far off the east coast of the United States (NWS New York).

As the figure shows the Euro accurately predicted Sandy’s turn to the coast two days before the GFS. Many wondered why the Euro was able to more accurately forecast Sandy’s evolution. One factor that needs to be examined is the amount of computing power that each numerical model had access to at the time of Hurricane Sandy. During Hurricane Sandy, the European model had superior computing power. This allowed the Euro to process at a higher resolution and resolve smaller scale phenomena, which can lead to a more encompassing and accurate numerical forecast (Nix, 2015).
GFS IMPROVEMENTS

On January 5th, 2015, it was announced that the GFS would be updating their systems as a part of the Disaster Relief Appropriations Act of 2013 which was brought up after the poor performance by the GFS during Hurricane Sandy. The act authorized $60 billion in disaster relief, of which $300 million was appropriated to the National Weather Service (NWS). Of the $300 million, $23.7 million was portioned to improving the American numerical models. Since the update the GFS now has superior computing power compared to the Euro, the GFS having 2,600 teraflops of computing power while the Euro has 2,217 teraflops of computing power. This marks the first time since the early 1990’s that the American models have superior computing power compared to the Euro (Nix, 2015).

Many wonder if these new improvements have solved the American model problem and if the GFS is now a more accurate model than the Euro. Recently, there was the Northeastern blizzard that was predicted to impact the Boston and New York areas with significant snowfall. Since this region was the same region impacted by Sandy, many people were looking to what the European model was predicting since it was a more accurate predictor in the last major storm to hit the region. However this time the GFS outperformed the Euro. Some people saw this as a sign that the GFS was now the better model. However, since this update to the GFS was very recent there is a small sample size of events, in addition to extreme events being rare to begin with. At this point it is far too early to tell if the GFS is now the better model and if the American model problem has been “solved.” However, the ECMWF did take notice of this event. Before the blizzard, they proclaimed themselves as the world leader in medium range forecasting. However, after the Euro was outperformed by the GFS they proclaimed themselves as “often” being a world leader in medium range forecasting. This can be seen in clippings from their website in Figures 10 and 11.

To conclude the model discussion, many people question why forecasters were so stubborn with the GFS predictions when the Euro was showing a turn to the coast 48 hours before the GFS. This could have given people and cities more time to evacuate or prepare. However, it is easy to judge after the fact. Of course we know now that Sandy was going to turn the coast but at the time of the model forecasts, for all the forecasters knew Sandy could have just as easily gone out to the open ocean without impacting any US cities. Additionally, forecasters did not want to cause panic if there was a possibility of a non-event, creating a “boy who cried wolf” type scenario. We must also keep in mind that these are just two models, one model versus another. It was not the case that there were dozens of models showing a turn to the coast and the GFS was the only one that was not showing it and forecasters were being stubborn and ignorant sticking with the GFS. Again, this was just one model versus another and there was not overwhelming evidence or number of models to suggest that the GFS would not be as accurate.

CONCLUSIONS

Hurricane Sandy was one of the most devastating storms to hit the United States in recent history. Due to its unpredicted turn from the Atlantic Ocean towards the eastern US, it had a very destructive impact on many coastal cities that were improperly prepared for its landfall. Sandy’s storm surge caused roughly $65 billion in damages and required a major response from the federal and local governments. When an event of such magnitude occurs it is almost always followed by the question; did this happen because of climate change?
The immediate answer is that no individual event can be attributed to anthropogenic climate change. However, to leave the discussion to an oversimplified yes-or-no narrative misses the point, because it treats climate and weather as separate entities when they are in fact descriptions of the same phenomena. Climate change merely means a shift in average weather behavior. Thus, the occurrence of a specific weather event cannot be definitively attributed to climate change, but cannot be used as evidence against climate change either. The appropriate question is not if Hurricane Sandy was caused by climate change, but how anthropogenic emissions may have changed climate conditions in a way that makes an event similar to Sandy more likely to occur. The discussion must shift to this more realistic setting in order to clear up misconceptions surrounding climate change so that we can focus on the imminent threat that it presents us with.

With this in mind, by using what we do know about how anthropogenic climate change will affect weather patterns, several predictions can be made on future tropical cyclone behavior. Tropical cyclones in particular are difficult to analyze; while the variables that affect tropical cyclone behavior have robust predictions with climate change, how these variables will converge to change future tropical cyclones is not well understood. Yet there is agreement on some aspects of future tropical cyclones, including an increase in average intensity but decrease in overall frequency. Moreover, sea level rise will amplify storm surge impacts and flooding, so regardless of the link between tropical cyclones and climate change their impact will worsen with anthropogenic forcing, and sensitive regions such as coastal areas should prepare appropriately.
REFERENCES


Shearer, C., and R. B. Rood, 2011: Changing the Media Discussion on Climate and Extreme Weather. earthzine.


Figure 1) Hurricane Sandy’s path and intensity over time. Source: Blake et al., 2013

Figure 2) GOES-E infrared image of Hurricane Sandy near its secondary peak intensity on October 29th, 2012. Source: Blake et al., 2013
Figure 3) “Inundation is the total water level that occurs on normally dry ground as a result of the storm tide”. Source: Blake et al., 2013

Figure 4) Representation of climate change as a shift in average weather patterns (temperature specifically in this case). Source: http://www.southwestclimatechange.org
Figure 5) Tropical cyclone frequency trends from 1878-2006 in the Atlantic basin. The yellow trendline represents the unaltered historical data while the green trendline accounts for underreporting in the past. Source: Vecchi and Knutson, 2007, Figure 5 (a)
Figure 6) Projected tropical cyclone frequency and storm track changes for a control climate and anthropogenically forced climate in the late 21st century. An increase in Category 4 and 5 storms is expected, along with a decrease in storm count in the Gulf of Mexico and increase for the East Coast.
Source: Bender et al., 2010, Figure 3
Figure 7) Current recurrence intervals for varying storm surge and storm tide (surge plus astronomical tide) at the Battery. Hurricane Sandy’s storm surge at the Battery peaked at 2.87 m. Source: Lin et al., 2012, Figure 2

Flood frequency analyses considering a constant trend in sea-level rise

<table>
<thead>
<tr>
<th>Year</th>
<th>Tidal constituent m (ft)</th>
<th>Storm surge m (ft)</th>
<th>Recurrence interval (yr)</th>
<th>Minimum recurrence interval (% certainty)</th>
<th>Maximum recurrence interval (% certainty)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1921</td>
<td>0.38 (1.25)</td>
<td>3.12 (10.23)</td>
<td>934</td>
<td>687 (90%)</td>
<td>1,407 (90%)</td>
</tr>
<tr>
<td>2012</td>
<td>0.64 (2.09)</td>
<td>2.87 (9.40)</td>
<td>559</td>
<td>431 (90%)</td>
<td>763 (90%)</td>
</tr>
<tr>
<td>2112</td>
<td>0.92 (3.01)</td>
<td>2.58 (8.47)</td>
<td>373</td>
<td>293 (90%)</td>
<td>477 (90%)</td>
</tr>
</tbody>
</table>

Figure 8) Recurrence intervals for a flood of Sandy’s magnitude at the Battery, with a constant increase in sea-level rise. Source: Shrestha et al., 2014, Table 3
Model forecast tracks at 0000 UTC 23 October 2012 (a), 0000 UTC 24 October 2012 (b), 0000 UTC October 25 2012 (c), and 0000 UTC 26 October 2012 (d). Solid color lines are for forecasts through 72 hours, while dashed lines are from 72-120 hours, and dotted lines represent the 120-168 hour forecasts (top panels only). The official track is in white, the European Centre for Medium Range Weather Forecasts (ECMWF) is in coral, the Global Forecast System (GFS) is in cyan, the GFS ensemble is in yellow, and the Track Variable Consensus Aids (TVCA) model consensus is in red.

Source: National Hurricane Center (NHC) Sandy Report

Figure 9) Model forecast tracks on the evenings of October 22, 23, 24, and 25 with the actual track in white, GFS in light blue, and Euro in coral. Source: NWS New York
Figure 10) ECMWF website main page before the blizzard event, claiming themselves as the world leader in medium range forecasting

Figure 11) ECMWF website main page after the blizzard event, claiming themselves as “often” a world leader in medium range forecasting