LLOYD'S

HURRICANES AND LONG-TERM CLIMATE VARIABILITY

Met Office

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Acknowledgements
Lloyd's and the Met Office would like to thank Thomas R. Knutson, Geophysical Fluid Dynamics Laboratory and the various other reviewers both in the Met Office and Lloyd's market for their invaluable comments.

CONTENTS

1 GLOSSARY 4

2 EXECUTIVE SUMMARY 5

3 BACKGROUND 7

3.1 Introduction to long-term climate variability 7

3.2 Introduction to influences on hurricane development and tracks 9

4 TROPICAL ATLANTIC CLIMATE VARIABILITY AND HURRICANE LANDFALL 13

4.1 Impact of tropical Atlantic climate variability on hurricane activity 13

4.1.1 Atlantic Meridional Mode 13

4.1.2 Atlantic Warm Pool 14

4.1.3 El Niño-Southern Oscillation 14

4.1.4 Northern North Atlantic 15

4.1.5 African Easterly Waves 15

4.2 How does climate variability in the tropical Atlantic modulate hurricane tracks and landfall risk? 16

4.2.1 Atlantic Multi-decadal Variability 16

4.2.2 North Atlantic Subtropical High 17

4.2.3 El Niño-Southern Oscillation 18

4.3 Forecasting tropical Atlantic climate variability and its impacts 19

4.3.1 Dynamical models 19

4.3.2 Statistical models 20

4.3.3 Hybrid models 20

4.3.4 US landfall forecasts 21

5 CONCLUSIONS 22

6 REFERENCES 24

1 GLOSSARY

AEW	African Easterly Waves
AMM	Atlantic Meridional Mode
AMO	Atlantic Multi-decadal Oscillation
AMV	Atlantic Multi-decadal Variability
AWP	Atlantic Warm Pool
ENSO	El Niño Southern Oscillation
MDR	Main Development Region
NASH	North Atlantic Subtropical High
PDO	Pacific Decadal Oscillation
SST	Sea Surface Temperature

2 EXECUTIVE SUMMARY

THE SEVERITY AND FREQUENCY OF HURRICANES ARE INFLUENCED BY CHANGES IN THE CLIMATE OF THE ATLANTIC OVER THE LONG TERM, AND IN PARTICULAR, THE CHANGES OVER MANY DECADES OF SEA SURFACE TEMPERATURES. THIS IS CALLED ATLANTIC MULTI-DECADAL VARIABILITY (AMV).

This variability of sea surface temperatures occurs naturally[1], but is also caused by external factors, such as volcanic eruptions and changes in man-made emissions.

WARM SEA SURFACE TEMPERATURES ARE A PRE-CONDITION FOR TROPICAL DISTURBANCES TO BECOME HURRICANES, BUT ATMOSPHERIC CONDITIONS ARE ALSO IMPORTANT.

The atmosphere must have favourable winds and a seed of circular motion, be unstable to convection[2] and humid enough to make it likely that hurricanes will form. Forecasts and analyses based on the atmospheric state, as well as Atlantic sea surface temperatures, are likely to be more accurate than those that are not.

ATLANTIC MULTI-DECADAL VARIABILITY OF SEA SURFACE TEMPERATURES IS LIKELY TO INFLUENCE HURRICANE LANDFALL REGIONALLY.

An observed increase in total hurricane activity during positive Atlantic Multi-decadal Variability (AMV) years is likely to increase the incidence of hurricanes making landfall. It may be possible to see regional differences in landfall risk between different AMV phases. These differences may also depend on the strength of the storm. To achieve greater certainty, further research is required to improve the understanding of the relationship between landfall risks and Atlantic, Pacific and global climate variability.

SOME OF THE MOST DAMAGING HURRICANES MAY BE MODULATED BY EASTERN ATLANTIC VARIABILITY – THIS IS LINKED TO THE ATLANTIC MERIDIONAL MODE (AMM).

As the AMM includes both ocean and atmosphere variability, it can be useful as an indicator of hurricane activity. Hurricanes that form in the eastern tropical Atlantic are probably those that are most influenced by the AMM. As these hurricanes travel the furthest before making US landfall, they also have more time to strengthen their winds and gain moisture.

[1] Natural variability is the variability that exists even without changes in external factors. It typically originates in the ocean, though the sea-ice and the land surface can be important locally as well.
[2] Convection is the rising of air that has been heated from underneath by a warm surface.

WARM WATER IN THE WESTERN ATLANTIC – THE ATLANTIC WARM POOL (AWP) - CAN INFLUENCE HURRICANE ACTIVITY AND HURRICANE TRACKS.

During periods when the Atlantic is warmer, it is more likely that some hurricane seasons will see relatively warm sea surface temperatures across the Caribbean and the tropical Atlantic, called the Atlantic Warm Pool. Early research suggests that variability in this warm pool of water may alter winds and could either steer hurricanes towards the US coast or allow them to recurve and not make landfall.

EL NIÑO TENDS TO SUPPRESS HURRICANE ACTIVITY AND THEREFORE LANDFALL. THE INFLUENCE OF THE EL NIÑO-SOUTHERN OSCILLATION (ENSO) ON HURRICANE LANDFALL IS GREATER WHEN COMBINED WITH ATLANTIC MULTI-DECADAL VARIABILITY.

The combined conditions of a cold AMV period and an El Niño, makes hurricane formation infrequent in those years. For example, between 1900 and 2009 no major hurricane made landfall in the US in a year with cold AMV and El Niño. During a warm AMV period multiple hurricanes can still occur in an El Niño year.

3 BACKGROUND

This section will first give a brief background on general climate variability that is relevant for the tropical Atlantic and hurricanes. Then a background will be given on the climate influences on hurricane development and tracks.

3.1 INTRODUCTION TO LONG-TERM CLIMATE VARIABILITY

The climate varies on all time scales from months and seasons to decades, centuries and longer. In this report we use 'long-term' to refer to a time scale of years to decades. On this time scale, climate is influenced both by external factors and natural internal variability. External factors include natural changes in solar irradiance and volcanic aerosols, and anthropogenic emissions of greenhouse gases and aerosols. Natural internal variability is the variability that exists even without changes in external factors. It typically originates in the ocean, though the sea-ice and the land surface can be important locally as well.

The most well-known example of internal variability is El Niño, which affects climate on seasonal to annual timescales. It will be described in more detail later in the report. On multi-year to decadal timescales internal variability is often described by certain modes of variability, such as the Atlantic Multi-decadal Oscillation (AMO) and the Pacific Decadal Oscillation (PDO). There is currently no clear evidence for strong links between the PDO and hurricanes in the Atlantic, so this oscillation will not be discussed in this report.

The AMO is believed to influence tropical rainfall, hurricanes and North American and European summer climate[i,ii,iii]. The AMO is commonly defined as an index of the mean Sea Surface Temperatures (SST) over the North Atlantic with any trend over time removed. Removing the trend attempts to isolate the cycles of the oscillation from the multi-decadal trend in Atlantic SST arising from external factors such as anthropogenic global warming. There are several ways to define the decadal trend in SST. For example, it can be a simple best-fit line to the North Atlantic SST index, the global mean temperature or the mean or other combination of several dynamical global climate model simulations of the 20th century[iv,v]. The details of the regional impacts of the AMO can vary depending on the definition of the trend. An example of an AMO time series is shown in Figure 1.

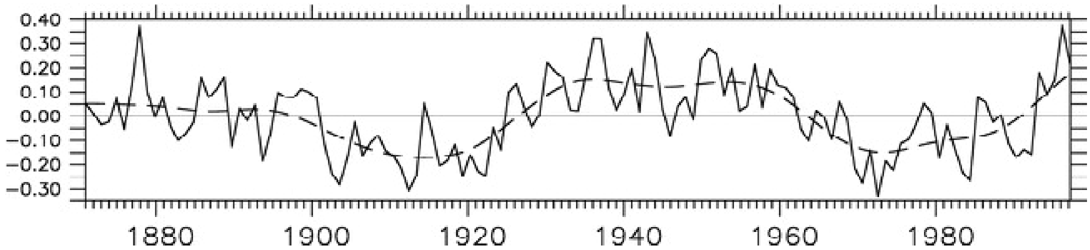

Figure 1: An example of an AMO (also known as AMV as described below) index. It shows the mean of observed North Atlantic SSTs over the region 0°–60°N, 75°–7.5°W with the trend removed. If the trend is not removed this time series shows an increasing trend due to climate change. The solid line shows annual means and the dashed line is the same time series with only long time-scales retained. The units on the vertical axis are °C. Source: Sutton, R.T. and D.L.R. Hodson (2007): Climate Response to Basin-Scale Warming and Cooling of the North Atlantic Ocean. J. Climate, 20, 891–907. © American Meteorological Society. Reprinted with permission.

Recent research[vi] has cast doubt on whether the AMO is really an oscillation[3]. This is because it is difficult, if not impossible, to separate the influence of internal ocean processes on Atlantic SST from that of forcing from external factors[4]. Both the trend and the multi-decadal variability of 20th century North Atlantic SST might be largely explained by the combined forcings of aerosols and greenhouse gases. Some scientists go as far as to claim that the last 600 years of AMO variability can be explained by changes in volcanic and solar forcing[vii]. To reflect the fact that the AMO is not necessarily an oscillation, it is now often known as Atlantic Multi-decadal Variability (AMV). This term will be used in the rest of this report.

The evidence that AMV can occur as an internal ocean process comes from modelling the ocean-atmosphere system with constant aerosol and solar influences. Despite the constant external factors, these models show multi-decadal Atlantic variability in the ocean and atmosphere[i]. There is also evidence from tree-ring chronologies that show multi-decadal fluctuations since the 16th century[viii], though these could also be influenced by volcanic and solar variability. However, the observed North Atlantic SST over the 20th century probably results from a combination of internal climate variability and anthropogenic and volcanic forcing. Any prediction of AMV should therefore include both the internal variability and changes in external factors (solar variation, aerosols from pollution and volcanoes, etc).

STORMS, CYCLONES AND HURRICANES

The words "tropical storm", "tropical cyclone", "hurricane" and "major hurricane" have specific meanings in this report. In accordance with the Saffir-Simpson Hurricane Scale, for a system of tropical thunderstorms with an organised circulation to be called a tropical storm requires sustained winds of 39mph or above. A tropical storm can also be called a tropical cyclone if sustained winds reach 74mph or above. A hurricane is simply a tropical cyclone in the Atlantic basin. A major hurricane has sustained winds of 111mph or above.

The AMV is believed to modulate SST in ways which are relevant to hurricane formation and propagation. One region where SST is thought to influence hurricane activity is the Main Development Region (MDR, see Figure 2). Related to this is the Atlantic Meridional Mode (AMM), which is characterised by a North-South (meridional) gradient in SST across the tropical Atlantic. The AMM is also linked with coherent changes in tropical winds and the location of the peak in convection and rainfall[5]. Also of interest is the Atlantic Warm Pool (AWP), which is an area of relatively warm SST. It normally comprises the Gulf of Mexico, the Caribbean Sea and the western tropical Atlantic (see Figure 2).

The influence of the AMV on hurricanes is not merely through SSTs. It is also likely to influence the large-scale tropical circulation changing winds and other relevant variables. These effects are introduced in the next section.

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[3] An oscillation implies cyclical variability that will continue indefinitely if not disturbed by external factors (though it may reduce in amplitude).
[4] These sources include direct solar forcing, but also modification of this forcing by clouds and aerosols (volcanic and anthropogenic)
[5] This is sometimes known as the inter-tropical convergence zone (ITCZ)

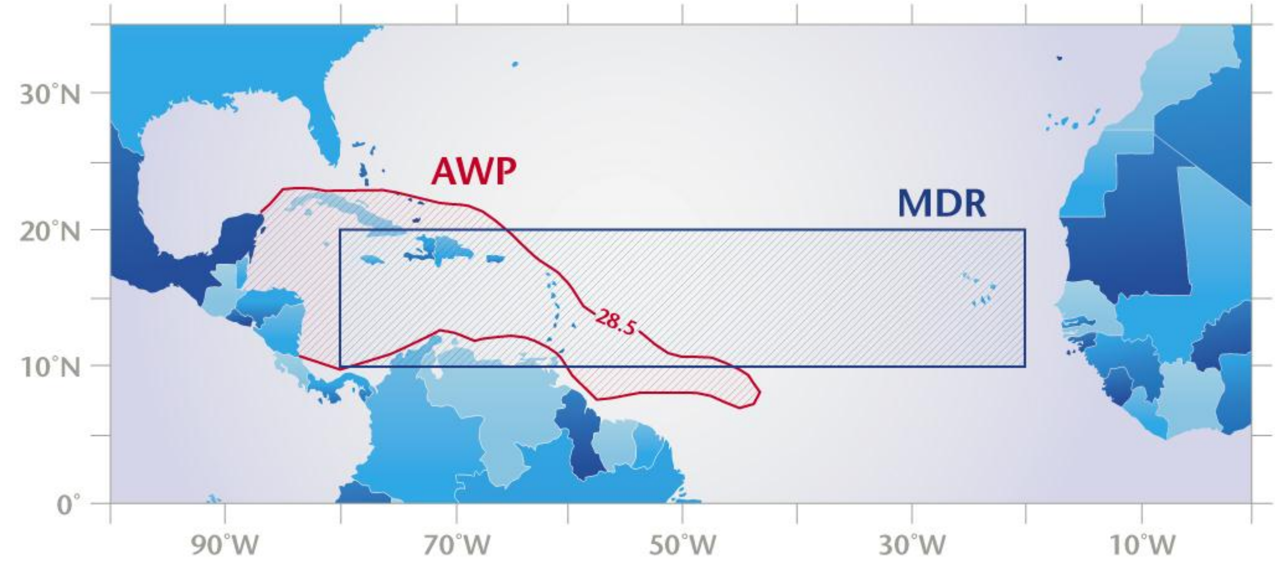

Figure 2: Schematic showing regions where the SST are believed to be important for determining hurricane activity. The MDR (blue box) covers the region 10°–20°N, 80°–15°W. The AWP (enclosed by red lines) is the region over which SST exceed 28.5°C. The size of this region varies from year to year and throughout the hurricane season. Source: © Crown copyright 2012 Met Office.

3.2 INTRODUCTION TO INFLUENCES ON HURRICANE DEVELOPMENT AND TRACKS

A hurricane begins when thunderstorms over warm water become organised and start to rotate, forming an area of low atmospheric pressure. For thunderstorms to develop there needs to be atmospheric instability and high humidity as shown in Figure 3. Any pre-existing circular motion in the atmosphere (known as vorticity) aids the organisation of the thunderstorms and enhances the rotation and formation of the low pressure centre. Air converges at low levels towards the centre and it is lifted by the thunderstorms (through convection) and carried away by strong upper-level winds. As the low level winds strengthen, more air is carried away at upper levels, deepening the low pressure, which further strengthens the low level winds. Through this mechanism the winds continue to strengthen and, if the conditions are right, eventually reach hurricane strength.

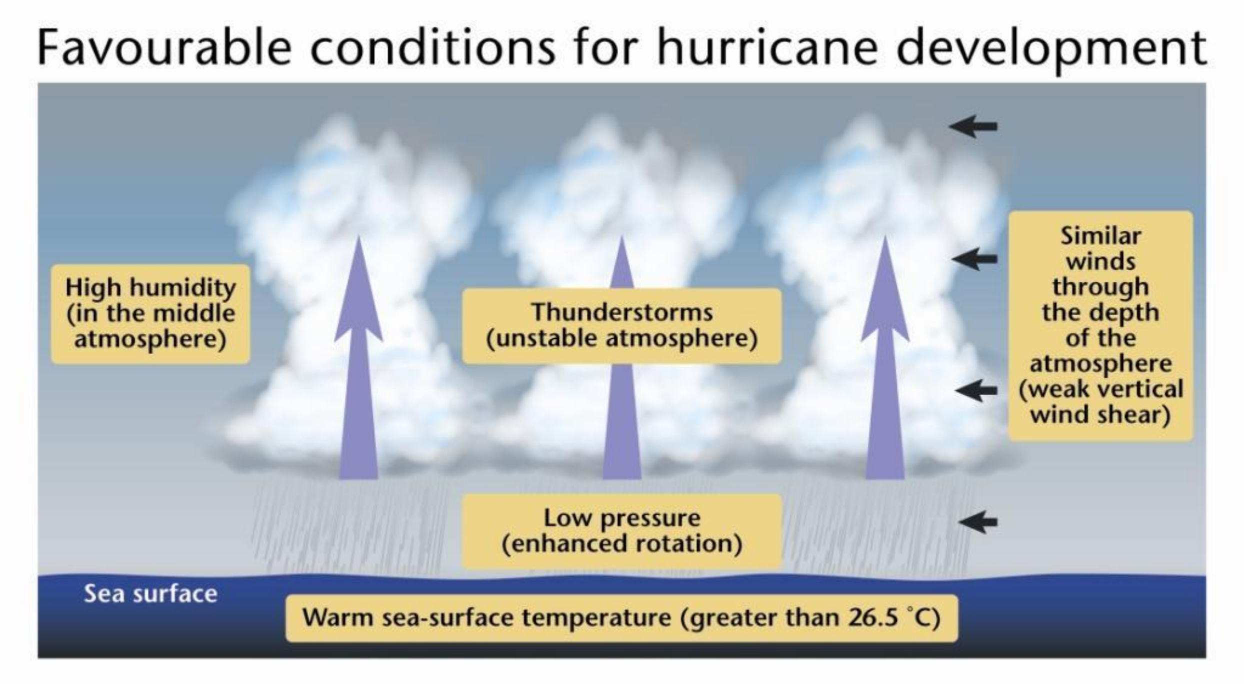

Figure 3: Schematic of conditions that favour the development of thunderstorms. The arrows pointing upwards represent the vigorous lifting of air by convection within the thunderstorms that sets up the conditions for hurricane formation. Source: © Crown copyright 2012 Met Office.

If there is a large difference between the low-level and high-level winds, known as vertical wind shear (see Figure 4), then the towers of convection get torn and the thunderstorms are less likely to become organised. Further, if the atmosphere is stable and the humidity is low, then the convection will be weaker, meaning less air will be lifted to higher levels. The role of warm Sea Surface Temperatures (SST) in encouraging hurricanes is to strengthen the convection, but they cannot create a hurricane in isolation if the other factors are unfavourable[6]. With this in mind, relying only on an index of tropical Atlantic SST will probably not be sufficient to successfully forecast a hurricane season.

A major well-known influence on hurricanes is the El Niño Southern Oscillation (ENSO) in the tropical Pacific (see inset box on tropical climate variability). During El Niño years the tropical circulation changes and upper-level winds increase over the tropical Atlantic, which in turn increases the vertical wind shear. El Niño also tends to warm the upper atmosphere over the tropical Atlantic leading to increased stability[ix]. Both of these factors tend to inhibit hurricane development.

[6] It should also be noted that tropical storms cause stirring of the ocean that brings up subsurface water. So for hurricane development it is not enough that the surface is warm, the subsurface must be warm as well (typically at least the top 50m).

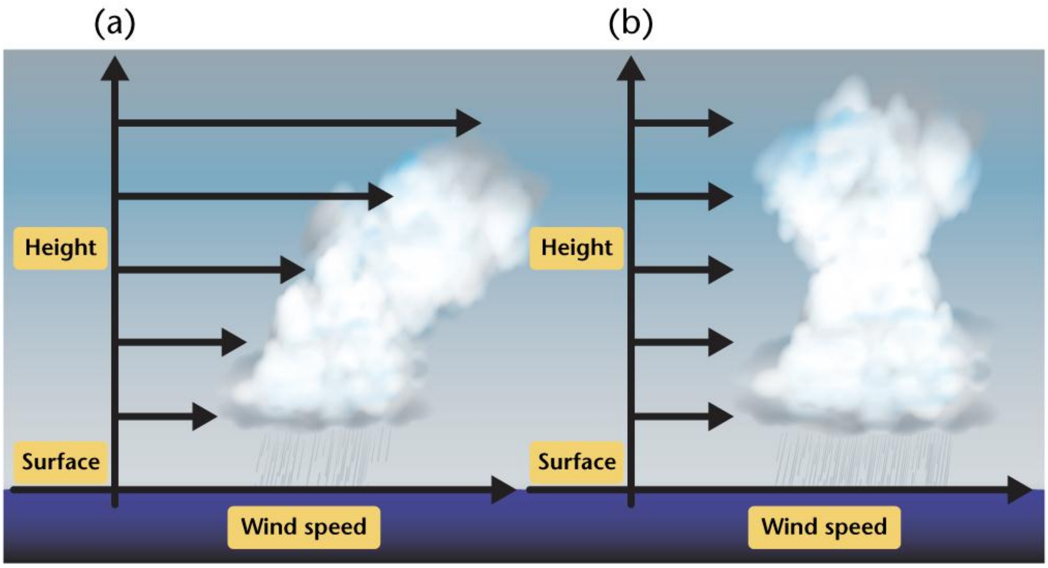

Figure 4: Schematic showing how winds that increase strongly with height can reduce the vigour of thunderstorms. In (a), a case with high vertical wind shear, the thunderstorm is much less likely to eventually develop into a hurricane than in (b), where the vertical wind shear is low. Source: © Crown copyright 2012 Met Office.

In the Atlantic, roughly half of all Atlantic tropical cyclone development 1948-2004 was strongly influenced by weather features coming from higher latitudes, such as fronts and waves[x]. These disturbances provide environments conducive to organised convection and enhance circular motion of storms. Hurricanes formed in the tropical East Atlantic are in a similar way often enhanced by African Easterly Waves (AEWs). These waves appear as meandering jets of strong winds that exist in the upper atmosphere. The waves are linked to increased convection, enhanced circular motion and sometimes reduced vertical wind shear – all of which favour storm formation.

Once a hurricane is formed its track is determined by the interaction with the surrounding winds, known as the steering flow. One major influence on the steering flow is the North Atlantic Oscillation (NAO). The NAO is one of the major modes of variability in the North Atlantic and is characterised by a see-saw of pressure between Iceland and the Azores. The almost permanent high pressure over the Azores is often called the North Atlantic Subtropical High[7] (NASH). At the southern edge of the NASH, westward (easterly) trade winds prevail. If NASH is strong the winds steer hurricanes westward increasing the chance of landfall in the US. If it is weak the path of the hurricane is more uncertain and it might recurve toward the north and north-east and not make landfall.

[7] The NASH will be discussed in more detail later, but see Figure 7 for an illustration.

TROPICAL CLIMATE VARIABILITY

Tropical climate variability is dominated by interactions between the atmosphere and the ocean. The interaction is both ways and this is called "coupled" climate variability. As an example, the warm ocean surface in the West Pacific heats the overlying air and causes it to rise. Air rushes in from the east to replace the rising air. On the way it picks up water vapour, increasing humidity and therefore enhancing convection. The winds also move the water at the ocean surface causing deeper, colder water to be brought up at the surface in the East Pacific. This is the normal state of the Pacific. Disturbances to this state cause the El Niño-Southern Oscillation (ENSO) phenomenon. During El Niño winds across the Pacific weaken and so less cold water is brought up at the surface in the East Pacific, warming the region. The opposite happens during a La Niña. For geographic reasons the Atlantic cannot have strong variability in the East-West (zonal) direction but it does have it in the North-South (meridional) direction instead.

Apart from the steering flow, one of the biggest influences on whether a tropical storm makes landfall in the US is its point of origin. One study[xi] shows that during the period 1950-2007:

- tropical storms originating in the sub-tropical North Atlantic were most likely to strike the US east coast and Florida;
- tropical storms originating in the Caribbean, Gulf of Mexico and western tropical Atlantic were most likely to strike the Gulf States and Florida;
- tropical storms originating in the eastern tropical Atlantic could strike any of the Atlantic coast states.

4 TROPICAL ATLANTIC CLIMATE VARIABILITY AND HURRICANE LANDFALL

This section is divided into three parts. The first part presents recent research on the impact of tropical Atlantic climate variability on hurricane activity in general. The second part then focuses on hurricane tracks and landfall risk. The third part uses the information from the first two parts to discuss forecasting of hurricanes.

4.1 IMPACT OF TROPICAL ATLANTIC CLIMATE VARIABILITY ON HURRICANE ACTIVITY

This section will discuss further the climate variability patterns introduced in section 3.1 and their impact on hurricane activity. Atlantic Multi-decadal Variability (AMV) is highly correlated (correlation of more than r=0.9) with hurricane numbers[ii], but only when inter-annual variability in both time series has been removed to retain only time scales of longer than 10 years. On inter-annual time scales the Atlantic Meridional Mode (AMM) is more highly correlated (r=0.54 compared with r=0.35) with seasonal mean storm frequency and duration than AMV[xii].

4.1.1 Atlantic Meridional Mode

The AMM explains a large part of coupled[8] ocean-atmosphere variability in the Atlantic (Figure 5). In addition to variations of Sea Surface Temperatures (SSTs) in the region of hurricane activity, it also affects other variables that influence hurricane activity, such as vertical wind shear and atmospheric circular motion[xiii]. Its inter-annual variability is irregular rather than periodic.

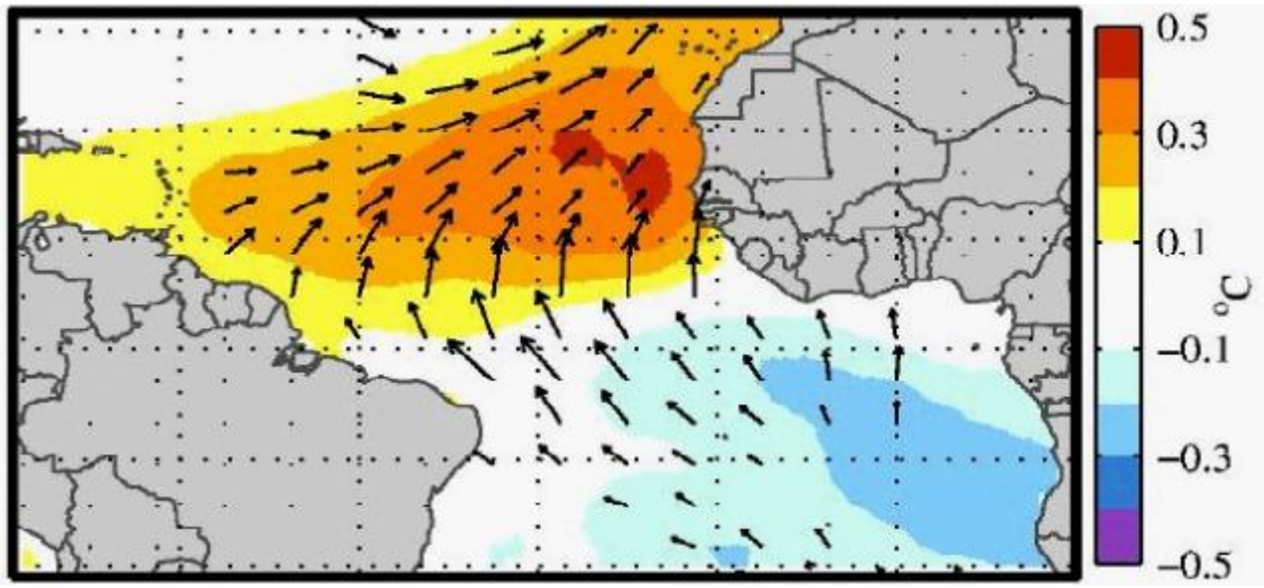

Figure 5: This is a typical pattern of SST anomalies and wind anomalies for a positive AMM. The SST are shown by shaded colours and low level winds are shown by arrows. Source: Figure adapted from Chiang,

[8] See inset box on tropical climate variability in the previous section

J.C.H., D.J. Vimont, 2004: Analogous Pacific and Atlantic Meridional Modes of Tropical Atmosphere–Ocean Variability. J. Climate, 17, 4143–4158. © American Meteorological Society. Reprinted with permission.

During strongly positive AMM years there are more frequent and more intense hurricanes and a greater number of major hurricanes[xii]. Hurricanes also originate more often in the Main Development Region (MDR)[xiii]. During strongly negative AMM years the hurricanes are fewer and weaker[xii]. Hurricane formation is increased off the US East Coast compared to during the positive phase[xiii].

The AMM is a climate pattern that is probably initiated and strengthened at least in part by external factors and this is more likely to happen when the AMV is positive[xiii]. There are indications that African dust outbreaks can trigger the AMM[xiv]. Also, according to one study, over the 20th century, half of the trend in the tropical Atlantic North-South SST difference (related to the AMM) can be explained by changes in sulphate aerosol in the atmosphere[xv]. Aerosols not only cool SSTs, but also induce changes in clouds that can impact on the strength of deep convection. The decrease in hurricane counts in the 1950s and the low counts of the 1960s may therefore have been caused at least in part by aerosols[xvi].

4.1.2 Atlantic Warm Pool

The Atlantic Warm Pool (AWP), shown in figure 2, is an important part of tropical Atlantic climate variability and is thought to influence hurricane starting points and activity. During years when the AWP is large (compared to small AWP years) there is more hurricane activity – in particular, there are more hurricanes originating east of 40°W[xvii]. The reason for the increased hurricane activity is that a large AWP is associated with higher SSTs and less vertical wind shear in the tropical Atlantic. In addition the response of the atmospheric circulation to a large AWP increases the humidity and supports stronger convection, which also encourages hurricanes[xviii].

The AWP is strongly linked to the AMV. Large AWPs are more likely during the positive phase of AMV and small AWPs are more likely during the negative phase. It has been suggested that the AWP is the mechanism that links the AMV to hurricane variability[xviii].

4.1.3 El Niño-Southern Oscillation

The El Niño-Southern Oscillation (ENSO) influences seasonal hurricane activity by modifying the circulation in the tropics and changing the vertical wind shear in the Atlantic. In its positive El Niño phase, hurricane activity is generally reduced (exceptions to this can occur). Using data from 1900-2009 one study[xix] finds that El Niño years have an average of 14.9 days with hurricanes compared to 28.7 days during La Niña. However, the strength of this modification may depend whether the El Niño is centred in the East Pacific or the central Pacific[xx]. Rather than consider ENSO on its own, it is more useful to consider ENSO in combination with tropical Atlantic climate variability.

When considering the observed record, subdividing seasons according to the ENSO phase within the AMV cycles inevitably leads to shrinking sample sizes. With that caveat in mind, the following general trends can be found[xix]. In the positive phase of AMV, a weak to moderate El Niño can still result in an active hurricane season. However, during a strong El Niño activity is suppressed regardless of AMV phase. In the negative phase of AMV, La Niña conditions are required for an active season.

The AMM and ENSO are both examples of tropical climate variability. It has been suggested that while ENSO mainly affects vertical wind shear in the western tropical Atlantic basin, the AMM affects the wind shear in the whole basin[xii]. Therefore variability of hurricane activity is dependent on both these sources of climate variability in the Caribbean. In the MDR region, particularly east of 60°W, activity is mostly influenced by the AMM.

4.1.4 Northern North Atlantic

In addition to local tropical Atlantic and Pacific influences, it has also been suggested that the temperatures in the northern North Atlantic (especially the so-called Atlantic sub-polar gyre region) may play an active role in forcing tropical storm variability.

One study[xxi] found that the temperature changes in the northern North Atlantic were highly correlated with variables important for controlling Atlantic tropical storm development. A linked study[xxii] showed in model simulations that the northern North Atlantic ocean was a key region to observe when predicting Atlantic tropical storms on multi-annual timescales. The mechanism that links the Northern North Atlantic and hurricanes is not yet fully known, but it may be through the AMM or AMV.

4.1.5 African Easterly Waves

It has long been known that there is a statistical link between West African monsoon[9] rainfall and the number of Atlantic hurricanes. During the ten wettest monsoon years between 1949-1990, there were significantly more named storms and hurricanes than during the ten driest years[xxiii]. The difference is largest when only major hurricanes are considered. The wettest years had more than two times more major hurricanes than the driest years (an average of 2.8 compared to 1.2).

The multi-decadal variability of the rainfall varies in step with the low-frequency changes in hurricane activity. It is likely that the link between the West African monsoon and hurricane activity is African Easterly Waves (AEW), which, as mentioned in section 3.2, favour storm formation. This link is corroborated by the fact that on inter-annual time scales the variability of winds related to AEW shows an even stronger correlation with hurricane activity, than is shown in the rainfall relationship[xxiv].

The correlation between West African rainfall and hurricanes has decreased since the mid-1990s. The variability in the strength of the correlation over the period 1921-2007 has been studied[xxv]. It appears that the correlation is strongest in years when conditions in the MDR are less favourable for tropical storms. This suggests that when conditions in the MDR are favourable for hurricane development, this reduces the influence of African rainfall.

[9] A monsoon is characterised by seasonally shifting winds and rainfall. The West African monsoon coincides with the Atlantic hurricane season.

4.2 HOW DOES CLIMATE VARIABILITY IN THE TROPICAL ATLANTIC MODULATE HURRICANE TRACKS AND LANDFALL RISK?

Landfall risk is of great interest to communities, businesses and insurers. Unfortunately there is a lack of data as most areas on the US coast are only occasionally impacted by hurricanes. Three factors are of importance for landfall: storm origin, storm development and steering flow. The point of origin of a hurricane obviously has a strong influence on whether it will make landfall. Wind speeds at landfall will depend on whether the conditions along its track are favourable for deepening and intensifying of a storm. For hurricanes that originate far away from the coast, atmospheric winds can steer the hurricane towards or away from landfall.

4.2.1 Atlantic Multi-decadal Variability

The impact of AMV on landfall risk is still poorly understood and a topic of active research. There are two major studies in the literature[xxvi,xxvii] and they do not always agree. However, it is likely that as total hurricane activity increases during positive Atlantic Multi-decadal Variability (AMV) years, hurricane landfall typically increases as well (but the 2010 and 2011 seasons were exceptions to this rule).

The landfall risk may depend on the strength of the storm[xxvi]. During positive AMV years, compared to negative AMV years, the Gulf Coast is likely to see an increase in tropical storm landfall, but no detectable change in hurricane landfall. This is contradicted by one study[xxvii], which does not find that either AMV phase increases the likelihood of tropical storm landfall on the US Gulf Coast. The results are different as the two studies define positive AMV years differently and calculate landfall risk differently.

The US southeast coast (from North Carolina to the tip of Florida) is likely to see an increase of storms of hurricane strength during positive AMV years[xxvi]. Further north on the East Coast, this study found that hurricanes are too infrequent to draw any robust conclusions with their method.

These patterns of landfall can largely be explained by the changes in the point of origin between AMV phases. Figure 6 shows tropical storm starting points and their resulting density for negative and positive AMV years. In positive years there are more storms originating in or close to the Gulf of Mexico. This could increase tropical storm landfall along the Gulf Coast. However, as the distance between the starting point and the coast is relatively short, the storm has little time to strengthen and so is less likely to reach hurricane strength than a storm which starts further away from the coast.

During positive AMV years there is also an increase in tropical storms and hurricanes originating in the MDR, especially in the East Atlantic. These are the storms that are likely to strike the US southeast coast. As they will have travelled long distances over warm waters they can, if atmospheric conditions are favourable, intensify and strike the coast as hurricanes or major hurricanes.

During positive AMV years, hurricanes that make landfall are more likely to make landfall in Florida than elsewhere. This last result is explained by the most likely point of origin being shifted equatorward in the central tropical Atlantic, which is where hurricanes that strike Florida often originate[xxvii]. During negative AMV years, one study finds hurricanes that make landfall are more likely to strike on the Gulf Coast[xxvii].

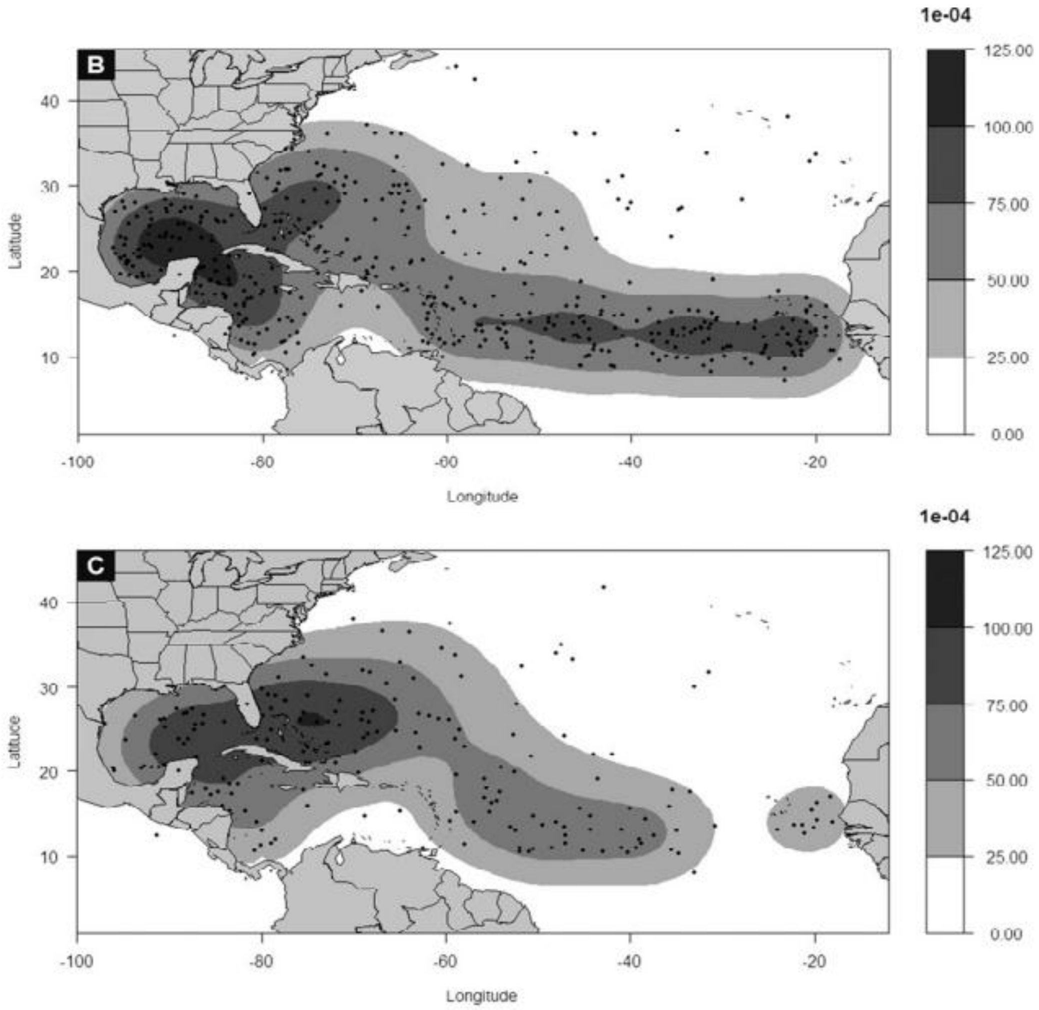

Figure 6: Spatial distribution of the origin of tropical storms and hurricanes 1948-2007. Each dot represents the starting point for each tropical storm or hurricane and the shading represents the density of storm creation (in units of starting points per square km per year, the scale on the right hand side should be multiplied by 0.0001). The top plot represents the distribution during positive AMV years and the bottom plot during negative AMV years. Source: Dailey, P.S., G. Zuba, G. Ljung, I.M. Dima, J. Guin (2009): On the Relationship between North Atlantic Sea Surface Temperatures and U.S. Hurricane Landfall Risk. J. Appl. Meteor. Climatol., 48, 111–129. © American Meteorological Society. Reprinted with permission.

4.2.2 North Atlantic Subtropical High

As mentioned in section 3.2, tropical storms originating in the eastern tropical Atlantic are likely to strike any part of the US coast[xi]. In section 4.1, it was noted that the number of hurricanes originating here were most strongly modulated by the Atlantic Meridional Mode (AMM)[xii]. These hurricanes travel far and have time to intensify, so influences on their tracks are important to consider. The size of the Atlantic Warm Pool (AWP) is thought to be linked to the North Atlantic Subtropical High (NASH) and might therefore influence the steering flow[xvii]. However, it is not yet known how this may occur.

A strong NASH tends to steer hurricanes towards landfall in the US, rather than recurving before reaching the coast (see Figure 7). The atmosphere responds to a large AWP with eastward wind anomalies along the eastern seaboard of the US. These anomalies weaken the NASH and allow hurricanes to recurve and miss the US coast. This may be what happened in 2010. There was a large AWP and La Niña conditions, which both contributed to an active season, but the weak NASH may have allowed more hurricanes to recurve away from the US coastline and therefore may have been the reason there were was no hurricane landfall[xvii].

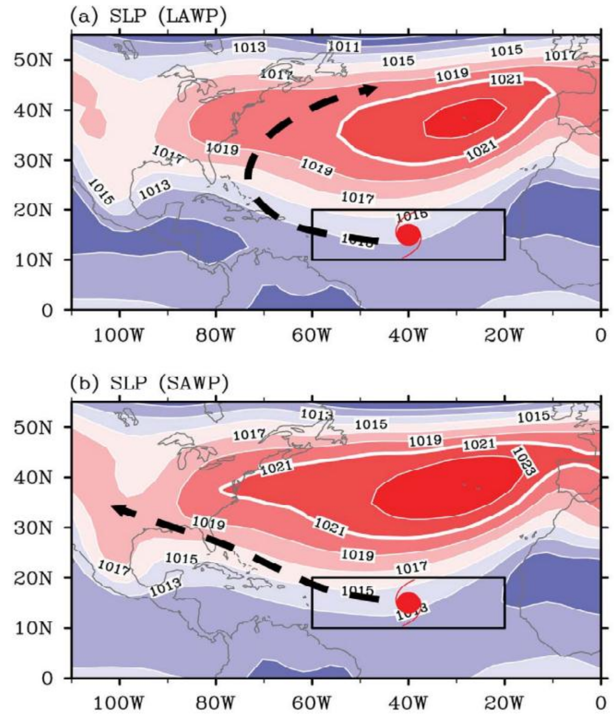

Figure 7: Schematic of the influence of the NASH Sea Level Pressure (SLP) on hurricane paths. In (a) the SLP associated with a Large AWP (LAWP) is shown with a hurricane recurving without making landfall (though this will not necessarily be the case). In (b) the SLP associated with a Small AWP (SAWP) is shown with a now more likely path of landfall. Source: Figure adapted from Wang, C., H. Liu, S.-K. Lee and R. Atlas (2011): Impact of the Atlantic warm pool on United States landfalling hurricanes, Geophys. Res. Lett., 38, L19702 by permission of American Geophysical Union.

Recognising the importance of NASH for landfall, it is possible to make an index that combines the AMV and NASH[xxviii]. The combined index is equivalent to AMV minus NASH. When this index is high then landfalling hurricanes become more frequent, especially on the US East Coast and the Florida Peninsula.

This result perhaps contradicts that obtained from studying the AWP, where a strong NASH was found to increase the risk of landfall. In contrast, a strong NASH would decrease this combined index. Indications have also been found that during positive AMV years, a weakened NASH is more likely[xxix]. More work is needed on this poorly understood area.

4.2.3 El Niño-Southern Oscillation

It is known that US landfalls are usually reduced in El Niño years[xix]. The risk of landfall is particularly reduced for major hurricanes impacting on the Florida Peninsula and the US East Coast. In section 4.1, it is mentioned that the AMV modulates the impact of ENSO, with the modulation being largest during negative AMV years. The same is true for landfall risk. The biggest difference is found when comparing El Niño and negative AMV against La Niña and positive AMV for landfall risk in Florida and the US East Coast. The landfall risk is three times higher in the latter case compared to the former (2.7 hurricanes per year against 0.9 hurricanes per year). No major hurricane made landfall in the US between 1900-2009 in a year with negative AMV and El Niño.

4.3 FORECASTING TROPICAL ATLANTIC CLIMATE VARIABILITY AND ITS IMPACTS

There are three types of forecasts: statistical forecasts, dynamical forecasts and hybrid forecasts. A statistical forecast is based on historical relationships between an index and the variable to be forecast. A dynamical forecast uses physical equations to simulate the evolution of the variable to be forecast. A hybrid model is a combination of the two, with typically the output of a dynamical model being used as input to a statistical model.

For a forecast to have a good chance of being useful, it must contain information about the state of Atlantic climate variability during the hurricane season. At least it should take into account the current state of the variability under the assumption that it will persist into the forecast period. A five-year forecast should ideally include information about the Atlantic Multi-decadal Variability (AMV) and its impact on the Atlantic Meridional Mode (AMM) and the Atlantic Warm Pool (AWP). As seen in section 3.1, the model may also need to incorporate the effects of solar forcing and aerosols to model AMV realistically. Any model will also benefit from including the influences of El Niño-Southern Oscillation (ENSO), as well as the North Atlantic Subtropical High (NASH), the vertical wind shear in the main development region (MDR), atmospheric instability, humidity and circular motion.

4.3.1 Dynamical models

A dynamical model is potentially capable of simulating all the factors mentioned in the previous paragraph. It uses equations based on fundamental laws of physics that help to predict the evolution of future climate variability. Minor variations can also be introduced into the initial conditions to represent uncertainty in real-world observations (like surface pressure measurements, temperatures readings etc), with the aim of producing a range of results from parallel model runs that form an “ensemble” of forecasts. Studying the range of individual model forecasts (called “ensemble members”) may provide a way to estimate the uncertainty[10] in the forecast. This is a useful measure as it allows more confidence to be put in a forecast with low uncertainty.

Running dynamical models on computers can be very expensive on computer time. Due to limitations of present day computers, it is currently not possible to simulate hurricanes explicitly in multi-year predictions. However, tropical storm-like features can be identified in the model output and used to make predictions. In this way, potentially useful forecasts of five year mean storm counts have been made[xxi]. Much of the forecast skill found comes from the strong influences of external factors (as mentioned in the introduction), with some influence from starting the model from observed ocean conditions in the North Atlantic and tropical Pacific.

It is a key question how well dynamical models can predict future Atlantic climate variability. The AMV varies on multi-decadal time scales and therefore the potential exists for extended-range predictability, but there is no robust evidence yet that it can be done. Dynamical models may be able to predict ENSO up to two years ahead in the Pacific[xxx], but that is obviously not long enough for a five-year forecast.

[10] Uncertainty can also be called confidence or error bar in this context.

In a recent study, a dynamical climate model was used for the first time to identify the link between aerosols from industrial pollution and regional climate trends[xxxi]. Following on from this work with dynamical climate models, it may become possible physically relate aerosols (including volcanic activity and industrial pollution) with hurricane activity.

4.3.2 Statistical models

Statistical models are not based directly on physics but instead rely on historical statistical relationships between the past and the future. It is possible, for example, to use July wind anomalies to predict the wind energy of US landfalling hurricanes for the following season (August-October)[xxxii]. This is because winds often evolve in a consistent manner as a response to the seasonal cycle. Winds are also important for both hurricane formation (through the vertical wind shear) and steering of existing hurricanes. However, a prediction would be more useful if it could be made further than one month in advance.

The MDR sea surface temperatures (SST) are correlated with hurricane activity in the historical record. However, future projections of hurricane activity based on projected changes in MDR SST do not agree with model simulations[xxxiii], and it is thought that the relative difference between MDR and tropical mean SST may be a more reliable statistical predictor[xxxiv,xxxv,xxxvi,xxxvii]. This is because tropical mean SST can influence the large scale upper atmosphere leading to changes in vertical wind shear and atmospheric stability. Therefore a combination of MDR SST (which gives information on the local variability) and mean tropical SST (which gives information on large scale upper atmosphere variability) is more reliable than tropical SST alone.

CORRELATIONS AND CAUSATION

A correlation between the time series of two variables indicates the degree to which the variations of those two variables coincide. A strong correlation does not necessarily imply that the two variables are linked physically, they could both be influenced by a common third variable. The strength of a correlation is also very sensitive to large deviations from the mean, so two time series with a few large deviations by chance at the same time can have a misleadingly large correlation. Adding a few more time points to those series can often dramatically reduce the correlation. A trend is a large deviation from the mean at the beginning and at the end of the time series. Two variables might both have a trend for completely different reasons, but even if the trends are of different magnitudes this can increase the correlation for the wrong reasons. Large correlations can arise more easily by change in small sample sizes. The effective sample size may also be reduced if there is persistence in the data, meaning that not all of the individual time periods represent independent samples.

4.3.3 Hybrid models

As mentioned earlier, global dynamical models have the potential to predict the Atlantic climate variability, but generally lack the ability to model hurricanes explicitly. One form of hybrid model uses a dynamical model to predict the hurricane season SST and then an SST-based statistical model to predict hurricanes[xxxviii]. By only taking the SST from the model, it means that some information pertinent to hurricane formation and propagation is not used (e.g. wind shear and atmospheric stability). However, as mentioned above, a statistical model that uses both MDR SST and tropical mean SST potentially recovers some of that information.

4.3.4 US landfall forecasts

Capability in predicting basin-wide hurricane activity is still a developing research area. As a result, regional US landfall forecasts for the next few years are still experimental. The important role of the atmosphere is highlighted in one study which concluded that it is ‘‘dangerous’’ to infer numbers of US landfalling storms and hurricanes solely from numbers that occur or are expected to occur across the Atlantic basin[xxxix].

There is a study that considers the impact of MDR SST on landfall[xl], but it is not peer-reviewed[11]. The study investigates the possibility of using SST to model US landfall rates by conditioning the model on the 19 hottest and 19 coldest years in the MDR between 1950-2005. The study finds that the change in landfall rate between hot years and cold years is most likely attributable to the change in total hurricane numbers. As other studies mentioned in this report[xxvi,xxvii] find that AMV can influence regional hurricane landfall rates, one possible conclusion is that MDR SST is not particularly useful as a predictor of landfall rates. Such a viewpoint is consistent with the important role of the atmosphere found in the study mentioned above[xxxix] and elsewhere in this report.

[11] Peer-review is the standard process of quality assurance in scientific research and involves a set of checks to ensure quality, consistency and impartiality, and therefore suitability for publication.

5 CONCLUSIONS

In preparing this paper we have examined the latest peer-reviewed published research on Atlantic climate variability and its impact on hurricane formation and tracks. Long-term climate variability in the Atlantic largely depends on Atlantic Multi-decadal Variability (AMV). We use the term “variability”, rather than the previously used term “oscillation”, because external factors, such as volcanic eruptions and changes in man-made emissions, influence North Atlantic temperatures. This implies that some hurricane variability may be caused by volcanic eruptions, man-made emissions and changes in the solar output of radiation.

The formation and intensification of a hurricane requires warm SSTs, but hurricanes are also influenced by atmospheric conditions. One of the most important factors is the vertical wind shear, which when large, will significantly reduce the development of hurricanes. For hurricanes to form the atmosphere must be unstable enough to allow convection, be sufficiently humid and must have a seed of circular motion. For these reasons forecasts which include the current or forecast state of the atmosphere will be more skilful than those that do not, and therefore potentially be more useful to the insurance industry.

AMV is defined as the multi-decadal variability of North Atlantic mean sea surface temperatures (SST) with the trend removed. As there is no agreed method on how to remove the trend, definitions of AMV may vary between publications. AMV is believed to influence climate variability which affects hurricane activity. These include the Main Development Region (MDR) SST, the Atlantic Meridional Mode (AMM) and the Atlantic Warm Pool (AWP), all of which are thought to influence hurricane activity and landfall risk.

More storms are formed, especially in the MDR region, during a period of consistently positive AMV years. The different phases of AMV are also thought to influence the point of origin of hurricanes. Where a tropical storm originates is one of the biggest influences on whether it makes landfall. It is more likely to make landfall if it forms close to a coast line, but is less likely to have undergone significant intensification. It is less likely to make landfall if it forms far from a coast line but if it does make landfall, it is more likely to be a major hurricane.

It is difficult to draw definite conclusions on the impact of Atlantic climate variability on regional landfall risk. This is mainly because of a lack of historical data for many regions. More research is needed to be able to understand how landfall risks are changing and their relationships to Atlantic, Pacific and global climate variability.

It is not known whether AMV changes the proportion of total hurricanes that make US landfall, but the change in where hurricanes originate during different AMV cycles is likely to influence landfall regionally. The US East Coast in particular may have an increased probability of hurricane landfall during positive AMV years.

The AMM is a coupled climate mode made up of both the ocean and the atmosphere and so can be a useful indicator of hurricane activity. It can be influenced by external factors (for example volcanic eruptions and man-made emissions) and is more likely to occur when the AMV is positive. Both the ocean and atmosphere become more favourable to hurricane formation when the AMM is positive and more hurricanes form in the MDR. Hurricanes that form in the eastern tropical Atlantic are probably most modulated by the AMM. These also travel the furthest and can be the most damaging hurricanes on making US landfall.

The AWP is an important element of tropical Atlantic climate variability, influencing both where hurricanes originate and their overall seasonal activity. A large AWP is more likely during positive AMV years. The AWP has also been linked to the North Atlantic Subtropical High (NASH), which can steer hurricanes towards the US coast or allow them to recurve and not make landfall. The relationship between AMM and AWP is unclear and a better understanding of it, and other factors affecting Atlantic climate variability, would enable more accurate landfall forecasts.

The impact of the El Niño-Southern Oscillation (ENSO) on hurricane activity and landfall is modulated by the AMV. When AMV is in its negative phase and there is an El Niño, these conditions mean there is likely to be lower than average hurricane activity. When the AMV is in its positive phase, hurricanes can still occur in an El Niño year. Both ENSO and AMM impact on hurricane activity in the western tropical Atlantic, while in the MDR region, particularly east of 60°W, the AMM is thought to be dominant. This means, if successful prediction of the AMM can be achieved, it may provide the ability to forecast its influence on landfalling hurricanes that reach the US.

West African monsoon rainfall can impact on Atlantic hurricanes possibly through African Easterly Waves (AEWs) that encourage convection and circular motion. The result is an especially strong modulation of major hurricanes. However, in common with ENSO, when the conditions in the MDR already increase the likelihood of hurricane formation, the impact of AEWs on hurricanes is weaker. This implies that when conditions in the MDR are less likely to form hurricanes, then remote influences may be more important. However, only further research can confirm this.

Most aspects of Atlantic climate variability discussed in this report will help develop forecasts of hurricane activity and landfall. Forecasting climate variability over the next seasons and years by using observations of the state of the current climate state is still a new area of science. Dynamical models are based on fundamental equations and can predict some aspects of Atlantic climate variability, but the models used in seasonal and inter-annual prediction cannot directly predict individual hurricanes. Statistical models use historical relationships between hurricanes and the climate state before the hurricane season starts. They can be skilful for forecasts of the near future, but it is uncertain how well historical statistical relationships will prove in a changing climate.

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