The Madden-Julian Oscillation and tropical cyclone frequency variability

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THE MADDEN-JULIAN OSCILLATION AND TROPICAL CYCLONE FREQUENCY VARIABILITY

A Thesis
Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Master of Science
in
The Department of Geography and Anthropology

by
Stephen Caparotta
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ABSTRACT

Recent years have seen a dramatic increase in monetary losses from hurricanes along the U.S. coastline. The vast majority of the damage resulted from major hurricanes (Category 3-5), with 2005’s Katrina, Rita, and Wilma producing an estimated $60 billion in insured losses alone (Insurance Information Institute, 2008). In light of these record damages, it is crucial to have a better understanding of the atmospheric and oceanic conditions that produce the most powerful hurricanes.

Prior research has focused on interseasonal variability in tropical cyclones, but much less attention has been devoted to intraseasonal variability. Maloney and Hartmann (2000a) showed that hurricanes are four times more likely to form in the western Atlantic and Gulf of Mexico when the Madden-Julian Oscillation (MJO) is in its “enhanced convection” phase. This study follows the work of Maloney and Hartmann but focuses on intense tropical cyclones (Category 3-5).

Formation points of intense tropical cyclones were overlaid on plots of MJO indices extending from the western Pacific to the eastern Atlantic. For each tropical season, tropical cyclones were classified as having formed during favorable (enhanced convection), unfavorable (suppressed convection), or neutral phases of the MJO. Chi-squared testing was performed to determine the degree to which associations could be made between the MJO and tropical cyclone variability in the Western Pacific (WPAC), Eastern Pacific (EPAC), and Atlantic (ATL) basins. It was found that the MJO is not linked to overall tropical cyclone frequency variability in these three basins. However, testing did reveal some significant associations through time.

These results do not corroborate those of Maloney and Hartmann (2000a). Two key changes in methodology are the likely driving forces behind the differing results. First, this study uses an
MJO index from the CPC based on 200 hPa velocity potential anomalies, while Maloney and Hartmann (2000a) used an MJO index based on 850 hPa wind anomalies. Second, the study period here is 1978 – 2006, while Maloney and Hartmann (2000a) used data from 1949 – 1997. Future research should be conducted to examine the relationship between the MJO and tropical cyclones in more detail.
I. INTRODUCTION

Preliminary estimates from the Insurance Information Institute indicate that the 2004 and 2005 Atlantic hurricane seasons produced unprecedented monetary losses for the insurance industry in the United States. Four hurricanes in 2004 – Charley, Frances, Ivan, and Jeanne – are believed to have produced at least $23 billion in insured losses. In 2005, Katrina’s $38 - $45 billion in losses easily made it the costliest single natural disaster in U.S. history, while Hurricanes Rita and Wilma produced an additional $13.4 billion in losses (Insurance Information Institute, 2007). In light of these record damages and predictions that above-normal tropical cyclone counts could continue for another 10 to 20 years or more (Goldenberg et al. 2001), it is crucial to have a better understanding of the atmospheric and oceanic conditions that led to the devastating 2004 and 2005 hurricane seasons for the United States.

Considerable scholarly attention has been devoted to the interseasonal variability in tropical cyclone frequency. Dr. William Gray of Colorado State has been the leader in this field, producing seasonal forecasts of Atlantic tropical cyclone activity since 1984. Gray is perhaps best known for establishing a correlation between the El Niño/Southern Oscillation (ENSO) phenomenon and tropical cyclone frequency in the Atlantic (Gray 1984a). Examples of other predictors used by Gray and his colleagues for forecasting Atlantic tropical cyclone frequency include: 500 hPa heights in the North Atlantic, sea level pressure (SLP) in the Gulf of Alaska, 500 hPa heights in western North America, the quasi-biennial oscillation (QBO), SLP in the Caribbean, Gulf of Mexico, and southeastern U.S., and SLP in the northeast Pacific (Gray 1984a,b; Gray et al. 1984-2005; Gray et al. 1992; Gray et al. 1993; Gray et al. 1994; Landsea et al. 1994). Two of Gray’s former students – Dr. Chris Landsea and Eric Blake – are now part of
a team producing similar seasonal forecasts for the National Oceanic and Atmospheric Administration (NOAA).

Interdecadal variability in tropical cyclone frequency has also been addressed in several different contexts. The Pacific Decadal Oscillation (PDO) is a mode of climatological and oceanic variability first identified by Steven Hare in 1996 while investigating patterns of salmon production off the Alaska coast. The PDO will be described in detail in the section that follows. Some researchers believe that a connection may exist between variability exhibited by the PDO and tropical cyclone frequencies on interdecadal time scales. In investigating the relationships between ENSO and Atlantic tropical cyclones, Lupo and Johnston (2000) noticed variability on a time scale longer than can be attributed to ENSO and they suggested that this interdecadal relationship may be a reflection of PDO influences.

The Atlantic component of the global thermohaline circulation has also been shown to influence Atlantic tropical cyclones on interdecadal scales. The thermohaline circulation transports warm water northward in the north Atlantic Basin, where it then sinks as it cools and becomes more saline (when evaporation exceeds freshwater input from streams in that region), and returns southward as part of the global conveyor belt of oceanic circulation (Figure 1.1) (Broecker 1991). Gray et al. (1997) hypothesized that the strength of the Atlantic thermohaline circulation regulates decadal trends in hurricane activity. Goldenberg et al. (2001) also examined the influences of decadal sea surface temperature (SST) trends on tropical cyclone frequency.

A relatively new science – paleotempestology – has begun to examine hurricane trends on centennial to millennial scales. Paleotempestology examines past hurricane activity through geological techniques and historical records. Several studies of paleohistorical hurricane trends
Substantially less attention has been devoted to interseasonal variability in tropical cyclone intensity. Even less scholarly work has focused on intraseasonal variability in tropical cyclone frequency and intensity. A notable exception is the work of Landsea et al. (1998), which examined the intraseasonal variability of the 1995 Atlantic hurricane season. However, Landsea et al. (1998) seemed to link most of the variability of both frequency and intensity of tropical cyclones with the same atmospheric and oceanic variables (e.g. vertical wind shear and SSTs) that are considered important on interseasonal scales. Other factors that may impact the intraseasonal variability of tropical cyclone frequencies and intensities include ocean eddies (Black and Shay 1998; Shay et al. 2000) and a mode of climatic variability known as the
Madden-Julian Oscillation (MJO; Maloney and Hartmann 2000a) to be described more fully in the next section.

Maloney and Hartmann (2000a) established a correlation between MJO phases and tropical cyclone frequencies in the Gulf of Mexico and western Caribbean. Their research showed that tropical cyclones are four times more likely to form in these areas when the MJO is in a certain (westerly) phase. They also noted that major hurricanes (Category 3-5 on the Saffir-Simpson scale) show an even greater preference to form in these areas during the westerly phase, but fail to provide any further details. This study aims to follow the methodology of Maloney and Hartmann, but to expand by examining the MJO’s impact on Atlantic hurricane frequencies across the entire Atlantic basin. Specifically, the project will seek answers to the following questions:

1) Can specific MJO phases be linked to variability in major hurricane frequencies over the Atlantic and Gulf of Mexico?

2) Can the MJO be more closely linked to variability in Atlantic hurricane frequencies in certain parts of the basin?

3) Can the results of Maloney and Hartmann (2000a) be corroborated using a different methodology and different MJO index?

Before atmospheric variability can be examined on an intraseasonal scale, it is important to have an understanding of modes of climatic variability known as teleconnections that take place on longer time scales. Wallace and Gutzler (1981) defined teleconnections as “significant simultaneous correlations between temporal fluctuations in meteorological parameters at widely separated points on earth.” Rogers et al. (2003) noted three teleconnection patterns – the Southern Oscillation (SO), the Pacific-North American (PNA) pattern, and the North Atlantic
Oscillation (NAO) – that seem to be important for explaining variability in a multitude of surface environmental features in North America. In addition to those teleconnections, a brief overview of the Arctic Oscillation (AO), the Pacific Decadal Oscillation (PDO), and the Quasi-biennial Oscillation (QBO) will be provided here. A description of the MJO and discussion of the research question will follow. Finally, a proposed method of study for examining possible links between the MJO and major hurricane frequencies will be outlined.
II. LITERATURE REVIEW

a. Arctic Oscillation (AO) and North Atlantic Oscillation (NAO)

The AO is a large-scale mode of climatic variability, sometimes also referred to as the Northern Hemisphere annular mode or the NAO. Considerable debate in recent years has focused on whether the AO and NAO are separate modes of climatic variability, or whether the NAO is simply a regional reflection of the AO. Walker and Bliss (1932) first identified the oscillation as a regional phenomenon. van Loon and Rogers (1978) and Hurrell (1995) offered support for this teleconnection being designated a regional phenomenon named the NAO. Wallace (2000) argued that the AO and NAO are inseparable, thus deeming them a single phenomenon known as the Northern Hemisphere annular mode. Rogers and McHugh (2002) showed that while the two modes of variability may be inseparable during the winter, rotated principal components analysis (RCPA) results in separate modes of variability during non-winter months. Rather than joining the ongoing debate, a simple discussion of the AO and NAO and their impacts follows.

Thompson and Wallace (1998) first identified the AO as the leading mode of variability of the extratropical Northern Hemisphere. While Thompson and Wallace (1998) first used empirical orthogonal function (EOF) analysis of SLP anomalies to identify the mode of variability, it is important to note that the AO is also apparent at other levels of the atmosphere. The AO has been shown to be strongly correlated to the strength of the polar stratospheric vortex (or circumpolar vortex), and circulation anomalies from this vortex have been shown to propagate down to the Earth’s surface (Baldwin and Dunkerton 1999). The “high index” phase of the AO is characterized by Wallace (2000) by below-normal Arctic SLP, anomalously strong surface westerlies in the subpolar regions of the North Atlantic, and warmer-and wetter-than-
normal resultant conditions in portions of northern Europe. By contrast, during the “low index” phase of the AO, SLP is anomalously high in the Arctic, lower temperatures are experienced in portions of eastern North America and Europe, and the primary storm track tends to shift southward. As is apparent in the discussion of the NAO below, these high and low index conditions are very similar to those shown to occur during the same phases of the NAO.

Walker and Bliss (1932) described the NAO as “the tendency for pressure to be low near Iceland in winter when it is high near the Azores and southwest Europe.” Marshall et al. (2001) supported this initial statement by noting that the NAO is essentially a pressure dipole that can be approximated by the simultaneous behavior or the Icelandic Low and the Azores High. In fact, the NAO is typically defined by an index of pressure differences between Iceland and the Azores (Rogers 1984; Hurrell 1995). The most commonly used index is calculated using SLP data from Lisbon, Portugal, and Stykkisholmur, Iceland (Hurrell 1995).

While Walker and Bliss were the first to identify the NAO, van Loon and Rogers (1978) spurred new interest in the subject when they identified a “temperature seesaw” between Greenland and northern Europe. van Loon and Rogers made use of temperature trends that were first noted by missionaries in the 18th century. The authors showed that when winter temperatures were below normal in Greenland, they tended to be above normal in Scandinavia, and vice-versa. The discovery of this seesaw was not only important on local scales, but also encouraged future research on regional climate impacts of the NAO.

The NAO has been shown to be responsible for fluctuations in temperature, precipitation, and SLP from North America to Europe and the Mediterranean (Marshall et al. 2001). Shifts in both wind patterns and storm tracks can have significant impacts on regional climate. During “high index” winters, the anomalously strong westerly winds onto Europe and northward shift of
the mean storm track produce warmer- and drier-than-normal winters over central and southern Europe, the northern Mediterranean, and western portions of North Africa. At the same time, conditions are generally cooler- and wetter-than-normal from Iceland to Scandinavia (Marshall et al. 2001) (Figure 2.1). During “low index” winters, the pressure dipole (from Iceland to the Azores) is weaker. The resultant storm track is farther south, with a general reversal of climatic anomalies from eastern North America to Europe and the Mediterranean. During these winters, conditions are generally cooler- and wetter-than-normal in eastern North America, central and southern Europe, and the Mediterranean (Figure 2.2). Climatic anomalies are most prominent during the winter since the NAO has been shown to be most pronounced in both strength and areal coverage during the December – March period (Marshall et al. 2001) when pressure gradients are strongest due to a maximized equator-to-pole gradient in incoming solar radiation.

![North Atlantic Oscillation](image)

**Figure 2.1** Typical NAO impacts during “high index” winters (Lamont-Doherty Earth Observatory 2008a)
The NAO has been shown to be the primary mode of climatic variability over the North Atlantic. Rogers (1990) found that the NAO accounts for the largest amount of interannual variability in monthly SLP in eight months of the year. Marshall et al. (2001) stated that the NAO is the “key and primary source of variability for North Atlantic climate on many time scales.” Finally, Hurrell (1996) showed that the NAO and SO (discussed later) explained nearly half of the interannual variance in hemispheric extratropical temperatures.

Temporal trends in the NAO have also been examined by several researchers. Spectral peaks of the oscillation were shown at approximately 24, 8, and 2.1 years by both Hurrell and van Loon (1997) and Cook et al. (1998). While numerous studies have identified the importance of the NAO on interannual scales, Hurrell (1995) discovered decadal trends. Generally speaking, the NAO has been in a high index pattern during most of the post-1980 months. The persistence of
this high index pattern has led some to question the possible connections between the NAO and
global warming. However, when one considers the decadal shifts in climate that Hurrell (1995)
showed through the use of Greenland ice-core data, it becomes difficult to draw any conclusions
on possible connections between global warming and the persistent “high index” pattern of the
NAO.

Connections between the NAO and Atlantic hurricanes have been established in previous
research. Elsner et al. (2000) showed that U.S. hurricane landfall locations show a relationship
to NAO phases. Specifically, they showed that during “excited phases” [high index patterns],
major hurricanes are more likely to recurve in the Atlantic, lessening the probability of a landfall
along the Gulf Coast. During “relaxed phases” [low index patterns], the opposite is true, with
the Gulf Coast having a higher likelihood of a major hurricane landfall. Elsner et al. (2000)
reasoned that these trends are a reflection of the strength of the subtropical (or Bermuda) high in
the Atlantic. Jagger et al. (2001) found that when a mature La Niña is coincident with a weak
NAO, the likelihood of a major hurricane landfall along the central Gulf Coast is increased.

b. El Niño/Southern Oscillation (ENSO)

The ENSO phenomenon is a complex ocean-atmosphere mode of climatic variability in the
Pacific Ocean that has been shown to have global climate impacts (Ropelewski and Halpert
1989; Kiladis and Diaz 1989). El Niño (La Niña) represents the oceanic component of ENSO
characterized by warm (cold) SST anomalies in the central and eastern tropical Pacific Ocean.
The SO is the atmospheric component of ENSO characterized by an oscillation between high
(low) SLP anomalies across the tropical western Pacific basin and low (high) SLP anomalies
across the tropical central and eastern Pacific basin.
ENSO has been well-known, but not well-understood, for centuries. Peruvian fishermen were the first to coin the term El Niño. They used it to refer to the warm current of water that often appeared along the Peruvian and Ecuadorian coastlines near Christmas (hence the term El Niño, meaning, “the Christ child”) (Trenberth 1997). In recent years, it has become apparent that El Niño is better defined by SST anomalies that extend across much of the equatorial Pacific (Trenberth 1997).

Walker (1928) was the first to identify the atmospheric component of ENSO known as the SO. During the 1920s, he noted an oscillation in SLP between the eastern and western Pacific. Walker and Bliss (1932) first quantified this oscillation by constructing the Southern Oscillation Index (SOI). The original SOI was calculated using several different meteorological variables at a number of stations. In more recent years, the generally accepted version of the SOI has been calculated using only the difference in SLP at two points – Tahiti and Darwin, Australia (Trenberth 1997). Amazingly, it was not until 1969 when Bjerknes was the first to propose that the oceanic (El Niño/La Niña) and atmospheric (the SO) modes of variability in the Pacific were linked.

The typical state of the ocean-atmosphere system in the Pacific features persistent easterly trade winds that lead to a “pooling” of warmer waters in the western Pacific (Figure 2.3). The east-to-west transport process then results in upwelling of cooler sub-surface waters along the South American Pacific coast. Low SLP/ascending air accompanies this SST pattern in the west, while higher SLP/descending air occurs in the east. Bjerknes (1969) termed this atmospheric circulation pattern the “Walker circulation.”

El Niño is characterized by higher-than-normal SSTs and lower-than-normal atmospheric pressure in the eastern Pacific (Figure 2.4). El Niño events take place when the typical easterly
trade winds slacken and warmer water is allowed to move from west to east across the equatorial Pacific. The result is a shift in the atmospheric circulation that allows for increased convection in the central and eastern Pacific.

La Niña, on the other hand, is simply an amplification of the “usual” ocean-atmosphere state in the Pacific. Anomalously strong easterly trade winds increase the east-to-west transport of water across the equatorial Pacific, strengthening the coastal upwelling near South America and resulting in even lower SST anomalies than usual in the eastern Pacific (Figure 2.3).

Figure 2.3  Schematic of the typical ocean-atmosphere state in the Pacific (NOAA/PMEL/TAO, 2008a)

Much research has been undertaken on the correlations between El Niño/La Niña and tropical cyclone frequencies, particularly in the Atlantic basin (e.g., Gray 1984a; Bove et al. 1998; Pielke and Landsea 1999). Gray (1984a) was the first to show that El Niño events typically are associated with fewer hurricanes in the Atlantic basin. He showed that the decrease in hurricane frequency was related to physical processes associated with El Niño (increased upper-level wind
shear, for instance). Bove et al. (1998) reanalyzed hurricane data from 1900 – 1997 and found that while the probability of two or more hurricanes making landfall in the U.S. during an El Niño year is only 28 percent, the probabilities are significantly higher for neutral-phase years (48 percent) and La Niña years (66 percent). They showed similar numbers for major hurricanes, stating that, “the mean annual number of major U.S. [landfalling] hurricanes is 0.23 for El Niño, 0.68 for neutral conditions, and 0.95 for El Viejo [La Niña] conditions.” Given their results, it is not at all surprising that Pielke and Landsea (1999) found that U.S. hurricane damages rise significantly during La Niña years.

c. Pacific/North American (PNA) Pattern

The Pacific/North American (PNA) pattern is another prominent mode of climatic variability during the Northern Hemisphere winter. Wallace and Gutzler (1981) were the first to name the pattern that had been identified in some form or another by several other atmospheric scientists. Allen et al. (1940) were perhaps the first to note a SLP dipole with centers of action located
south of the Aleutian Islands and over the western United States. Today, the PNA pattern is identified using geopotential height anomalies, usually either at 500 hPa or 700 hPa. Height anomalies of the same sign are located south of the Aleutian Islands and over the southeastern U.S., while corresponding height anomalies of opposite sign are found near Hawaii and western North America (Wallace and Gutzler, 1981).

Like the AO and NAO, the PNA pattern has two phases. During the so-called positive phase, negative height anomalies are located near the Aleutian Islands and southeastern U.S. centers of action, while positive height anomalies are located near the Hawaiian and western North American centers of action (Wallace and Gutzler, 1981). The resultant pattern is meridional – meaning that troughs and ridges are accentuated, and atmospheric flow patterns have a strong north-south or south-north component. In the U.S., a positive phase PNA pattern typically results in warmer- and drier-than-normal conditions for the West, while much of the Southeast is cooler- and wetter-than-normal (Yin 1994). During a negative phase PNA pattern, the trough-ridge configuration is generally much more zonal – meaning the upper-air flow is primarily west-to-east. In this instance, the temperature and moisture anomalies are generally opposite of those which occur during the positive phase.

Potential connections between the PNA pattern and Atlantic tropical cyclone frequencies are not yet well-understood. However, Randel (2004) noted that ENSO can modify North American climate through the PNA pattern. Given that the connections between ENSO and tropical cyclone frequencies in the Atlantic are well-established, it seems quite possible that future research may discover a link between the PNA pattern and Atlantic tropical cyclone activity. A positive (negative) phase PNA pattern is generally linked to El Niño (La Niña) – like conditions,
leading to the hypothesis that Atlantic hurricane frequencies may be decreased (increased) during these times. Further research will be necessary to examine the validity of this hypothesis.

d. Pacific Decadal Oscillation (PDO)

The PDO is defined as the leading mode of SST variability in the Pacific north of 20°N (Mantua et al. 1997). The PDO is widely considered to be a similar mode of climatic variability to ENSO, but it occurs on longer time scales (Zhang et al. 1997; Mantua et al. 1997; Gershunov and Barnett 1998; McCabe and Dettinger 1999). Despite the similarities between the PDO and ENSO, Mantua and Hare (2002, p. 36) identified three differences between the two modes of climatic variability:

1) “20th century PDO events persisted for 20-to-30 years, while typical ENSO events persisted for 6 to 18 months,”

2) “the climatic fingerprints of the PDO were most visible in the extratropics, especially the North Pacific/North American sector, while secondary signatures existed in the tropics, and the opposite was true for ENSO,”

3) “the mechanisms causing PDO variability were not known, while causes for ENSO variability were relatively well-understood.”

During the “warm” phase of the PDO, SSTs are anomalously high along the west coast of North America and anomalously low in the central North Pacific. SLP anomalies occur simultaneously, with anomalously low pressures in the North Pacific and anomalously high pressures in western North America and the subtropical Pacific (Hare et al. 1999). In general, a “warm” phase PDO results in El Niño-like anomalies (though generally not as extreme) during winter months – warmer- and drier-than-normal conditions in the southern United States. A “cool” phase PDO produces La Niña-like impacts, with generally opposite anomalies (Mantua
and Hare 2002). A number of other studies have found similar results for other parts of the world (Zhang et al. 1997; Garreaud and Battisti 1999; Power et al. 1999a,b). During the past century, the PDO was generally considered to be in a “cool” phase from 1890 to 1924 and from 1947 to 1976, while “warm” phase conditions dominated from 1925 to 1946 and from 1977 through at least the mid-1990s (Mantua and Hare 2002).

As Mantua and Hare (2002) noted, one of the key differences between ENSO and the PDO is the temporal scales on which the two phenomena occur. In general, ENSO is considered an interannual mode of climatic variability, while the PDO is considered an interdecadal mode of variability. Using differing statistical techniques, several researchers have independently found similar periodicities for the PDO. Minobe (1999, 2000) identified reoccurrences of the PDO on scales of 15-to-25 years and 50-to-70 years. Chao et al. (2000) found spectral peaks at 15-to-20 years and near 70 years. Going farther back in time, Minobe (1997) and Fritts (1991) examined tree-ring data and found similar climate oscillations with a 50-to-70 year periodicity.

The connections between the PDO and tropical cyclone frequencies are still tenuous, but researchers have found some interesting links. Lupo and Johnston (2000) found that the reduced (increased) Atlantic tropical cyclone activity during El Niño (La Niña), identified by Gray (1984a), was also related to interdecadal variability in ENSO that they believed to be related to the PDO. On the other hand, Zuki and Lupo’s (2008) examination of tropical cyclone frequencies in the South China Sea found similar connections to ENSO, but they were unable to find any significant correlations between tropical cyclone frequencies and the PDO in this region. Given the well-established effects of ENSO on tropical cyclone frequencies in many parts of the world, further research on possible ties to the PDO is necessary.
e. Quasi-biennial Oscillation (QBO)

The QBO was first identified during the early 1960s when studies by Reed et al. (1961) and Veryard and Ebdon (1961) independently identified temporally-alternating easterly and westerly stratospheric winds at equatorial latitudes. The QBO has been shown to have connections to such atmospheric variables as temperature and rainfall in eastern Africa (Ogallo 1979) and Brazil (Chu 1984), and tropical cyclone frequencies in the Atlantic (Gray 1984a), the southwest Indian Ocean (Jury 1993), and the western North Pacific (Chan 1995).

Considerable strides have been made in understanding the QBO and its role in climatic variability, but many questions remain. A few aspects of the QBO that are well-established are:

1) Holton and Lindzen (1972) showed that the easterly and westerly phases of the QBO alternate on temporal scales ranging from 24 to 30 months. More specifically, Fraedrich et al. (1993) showed that the shortest oscillation is close to 20 months, the longest is 36 months, and the mean is 28.2 months.

2) The easterlies and westerlies associated with the QBO propagate downward (Holton and Lindzen, 1972), with the westerlies generally descending quicker and more regularly than the easterlies (Naujokat 1986).

3) The QBO impacts tropical cyclone frequencies in several basins; Atlantic hurricanes are more frequent during westerly QBO phases and less frequent during easterly phases (Gray 1984a); tropical cyclone frequencies in the northwest Pacific also increase during westerly QBO phases (Chan 1995); however, tropical cyclone frequencies increase in the Indian basin during easterly QBO phases.
f. Madden-Julian Oscillation (MJO)

Roland Madden and Paul Julian – the namesakes of the MJO – stumbled upon the oscillation in 1971 when analyzing zonal wind anomalies in the tropical Pacific. The researchers were examining daily rawinsonde data at Canton Island (3°S, 172°W) when they noticed an oscillation in several atmospheric variables, including zonal winds at 850 hPa and in the upper troposphere, and station pressures (Madden and Julian 1971). The MJO is the dominant mode of intraseasonal variability in the tropics and has periods of 30-60 days (Madden and Julian 1994). Because of its varying periodicities, it is also sometimes referred to as the 30-50 day (Krishnamurti and Subrahmanyam 1982), 30-60 day (Weickmann et al. 1985), or 40-50 day (Madden and Julian 1971) oscillation.

The MJO involves fluctuations in wind, SST, rainfall, and cloudiness, but Gruber (1974) was the first to provide evidence of eastward-moving cloud clusters associated with the oscillation. Madden and Julian (1971, p. 708) provided the following observation of their new discovery, “Summarizing the most fundamental characteristics of the oscillation evident from an analysis of Canton’s record, we conclude that it can best be described as [a] large circulation cell oriented in zonal planes rather than as a propagating wave.”

Building on Gruber’s (1974) discovery, the use of outgoing longwave radiation (OLR) data has become the standard for tracking the MJO’s progress (Knutson et al. 1986; Nakazawa 1988). Because tropical rainfall is generally convective and convective cloud tops are cold, use of satellite observations makes it rather simple to track the progress of these temperature-derived OLR anomalies and the MJO.

Rui and Wang (1990) were the first to show that the main formation region for the convective clusters identified by Gruber (1974) was the west-central equatorial Indian Ocean. Once these convective clusters or circulation cells form, they propagate eastward across the
Pacific and often into the Atlantic. The mechanisms behind this eastward movement are still not well-understood. It is also noteworthy that the OLR anomalies typically become more difficult to track once the oscillation moves into the Atlantic (Madden and Julian 1994). While one might expect the impacts of the MJO to be confined to the tropics, Anderson and Rosen (1983) showed that some effects of the oscillation can be seen propagating to the midlatitudes. For example, Yasunari (1979) was the first to relate the MJO to the Indian monsoon. In more recent years, Lawrence and Webster (2001) have also related the oscillation to the south Asian monsoon, while several others have investigated the MJO’s connections to precipitation patterns in North America (Mo and Higgins 1998; Mo 1999, 2000; Jones 2000).

The MJO and its connections to tropical cyclone frequencies have garnered a great deal of attention over the past decade. Virtually every tropical basin has a relationship established between the MJO and tropical cyclone frequencies. In general terms, most of the studies show that when the MJO is in its convectively-active phase in a given region, tropical cyclone activity is enhanced. When the MJO is in its reduced-convection phase, the opposite is true.

Liebmann et al. (1994) were the first to establish this relationship for the Indian and western Pacific basins, noting that cyclonic vorticity and divergence anomalies westward and poleward of the MJO circulation cells seem to be the driving forces behind increased tropical cyclone activity. Courtney (2005) showed that of the 18 tropical cyclones that formed in the South Pacific and southeast Indian Ocean between December 2002 and June 2003, 13 could be associated with convectively active phases of the MJO. Padgett (2004) noted that an active MJO, along with a well-established monsoon trough, aided in the development of five typhoons in the western North Pacific during June 2004. Hall et al. (2001) found similar results for the
Australian basin, but also noted that the relationship between the MJO and tropical cyclone activity was even stronger during El Niño events.

Maloney and Hartmann (2000a,b, 2001) and Hartmann and Maloney (2001) related tropical cyclone frequencies in both the eastern and western Pacific to phases of the MJO. Specifically, when 850 hPa wind anomalies are westerly in the Pacific, the MJO is generally in its enhanced-convection phase and Pacific tropical cyclogenesis is more likely (Hartmann and Maloney 2001). Maloney and Hartmann (2000a) found similar results for the Gulf of Mexico and western Caribbean. The opposite is true when 850 hPa wind anomalies are easterly.

The record-setting 2005 Atlantic hurricane season has also been tied to the MJO. Shein et al. (2006) described extended periods of anomalous upper-level convergence in the central Pacific that resulted in a stronger 200 hPa ridge in the western Atlantic. The strengthened 200 hPa ridge provided conditions more favorable for tropical cyclone development in the Atlantic, with Shein et al. (2006) noting that 10 of the season’s 15 hurricanes formed during such periods. Shein et al. stated that some of the shorter-period enhancements in upper-level convergence over the central Pacific are likely related to the MJO. The authors also attributed a somewhat quieter stretch in the Atlantic during the first half of August to a reversal of the MJO pattern in the Pacific.

Collectively, these studies support the notion that tropical and extratropical teleconnections exert an influence on the variability in frequency of mesoscale and regional-scale phenomena, including tropical cyclones. But because the relationship between tropical cyclones and the tropical MJO is known to exist but hypothesized to be more complex than previous studies have indicated, the MJO will be the focus of the thesis. As possible influences of other
teleconnections are identified, they will be noted. Chapter III will provide an overview of the data and methods that are used to support the hypotheses described in Chapter I.
III. DATA/METHODS

To investigate the connections between the MJO and tropical cyclone frequency variability in the western Pacific (WPAC), eastern Pacific (EPAC), and Atlantic (ATL) basins, plots of MJO indices in pentad format from 1978 – 2006 were generated using the National Center for Atmospheric Research (NCAR) Command Language (NCL). MJO indices were obtained from the Climate Prediction Center (CPC, 2007) for 10 different longitudes located in the tropical Pacific and Atlantic -- 20°E, 70°E, 80°E, 100°E, 120°E, 140°E, 160°E, 120°W, 40°W, and 10°W. The CPC’s MJO index has seen increased use in recent years, appearing in studies correlating the MJO to the severity of cold events in southern Brazil (Schneider et al. 2006), dry season storminess in Florida (Hagemeyer and Almeida 2004), variability in upper tropospheric humidity (Ryoo et al. 2008), and variability in western hemisphere tropical cyclone activity (Barrett and Leslie 2008). It has also shown utility in climate forecast applications (Zhang et al. 2007).

NCL is a programming language developed by researchers at NCAR primarily for the analysis of atmospheric data. The language is capable of reading in many different data formats, including netCDF, HDF4, HDF4-EOS, GRIB, binary, and ASCII data. Since the language can handle many standard data formats, it has the potential of being used in numerous other fields and applications outside of the atmospheric sciences. NCL can be run on several different platforms, such as: AIX, IRIX, Linux, MacOSX, and Dec Alpha. However, to run the language on a Windows platform, one must either partition a hard drive and install Linux, or run a Linux emulator known as Cygwin.

In addition to mapping of standard weather and climate data, NCL can perform many different types of statistical analyses and output maps of the results. Most of the statistical
techniques are accomplished through the use of pre-written “NCL functions”, but programmers can write formulas and methods within the code itself. Statistical analyses and techniques that can be performed through NCL include: averages, standard deviations, correlations, regressions, filters, empirical orthogonal functions (EOFs), Fourier coefficients, singular value decomposition, spectral analysis, and wavelet analysis.

The MJO indices used to generate the plots in this study were obtained in ASCII format from the Climate Prediction Center (2008). The CPC indices were generated by applying extended EOF analysis to 200 hPa velocity potential (CHI200) anomalies in pentad format from 30°N to the equator. Anomalies are only used from ENSO-neutral and ENSO-weak winters as classified by the CPC (2008). The MJO indices used in this study are “the minus projection of the pentad CHI200 anomalies onto the ten time-lagged patterns of the first EEOF of pentad CHI200 anomalies.” (CPC, 2008) The CHI200 anomalies are based on the period 1979 – 1995, and each MJO index is normalized by its standard deviation during ENSO-neutral and ENSO-weak winters during the period 1979 – 2000.

The NCL script used to create the plots for this study contained eight sections: “data ingest”, “date labels”, “polymarkers”, “first x-axis plot resources”, “second x-axis plot values”, “second x-axis plot resources”, “polymarker resources”, and “create plot”. The data ingest section, as the name implies, is the part of the script that directs NCL to the file containing the MJO indices obtained from CPC. In this section, two files are actually referenced – the ASCII file containing the index values and a second text file that simply contains longitudes corresponding to the indices. The script directs NCL to assign the appropriate longitude values from the text file to a corresponding column in the ASCII file.
The date label section takes the numerical date values from the ASCII file of the format YYYYMMDD and translates them into a format that is easier to read on the finalized plots (i.e. 20060702 translates into 02JUL2006). The text equivalents of the numerical month values are achieved through the use of an if-then loop.

The polymarkers section defines the location of points plotted on top of the MJO index contours. Points are added to the plots to represent the longitudes and times at which tropical cyclones achieved “major” status (Category 3-5). NCL allows the user to choose from a number of different polymarker styles; in this study, triangles are used for WPAC tropical cyclones, squares for the EPAC, and dots for the ATL. Chapter IV provides an analysis of the importance of the major tropical cyclone formation points relative to the corresponding MJO indices displayed on the plots.

The first x-axis plot resources section defines the overall look of the plot. The appearance of a number of plot elements is defined within this section, including: contour colors, contour spacing, contour lines, contour labels, x-axis labels, and fonts appearing on the plots. In most cases, NCL provides default settings, depending on the plot type, but the user can customize the appearance of plots through the use of NCL “resources”. To display all ten longitudes represented by the different MJO indices from CPC, it was necessary to rotate the x-axis labels 90° to a vertical orientation.

Whereas the polymarkers section defines the location of major tropical cyclone formation points, the polymarkers resources section defines the size, color, and look of the points plotted by NCL. NCL provides 16 different polymarker types to choose from, but as of version 4.2.0.a030, users can also create custom polymarkers. For the purposes of this study, three existing
polymarker types – filled squares, triangles, and circles (or dots) – will suffice in delineating tropical cyclones in each basin of interest.

The create plot section pulls all of the scripting together and actually generates the final plots. Within this section, the plot type is defined as Hovmueller (time vs. longitude), the overall color scheme is determined, and NCL is directed to produce a layered plot. The bottom layer contains the contours and all text, and the top layer contains the polymarkers.

Major tropical cyclone formation points, reflected by the polymarkers on the plots, were obtained from two different sources: the Atlantic Oceanographic and Meteorological Laboratory (AOML) / Hurricane Research Division (HRD) for Atlantic tropical cyclones and Unisys for WPAC and EPAC tropical cyclones. The AOML Atlantic hurricane database (or HURDAT) is available for download online (Hurricane Research Division, 2008) and extends back to 1851. The Unisys database is also available online (Unisys, 2008) and extends back to 1945 for the WPAC and 1949 for the EPAC. However, because MJO indices are only available since 1978, this study focuses on major tropical cyclone formation points in the three basins during the same time period.

HURDAT was downloaded and then imported into a spreadsheet for further analysis. By applying filters within the spreadsheet, a list of major hurricanes forming during the study period was obtained. Each major hurricane formation point was then superimposed on the MJO indices for its corresponding year.

Scientists at HRD have begun a reanalysis of the HURDAT dataset to account for some known biases and errors. Over 5,000 adjustments have been made to the dataset for the period from 1851 to 1910, but our period of interest has yet to be analyzed, except for Hurricane Andrew in 1992. HRD researchers noted several reasons for the reanalysis (HRD, 2008):
1) HURDAT contained errors that were both systematic and random that could be corrected

2) Changing analysis techniques for tropical cyclones with time led to historical biases in the dataset

3) The exact timing, location, and intensity of tropical cyclones at landfall was often vague or missing

4) Researchers discovered a number of previously undocumented tropical cyclones, particularly in the late 19th and early 20th centuries

As it pertains to this study, points (1) and (2) above must be acknowledged, but uncertainty in determining the intensity of tropical cyclones (3), particularly those well-removed from land, is also a known weakness. It is assumed that point (4) is not problematic in this study because the period of record only dates back to 1978 and any major hurricanes were likely captured by satellite or aircraft reconnaissance. As in any empirical study, some caution should be exercised in the interpretation of results because of the data limitations.

The WPAC tropical cyclone archives contained on the Unisys website consist of data obtained from the Joint Typhoon Warning Center. Data are provided in 6-hour intervals and contain latitude, longitude, date/time, maximum winds (knots), central pressure (when available), and cyclone status (depression, tropical storm, typhoon, etc.). While a temporal resolution of six hours will cause some inaccuracies in the determination of the location at which storms reached hurricane or major hurricane status, it is generally acceptable for the purpose of this research.

The EPAC tropical cyclone archives contained on the Unisys website consist of data obtained from Colorado State University and the Tropical Prediction Center (TPC). Data are provided in
6-hour intervals and contain latitude, longitude, date/time, maximum winds (knots), central pressure (when available), and cyclone status.

Chapter IV provides the plots of MJO indices and the points at which tropical cyclones attained major status, along with an analysis of the results.
IV. RESULTS AND DISCUSSION

The MJO throughout the tropical cyclone seasons from 1978 through 2006, along with the longitude at which tropical cyclones reached major hurricane/typhoon (or hurricane/typhoon) status, are shown in Figures 4.1.1 – 4.2.29. Each storm was categorized as having occurred during “high convection” (MJO < -1.0; blue in Figures 4.1.1 – 4.2.29), “low convection” (MJO > 1.0; red in Figures 4.1.1 – 4.2.29), or “neutral” MJO phases. Chi-squared tests were performed (Table 4.1) to determine whether the MJO exerts a statistically significant influence on tropical cyclone frequency variability in the Atlantic basin. This test was chosen for two primary reasons. First, the categorization of the MJO into discrete phases (enhanced, suppressed, or neutral) in a manner in which the public is exposed to the phases of the Southern Oscillation (El Niño, La Niña, and La Nada) necessitated the non-parametric approach. Second, the exact MJO index values were not available for specific tropical cyclone formation points; instead, Figures 4.1.1 – 4.2.29 were merely used to discern the category. Furthermore, even if the MJO index values were available, it is possible that they may not be distributed normally, thus potentially violating one of the key assumptions of inferential statistical methods. The only assumption being made here is that we are examining a random sample.

This study was conducted to determine whether the results of Maloney and Hartmann (2000a) could be corroborated, but it also expanded on their work by segregating tropical cyclones into “major” (Cat. 3-5) storms, by providing more in-depth analysis by basin, and by expanding the number of storms in the analysis.

a. MJO and Cross-basin Associations

Initial chi-squared tests reveal that MJO phase is not linked to basin-wide (ATL, EPAC, and WPAC) shifts in frequencies of major tropical cyclones. While numerous prior studies have
established links between the MJO and tropical cyclone variability in each of these basins, a p-value of 0.38 in our chi-squared test reveals no significant association at first glance. Thus, it appears that other factors must be at work in allowing tropical cyclones to reach major storm status.

However, a closer look at the tropical cyclone frequencies indicates that a couple of factors may be influencing this initial result. First, 75 percent of the major tropical cyclones occurred during neutral MJO phases, indicating that a separate test could be conducted to examine the associations only during extreme (enhanced and suppressed convection) MJO phases. Second, an equal number of major tropical cyclones in the Atlantic basin occurred during enhanced MJO phases as in the suppressed MJO phases, while both the EPAC and WPAC show a ratio of 3-to-1 enhanced-to-suppressed during the same time period. This indicates a removal of the Atlantic basin may produce more robust results.

When the neutral MJO phases were removed, chi-squared tests produced a slightly more robust p-value of 0.18, but certainly these results are still far from being statistically significant. Therefore, it can be concluded that extremes of the MJO (enhanced and suppressed phases) are not associated with variability in cross-basin major tropical cyclone frequencies.

b. MJO and Cross-basin Associations with Time

While this study found no statistically significant associations between MJO phase and basin-wide major tropical cyclone frequencies, chi-squared testing did reveal some associations through time. Annual frequencies of major tropical cyclones appear to be affected by MJO phase preferentially in some years/basins over others, as indicated by a p-value of 9.0E-6. However, when neutral MJO phases are removed from the testing, the results identify no significant association between annual frequencies of cyclogenesis for major tropical cyclones.
by basin during extreme (enhanced and suppressed) MJO phases, as indicated by a p-value of 0.13. The results of these two tests suggest that differences in annual major tropical cyclone frequencies basin-wide are driven primarily by the neutral phase of the MJO.

<table>
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<tr>
<th>Variables</th>
<th>Null Hypothesis (H₀)</th>
<th>P-value</th>
<th>Interpretation</th>
</tr>
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<td><strong>All Basins vs. All MJO Phases</strong></td>
<td>MJO phase is not associated with variability in basin-wide major tropical cyclone</td>
<td>0.3802</td>
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<td></td>
<td>frequencies.</td>
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<td>cyclone frequencies.</td>
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<td>H₀ is rejected</td>
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<td>MJO phase preferentially in some basins over others.</td>
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<td><strong>Time vs. Favorable/Unfavorable MJO Phases for</strong></td>
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<td>0.3802</td>
<td>H₀ cannot be rejected</td>
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<th>P-value</th>
<th>Interpretation</th>
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<td>Time vs. Favorable/Unfavorable MJO Phases for Cat. 1-2 Atlantic Hurricanes</td>
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<td>Location of Major Hurricane Cyclogenesis in the Atlantic vs. Favorable/Unfavorable MJO Phases</td>
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<td>Time vs. Favorable/Unfavorable MJO Phases for Major W. Pacific Tropical Cyclones</td>
<td>Annual frequencies of major E. Pacific tropical cyclones are not associated with extreme MJO phases.</td>
<td>0.1748</td>
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</table>
Figure 4.1.1 MJO Indices and Longitudes at Which Tropical Cyclones Attained Category 3-5 Status in 1978.
Figure 4.1.2 As in Figure 4.1.1, for 1979.
Figure 4.1.3 As in Figure 4.1.1, for 1980.
Figure 4.1.4 As in Figure 4.1.1, for 1981.
Figure 4.1.5 As in Figure 4.1.1, for 1982.
Figure 4.1.6 As in Figure 4.1.1, for 1983.
Figure 4.1.7 As in Figure 4.1.1, for 1984.
Figure 4.1.8 As in Figure 4.1.1, for 1985.
Figure 4.1.9 As in Figure 4.1.1, for 1986.
Figure 4.1.10 As in Figure 4.1.1, for 1987.
Figure 4.1.11 As in Figure 4.1.1, for 1988.
Figure 4.1.12 As in Figure 4.1.1, for 1989.
Figure 4.1.13 As in Figure 4.1.1, for 1990.
Figure 4.1.14 As in Figure 4.1.1, for 1991.
Figure 4.1.15 As in Figure 4.1.1, for 1992.
Figure 4.1.16 As in Figure 4.1.1, for 1993.
Figure 4.1.17  As in Figure 4.1.1, for 1994.
Figure 4.1.18 As in Figure 4.1.1, for 1995.
Figure 4.1.19  As in Figure 4.1.1, for 1996.
Figure 4.1.20  As in Figure 4.1.1, for 1997.
Figure 4.1.21  As in Figure 4.1.1, for 1998.
Figure 4.1.22 As in Figure 4.1.1, for 1999.
Figure 4.1.23 As in Figure 4.1.1, for 2000.
Figure 4.1.24 As in Figure 4.1.1, for 2001.
Figure 4.1.25 As in Figure 4.1.1, for 2002.
Figure 4.1.26 As in Figure 4.1.1, for 2003.
Figure 4.1.27  As in Figure 4.1.1, for 2004.
Figure 4.1.28 As in Figure 4.1.1, for 2005.
Figure 4.1.29  As in Figure 4.1.1, for 2006.
c. MJO and Atlantic Basin Associations with Time

The raw numbers in this study are not able to corroborate the results of Maloney and Hartmann (2000a). During the 1978 – 2006 period, 46 Atlantic hurricanes (Categories 1-5) formed during enhanced MJO phases, while 43 formed during suppressed phases, indicating almost no difference. When only major hurricanes are examined, the numbers are an exact match, with seven each forming during the enhanced and suppressed phases of the MJO during the same stretch. As in the case of the cross-basin numbers, the majority of Atlantic hurricanes occurred during neutral phases of the MJO. When all Atlantic hurricanes are examined, 51 percent (92 out of 181) occurred during neutral phases. The numbers are even more pronounced for major Atlantic hurricanes, with 81 percent (59 out of 73) occurring during neutral phases. The reasons for the differing results in this study compared to Maloney and Hartmann (2000a) are discussed later in this section.

While no statistically significant associations between MJO phase and overall Atlantic hurricane frequencies were identified, results do show some significant associations (p-value = 0.01) between the MJO and annual Atlantic hurricane frequencies (Categories 1-5). The implication is that differences in annual (i.e., interseasonal) Atlantic hurricane frequencies are associated with the MJO. However, when only extreme MJO phases (enhanced and suppressed) are included in the test, the association disappears, with a p-value of 0.25 resulting from the chi-squared test. It should be noted that narrowing the dataset to major Atlantic hurricanes showed no significant associations between the MJO and annual major hurricane frequencies.

Parsing the dataset in the opposite direction does produce some statistically significant results. Looking at only Category 1 and 2 hurricanes in the Atlantic, the chi-squared test suggests that annual frequencies are associated with MJO phase, with a p-value of 0.05.
Figure 4.2.1 MJO indices and longitudes at which tropical cyclones attained hurricane status (for those which only reached Category 1 or 2 strength) or major hurricane status in 1978.
Figure 4.2.2 As in Figure 4.2.1, for 1979.
Figure 4.2.3 As in Figure 4.2.1, for 1980.
Figure 4.2.4 As in Figure 4.2.1, for 1981.
Figure 4.2.5  As in Figure 4.2.1, for 1982.
Figure 4.2.6 As in Figure 4.2.1, for 1983.
Figure 4.2.7 As in Figure 4.2.1, for 1984.
Figure 4.2.8 As in Figure 4.2.1, for 1985.
Figure 4.2.9 As in Figure 4.2.1, for 1986.
Figure 4.2.10  As in Figure 4.2.1, for 1987.
Figure 4.2.11  As in Figure 4.2.1, for 1988.
Figure 4.2.12  As in Figure 4.2.1, for 1989.
Figure 4.2.13 As in Figure 4.2.1, for 1990.
Figure 4.2.14 As in Figure 4.2.1, for 1991.
Figure 4.2.15 As in Figure 4.2.1, for 1992.
Figure 4.2.16 As in Figure 4.2.1, for 1993.
Figure 4.2.17  As in Figure 4.2.1, for 1994.
Figure 4.2.18  As in Figure 4.2.1, for 1995.
Figure 4.2.19 As in Figure 4.2.1, for 1996.
Figure 4.2.20  As in Figure 4.2.1, for 1997.
Figure 4.2.21  As in Figure 4.2.1, for 1998.
Figure 4.2.22  As in Figure 4.2.1, for 1999.
Figure 4.2.23 As in Figure 4.2.1, for 2000.
Figure 4.2.24 As in Figure 4.2.1, for 2001.
Figure 4.2.25 As in Figure 4.2.1, for 2002.
Figure 4.2.26  As in Figure 4.2.1, for 2003.
Figure 4.2.27  As in Figure 4.2.1, for 2004.
Figure 4.2.28 As in Figure 4.2.1, for 2005.
Figure 4.2.29  As in Figure 4.2.1, for 2006.
However, when the neutral MJO phase is removed, the association is lost, with a p-value of 0.32. Once again, it is shown that the neutral MJO phase seems to be most closely associated with annual hurricane frequencies in the Atlantic basin.

d. MJO Associations to Location of Cyclogenesis within the Atlantic Basin

Except perhaps for the last result described above, the results of this study thus far have been unable to corroborate those of Maloney and Hartmann (2000a). However, a key difference in the two studies must be addressed – Maloney and Hartmann (2000a) only examined Atlantic hurricanes west of 77.5°W, while to this point, this study has examined hurricanes forming in the entire Atlantic basin. To produce a better comparison, Atlantic hurricanes were divided into two groups – those which became Category 1 hurricanes west of 77.5°W and those reaching hurricane strength for the first time east of 77.5°W – and further chi-squared testing was performed.

When all MJO phases were tested against the location at which the tropical cyclone became a hurricane within the Atlantic basin, the results still showed no significant association. The resultant p-value of 0.86 provides no evidence that MJO phase is associated with the location at which hurricane status was reached in the Atlantic. Removing the neutral phase of the MJO still showed no significant associations. The resultant p-value of 0.91 provides no evidence to indicate that extreme MJO phases are linked to variability in location of Atlantic hurricane formation. In fact, an examination of the raw numbers shows that more hurricanes formed in the suppressed convection phase of the MJO than the enhanced convection phase of the MJO (9 to 7 west of 77.5°W; 24 to 20 east of 77.5°W) on both sides of the dividing line.

When only major Atlantic hurricanes are examined, there is still no association found between extreme MJO phase and cyclogenesis location within the Atlantic basin. A p-value of
0.91 once again resulted from the chi-squared test, but the raw numbers do show some interesting trends. Maloney and Hartmann (2000a) indicated that major hurricanes are four times more likely to form in the western Atlantic during enhanced convection MJO phases, but this study actually shows that only one major hurricane formed in the western Atlantic during an enhanced phase MJO, while six formed during suppressed phases of the MJO. The numbers are a bit different for the basin east of 77.5°W, with seven major hurricanes forming during enhanced phases of the MJO and four forming during suppressed phases of the MJO.

e. MJO and Pacific Basin Associations with Time

The results of this study have not supported those of Maloney and Hartmann (2000a), but statistically significant associations are found in other basins between MJO phase and annual major tropical cyclone frequencies. Specifically, chi-squared testing reveals that MJO phase is linked with annual EPAC major hurricane frequencies, with a p-value of 0.02. When the neutral phase of the MJO is removed, however, no significant association is found between extreme MJO phases and annual major EPAC hurricane frequencies, with a p-value of 0.75 calculated in the chi-squared test. Chi-squared testing for the WPAC showed nearly identical results. MJO phase shows an association to annual major tropical cyclone frequencies in the WPAC, with a p-value of 2.0E-3 resulting. When the neutral MJO phase was removed, the association was lost and the resultant p-value was 0.17. It is not surprising that a stronger association was found for the Pacific basin than the Atlantic, because the pulse of convective activity originates in the former basin.

The results here are somewhat similar to the Atlantic basin, but for a different subset of tropical cyclones. In the Atlantic, Category 1 and 2 hurricanes show an association with MJO phase, but when reduced to only extreme MJO phases, no association is found. However, major
Atlantic hurricanes show no association with MJO phase, unlike the results shown here for major EPAC and WPAC tropical cyclones.

f. Tropical Cyclone Frequency Variability and Other Teleconnections

Numerous studies have examined associations between teleconnection patterns and tropical cyclone variability. The most often studied and perhaps best understood teleconnection pattern is ENSO, including its relationship to tropical cyclone variability. While this study focuses on the MJO, strong phases of ENSO are clearly visible in our plots of MJO indices. The CPC MJO indices are calculated using 200 hPa velocity potential anomalies, an atmospheric variable that is representative of upper-level divergence. Areas of enhanced upper-level divergence can be considered a proxy for areas of enhanced convection (blue shading in Figures 4.1.1 – 4.2.29), while areas of little upper-level divergence (or increased upper-level convergence) can be considered a proxy for areas of suppressed convection (red shading in 4.1.1 – 4.2.29).

The strong El Niño events of 1982 and 1997 are clearly evident in Figures 4.1.5 and 4.1.20. A pattern of suppressed convection in the western Pacific and enhanced convection in the eastern Pacific is dominant during both hurricane seasons. Additionally, both seasons feature an above-normal number of major hurricanes in the EPAC basin (5 and 7, respectively; average is 4) and a below-normal number of major hurricanes in the ATL basin (1 both seasons; average is 2). The numbers in both seasons corroborate previous research by CPC (2005) showing an increased frequency of major hurricanes in the EPAC basin during El Niño events, and by Gray (1984a,b) showing a decrease in hurricane frequency in the ATL basin during El Niño events.

The strong La Niña event of 1988 is also evident in the plot for that season (Figure 4.1.11), with enhanced convection in the western Pacific and suppressed convection in the eastern Pacific noted throughout. Again, the number of major hurricanes also reflects trends in La Niña
influences established in previous research. The EPAC had a slightly below-average season in terms of major hurricanes (3 occurred, 4 is the average), while the Atlantic was slightly above-average (3 occurred, 2 is the average). The numbers once again corroborate the research of the CPC (2005) and Gray (1984a).

Bove et al. (1998) reanalyzed hurricane data from 1900 to 1997 and found that while the probability of two or more hurricanes making landfall in the U.S. during an El Niño year is only 28 percent, the probabilities are significantly higher for neutral-phase years (48 percent) and La Niña years (66 percent). They showed similar numbers for major hurricanes, stating that (p. 2481), “the mean annual number of major U.S. [landfalling] hurricanes is 0.23 for El Niño, 0.68 for neutral conditions, and 0.95 for El Viejo [La Niña] conditions.” Indeed, the strong El Niño and La Niña events within the 1978 - 2006 study period corroborate these results. The El Niño years of 1982 and 1997 had no major hurricane landfalls in the U.S., while Category 4 Hurricane Hugo made landfall in South Carolina during a La Niña year (1989).

The acknowledgment of previously-established associations between ENSO and tropical cyclone variability is important in this study because ENSO events are clearly reflected in the plots of MJO indices. Further investigation would be needed to determine if perhaps the shorter-frequency ENSO signal overwhelms any higher-frequency MJO signal that we are attempting to detect within these plots. The fact that ENSO is associated with interseasonal tropical cyclone frequencies may make intraseasonal associations between the MJO and tropical cyclone frequencies difficult to decipher.

The Pacific/North American (PNA) pattern is another prominent mode of climatic variability during the Northern Hemisphere winter. Potential connections between the PNA pattern and tropical cyclone frequency variability are not yet well-understood. However, a positive
The Pacific Decadal Oscillation (PDO) is defined as the leading mode of SST variability in the Pacific north of 20°N (Mantua et al. 1997). The PDO is widely considered to be a similar mode of climatic variability to ENSO, but occurs on longer time scales (Zhang et al. 1997; Mantua et al. 1997; Gershunov and Barnett 1998; McCabe and Dettinger 1999). Results of this study failed to identify potential associations between the PDO and tropical cyclone frequency variability because the temporal resolution of a tropical season is not adequate to identify associations to a 30-60 day oscillation in the MJO.

The Quasi-biennial Oscillation (QBO) was first identified during the early 1960s when studies by Reed et al. (1961) and Veryard and Ebdon (1961) independently identified temporally-alternating easterly and westerly stratospheric winds at equatorial latitudes. The QBO has been shown to have connections to tropical cyclone frequencies in the Atlantic (Gray 1984a), but Gray’s forecast team has given the QBO less weight in its seasonal Atlantic
hurricane forecast in recent years because the association appears somewhat weaker than in the past (Klotzbach and Gray 2005). However, further investigation to determine whether the QBO in any way modulates the MJO indices used in this study might prove helpful, since the stratospheric wind anomalies associated with the QBO are thought to propagate downward with time (Holton 1972, Naujokat 1986) and the CPC indices are constructed from 200 hPa velocity potential anomalies.

g. Differences from Maloney and Hartmann (2000a)

This study aimed to corroborate the results of Maloney and Hartmann (2000a), but was largely unable to do so. The results of this study do not necessarily refute those of Maloney and Hartmann (2000a), but are more likely a result of a difference in methodology and datasets.

The first key difference between the two studies is that Maloney and Hartmann examined tropical cyclone data from 1949-1997, while this study focused on the 1978-2006 period. The different periods of analysis were driven by the use of different MJO indices in each study.

Maloney and Hartmann (2000a) used an MJO index defined by 850 hPa wind anomalies. The wind data were collected from the NCEP/NCAR reanalysis dataset, with Maloney and Hartmann defining a positive MJO index as one in which 850 hPa wind anomalies were westerly over the eastern Pacific and Gulf of Mexico, while a negative MJO index was indicative of easterly 850 hPa wind anomalies over the same region. Maloney and Hartmann (2000a) showed that hurricanes are four times more likely to form in the Gulf of Mexico and western Atlantic when westerly 850 hPa wind anomalies were present, with major hurricanes showing an even greater preference to form during these times. By contrast, this study used an MJO index calculated by CPC using 200 hPa velocity potential anomalies calculated from 30°N to the equator. The CPC index only dates back to 1978, thus defining the period of study here.
It is proposed that these two key changes in methodology and datasets are likely the driving forces behind the differing results. Additionally, because this study used an index calculated from 200 hPa velocity potential anomalies and the MJO originates at the ocean’s surface, it is possible that there is some sort of lag-effect that has not been deciphered in this study. In fact, Liebmann et al. (1994) showed that cyclonic vorticity and divergence anomalies westward and poleward of MJO cells created increased tropical activity in the Indian and western Pacific basins. Further investigation is necessary to determine whether this is a possible explanation for the differing results.
V. CONCLUSION

Rapidly increasing coastal populations and soaring coastal property values necessitate a better understanding of tropical cyclone variability on all time scales. Jarrell et al. (1992) argued that most people overestimate their hurricane “experience level”, leading to complacency when a storm threatens. Pielke and Landsea (1998) showed that the potential for significant monetary losses in the U.S. has exploded in recent years for the above reasons. The 2004 and 2005 Atlantic hurricane seasons solidified this point, with seven hurricanes (Charley, Frances, Ivan, Jeanne, Katrina, Rita, and Wilma), six of which were “major” (Category 3-5 on the Saffir-Simpson scale), producing $71 - $78 billion in damage and ranking as seven of the nine costliest storms on record for the United States (Insurance Information Institute, 2007). Given these numbers, it seems crucial to gain a better understanding of major hurricane frequencies and the possible climatic influences. While a great deal of research has already been done on interannual to interdecadal scales, many questions remain about the intraseasonal variability of tropical cyclone frequencies and intensities.

This research initially investigated potential associations between the MJO – a teleconnection that operates on an intraseasonal scale – and tropical cyclone frequency variability in the Atlantic basin. Maloney and Hartmann (2000a) have already shown that all hurricanes (Saffir-Simpson 1-5) are four times more likely to form in the Gulf of Mexico and western Atlantic during certain phases of the MJO. However, because the 21 percent of the landfalling tropical cyclones in the U.S. classified as major hurricanes (Saffir-Simpson 3-5) account for 83 percent of hurricane damage (Pielke and Landsea, 1998), further analysis of the factors related to their formation and trajectories is warranted.
The results of this study did not corroborate those of Maloney and Hartmann (2000a), with no statistically significant associations found between extreme MJO phases and intraseasonal hurricane and major hurricane frequency variability in the Atlantic basin. This does not mean Maloney and Hartmann’s results should be dismissed; rather, it is proposed that the differing results between the two studies are likely a reflection of differing methodologies and differing study periods.

While this study was unable to find any association between extreme MJO phase and Atlantic hurricane frequency variability on an intraseasonal scale, further investigation revealed an association between all MJO phases and interseasonal hurricane frequency variability in the Atlantic. Somewhat surprisingly, the chi-squared test results indicated that the primary connection between the MJO and annual Atlantic hurricane frequency variability is the neutral phase, not the extreme phases (enhanced and suppressed convective phases) of the MJO. In fact, during the 1978-2006 study period, the raw numbers show that Atlantic hurricanes are as likely to form during the suppressed convection phase of the MJO as they are during the enhanced convection phase.

Maloney and Hartmann (2000a) focused on hurricane frequency variability as it relates to the MJO in only the Gulf of Mexico and western Atlantic. That study area seems logical considering that previous research by Madden and Julian (1994) showed the convective clusters associated with the MJO become more difficult to discern and track as they progress across the Atlantic. Since our study initially investigated potential associations across the entire Atlantic basin, the dataset was parsed to focus on the same regions as Maloney and Hartmann (2000a). Again, however, this study was unable to corroborate Maloney and Hartmann’s results, with the
raw numbers even showing that western Atlantic hurricanes were more likely to form during the suppressed convection phase of the MJO during the 1978-2006 period.

After failing to corroborate the results of Maloney and Hartmann, further testing was conducted to determine whether the MJO could be associated with tropical cyclone frequency variability in the WPAC and EPAC basins. The results were essentially the same, with no statistically significant associations found between the MJO and intraseasonal tropical cyclone variability in either the WPAC or EPAC. Much as was seen with the Atlantic results, however, associations were identified between MJO phase and interseasonal tropical cyclone frequency variability in these basins. Again, the primary association was shown to be with the neutral MJO phase and not the extreme phases (enhanced and suppressed convection).

The results of this study collectively indicate that more research must be conducted to investigate the driving mechanisms behind intraseasonal tropical cyclone frequency variability. Maloney and Hartmann (2000a) demonstrated clear associations in both the EPAC and western Atlantic between extreme MJO phases and hurricane frequency variability. Their results indicate that the use of an MJO index based on 850 hPa wind anomalies may be more prudent than the CPC MJO index (which is based on 200 hPa wind anomalies) since the MJO originates in the lower levels of the atmosphere. The CPC MJO indices may provide benefit in other research applications, particularly if sufficiently time-lagged correlations were employed. Future research investigating potential associations between individual CPC MJO indices and tropical cyclone frequency variability may prove interesting since this study looked at a cross-section of all ten CPC MJO indices.

Forecasters, emergency managers, and government officials seeking to use the MJO as a planning tool should also realize that it is only one of numerous factors influencing tropical
cyclone variability. Sea surface temperatures, upper-level winds, other teleconnection patterns, and numerous other atmospheric and oceanic variables exert an influence on tropical cyclone variability on both intraseasonal and interseasonal time scales. The proper understanding of the MJO and other ocean-atmosphere forcing mechanisms can only aid in understanding one of the most destructive and mysterious atmospheric phenomena.
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VITA

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