THE CORRELATION OF SEA SURFACE TEMPERATURES, SEA LEVEL PRESSURE AND VERTICAL WIND SHEAR WITH TEN TROPICAL CYCLONES BETWEEN 1981-2010

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

TC	tropical cyclone
SST	sea surface temperature
VWS	vertical wind shear
SLP	sea level pressure
ACE	accumulated cyclone energy
ENSO	El Niño Southern Oscillation
MDR	main development region
ROCI	radius of the out closed isobar
TIPS	Typhoon Intensity Prediction
AWP	Atlantic Warm Pool
NAO	North Atlantic Oscillation

INTRODUCTION

Hurricanes have recently become a popular topic among the public with many intense storms making landfall in 2004, the 2005 hurricane season having the most named storms, and Hurricane Isaac making landfall exactly seven years after Hurricane Katrina. But what is the best way to compare tropical cyclones? How much damage do they cause? How many lives were lost? What was the highest category reached or what was the category when it made landfall? The accumulated cyclone energy index (ACE) is used to compare hurricane seasons and is defined as the sum of the square maximum estimated 6-hour wind speed for the times the cyclone is at tropical storm or higher strength. The ACE "accounts for the combined strength and duration of tropical storms and hurricanes during a given season (Bell and Chelliah 2006, page 593)". A study by Latif et al. (2007) of sea surface temperatures (SSTs) and vertical wind shear (VWS) with regards to tropical cyclones (TCs) showed that the ACE follows closely with changes in SSTs and VWS; however, there is a large portion of variance in the ACE that is not explained by shear. Merrill (1984) stated "strength is measured by the average wind speed in the cyclone circulation;" therefore, wind speed is what determines the intensity of a tropical cyclone, but what intensifies the storm? There are many factors that can develop and intensify a storm (i.e. enhanced mid-level moisture, El Niño-Southern Oscillation (ENSO), West African rainfall, Quasi-Biennial Oscillation), but this paper will focus mainly on sea surface temperatures, vertical wind shear, and sea level pressure (SLP) because these factors are the primary ingredients to form and intensify a tropical cyclone. The purpose of this study is to help with forecasting intense hurricanes which could assist in predicting future hurricane strengths and giving earlier warnings.

BACKGROUND

Tropical cyclones are low pressure systems that form over subtropical or tropical oceans. Almost three quarters are in the Northern Hemisphere and most develop equatorward of 20°. The main development region (MDR) in the Atlantic is defined as 6-18°N and 20-60°W (Swanson 2008). In the North Atlantic, tropical cyclones develop from disturbances off the coast of West Africa (Gary 1968). These disturbances can travel long distances (10°-70°) before intensifying into a tropical storm, which is different from other development regions. North Atlantic is also unique in that it's the only basin where tropical cyclones can intensify poleward of 20°. Warm SSTs can extend north of 20° in the northwest Atlantic, Gulf of Mexico, and northwest Pacific. The region within 100 km of the Gulf coast is good for tropical cyclone intensification (DeMaria and Kaplan 1994). The Atlantic hurricane season is from June to November with the peak of the season, calculated by the number of storms at one time, occurring in early September. Storms during the early part of the season are less likely to reach their maximum possible intensity than storms during the mid to late season. To determine the seasonal amount of tropical cyclone activity is to sum the total number of days for each storm for the whole hurricane season (Landsea et al. 1999).

The intensification of a tropical cyclone is described either as the decrease of mean sea level pressure or an increase in maximum winds (Merrill 1984). There are many components that can determine the life of a cyclone. The initial intensity and thermodynamics of the storm will control the evolution of intensity. The storm's intensity is sensitive to the thermodynamics of the upper ocean along the storm track, which is why sea surface temperatures play an important role (Emanual 1999). DeMaria and Kaplan (1994) found that along with SSTs, vertical wind shear is important to determine a storm's intensity. The study was done by creating SST groups and determining the maximum storm intensity reached by using the theory that maximum intensity is only a function of SSTs. Landsea et al. (1999) found that the West Sahal rainfall also plays a part on intensity and on the number of storms in a season. Merrill (1984) studied the size and intensity of tropical cyclones for the Pacific and Atlantic basins. He discovered that tropical cyclones in the west North Pacific are notably larger than the storms in the North Atlantic; however, there was only a weak correlation between size and intensity. He used the ROCI (radius of the outer closed isobar) to measure the size of the cyclones at the 850mb level since the size difference was clearest at this level. The size of the storms is at the minimum in the beginning of the season and maximum in October; however, the intensity for the storms in September is just as intense as the storms in October. Fitzpatrick's (1997) research was to assist in forecasting tropical cyclone intensity in the Pacific using the Typhoon Intensity Prediction Scheme (TIPS). TIPS is similar to the Statistical Hurricane Intensity Prediction Scheme (which uses climatology, persistence, synoptic, and SST for the Atlantic Ocean) with one addition: the use of infrared satellite imagery. The addition of the satellite imagery was able to help show the difference between slow and fast developing storms. He used the definition of "fast intensification" as a 24-hr increase of maximum wind by 25 kt/day. It was discovered that cyclones free of upper-level anomalies (vertical wind shear) have a better chance of intensifying.

Vertical wind shear, which is the change in wind speed and direction with height, is a large factor in the formation and intensification of tropical cyclones. A study by Aiyyer and Thorncroft (2006) showed that VWS is the cause of almost half of the storms' variability in the main development region. There are some local and remote influences on the VWS in the Atlantic basin. The warming of the SSTs in the North Atlantic can reduce the shear over the Atlantic while warming in the Indian and Pacific Oceans increases it. Enhanced precipitation in West Africa, specifically in the Sahal, reduces the VWS in the MDR. In the northwest Atlantic a VWS of less than 10kt can reach as far north as 33°, which is higher than any other basin. Many authors believe the best representation of the tropospheric-deep shear is within 200mb and 850mb (Gray 1968, Shapiro and Goldenberg 1998, Swanson 2008, Aiyyer and Thorncroft 2006, Knaff 1997, Fitzpatrick 1997). A large VWS means the 200mb wind speed is stronger from the west than the 850mb level. A negative 200mb wind speed is associated with an easterly shear, which is better for storm development. Tropical cyclones develop and/or intensify in zero to minimal (less than 10kt) vertical wind shear and values greater than 17kt stopped intensification while 20kt slowed the formation (Fitzpatrick 1997). Large shear produces strong ventilation of heat away from the developing TC, which means the storm loses one source of fuel. Large vertical wind shear (20-40kt) can be found in the South West Atlantic and central Pacific where TCs do not occur (Gray 1968). Fitzpatrick (1997) computed VWS over a 5° circle and along the future storm track to get a better average for analysis; this also helped to reduce incorrect wind observations on the fringe of the storm.

Sea surface temperatures are studied a great deal for tropical storm formation and intensity. Tropical cyclones absorb latent and sensible heat from warm SSTs and release heat in the upper troposphere to stimulate the storm (Landsea et al. 1999). Gray (1968) and Webster et al. (2005) agreed that SSTs greater than 26°C is favorable for storm development in the Atlantic basin; while, DeMaria and Kaplan (1994) showed that the change in maximum intensity could also be seen in SSTs greater than 26°C. Wang et al. (2008) discussed the influence the Atlantic Warm Pool (AWP) has on rainfall and hurricanes. A large AWP, warmer than 28.5°C, is associated with heavier rainfall over the Caribbean, Mexico, and South Africa. The AWP usually peaks around September, which is also associated with the peak of the hurricane season. Large AWPs coincide with weaker vertical wind shear and lower sea level pressure. In Shapiro and Goldenberg’s (1998) study, they did not see a direct link between SST and hurricane formation. They discovered that SSTs are of secondary importance to VWS in storm formation and that the underlying SSTs may have a direct influence on the development of the hurricanes by changing the thermodynamic environment. Emanual (1999) discovered that the local SSTs responded to the passing of a tropical cyclone with a decrease in temperature. Remote SSTs can have an effect on the cyclone intensity as much as the local SSTs and other variables in the Atlantic; for example, extremely high SSTs in the tropical Pacific have been known to enhance vertical wind shear in the Atlantic (Latif et al. 2007). Differences in temperature between the north and south Atlantic basin can affect the increase or decrease of the number of intense hurricanes (Landsea et al. 2007). Swanson (2008) calculated the tropical mean sea surface temperature (SST averaged over 0-15°N) which explained more of the variance in the ACE than the MDR SST.

Sea level pressure (SLP) is another important factor in tropical cyclone formation. Elsner et al. (2000) confirmed when SLPs over Iceland are high there are a large number of major hurricanes, but there will need to be further study. It was also discovered when Iceland pressures are low the Bermuda-Azores high tends to be strong and shifts to the northeast hindering Cape Verde storms. This makes the connection to when the North Atlantic Oscillation is in its amplified state there are more major hurricanes on the east coast of the US. Sea level pressure can have effect on sea surface temperature and vertical wind shear. Knaff's (1997) study on the inverse relationship between SLP and tropical cyclones shows that with high pressure there will be dry and cooler mid-levels and stronger vertical wind shear due to upper-level westerlies and also by pressure gradient force (the increase in wind with the tightening of pressure) (Landsea et al. 1999). Within Knaff's research it was discovered that SSTs have a slight effect on the pressure of the tropical cyclone, but there was only a weak relationship with SSTs and SLP in the Atlantic. The fewer number of tropical cyclones in the beginning of the hurricane season could be due to the increase of subsidence from the Bermuda-Azores high (DeMaria and Kaplan 1994).

One cannot look at just one factor alone; they can have effects on each other. DeMaria and Kaplan (1994) discussed the connection between sea surface temperatures, sea level pressure, and storm intensity. Elsner et al. (2000) made the connection between sea level pressure and hurricane activity with SSTs being the cause behind it. While through Knaff's (1997) study of summertime SLP, it was shown that Caribbean SLPs were strongly linked to hurricane development and could be due to the 200mb westerlies.

DATA AND METHODS

Five data sets were used in this study. The first was tropical cyclone data from the National Climate Data Center (Knapp et al. 2010), which contained information on wind speed, storm pressure, latitude, and longitude for every six hours for storms occurring between 1948-2010. The next data set was daily average pressure from 200mb-1000mb from 1948-2010 at 2.5° spatial resolution, and V wind and U wind at the same spatial and temporal resolution and pressure levels (Kalnay et al. 1996). Lastly, the daily sea surface temperature was used at 0.5° spatial resolution from 1981-2010 (Reynolds et al. 2007).

Because of the limited time span on the sea surface temperature, I chose my ten tropical cyclones from 1981-2010. I calculated the ACE index for each storm to find the top ten TCs. Once I had my storms I determined the value of each variable at each point (every six hours) of the storm. I used the equation for vertical wind shear described by Gray (1968):

$$VWS = \surd(U_{200}-U_{850})^2 + (V_{200}-V_{850})^2$$

where U_{200} is the zonal winds at 200mb, U_{850} is the zonal winds at 850mb and V_{200} and V_{850} are the vertical winds at 200mb and 850mb respectfully.

This formula for VWS only takes into account the wind speed and not direction. I first performed single and multiple linear regressions over the full life of the storms on each variable using the wind speed of the storm as my dependent variable. Another set of linear regressions was done with a six-hour lag to see if the variables' effects on the storms appear later. To focus on the intensification part of the storm I did another set of regressions looking at only points of the storm south of 30°N. This helped to alleviate null values for the sea surface temperatures when or if the storm had made landfall. There still were a few storms that had made landfall before they reach 30°N, so I performed another set of linear regressions for those storms stopping before they make landfall to remove all null data for SSTs. I compared the coefficient of determination, r^2, for each linear regression. Because high correlation between the variables and the storms did not show sufficient evidence, I also looked at the significance, α, for each r^2 value to better understand the effect.

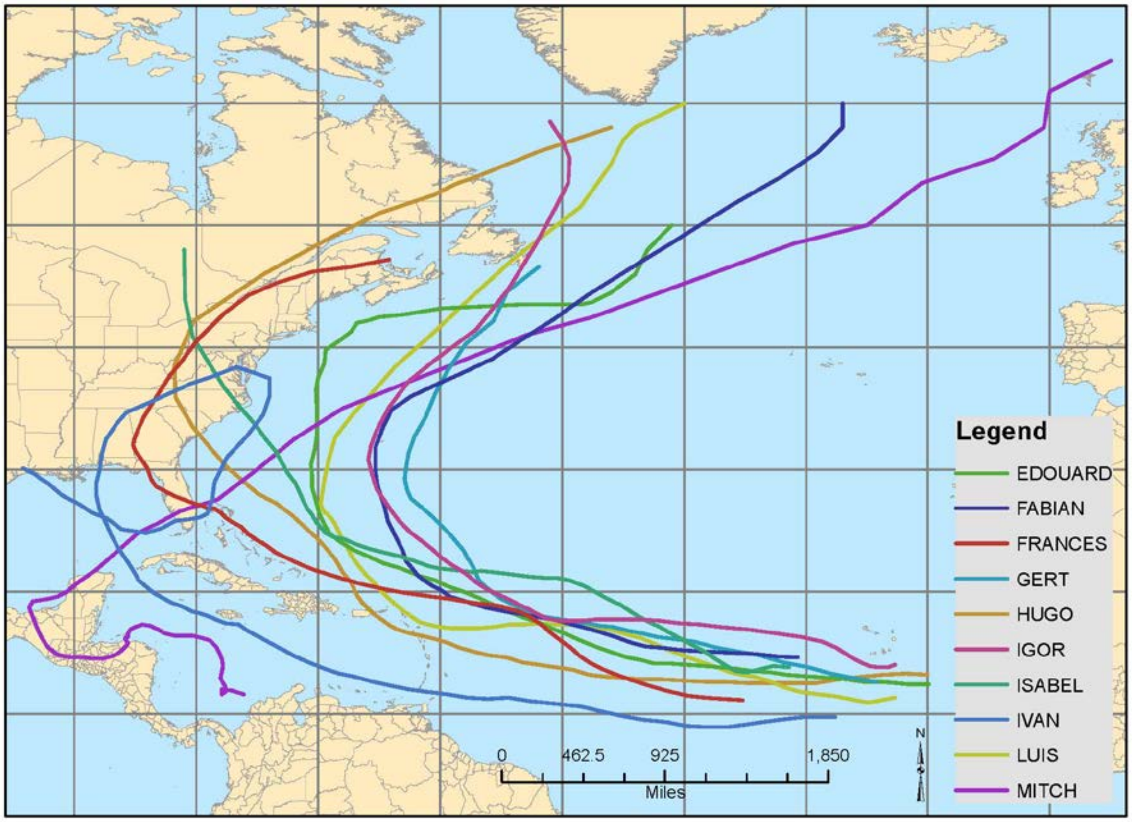
RESULTS

Calculating the ACE index for all the tropical cyclones from 1981-2010 resulted in ten storms which are listed in Table 1 along with the storm tracks that can be seen in Figure 1. Note that half of the tropical cyclones made landfall. The first run through of the data was single and multiple linear regressions on the entire life of the storms (results shown in Table 3). Frances and Ivan have the highest r^2 values of 0.5 and greater; however, the overall results were inconclusive to show that these variables were the cause of the cyclone. The sea surface temperatures by themselves seemed significant for most of the tropical cyclones, while all three variables together were significant to all of the storms. Another set of regressions was completed over the life of the storms with a 6-hour lag to see if the effects of the variables could be seen after the storm moved out of the area. The results can be seen in Table 4 (significance not shown). These results were inconclusive to determine if there is a lag in the effects.

Table 1. Top 10 ACE Index storms from 1981-2010

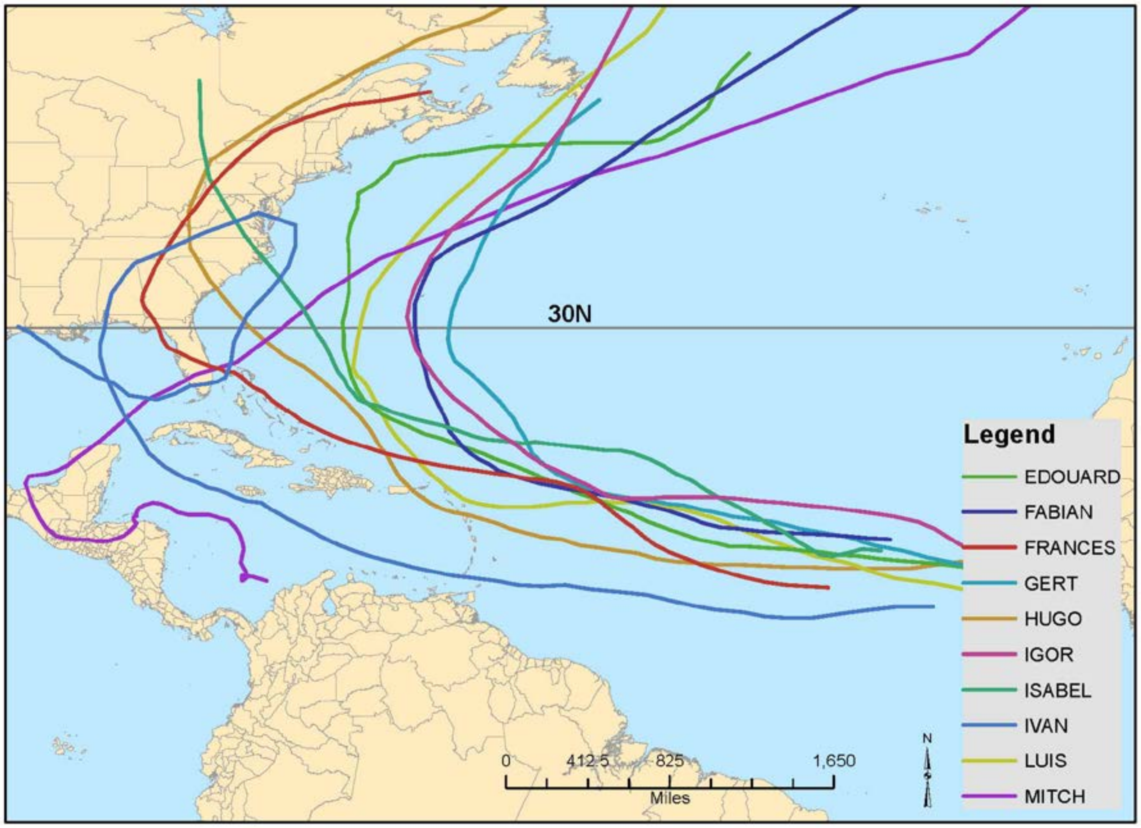
Name	**Year**	**ACE Index** (10^4 kt^2)
Ivan	2004	71.115
Isabel	2003	63.4025
Luis	1995	55.63
Edouard	1996	52.6175
Frances	2004	46.0425
Igor	2010	44.795
Fabian	2003	44.5975
Hugo	1989	44.4125
Gert	1999	42.6675
Mitch	1998	41.0375

Firgure 1. Storm tracks of the top 10 ACE Index Tropical Cyclones



The second run through of the data was to take a closer look at just the intensification portion of each storm. The linear regressions stopped when the storm reached 30°N. Figure 2 shows the location of 30°N and that there are three storms that make landfall before reaching 30°N. The results did show some improvement, which can be seen in Table 5. The significance of the sea surface temperatures and all three variables to tropical cyclones dropped for most of the storms, which showed better if there was a correlation of these variables to the tropical cyclones.

Firgure 2. Storm tracks of the top 10 ACE Index Tropical Cyclones with 30°N line



The three storms (Mitch, Frances, and Ivan) that made landfall before 30°N went through another run of statistics. The linear regressions stopped before the landfall, alliviating any eronous data from the sea surface temperatures. The results are shown in Table 6. There was some improvement in r^2 values for Ivan; however, there was not much change for Mitch and Frances. The combining of the 30°N and before landfall storms are shown in Table 2; this table gives the best understanding of the effect the variables have on the intensification of the tropical cyclones. The α values below 0.01 show that SST, VWS, or SLP by themselves are not significant for all TCs, but all three variables together are significant for six of the ten storms.

Table 2. Results of the linear regressions to 30°N and no landfall with α representing significance

Name		**VWS**	**SST**	**SLP**	**VWS/SST/SLP**
Hugo	r^2	0.16477	0.54412	0.01608	0.56776
	(α)	(0.4210)	(0.0000)	(0.1881)	(0.0000)
Luis	r^2	0.02867	0.09110	0.05740	0.13231
	(α)	(0.6886)	(0.0551)	(0.2597)	(0.0758)
Edouard	r^2	0.01579	0.04425	0.09878	0.14177
	(α)	(0.5241)	(0.1554)	(0.0351)	(0.0898)
Mitch	r^2	0.15195	0.21252	0.01380	0.40736
	(α)	(0.0049)	(0.0216)	(0.0078)	(0.0004)
Gert	r^2	0.19613	0.07854	0.34661	0.63311
	(α)	(0.0646)	(0.0008)	(0.0000)	(0.0000)
Fabian	r^2	0.00033	0.00225	0.38760	0.45977
	(α)	(0.3236)	(0.0995)	(0.0000)	(0.0002)
Isabel	r^2	0.00216	0.07566	0.01937	0.07923
	(α)	(0.7059)	(0.1048)	(0.9224)	(0.3093)
Frances	r^2	0.00016	0.00903	0.04986	0.05940
	(α)	(0.6458)	(0.9537)	(0.1932)	(0.4571)
Ivan	r^2	0.31899	0.15066	0.64957	0.74463
	(α)	(0.0008)	(0.0062)	(0.0000)	(0.0000)
Igor	r^2	0.30536	0.48888	0.19486	0.70643
	(α)	(0.0137)	(0.0000)	(0.0001)	(0.0000)

CONCLUSION AND DISCUSSION

There are many factors that affect the development and intensification of tropical cyclones: sea surface temperatures, vertical wind shear, sea level pressure, African rainfall, and teleconnections, to name a few; however, one cannot look at just one factor alone. Fitzpatrick (1997) said “the variance explained by any single variable alone is relatively small, indicating that tropical cyclone intensity change is dependent on a combination of many factors.” The results of the linear regressions do lead to this same conclusion even though it is not a definite answer; more study needs to be done to determine if these combined variables do effect the development and intensification of tropical cyclones.

The next steps would be to add more storms to compare, possibly look at ten low ACE index tropical cyclones, and find better spatial resolution of the sea level pressure and U and V winds. Also, one could normalize the variable data for each 6-hour point of the storm to get a better idea of the value of the variable under a larger portion of the cyclone.

Another step would be to add other variables to compare; for example, teleconnections or Africa rainfall. Interannual and multidecadal teleconnections can influence tropical cyclones in the Atlantic basin. El Niño Southern Oscillation shows some connection to the Atlantic sea surface temperatures; however, it has more effect on the Pacific tropical cyclones. A positive (negative) phase can result in below-normal (above-normal) tropical cyclone activity in the Atlantic basin. Landsea et al. (1999) saw an increase in vertical wind shear with positive events. Another teleconnection with a link to vertical wind shear is the Atlantic Multidecadal Mode, which could also be connected to local sea surface temperatures and influence from Sahal rainfall (Aiyyer and Torncroft 2006). Bell and Chelliah (2006) showed there is a large amount of evidence to a multidecadal climate occurring which can be noted by the North Atlantic Oscillation. Webster et al (2005) study compared the number of tropical cyclones, number of TC days, and the intensity distribution of the Atlantic, Pacific, and Indian basins. The study showed a global decadal trend. There was no trend in the number of TC with an increase in SSTs; however, the Atlantic basin does show an increase in tropical cyclones since 1995. Landsea el at. (1999) was able to see an interannual deviation between the Caribbean sea level pressure and the 200mb zonal winds. Landsea et al. (1999) and Elsner et al. (2000) saw a multidecadal time scale in variation of major hurricanes that had some correlation to Atlantic SSTs. DeMaria and Kaplan (1994) study on storm intensity saw an interannual seesawing with the average relative intensity. There was also a seesawing pattern in hurricane activity noted in Elsner et al. (2000) study. Latif et al. (2007) study showed a distinct multi-decadal signal in the accumulated cyclone energy index. Precipitation in Sahal Africa has an effect on vertical wind shear in the main development region (Aiyyer and Thorncorft 2006). Adding other factors may help narrow down what variables have the most effect on the intensification of tropical cyclones.

APPENDIX

Table 3. Results of the linear regressions of the full life of storm with α representing significance

Name (0hr)		**VWS**	**SST**	**SLP**	**VWS/SST/SLP**
Hugo	r^2	0.15223	0.29068	0.17611	0.29286
	(α)	(0.7137)	(0.0037)	(0.9339)	(0.0002)
Luis	r^2	0.00228	0.09454	0.02189	0.17312
	(α)	(0.1036)	(0.0013)	(0.0404)	(0.0078)
Edouard	r^2	0.00409	0.12837	0.00499	0.16889
	(α)	(0.7330)	(0.0006)	(0.0713)	(0.0050)
Mitch	r^2	0.04418	0.20296	0.00673	0.24521
	(α)	(0.0510)	(0.0000)	(0.2761)	(0.0001)
Gert	r^2	0.20357	0.11982	0.08559	0.30799
	(α)	(0.0971)	(0.4893)	(0.0125)	(0.0008)
Fabian	r^2	0.05261	0.17159	0.25529	0.39565
	(α)	(0.2189)	(0.1624)	(0.0001)	(0.0000)
Isabel	r^2	0.11406	0.28834	0.00095	0.28966
	(α)	(0.8432)	(0.0007)	(0.8044)	(0.0004)
Frances	r^2	0.22293	0.49052	0.04125	0.50529
	(α)	(0.1974)	(0.0000)	(0.9985)	(0.0000)
Ivan	r^2	0.53114	0.19244	0.43652	0.81487
	(α)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Igor	r^2	0.14301	0.05774	0.00000	0.33312
	(α)	(0.0034)	(0.0024)	(0.0002)	(0.0000)

Table 4. Results of the linear regressions of the full life of storm with 6-hour lag

Name (6hrs)	**VWS**	**SST**	**SLP**	**VWS/SST/SLP**
Hugo	0.14892	0.35089	0.20259	0.36273
Luis	0.01301	0.11071	0.03103	0.15663
Edouard	0.01772	0.14630	0.00000	0.18545
Mitch	0.04863	0.24298	0.01026	0.28908
Gert	0.26415	0.16812	0.03257	0.39779
Fabian	0.06787	0.20243	0.19032	0.36773
Isabel	0.14613	0.33909	0.00270	0.34548
Frances	0.23051	0.53916	0.09403	0.55797
Ivan	0.53822	0.22560	0.37170	0.82075
Igor	0.15009	0.06392	0.00209	0.26750

Table 5. Results of the linear regressions to 30°N with α representing significance

Name		**VWS**	**SST**	**SLP**	**VWS/SST/SLP**
Hugo	r^2	0.16477	0.54412	0.01608	0.56776
	(α)	(0.4210)	(0.0000)	(0.1881)	(0.0000)
Luis	r^2	0.02867	0.09110	0.05740	0.13231
	(α)	(0.6886)	(0.0551)	(0.2597)	(0.0758)
Edouard	r^2	0.01579	0.04425	0.09878	0.14177
	(α)	(0.5241)	(0.1554)	(0.0351)	(0.0898)
Mitch	r^2	0.06885	0.21529	0.02560	0.27505
	(α)	(0.0347)	(0.0002)	(0.4052)	(0.0003)
Gert	r^2	0.19613	0.07854	0.34661	0.63311
	(α)	(0.0646)	(0.0008)	(0.0000)	(0.0000)
Fabian	r^2	0.00033	0.00225	0.38760	0.45977
	(α)	(0.3236)	(0.0995)	(0.0000)	(0.0002)
Isabel	r^2	0.00216	0.07566	0.01937	0.07923
	(α)	(0.7059)	(0.1048)	(0.9224)	(0.3093)
Frances	r^2	0.00246	0.04992	0.00596	0.05505
	(α)	(0.6340)	(0.1274)	(0.7450)	(0.4420)
Ivan	r^2	0.30432	0.00684	0.63403	0.71561
	(α)	(0.0023)	(0.0120)	(0.0000)	(0.0000)
Igor	r^2	0.30536	0.48888	0.19486	0.70643
	(α)	(0.0137)	(0.0000)	(0.0001)	(0.0000)

Table 6. Results of the linear regressions before landfall

Name (0hr)	VWS	SST	SLP	VWS/SST/SLP
Mitch	0.15195	0.21252	0.01380	0.40736
Frances	0.00016	0.00903	0.04986	0.05940
Ivan	0.31899	0.15066	0.64957	0.74463

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