Abstracting ENSO Spatial Patterns' Impact on Atlantic Tropical Cyclone Seasonal Frequency

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Abstract

1 Introduction

Understanding and predicting tropical cyclone (TC) activity is of significant scientific and societal interest. Pacific Ocean sea surface temperatures (SSTs) have well documented global long-range teleconnections, including Atlantic TC activity [10, 4, 5, 6, 13]. The quasi-periodic cycle (2-7 years) of warming and cooling of the near equatorial Pacific Ocean, known as the El-Niño Souther Oscillation (ENSO), is characterized by the warm El-Niño (EN) phase and a cold La Niña (LN) phase. Researchers have traditionally used the phase of ENSO to predict Atlantic TC activity, however due to the large amplitude variations in seasonal TC counts, the difference in Atlantic TC activity based on the various phases of ENSO is not obvious (see Figure 1).

ENSO has been quantified using warming-based indices where SST anomalies are averaged over regions in the Pacific. Such indices include the Nino 1+2 (0-10S, 90-80W), Nino 3 (5N-5S, 150-90W), Nino 4 (5N-5S, 160E-150W), and Nino 3.4 (5N-5S, 170-120W). Some studies have suggested such indices do not capture ENSO's nature and evolution. Subsequently, more elaborate indices were developed some of which were linear combinations of the above-mentioned indices [17], while others have proposed indices using transformed data or non-linear combination of indices [14]. Despite the varying degrees of complexity, the majority of works attempting to capture ENSO focus on the intensity of warming in a given geographical region. While such indices might provide valuable insight into weather teleconnections (are there any good examples where ENSO does really well at predicting teleconnections?), they were not designed to capture the physical pathways by which Pacific SSTs may impact the large-scale conditions over the Atlantic.

In this paper we propose a novel spatial ENSO index that is designed specifically to capture the physical pathways by which Pacific SSTs may influence Atlantic TC activity. Our approach introduces a distance-based ENSO index that tracks the location of the location of maximum near-tropical Pacific warming anomaly instead of its absolute warming. We will demonstrate the performance of our index by comparing it to traditional ENSO indices in both predicting seasonal TC frequency as well as discriminating between the large-scale conditions that are favorable for Atlantic cyclogenesis.

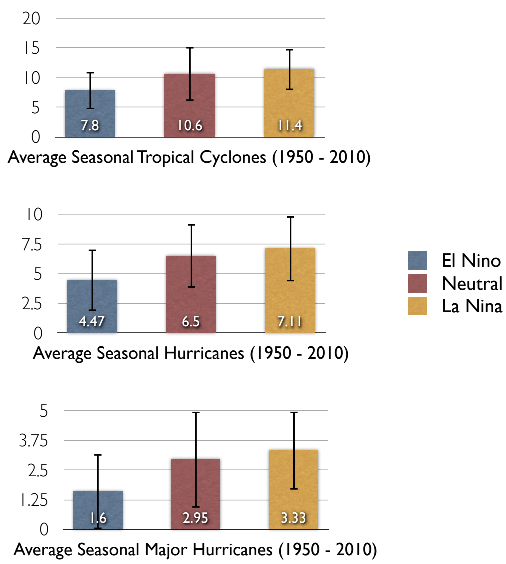

Figure 1: The $1950 - 2010$ seasonal mean Atlantic tropical cyclones (top), hurricanes (middle), and major hurricane (bottom) counts for El-Niño, neutral, and La Niña years. Vertical bars denote standard deviation. The overlap between between bars across categories make distinguishing between Atlantic TC activity based on the phase of ENSO ambiguous.

2 Spatial ENSO Index (S-ENSO)

An increasing number of studies have suggested changes in the spatial warming patterns of the Pacific Ocean and some have linked those changes U.S. hurricane landfall probabilities [11]. We propose that based on such results, the spatial distribution of Pacific Ocean warming might provide better predictive insights into ENSO-Atlantic TC activity than warming anomalies alone. We propose a distance-based ENSO index that tracks the location of maximum near-tropical Pacific warming anomaly (Pacific Warm Pool or PWP thereafter) instead of its absolute warming.

For each season, we search for the maximum positive warming anomaly in regions of size comparable to that of warming-based ENSO indices. The PWP is selected by searching the Northern Tropical Pacific ($0 - 30°$ N). The time

Acronym	Quantity
PWP-Lon	The longitude of the warmest SST pool in the northern near equatorial Pacific
PWP-Pres	The mean presure of PWP
PWP-OLR	The mean OLR of PWP
MinPres-Lon	The longitude of the region with the lowest mean central pressure
PWP-PCP	The longitudinal distance between PWP and PCP
Combo Index	A linear combination of xxxx

Table 1: A List of all quantities computed for this study with their corresponding acronyms.

series of the longitude of the PWP is then correlated with various quantities that communicate August-October Atlantic TC activity: number of tropical cyclones, number of major hurricanes, potential dissipation index (PDI) [8], accumulated cyclone energy (ACE) [3], and net tropical cyclone energy (NTC) [9].

In addition to tracking the longitude of the PWP, we also monitored other environmental factors that might influence Atlantic TC activity: the mean pressure value over the PWP, the mean Outgoing Longwave Radiation (OLR) of the PWP to monitor atmospheric deep convection, the longitude of the minimal pressure region to approximate Pacific cyclone activity, and finally the longitudinal distance between PWP and the coldest near equatorial Pacific SST region (Pacific Cold Pool or PCP). Finally, we ran a series of exhaustive experiments to linearly combine the above mentioned quantities into a single index (named Combo Index). Each index is built by computing the z-score for each quantity (i.e. mean OLR, etc.) then we add each normalized quantity to build a single index to use for analysis. Please see table **??**

Tables **??** through **??** show the linear correlation coefficients between August-October TC Atlantic TC activity and our ENSO spatial index for Feb-April, April-June, and August-October respectively. In all cases our spatial ENSO index correlates better than traditional warming-based indices. The improvements increase as we increase lead time, with April lead times improving by more than an order of magnitude. This improvement is because traditional ENSO indices suffer from a "predictability barrier" that make it difficult to use them to predict TC activity before June [18].

2.1 Lead times

To test the robustness of our indices, we also increased computed the correlation between our indices and Atlantic TC activity with increasing lead times. Tables 3 and 4 show the correlations as a function of lead time for ASO TC and major hurricane counts respectively. The Combo Index has limited long range prediction as it doesn't have much skill until July for both hurricanes and TCs. Our SST-based indices (PWP-lon and PWP-PCP) have better long-range predictability. Our improvement over major NINO indices is significant with

	TCs	Major Hurricanes	NTC	PDI	ACE
Combo Index	**0.81**	**0.81**	**0.77**	**0.71**	**0.75**
PWP-Pres	0.61	0.65	0.57	0.56	0.58
PWP-OLR	0.55	0.57	0.50	0.46	0.48
MinPres-Lon	0.15	0.12	0.19	0.17	0.20
PWP-PCP	0.67	0.66	0.64	0.6	0.58
maxSSTLon	-0.64	-0.5	-0.55	-0.44	-0.49
Nino1+2	-0.42	-0.42	-0.40	-0.3	-0.35
Nino 3	-0.44	-0.5	-0.44	-0.39	-0.40
Nino 4	-0.24	-0.41	-0.23	-0.2	-0.2
Nino 3.4	-0.42	-0.53	-0.42	-0.38	-0.40
Modoki Box A	-0.28	-0	-0.26	-0.24	-0.3
Modoki Box B	-0.41	-0.40	-0.4	-0	-0.33
Modoki Box C	0.55	0.57	0.57	0.57	0.59
Modoki EMI	-0.062	-0.21	-0.088	-0.11	-0.12

Table 2: Linear correlation scores between various indices computed over the March-October period and August-October Atlantic TC activity. The highest score for each category is highlighted in **bold**

increased lead time (up to an order of magnitude better in some cases). This improvement is because traditional ENSO indices suffer from a "predictability barrier" that make it difficult to use them to predict TC activity before June [18]. However, it is important to note that one static region in the Pacific (Modoki Box C) has good long-range correlations to both TCs and major hurricanes. However, that region alone isn't known to be used to TC or hurricane prediction. Another interesting observation, is the high correlation with both TCs and major hurricanes for the Jan-Dec month range for the Combo Index.

2.2 Seasonal TC forecasting

To asses our index' ability to forecast seasonal TC activity. We built a linear regression model using a leave k-out cross validation ($k = 1, 2, 4, 8$) Tables 5 - **??** show the results. We can see that our Combo Index is very robust regardless of how many observations are held out during training. However, it is important to note that the Modoki EMI index has an original correlation of -0.062 (no cross-validation) and a LOO cross-validation correlation of -0.56. It seems that straight non-random cross-validation might not fully address the "Faghmous Paradox"

2.3 Impact on large-scale conditions over the Atlantic

To propose possible physical pathways by which our index impact Atlantic TC activity, we compute the composites for factors known to influence Atlantic TC activity: SST, central pressure, potential intensity (PI), and vertical wind

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Combo Index	-0.027	0.038	0.11	0.22	0.2	0.40	0.5	**0.62**	**0.71**	**0.68**	**0.70**	**0.68**
PWP-Pres	0.068	0.10	0.042	0.075	0.19	0.3	0.38	0.48	0.52	0.52	0.54	0.58
PWP-OLR	-0.35	-0.21	-0.13	0.03	0.054	0.2	0.21	0.4	0.48	0.50	0.51	0.57
MinPres-Lon	-0.21	-0.17	-0.068	-0.0013	-0.37	-0.18	-0.095	0.025	0.094	-0.14	-0.13	-0.25
PWP-PCP	**0.44**	0.35	0.35	0.36	0.43	0.53	0.53	0.60	0.63	0.7	0.68	0.6
PWP-lon	-0.3	-0.36	-0.38	-0.37	-0.39	-0.4	-0.53	-0.53	-0.55	-0.56	-0.59	-0.56
Nino1+2	0.053	-0.0094	-0.067	-0.13	-0.19	-0.23	-0.27	-0.30	-0.34	-0.37	-0.40	-0.42
Nino 3	-0.011	-0.036	-0.044	-0.077	-0.15	-0.22	-0.28	-0.33	-0.39	-0.44	-0.48	-0.51
Nino 4	-0.0090	-0.036	-0.056	-0.076	-0.11	-0.15	-0.19	-0.24	-0.28	-0.33	-0.37	-0.40
Nino 3.4 -0.026	-0.061	-0.074	-0.11	-0.16	-0.23	-0.29	-0.34	-0.40	-0.45	-0.49	-0.53	
Modoki Box A	-0.03	-0.070	-0.087	-0.11	-0.15	-0.19	-0.24	-0.29	-0.32	-0.36	-0.39	-0.42
Modoki Box B	0.02	-0.026	-0.063	-0.10	-0.2	-0.21	-0.25	-0.28	-0.3	-0.35	-0.38	-0.40
Modoki Box C	0.42	**0.47**	**0.52**	**0.52**	**0.54**	**0.56**	**0.59**	0.60	0.59	0.58	0.57	0.57
Modoki EMI	-0.14	-0.16	-0.16	-0.16	-0.16	-0.16	-0.17	-0.19	-0.20	-0.21	-0.23	-0.24

Table 3: Linear correlation scores between various indices computed over decreasing lead times and August-October Atlantic TC season counts. Each column header signifies the end month of the The highest score for each category is highlighted in **bold**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Combo Index	-0.12	0.020	0.074	0.19	0.29	0.40	0.45	0.57	0.58	**0.67**	**0.72**	**0.76**
PWP-Pres	0.18	0.026	0.07	0	0.23	0.29	0.32	0.3	0.37	0.39	0.48	0.56
PWP-OLR	-0.50	-0.29	-0.20	-0.041	0.0039	0.13	0.17	0.28	0.35	0.4	0.42	0.50
MinPres-Lon	-0.26	0.0025	0.015	-0.025	-0.11	-0.11	0.0023	0.12	0.075	0.053	0.025	-0.04
PWP-PCP	**0.33**	0.30	0.25	0.31	**0.46**	**0.50**	0.52	0.60	0.61	0.68	0.72	0.71
PWP-lon	-0.21	-0.28	-0.30	-0.33	-0.46	-0.48	**-0.62**	**-0.62**	**-0.64**	-0.64	-0.70	-0.67
Nino1+2	0.076	0.015	-0.035	-0.067	-0.12	-0.16	-0.21	-0.27	-0.31	-0.36	-0.41	-0.44
Nino 3	0.084	0.061	0.06	0.041	-0.023	-0.096	-0.16	-0.22	-0.29	-0.36	-0.42	-0.47
Nino 4	0.18	0.15	0.12	0.093	0.060	0.028	-0.002	-0.039	-0.086	-0.14	-0.18	-0.23
Nino 3.4	0.10	0.082	0.067	0.04	-0.0099	-0.068	-0.12	-0.18	-0.25	-0.3	-0.37	-0.43
Modoki Box A	0.14	0.10	0.078	0.049	0.0057	-0.03	-0.071	-0.12	-0.15	-0.19	-0.23	-0.26
Modoki Box B	0.016	-0.018	-0.04	-0.051	-0.10	-0.17	-0.22	-0.26	-0.31	-0.36	-0.41	-0.44
Modoki Box C	0.29	**0.34**	**0.39**	**0.41**	0.44	**0.5**	0.51	0.55	0.55	0.54	0.54	0.54
Modoki EMI	0.081	0.044	0.020	-0.0097	-0.02	-0.018	-0.023	-0.039	-0.034	-0.038	-0.045	-0.053

Table 4: Linear correlation scores between various indices computed over decreasing lead times and August-October Atlantic major hurricane (CAT 4-5) season counts. Each column header signifies the end month of the The highest score for each category is highlighted in **bold**

	TC	Major Hurricanes	PDI	NTC	ACE
Combo Index	0.78	0.79	0.68	0.7	0.71
PWP-Pres	0.6	0.59	0.50	0.5	0.53
PWP-OLR	0.47	0.51	0.35	0.41	0.38
MinPres-Lon	-0.32	-0.50	-0.27	-0.22	-0.19
PWP-PCP	0.62	0.61	0.50	0.59	0.51
PWP-lon	0.6	0.4	0.31	0.47	0.37
Nino1+2	0.30	0.32	0.17	0.27	0.18
Nino 3	0.35	0.4	0.3	0.35	0.29
Nino 4	0.0022	0.27	-0.099	-0.022	-0.035
Nino 3.4	0.31	0.45	0.27	0.33	0.30
Modoki Box A	0.090	0.32	0.011	0.07	0.049
Modoki Box B	0.30	0.30	0.14	0.24	0.15
Modoki Box C	0.49	0.50	0.5	0.51	0.53
Modoki EMI	-0.55	-0.11	-0.5	-0.51	-0.44

Table 5: Linear correlation between actual and predicted ASO Atlantic TC activity using **Leave One Out** cross-validation for each our indices and standard NINO indices.

	TC	Major Hurricanes	PDI	NTC	ACE
Combo Index	0.79	0.79	0.66	0.74	0.70
PWP-Pres	0.57	0.59	0.48	0.50	0.5
PWP-OLR	0.48	0.51	0.34	0.41	0.37
MinPres-Lon	-0.37	-0.55	-0.35	-0.30	-0.3
PWP-PCP	0.65	0.61	0.46	0.57	0.49
PWP-lon	0.60	0.39	0.29	0.46	0.36
Nino1+2	0.32	0.31	0.14	0.25	0
Nino 3	0.35	0.4	0.25	0.32	0.27
Nino 4	-0.025	0.23	-0.23	-0.13	-0.15
Nino 3.4	0.31	0.44	0.22	0.29	0.26
Modoki Box A	0.077	0.29	-0.090	-0.018	-0.043
Modoki Box B	0.32	0.29	0.12	0.22	0.14
Modoki Box C	0.51	0.50	0.49	0.5	0.51
Modoki EMI	-0.50	-0.15	-0.52	-0.5	-0.48

Table 6: Linear correlation between actual and predicted ASO Atlantic TC activity using **Leave Two Out** cross-validation for each our indices and standard NINO indices.

	TC	Major Hurricanes	PDI	NTC	ACE
Combo Index	0.8	0.79	0.63	0.71	0.67
PWP-Pres	0.55	0.59	0.44	0.47	0.47
PWP-OLR	0.46	0.51	0.29	0.38	0.32
MinPres-Lon	-0.37	-0.40	-0.40	-0.33	-0.34
PWP-PCP	0.65	0.62	0.42	0.5	0.45
PWP-lon	0.58	0.38	0.25	0.43	0.31
Nino1+2	0.27	0.28	0.12	0.22	0.14
Nino 3	0.29	0.38	0.18	0.25	0.2
Nino 4	-0.11	0.15	-0	-0.26	-0.29
Nino 3.4	0.2	0.40	0.11	0.19	0.15
Modoki Box A	-0.0038	0.2	-0.23	-0.14	-0.18
Modoki Box B	0.27	0.26	0.081	0.17	0.098
Modoki Box C	0.48	0.48	0.44	0.46	0.46
Modoki EMI	-0.56	-0.23	-0.6	-0.60	-0.56

Table 7: Linear correlation between actual and predicted ASO Atlantic TC activity using **Leave Four Out** cross-validation for each our indices and standard NINO indices.

	TC	Major Hurricanes	PDI	NTC	ACE
Combo Index	0.77	0.78	0.65	0.72	0.67
PWP-Pres	0.49	0.53	0.42	0.44	0.43
PWP-OLR	0.35	0.44	0.25	0.32	0.25
MinPres-Lon	-0.55	-0.54	-0.49	-0.45	-0.46
PWP-PCP	0.64	0.61	0.43	0.6	0.45
PWP-lon	0.55	0.35	0.2	0.4	0.25
Nino1+2	0.12	0.15	0.0052	0.096	0.0055
Nino 3	0.16	0.2	0.051	0.14	0.053
Nino 4	-0.25	-0.00059	-0.52	-0.42	-0.45
Nino 3.4	0.13	0.27	-0.046	0.073	0.0024
Modoki Box A	-0.2	0.042	-0.44	-0.34	-0.38
Modoki Box B	0.12	0.13	-0.026	0.060	-0.031
Modoki Box C	0.45	0.47	0.47	0.47	0.48
Modoki EMI	-0.57	-0.37	-0.66	-0.64	-0.63

Table 8: Linear correlation between actual and predicted ASO Atlantic TC activity using **Leave Eight Out** cross-validation for each our indices and standard NINO indices.

shear. Each composite was for the August-October period - the peak hurricane season. To compare how well our index resolves the large-scale conditions that are critical to seasonal TC activity we compare our index' composites to those of the seasonal TC count composites (ground truth) and that of the NINO3.4 composites. The rational is that if our index is better able to distinguish between the large-scale conditions for active and inactive hurricane seasons its composite should closely resemble that of the ground truth (i.e. active minus inactive hurricane years).

Figures 2 - **??** show the composites (active years minutes inactive years) for NINO3.4 (top), Combo Index (middle) and ground truth (bottom).

2.3.1 Central Pressure

Tropical cyclones are low pressure systems, therefore seasons with high TC activity tend to have low pressure means as seen in Figure 2. Our index is able to resolve much lower central pressure across the Atlantic Main Development Region (MDR) than the NINO3.4 index. It is not clear from this composite whether high TC activity is a cause or effect of large-scale low pressure.

2.3.2 Potential Intensity (PI)

Potential intensity is a variable computed by combining the column integrated air temperature and relative humidity. PI has been shown to provide the theoretical upper bound on storm intensity given air temperature and relative humidity [7]. PI has also been used as a proxy of how conducive an environment is for tropical cyclogenesis [6]. As shown in Figure 3 (bottom), active TC seasons tend to have high PI values along the MDR especially right off the West African coast where African Easterly Waves (AEWs) exit the continental mass. Similar to central pressure, our index (Figure 3 middle panel) resolves similar spatial patterns for PI than the ground truth.

2.3.3 Relative Humidity (RH)

In order for TCs to develop a minimal amount of moisture must be present in the vertical column [7]. That is why active TC seasons tend to have high RH in the East Atlantic where most hurricane form (figure 4). While our index resolves the conditions over the Atlantic better than NINO3.4 (Figure 4 top), it over estimate RH in the Western Atlantic. Other moisture variables to look into are precipitable water and saturation deficit.

2.3.4 Sea Surface Temperatures (SST)

Our index is particularly better at resolving seasonal SSTs compared to NINO3.4.

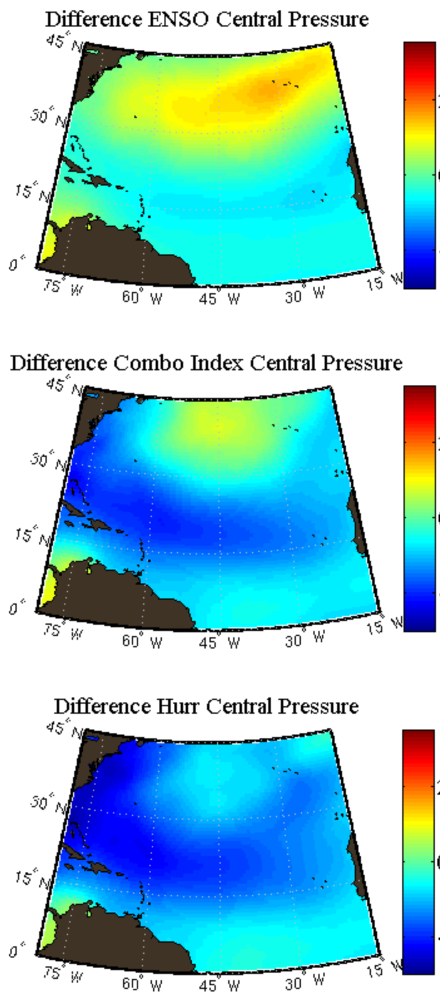

Figure 2: Central pressure composites for NINO3.4 (top), Combo Index (Middle), and Ground Truth (Bottom). Active TC seasons tend to have low pressure.

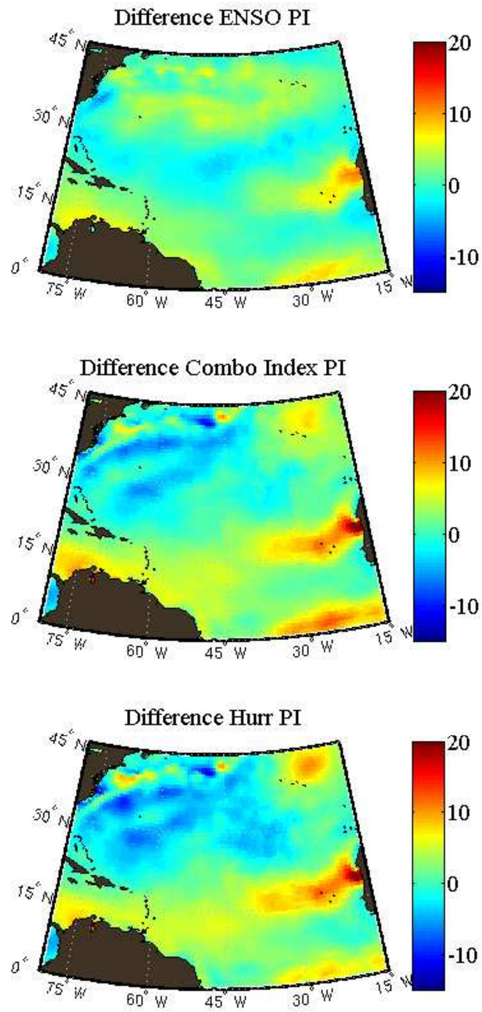

Figure 3: Central pressure composites for NINO3.4 (top), Combo Index (Middle), and Ground Truth (Bottom). Active TC seasons tend to high PI values along the MDR and right off the West African coast.

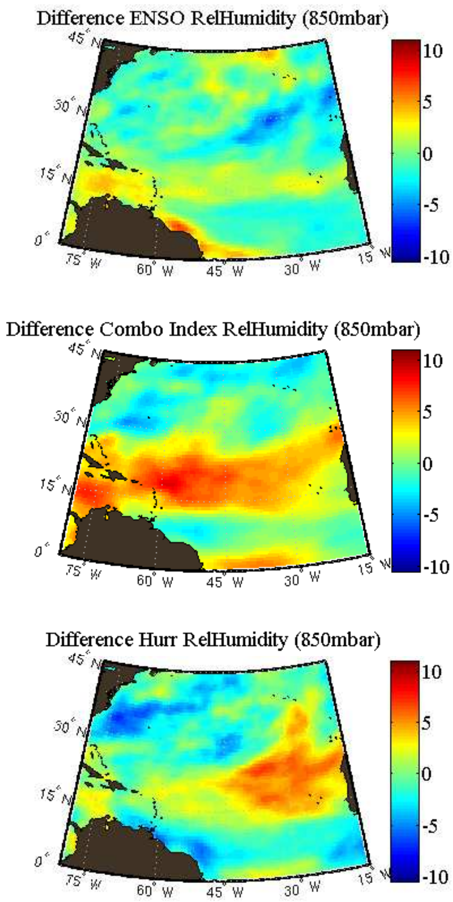

Figure 4: 850 mb Relative Humidity composites for NINO3.4 (top), Combo Index (Middle), and Ground Truth (Bottom). Active TC seasons tend to have high RH along the MDR.

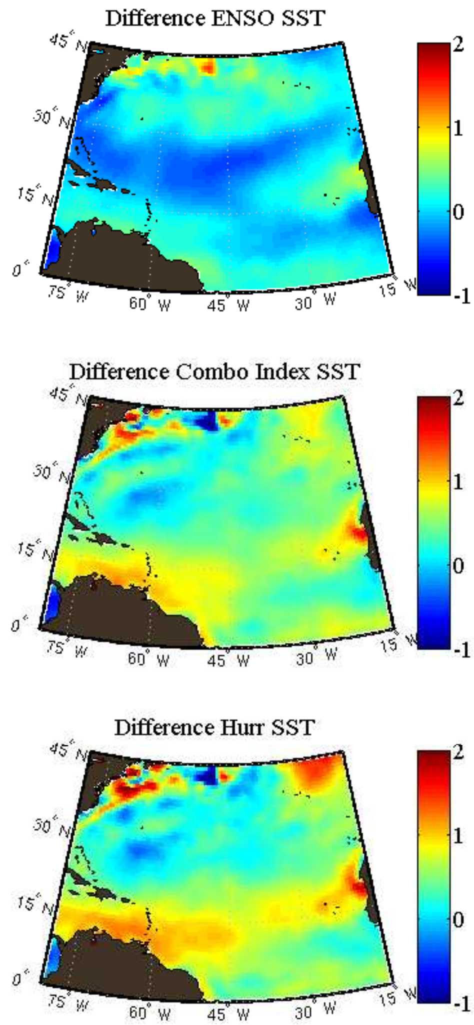

Figure 5: SST Composites for NINO3.4 (top), Combo Index (Middle), and Ground Truth (Bottom). Active TC seasons tend to have high SSTs along the MDR and in the North Atlantic.

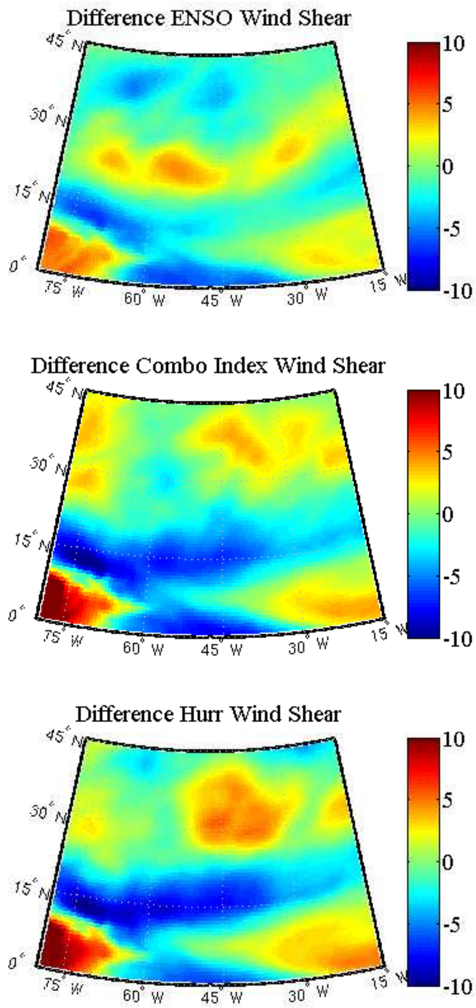

Figure 6: Vertical wind shear (VWS) Composites for NINO3.4 (top), Combo Index (Middle), and Ground Truth (Bottom). Active TC seasons tend to have low VWS along the MDR.

3 Appendix

3.1 ENSO Overview

The quasi-periodic cycle (2-7 years) of warming and cooling of the near equatorial Pacific Ocean, known as the El-Niño Souther Oscillation (ENSO) is associated with anomalous atmospheric circulation and alterations to the Eastern Pacific thermocline (the subsurface boundary between upper warm waters and deep cool waters). During its warm, El-Niño (EN) phase, the equatorial Pacific Ocean experiences weak easterly winds causing an increase in Eastern Pacific SSTs, that in turn alters the atmospheric zonal (Walker) circulation, generally resulting in prevailing westerlies. ENSO's cold, La Niña (LN) phase, is characterized by the opposite atmospheric conditions – with cold SST anomalies along the Eastern Pacific and warm ones near the Western Pacific as a result of prevailing easterly winds (see Figure 12). The mechanisms that control the reversal to the opposite LN phase are not fully understood [12, 15]. Recent research has suggested that to fully capture ENSO activity, it is no longer sufficient to monitor the warm and cold phases in the Eastern Pacific. Instead, warming patterns in the Central Pacific must be monitored as well [1]. Warming in the Central Pacific, known as El Niño Modoki, where a warm waters are surrounded by cold ones has been observed with increased frequency since the 1990s. Such changes have been attributed to anthropogenic global warming [20] as well as natural climate variability [19].

Enhanced convection as a result of anomalous Pacific Ocean warming is associated with strong westerly upper tropospheric wind over the Caribbean basin and tropical Atlantic, resulting in low TC activity during EN events and high TC activity LN [10]. Other studies have suggested that ENSO impact Atlantic TC activity via tropospheric warming [16].

3.2 Combo Index Cross Validation Month Range Sensitivity Experiment

In this section we compute the combination index in the same fashion as described in the previous section. These results are for building the index with varying month ranges, and then performing leave one-out cross validation with the combination index and 5 different hurricane statistics

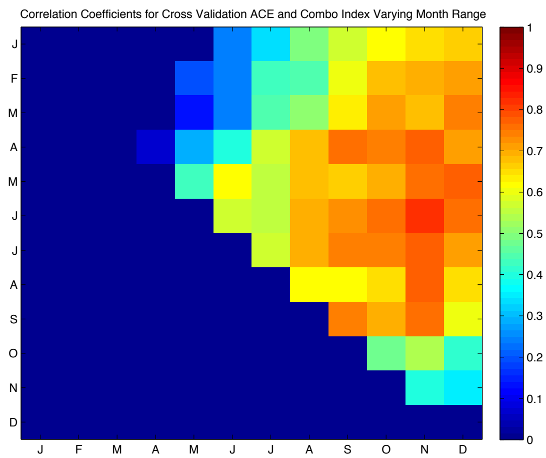

Figure 7: Corr Combo Index vs. ACE

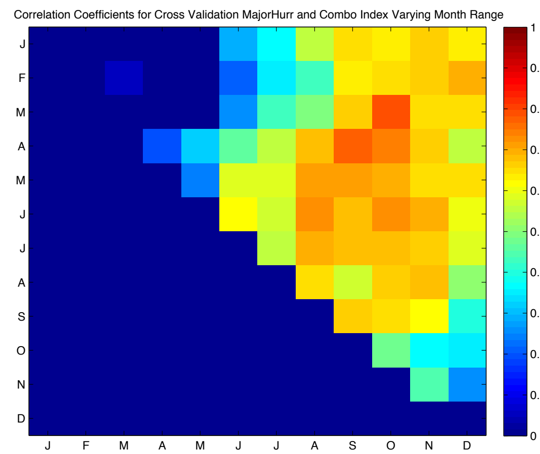

Figure 8: Corr Combo Index vs. Major Hurr

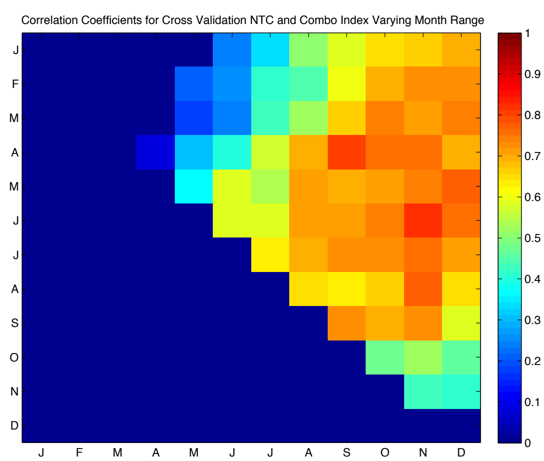

Figure 9: Corr Combo Index vs. NTC

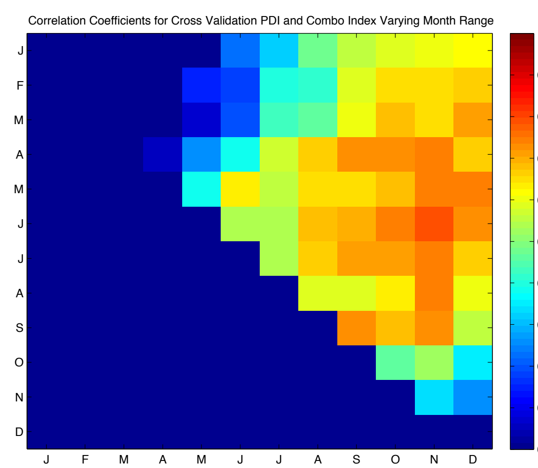

Figure 10: Corr Combo Index vs. PDI

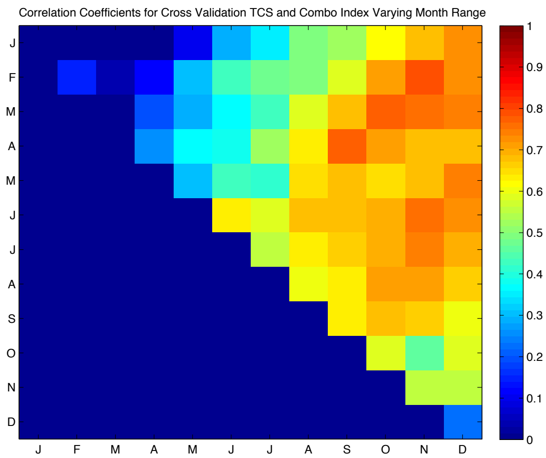

Figure 11: Corr Combo Index vs. TCs

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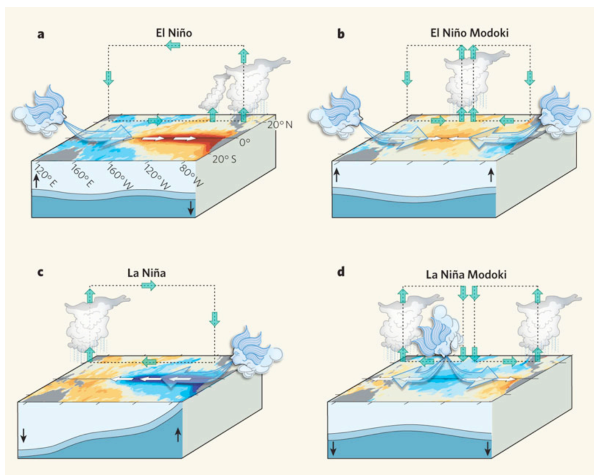

Figure 12: (a), An El Niño event is produced when the easterly winds weaken; sometimes, in the west, westerlies prevail. This condition is categorized by warmer than normal sea surface temperatures (SSTs) in the east of the ocean, and is associated with alterations in the thermocline and in the atmospheric circulation that make the east wetter and the west drier. (b), An El Niño Modoki event is an anomalous condition of a distinctly different kind. The warmest SSTs occur in the central Pacific, flanked by colder waters to the east and west, and are associated with distinct patterns of atmospheric convection. (c), (d), The opposite (La Niña) phases of the El Niño and El Niño Modoki respectively. Image and caption used for illustration purposes only taken from [2]

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