Climate Forecast Applications Network (CFAN)

Causes and Predictability of the Exceptionally Active 2017 Atlantic Hurricane Season

November 30, 2017

Summary

CFAN's inaugural seasonal forecasts of Atlantic hurricanes, issued in June and August 2017, predicted above-normal ACE and US landfalls, but did not foresee the exceptionally high levels of ACE. This report is a 'hindsight' analysis of the causes of the exceptionally active 2017 Atlantic hurricane season, addressing the question of whether this high level of activity was predictable.

- The rapid transition towards La Nina conditions during early summer contributed to the high level of Atlantic hurricane activity but accounted for only a modest fraction of the extreme hurricane activity that later developed.
- Hurricane-favorable divergence anomalies in the lower atmosphere of ASO 2017 were already established in early summer (May-July, MJJ). Analogue years for this circulation pattern were 2008 (ACE 146, 3 US landfalls) and 1999 (ACE 173, 3 US landfalls).
- The combined effects of Pacific and Atlantic Meridional Mode feedbacks were likely important contributors to high US landfall totals and extreme ACE anomalies over the broader North Atlantic.
- Spring conditions in the Arctic proved to be a reliable indicator of U.S. landfalls

Overview

The 2017 North Atlantic hurricane season was unusually active, attaining twice the normal levels of Accumulated Cyclone Energy (ACE) and US hurricane landfalls. The 2017 season ranks 7th in overall activity among all years since 1920 (Fig. 1A), reaching an ACE total of 226 that far exceeds the mean level of 105 from 1980 to 2016. Over the same period, 1.5 hurricanes, on average, reached the US coastline each year, while three (Harvey, Irma and Nate) made landfall in 2017 (Fig. 1B).

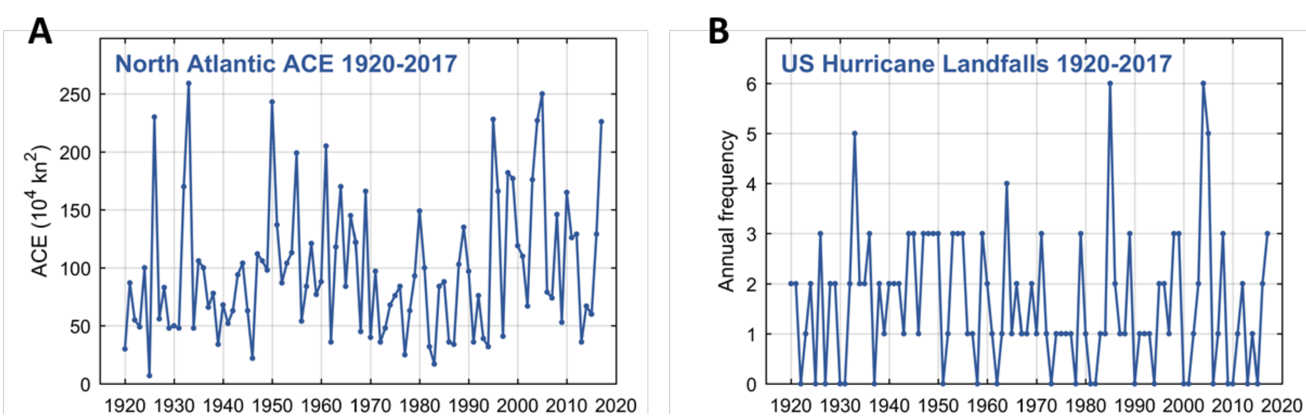

Figure 1. Historical North Atlantic hurricane variability, 1920-2017. A. North Atlantic Accumulated Cyclone Energy (ACE). B. United States hurricane landfalls.

CFAN's inaugural hurricane forecasts, issued in early June and early August 2017, predicted above-normal ACE and US landfalls, but did not foresee the exceptional degree of overall North hurricane activity.

	ACE	# US landfalls
Observed	226	3
Jun 2017 fcst	135 (100-170)	3 (2-4)
Aug 2017 fcst	130 (100-160)	2 (1.5-2.5)

This report is a 'hindsight' analysis of the causes of the exceptionally active 2017 Atlantic hurricane season, addressing the question of whether this high level of activity was predictable. Such analyses help CFAN improve its seasonal forecast methodology.

North Atlantic hurricane behavior differs considerably from year to year due to changing ocean-atmosphere conditions at regional and global scales. While ordinary weather events are challenging to predict more than several days in advance, late-summer hurricane activity responds to processes that tend to evolve slowly over months, allowing probabilistic forecasts to be made 1 to 2 seasons ahead, and perhaps even earlier.

La Nina

The El Niño – Southern Oscillation (ENSO) is a well-known source of North Atlantic hurricane variability. ENSO originates from coupled ocean-atmosphere processes spanning the vast tropical Pacific Ocean, alternating every few years between warm El Niño and cool La Niña states and generating characteristic changes in temperature and weather over much of the globe. When La Niña conditions are present during the late-summer (August-October, ASO) peak of the North Atlantic hurricane season, above-normal activity typically occurs. La Niña is commonly defined by conditions of below-normal sea surface temperatures (SSTs) in the equatorial eastern Pacific, but also involves large-scale atmospheric anomalies that tend to reduce wind shear high above the tropical North Atlantic, enabling cyclones to achieve greater vertical extent and intensify into hurricane-level storms.

Figure 2 shows the composite pattern of ASO SST anomalies during recent highly-active hurricane seasons (ACE $\geq$ 175) from 1980 to 2016. La Niña's signature pattern of cool equatorial Pacific water is apparent during summers with ACE totals greater than 175 (1995, 1998, 1999, 2003, 2004 and 2005) (Fig. 2A), and those with 3 or more US hurricane landfalls (1985, 1989, 1998, 1999, 2004, 2005, 2008) (Fig. 2B). Warm SSTs in the tropical North Atlantic also contribute to greater activity by promoting instability in the overlying atmosphere and facilitating convergence of low-level winds, moisture and energy from surrounding ocean areas. La Niña conditions (Fig. 2C) and warm Atlantic surface temperatures were both in place during ASO 2017 (Fig. 2D), accounting in part for the heightened hurricane activity. CFAN's

June ACE forecast of 134 was based partly on early identification of these developing SST tendencies.

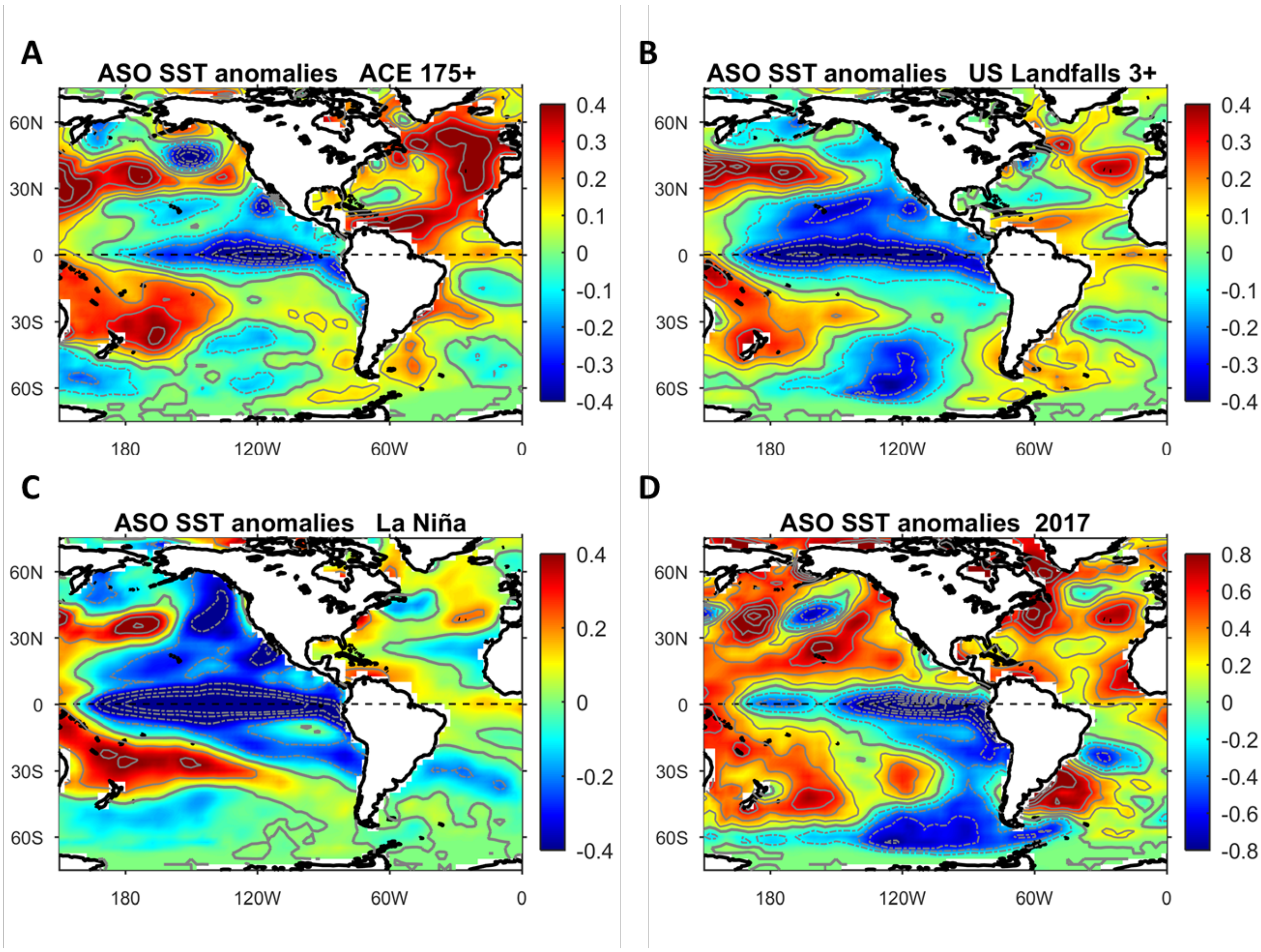

Figure 2. Patterns of August-October (ASO) sea surface temperature (SST) anomalies associated with enhanced North Atlantic hurricane activity (1980-2017). A. ACE ≥ 175 B. US Landfalls ≥ 3. C. La Niña (Niño 3.4 SST < -0.7σ). D. 2017.

Underpredictions of high 2017 hurricane activity can be explained in part by the unusually rapid growth of La Niña during early summer, reflected by a steep 1°C decline in east-central Pacific (Niño 3.4) SST from April to August (Fig. 3A). Summer cooling of this magnitude generally occurs with the termination of large winter El Niño events and oscillatory reversals to La Niña conditions by the following winter. In 2017, however, La Niña cooling developed uncharacteristically from neutral winter ENSO conditions, leading to summer ENSO changes with a magnitude unwitnessed in the past several decades (Fig. 3B).

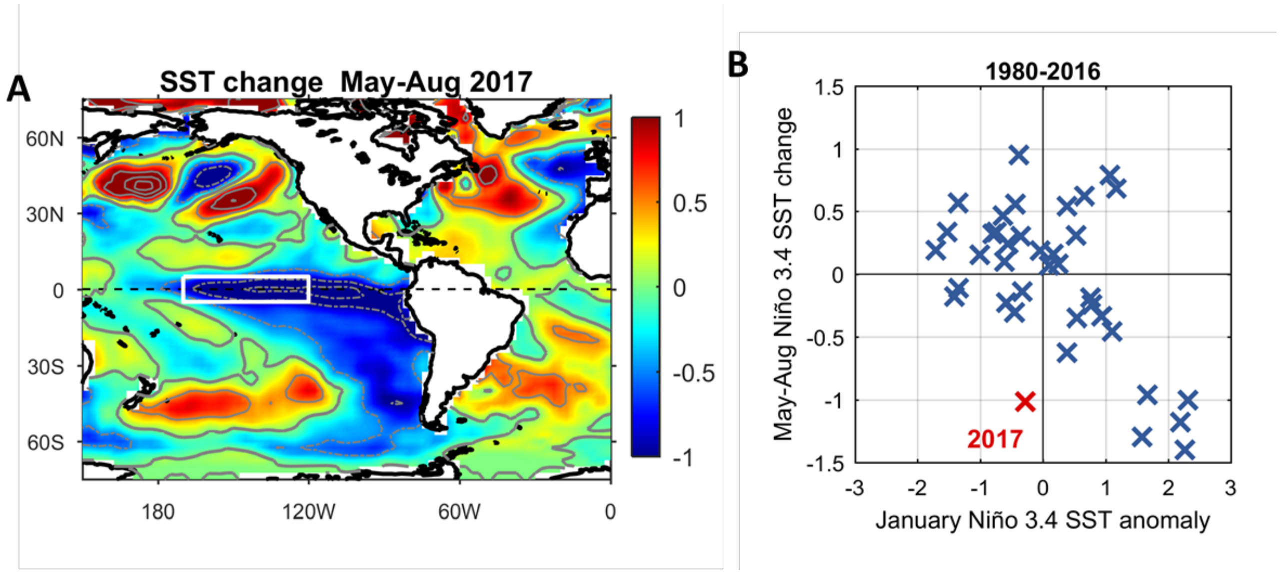

Figure 3. Summer sea surface temperature (SST) changes and anomalies. A. SST changes (°C) from May to August 2017. Box encloses the Niño 3.4 SST region used to define ENSO anomalies and changes. B. Comparison of winter (January) Niño 3.4 SST anomalies (x-axis) with summer (May-August) Niño 3.4 SST changes (y-axis). 2017 (red) stands out as a summer of negative Niño 3.4 SST change (La Niña development) in the absence of strong winter El Niño conditions.

The unusual 'late-breaking' La Niña was remarkable in its combined magnitude and timing, but accounts for only a modest fraction of the extreme hurricane activity that later developed. The statistical relationship between Niño 3.4 SST and ACE, for example, suggests an ACE total of ~150, considerably lower than the current 2017 estimate of 226.

Atmospheric wind and divergence patterns

Additional causes of strong 2017 hurricane activity are suggested by regional ASO atmospheric anomalies, illustrated in patterns of lower-tropospheric (925 hPa) winds and relative divergence (Fig. 4A). Negative divergence anomalies (blue shading) reflect areas of enhanced low-level wind convergence, including a well-defined cell of over the Gulf of Mexico, the most extreme observed across the globe. In the tropics, anomalous low-level convergence favors stronger convective ascent and greater accumulation of water vapor and associated latent heat energy from surrounding ocean areas, conditions strongly associated with cyclone formation and intensification. During ASO 2017, strong convergence over the Gulf of Mexico coincided with hurricanes Harvey, Irma, Nate and Katia, which impacted surrounding Gulf coastal areas of the United States and Mexico. ASO wind patterns (Fig. 4A) show that anomalous low-level flow was directed toward the Gulf of Mexico from a coherent zone of enhanced divergence in the subtropical SE Pacific. Over the South Atlantic, a secondary cell of positive divergence anomalies funneled moisture northward over tropical South America and further across the equator toward the tropical North Atlantic.

During La Niña summers (Fig. 4B), anomalous divergence over the central and eastern Pacific generally coincides with enhanced convergence to the east over the Gulf of Mexico, Caribbean

Sea, and tropical North Atlantic (Fig. 4B). However, during ASO 2017, regional divergence anomalies displayed a predominantly meridional (north-south) orientation, particularly notable along 90°W (Fig. 4A) where enhanced convergence at 20°N over the Gulf of Mexico contrasted with a cell of anomalous divergence at 20°S in the SE Pacific. Comparable meridional patterns can be seen in composite ASO wind and divergence anomalies during summers with unusually high levels of ACE (≥ 175) (Fig. 4C) and US hurricane landfalls (≥ 3) (Fig. 4D).

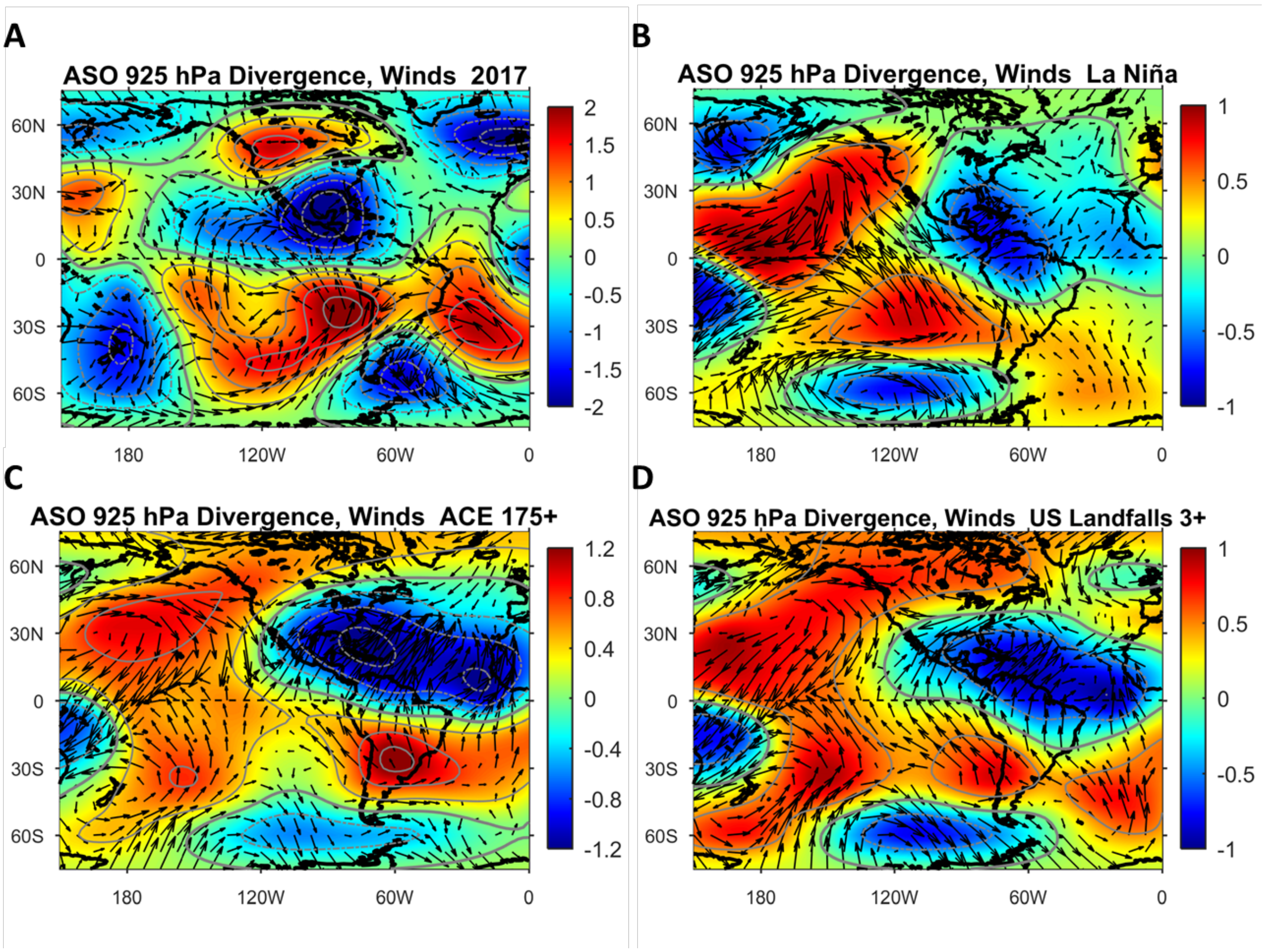

Figure 4. August-October (ASO) atmospheric anomalies of low-level (925 hPa) relative divergence (shading) and winds (vectors). A. 2017. B. La Niña. C. ACE ≥ 175. D. US Landfalls ≥ 3.

Remarkably, the hurricane-favorable divergence anomalies of ASO 2017 were already established in early summer (May-July, MJJ) (Fig. 5A), preceding development of La Niña and strong late-summer hurricane activity. The persistence of this regional circulation pattern from early to late summer (Figs. 5A, 5C) can likely be attributed to interactions between the upper ocean and the overlying atmosphere that tend to reinforce pre-existing anomalies of SST, divergence and regional winds.

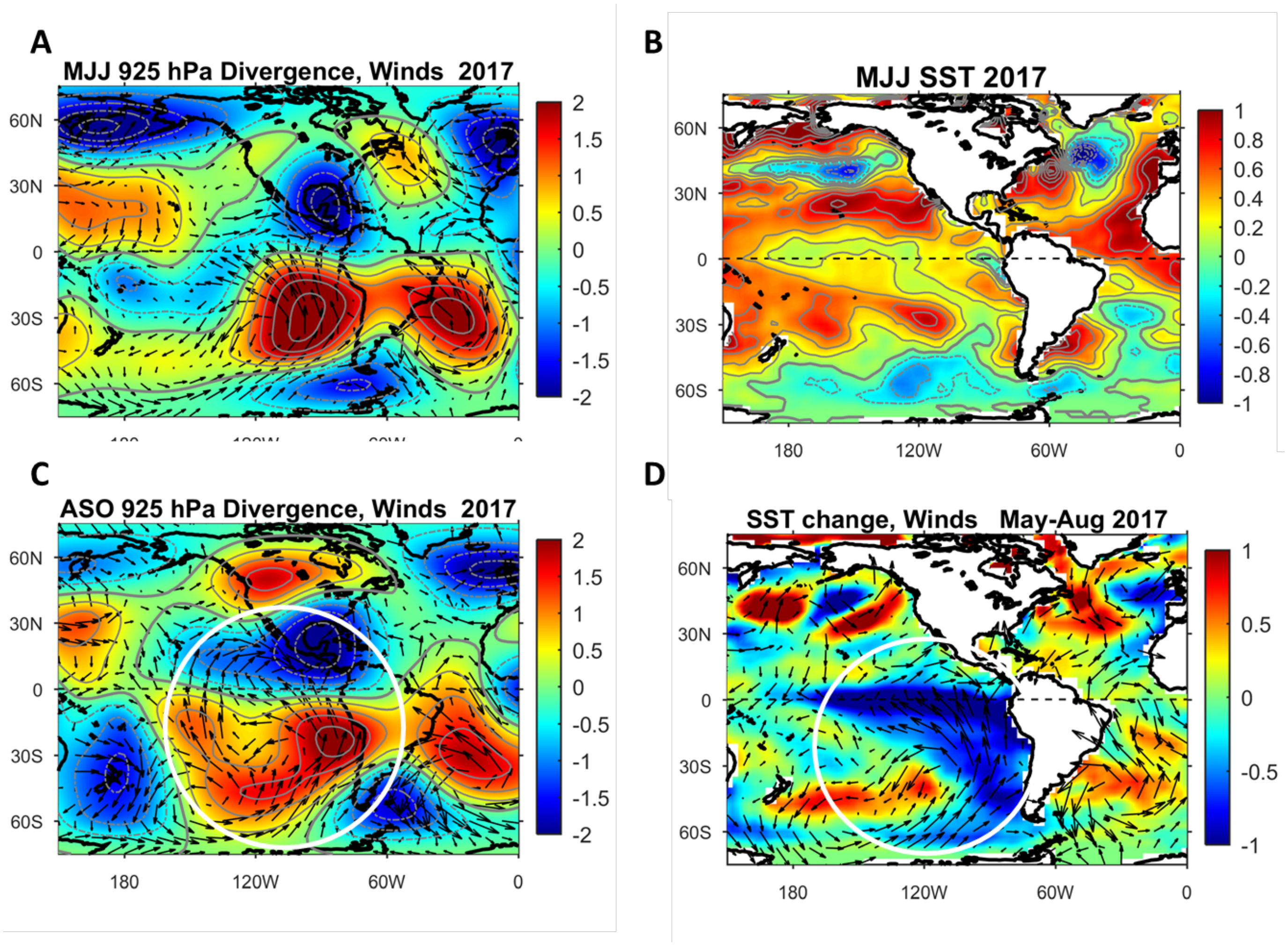

Figure 5. Atmosphere-ocean anomalies and changes during the summer of 2017. A. May-July (MJJ) anomalies of atmospheric 925 hPa divergence (shading) and winds (vectors). B. MJJ SST anomalies (°C). C. August-October (ASO) divergence and wind anomalies (same as Fig. 4A). D. Anomalous winds (vectors) and SST changes (°C shading) during May-August 2017. Pacific Meridional Mode signatures are highlighted by ovals in panels C and D.

Atlantic and Pacific Meridional Modes

The Atlantic and Pacific Meridional Modes (AMM and PMM) (Chiang and Vimont 2004)[1] describe recurrent, organized patterns of opposite SST and atmospheric divergence anomalies that tend to form on either side of the equator in the tropical Atlantic and eastern Pacific. In each

[1] Chiang, John CH, and Daniel J. Vimont. Analogous Pacific and Atlantic meridional modes of tropical atmosphere–ocean variability. Journal of Climate 17.21 (2004): 4143-4158.

basin, meridional dipole anomaly patterns tend to be sustained or amplified by anomalous low-level cross-equatorial winds that are strong in areas of anomalous divergence and lower SST, and weak in areas of convergence and warmer SSTs in the opposite hemisphere.

During early summer (MJJ) 2017, warm SSTs (Fig. 6B) and anomalous convergence (Fig. 6A) prevailed in tropical areas north of the equator from the NE Pacific to the Atlantic. Anomalous convergence in the north, centered over the Gulf of Mexico, was fed largely by cross-equatorial southerly winds originating from areas of anomalous divergence and relatively low SSTs in the SE Pacific and South Atlantic. From May to August, mean southerly winds intensified along the Pacific coast of South America, increasing evaporative cooling rates and lowering SE Pacific SSTs, while La Niña conditions developed simultaneously with cooling of the equatorial eastern Pacific (Fig. 6D).

Equatorward winds in the Southern Hemisphere tend to veer westward due to the Coriolis effect, a consequence of the earth's rotation. In the SE Pacific, anomalous equatorward flow from May to August 2017 shows a pattern of westward steering favorable to reinforcement of the mean southeasterly trade winds, increases in overall wind speeds and anomalous turbulent heat losses by the surface ocean.

During this period, SE Pacific SST cooling coincides with areas of anomalous equatorward and southeasterly winds, but displays a sharp northern boundary along the equator. This spatial pattern of cooling is also consistent with distinctive cross-equatorial ocean-atmosphere patterns associated with the Pacific Meridional Mode and the Coriolis effect. As anomalous southerly flow crosses the equator into the Northern Hemisphere, the Coriolis effect generates an opposite eastward steering of poleward winds that counters the flow of mean northeasterly trade winds, reducing wind speeds and producing a warming tendency that enhances the cross-equatorial SST gradient, a key indicator of PMM processes. While NE Pacific warming is not apparent from May to August 2017, the SST contrast across the equator clearly intensified with with cooling in the south, while convergence increased over the Gulf of Mexico with anomalous cross-equatorial winds originating in the SE Pacific. Opposite, equatorially-symmetric divergence anomalies in the eastern Pacific provide additional evidence suggesting that positive ocean-atmosphere feedbacks of the Pacific Meridional Mode contributed to exceptional levels of low-level atmospheric convergence and hurricane activity over the Gulf of Mexico. The combined effects of PMM and AMM feedbacks were likely important contributors to high US landfall totals and extreme ACE anomalies over the broader North Atlantic.

Regional divergence anomalies in ASO 2017 (Fig. 7A) share general features with those of active hurricane seasons in 2008 (ACE 146, 3 US landfalls, Fig. 7B) and 1999 (ACE 173, 3 US landfalls, Fig. 7C). In each case, high levels of ACE and US landfalls coincided with a coherent cell of anomalous ASO convergence that covered much of the area from the tropical NE Pacific to the tropical North Atlantic. By contrast, anomalous low-level divergence was fully or nearly continuous in a surrounding horseshoe pattern above the subtropical South Atlantic, tropical and subtropical areas of the central and eastern Pacific, and midlatitude areas of North America and the North Atlantic.

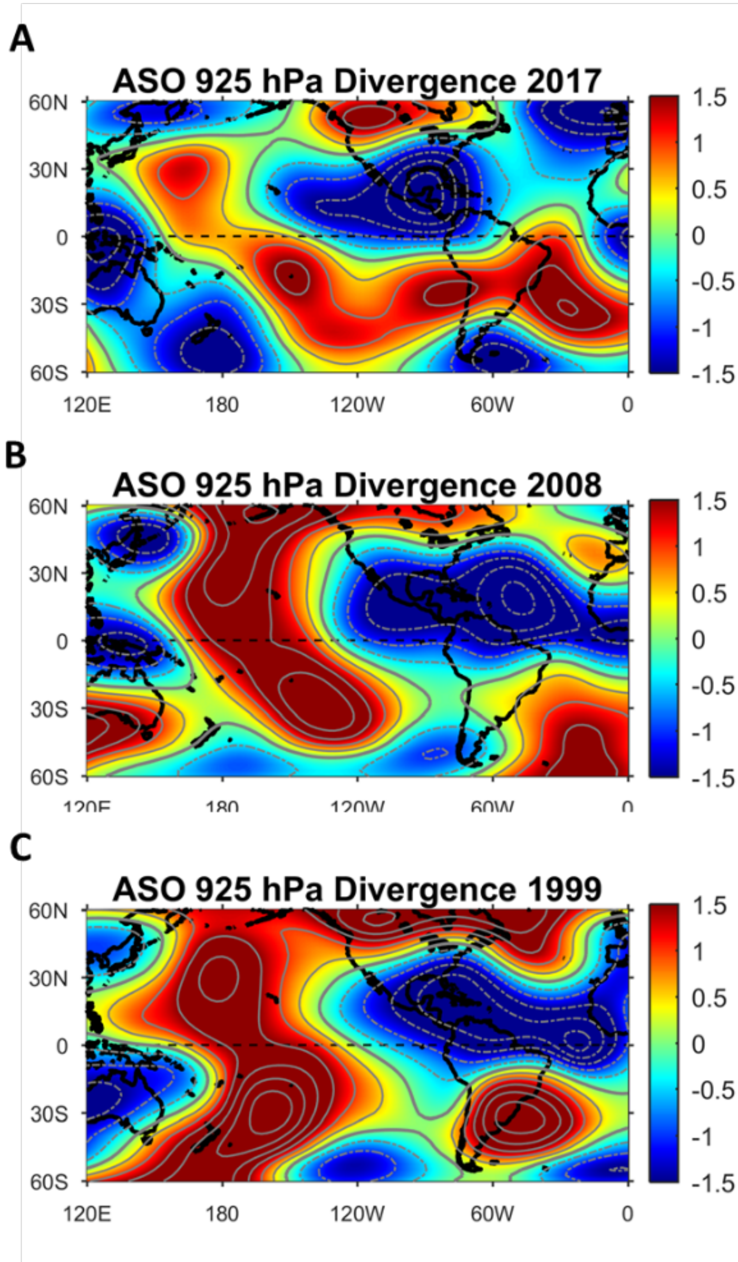

Figure 6. Historical analogues to 2017 summer atmospheric conditions. A. August-October (ASO) normalized anomalies of 925 hPa relative divergence during 2017 (ACE ~226, 3 US landfalls). B. 2008 (ACE 146, 3 US landfalls). C. 1999 (ACE 173 , 3 US landfalls). Each season displayed anomalous low-level convergence (negative divergence anomalies, blue shading) from the tropical NE Pacific to the tropical North Atlantic, and anomalous divergence (red shading) in a surrounding horseshoe involving areas of the subtropical South Atlantic, South America and the SE Pacific, the tropical-subtropical central Pacific (both hemispheres), and midlatitude areas of North America and the North Atlantic.

Arctic influences

A remarkably stable connection between spring Arctic conditions and US hurricane landfalls (Fig. 7) contributed to our June forecast of 3 landfalling storms in 2017, as later observed. While this Arctic index displays a highly-significant relationship with US landfalls, the underlying processes are not widely known, and remain a subject of continued investigation. In our August forecast update, landfall and ACE estimates were revised downward to modestly above-normal levels of 1.6 and 128, respectively, due competing positive and negative circulation influences suggested by an ensemble of statistical models.

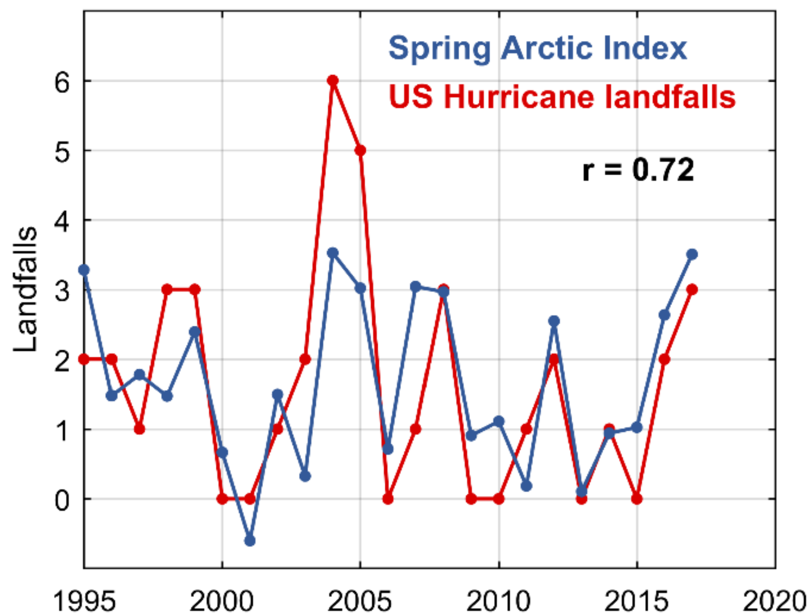

Figure 7. Spring Arctic index and US hurricane landfalls, 1995-2017.

Conclusions

Evidence from the ocean and atmosphere suggests that North Atlantic and US hurricanes vary in response to the combined influences of ENSO, the Atlantic and Pacific and Meridional Modes, and less-understood, but important extratropical processes. CFAN is presently considering these factors and others in our ongoing assessment of the upcoming 2018 North Atlantic hurricane season. Recent history shows that highly active years have occurred consecutively (1998-99, 2003-05), warranting particular attention to developing changes in late 2017 and early 2018.

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