Influence of Tropical Pacific Sea Surface Temperature on the Genesis of Gulf Stream Cyclones

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ABSTRACT

This study investigates the relationship between tropical Pacific sea surface temperature (SST) variability and cyclogenesis over the Gulf Stream region of the North Atlantic. A cyclone identification scheme and Lagrangian trajectories are used to compare preferred cyclogenesis locations and precyclogenesis flow paths associated with three patterns of tropical Pacific SST variability: eastern Pacific (EP) El Niño, central Pacific (CP) El Niño, and La Niña. During EP El Niño and La Niña winters, the upper-level precyclogenesis flow takes a subtropical path over North America and Gulf Stream cyclogenesis predominantly occurs under the North Atlantic jet entrance, which is the climatologically preferred location. In contrast, during CP El Niño winters, when the warmest SST anomalies occur in the central tropical Pacific, the precyclogenesis flow takes a northern path across North America and Gulf Stream cyclogenesis tends to occur farther north under the jet exit. The shift in preferred cyclogenesis is consistent with changes in transient upstream flow perturbations, detected using potential vorticity (PV) streamer frequencies, which are associated with the stationary wave response. Compared to EP El Niño winters, CP El Niño winters exhibit fewer southward-extending streamers and cyclonic (LC2) flow behavior, resulting in precyclogenesis air bypassing the right entrance of the North Atlantic jet. Downstream, Gulf Stream cyclones penetrate deeper into high Arctic latitudes during CP El Niño winters than in other cases. The results highlight distinct signatures of tropical SST anomalies on synoptic-scale atmospheric features and could help constrain future changes in the North Atlantic storm track and the associated poleward heat transport.

1. Introduction

The North Atlantic storm track moderates climate over the Atlantic–European sector, and an understanding of the physical mechanisms behind its variability is needed to better constrain the regional impacts.

Factors that control the mean strength, position, and orientation of the storm track are well documented (Shaw et al. 2016): these include underlying SST patterns (Brayshaw et al. 2008, 2011), the equator-to-pole temperature gradient (Chang et al. 2002; Schneider 2006), and the upper-tropospheric jet stream (Hoskins and Valdes 1990; Chang et al. 2002; Schneider 2006). However, factors that control variations in its anchor point (i.e., the main region of cyclogenesis over the warm Gulf Stream) have received less attention. The current study examines the influence of tropically induced flow perturbations on cyclogenesis and the storm track.

The Gulf Stream acts as an “anchor” for the North Atlantic storm track. It maintains a low-level zone of enhanced baroclinicity (Hoskins and Valdes 1990; Kwon et al. 2010), which, together with the overlying jet stream, makes the region between Cape Hatteras and

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Nova Scotia amenable for explosive cyclogenesis and deepening of existing cyclones during all seasons (Sanders 1986; Hoskins and Valdes 1990; Neiman and Shapiro 1993; Bosart 1999; Jacobs et al. 2005; Booth et al. 2012). However, the interaction between the Gulf Stream SSTs and the storm track is complex. While surface turbulent fluxes have been shown to be one driving agent behind the tropospheric circulation in this region (Nakamura et al. 2008; Kwon et al. 2010), much of their variability on and below synoptic time scales is controlled by the atmosphere itself (Shaman et al. 2010). For example, Booth et al. (2012) showed that the spatial variability of the surface storm track over the Gulf Stream, in particular the 10-m wind, is strongly affected by the stability of the marine planetary boundary layer and preconditioning by surface fluxes, but much of the temporal variability of the surface storm track is controlled by variability in the free troposphere.

Tropical Pacific SST variability is known to be an important driver of extratropical climate variability in both hemispheres, with consequences for regional weather patterns (Trenberth et al. 1998; Hoerling et al. 2001; Alexander et al. 2002; Seager et al. 2003; Ding et al. 2014). The remote influence of El Niño on the North Atlantic–European sector was previously thought to be small compared to other regions of the globe (Trenberth et al. 1998), but recent studies document possible teleconnections to the North Atlantic (Larkin and Harrison 2005; Brönnimann et al. 2007; Ineson and Scaife 2009; Graf and Zanchettin 2012) and Arctic (Ding et al. 2014; Baggett and Lee 2015) regions. Suggested mechanistic pathways from the tropical Pacific to the North Atlantic include a “stratospheric bridge” (Ineson and Scaife 2009; Butler et al. 2011) and a “subtropical bridge” (Graf and Zanchettin 2012) involving changes to the large-scale atmospheric circulation. The diversity of El Niño must also be accounted for (Capotondi et al. 2015), especially given that longitudinal variations in tropical SST anomalies can produce distinct stationary wave trains (Hoskins and Karoly 1981; Palmer and Mansfield 1984; Kao and Yu 2009; Ciasto et al. 2015). In particular, warming in the central Pacific (CP) produces a statistically significant surface cooling over Europe, but no such significant influence is identified for a warming in the eastern tropical Pacific (EP; Graf and Zanchettin 2012). Since tropical Pacific SST variability is known to affect extratropical cyclone activity (Eichler and Higgins 2006) and daily temperature extremes (Bengtsson et al. 2006), it is reasonable to assume that circulation changes on synoptic scales as well as at monthly or seasonal scales must be important in determining tropical–extratropical teleconnections. Yet there is limited understanding of how tropical

perturbations influence the development of the transient synoptic weather systems that shape extratropical climate.

This study analyzes the extratropical synoptic features associated with warm SST anomalies in the eastern (EP El Niño), central (CP El Niño), and western (La Niña) tropical Pacific to help better constrain the mechanisms underlying the associated changes North Atlantic storm track. Analyzing 6-hourly reanalysis data, we find a shift in the preferred location of Gulf Stream cyclogenesis (i.e., the formation of extratropical cyclones) during CP El Niño winters compared to La Niña and EP El Niño winters. We also find upstream differences and downstream effects associated with highly transient flow structures that are robustly linked to cyclogenesis events but partially masked in monthly or seasonal averages. We focus on Gulf Stream cyclogenesis and precyclogenesis time steps during EP El Niño-, CP El Niño-, and La Niña-influenced winter months, because transient dynamically relevant flow structures that precede cyclogenesis might become masked in monthly averaged data.

2. Data and methods

Wintertime [December–February (DJF)] extratropical cyclogenesis is identified in 6-hourly ERA-Interim data on a $1^\circ \times 1^\circ$ grid (Dee et al. 2011) from 1979 to 2014 using the cyclone identification and tracking scheme of Wernli and Schwerz (2006). The detection scheme identifies and tracks closed contours of mean sea level pressure.

Trajectory calculations are performed using the Lagrangian Analysis Tool (LAGRANTO) (Sprenger and Wernli 2015). At every cyclogenesis event, trajectories are calculated backward starting at each grid point within a 500-km radius centered on the location of cyclogenesis. In the vertical, the starting positions are staggered by increments of 5 hPa in the layers 1000–800, 600–400, and 300–100 hPa. To obtain a smooth, gridded position density field from the bundle of backward calculated trajectories, all grid points within a radius of 300 km around the interpolated position of the individual trajectories are flagged with a value of one to indicate the presence of a trajectory. The resulting sum at every grid point represents the number of trajectories located near this grid point at a certain time step—for example, 48 h before cyclogenesis. The summed field is normalized by area and the total number of trajectories, then by its integral over Earth’s surface such that we obtain an air-parcel probability that integrates to unity at each time step.

The detection of potential vorticity (PV) streamers, surrogates for wave breaking (Thorncroft et al. 1993; Wernli and Sprenger 2007), uses the shape of the

dynamical tropopause (2 PV unit contour; 1 PVU = $10^{-6} \text{ K kg}^{-1} \text{ m}^2 \text{ s}^{-1}$) on the 320-K isosurface. If the great-circle distance between one grid point and any other grid point on the contour is less than the distance between the two grid points along the contour, a streamer is identified (Wernli and Sprenger 2007). Grid points where a streamer is detected are flagged with a value of one, and these distributions are time averaged to yield the streamer composites, which indicate the percentage of total time steps when a streamer is present at a particular grid point. The dynamical tropopause marks the zone of the strongest PV gradient between low-PV tropospheric air and high-PV stratospheric air on an isentropic surface. This zone collocates with the jet stream. Therefore, PV streamers, as reflected by excursions of the dynamical tropopause, are useful to shed light on transient jet stream excursions.

The definitions of El Niño and La Niña seasons are based on NOAA's Oceanic Niño index (ONI), and the separation into EP and CP El Niño seasons is based on a consensus of three indices following Yu et al. (2012). The seasons are EP El Niño: 1982/83, 1986/87, 1997/98, and 2006/07; CP El Niño: 1987/88, 1991/92, 1994/95, 2002/03, 2004/05, and 2009/10; and La Niña: 1988/89, 1998/99, 1999/2000, 2007/08, and 2010/11 (ONI > 1).

3. Results

Climatologically, cyclogenesis occurs most frequently over the Gulf Stream east of Cape Hatteras (35°N, 75°W; Fig. 1), consistent with the findings of Hoskins and Hodges (2002). The upper-tropospheric flow in this region is typically characterized by a jet streak extending from Cape Hatteras northeastward toward Newfoundland. Cyclogenesis requires a combination of a flow anomaly at upper levels and a zone of enhanced baroclinicity at lower levels. The latter is found above the warm Gulf Stream as a result of strong ocean-to-atmosphere heat fluxes, making the area favorable for cyclogenesis during all seasons. However, the position of the jet is critical. Quasigeostrophic theory predicts that cyclogenesis should preferentially occur under either the right entrance or left exit of a jet streak, where rising motion is favored owing to divergence of the ageostrophic wind aloft (Keyser and Shapiro 1986). Observations support this prediction, with the right jet entrance dominating (Fig. 1; Keyser and Shapiro 1986).

Using trajectory analysis, we first examine the origin of air associated with cyclogenesis for climatological-mean winter conditions (section 3a), then during EP El Niño winters, CP El Niño winters, and La Niña winters (section 3b). Next, we investigate upstream flow anomalies preceding cyclogenesis during the three types of

winters (section 3c). Finally, we look downstream to document the effects of shifting the preferred location of cyclogenesis on North Atlantic cyclones (section 3d) before we conclude (section 4).

a. Climatological pathways to Gulf Stream cyclogenesis

In the upper troposphere (300–100 hPa; Fig. 1), the precyclogenesis flow predominantly follows the path of the subtropical jet, is adiabatic and dry, and slants gradually upward (Fig. 2; blue shading) from the Pacific to the Atlantic. Starting 72 h before cyclogenesis, precyclogenesis air is located at the exit region of the Pacific jet stream (Fig. 1e). The air crosses the southern United States from 48 h (Fig. 1d) to 24 h before cyclogenesis (Fig. 1c). At 6 h before cyclogenesis over the Gulf Stream, the air parcels in the upper troposphere (Fig. 1b, left) sit over the southeastern United States (33°N, 82°W), upstream of the right jet entrance.

Diabatic effects are more important for the precyclogenesis flow at lower levels. In the midtroposphere (600–400 hPa), precyclogenesis air starts off over the Gulf of Mexico 72 h before cyclogenesis (Figs. 1e,d) and moves along the Gulf coast before turning northeastward toward Cape Hatteras 12–24 h before cyclogenesis. During these last 24 h, the air ascends by 100 hPa while relative humidity increases (Fig. 2c; red). In the lower troposphere (1000–800 hPa), precyclogenesis air starts off over the Great Lakes (42°–44°N, 81°–86°W) 72 h before Gulf Stream cyclogenesis, then moves toward Cape Hatteras, where it aligns along the line of neutral moist static stability (Figs. 1e–a). On the way, the air descends by 100–150 hPa (Fig. 2a). At 1 day (24 h) before cyclogenesis, the flow is diabatically modified, picking up moisture above the ocean to approach saturation (Figs. 2b,d; gray).

b. Gulf Stream cyclogenesis during EP El Niño, CP El Niño, and La Niña winters

The EP El Niño, CP El Niño, and La Niña winters exhibit differences in precyclogenesis flow paths starting 36 h before cyclone formation, primarily in the upper troposphere (Fig. 3d). During EP El Niño and La Niña winters, the main pathway is subtropical, similar to climatology, with the maximum in density (black triangles) moving across the southern United States (Figs. 3b–d, left and right). In CP El Niño winters, however, the primary maximum in density (black diamond) takes a different path across the northern part of the United States, bypassing the jet entrance to the north (Figs. 3b–d, middle). The La Niña pathway is generally quite confined to the subtropical route. El Niño winters show some secondary maxima in density 36 and 24 h before

FIG. 1. The history of air associated with Gulf Stream cyclogenesis during winter (DJF) at different levels in the troposphere. Shown is the climatological probability density (shading) for air that, at cyclogenesis, is located in a layer between (left) 300 and 100, (center) 600 and 400, and (right) 1000 and 800 hPa at (a) genesis and (b) 6, (c) 24, (d) 48, and (e) 72 h before cyclogenesis. (left) Pink contours indicate 300-hPa seasonal winter-mean wind speed (contours at 35 and 40 m s^{-1}), (center) red contours indicate the winter-mean 500-hPa geopotential height (from 540 to 580 gpm at intervals of 10 gpm), and (right) low-level averaged neutral moist (yellow) and dry (red) static stability ($0.9, 1.3 \times 10^{-4} \text{ s}^{-2}$).

FIG. 2. Temporal evolution of (a) pressure (hPa), (b) specific humidity (g kg^{-1}), (c) relative humidity (%), and (d) equivalent potential temperature (K) along precyclogenesis trajectories for air parcels located between 300 and 100 (blue), 600 and 400 (red), and 1000 and 800 hPa (gray) at genesis over the Gulf Stream. The thickness of the colored shading indicates plus or minus half the standard deviation of the trajectory sample. Center contours correspond to mean full (solid), EP (dotted), and CP (dashed) El Niño trajectories. The differences in the mean evolution are marginal.

cyclogenesis indicating that some trajectories take a more polar route across North America (Figs. 3c–d, left and middle). Despite their different flow paths, the precyclogenesis air associated with all three tropical Pacific SST patterns exhibits similar temporal evolutions of pressure, relative, and specific humidity (cf. Fig. 2).

Because precyclogenesis flow paths are shifted north in CP El Niño relative to EP El Niño and La Niña winters, there is also a northward shift in the preferred cyclogenesis location. In the EP El Niño and La Niña composites, the precyclogenesis flow enters the right jet entrance 6 h before cyclogenesis (Fig. 3b, left and right), creating a cyclogenesis maximum near Cape Hatteras (Fig. 3a, left and right) just as in climatology (Fig. 1a). In contrast, in the CP El Niño composite, the northward-deflected flow

results in surface depressions that form below the left jet exit, shifting the cyclogenesis maximum northeastward to the coast of Nova Scotia (Fig. 3a, middle).

The robustness of the CP El Niño-related findings is verified by reversing the analysis to detect CP El Niño winters from cyclogenesis location. Selecting seasons with preferred cyclogenesis below the jet exit (1979–2014) returns four of the six previously defined CP El Niño winters (1991/92, 1994/95, 2004/05, and 2009/10), plus two additional winters that are neither CP El Niño nor EP El Niño winters (1992/93 and 1996/97). Of the two remaining CP El Niño winters, one has an almost equal number of entrance and exit genesis events (2002/03) and one is an outlier (1987/88). No EP El Niño winter is falsely identified, demonstrating that CP and EP El

FIG. 3. The history of upper-tropospheric (300–100 hPa) air involved in Gulf Stream cyclogenesis during El Niño-influenced winter seasons (DJF). Shown is the probability density of air (shading) for (left) EP El Niño, (center) CP El Niño, and (right) La Niña winters at (a) genesis and at (b) 6, (c) 24, and (d) 36 h prior to cyclogenesis. Pink contours correspond to the mean 300-hPa wind speed at these time steps (from 35 m s^{-1} at 5 m s^{-1} intervals). Markers highlight the maxima in densities (upward triangle for EP El Niño; diamond for CP El Niño; downward triangle for La Niña).

Niño-related cyclogenesis signatures are broadly independent of analysis approach. Further, the result shows that the composites (Fig. 3) are not governed by a single extreme season. When we select winter seasons during which the subtropical maximum in the -24-h -precyclogenesis density (Fig. 3c) is north of 36°N and east of 100°E , we identify the three of the six CP El Niño winters (1994/95, 2004/05, and 2009/10) and one neutral winter (1992/93). These checks provide a measure of confidence in the results despite the small sample size. A north-eastward shift of the precyclogenesis flow compared to climatology, EP El Niño winters, and La Niña winters is hence a strong indicator for CP El Niño-influenced flow conditions over North America.

While CP El Niño has a special precyclogenesis pathway for upper-tropospheric air, the same is not true at lower levels. The low-level precyclogenesis pathways during CP El Niño winters show only small differences compared to EP El Niño (Fig. S1), the climatology (cf. Fig. 1, right), and La Niña (not shown) winters. The maximum in density for low-level precyclogenesis air 72 h before cyclogenesis (Fig. S1d) is over the Great Lakes, similar as for the climatology. The air initially advects eastward toward Cape Cod in both cases; during EP El Niño winters, the air then turns southwestward to end up below the jet entrance, while during CP El Niño winters it turns northeastward to end up below the jet exit (Figs. S1c,b). Furthermore, there are no obvious

FIG. 4. Winter 300-hPa geopotential height composites for (a) climatology, (b) La Niña seasons, (c) EP El Niño seasons, and (d) CP El Niño seasons. Black contours show the composite mean (from 890 to 940 gpdm at intervals of 10 gpdm) and color shading shows the departure from the climatological mean (gpdm). The thick gray contour is the climatological 930-gpdm contour superimposed on each composite for comparison; the red contour indicates the 930-gpdm contour for the other composites. Because of the small sample of seasonal means, departures from climatology have large uncertainties and should be considered qualitative features.

differences in the history of pressure or moisture along the EP El Niño and CP El Niño precyclogenesis flow paths in the lower troposphere (Fig. 2), which highlights the importance of upper-level forcing for Gulf Stream cyclogenesis.

c. Upstream flow conditions for Gulf Stream cyclogenesis

To investigate the mechanisms underlying the latitudinal shift of precyclogenesis pathways during EP El Niño, CP El Niño, and La Niña winters, we examine associated perturbations in the large-scale atmospheric circulation. The presence of the Rocky Mountains forces a climatological stationary wave pattern consisting of a trough downstream of the mountain barrier over North America [Fig. 4a; see also Fig. 1 (middle) and Held et al. (2002)]. The trough tends to steer precyclogenesis air coming across North America on a subtropical path toward the right entrance of the Atlantic jet, thus favoring entrance cyclogenesis (cf. Fig. 1). Because the North American trough is present regardless of El Niño or La Niña conditions (Figs. 4b–d), we expect entrance cyclogenesis to dominate, as in the climatological mean. There are differences in the stationary

wave pattern of La Niña compared to El Niño winters, indicating a more pronounced ridge during La Niña and an equatorward shifted Pacific jet during El Niño (Fig. 3 and Figs. 4b–d), consistent with previous findings (Palmer and Mansfield 1984; Hoerling et al. 1997; Seager et al. 2003). However, differences between EP and CP El Niño seasons are modest. (There is a slight cyclonic tilt of the seasonal-mean CP El Niño anomaly pattern with respect to the EP El Niño pattern, which could be associated with changes in the nature of the transient wave life cycles, as will be discussed below.) The emerging question then is why CP El Niño winters experience a northern precyclogenesis flow path compared to EP El Niño and La Niña winters with preferred exit rather than entrance cyclogenesis. The answer requires us to consider higher-frequency variability in the stationary wave patterns via transient perturbations that can affect flow paths during the days just prior to Gulf Stream cyclogenesis.

The upper-level midlatitude flow follows the jet stream, and meanders of the jet form a hemispheric pattern of Rossby waves that create ridges and troughs such as the ones over North America. Troughs represent the equatorward excursion of strongly stratified air with

high PV from the poles, while ridges represent the northward excursion of weakly stratified air with low PV from the tropics. In the case of a pronounced southward (northward) excursion of a trough (ridge), the flow may wrap up and undergo irreversible deformation in a wave breaking event (McIntyre and Palmer 1983). During wave breaking of a trough, the flow deformation pulls narrow bands (streamers) of high-PV polar air into lower latitudes (Thorncroft et al. 1993; Wernli and Sprenger 2007); this tends to occur during anticyclonic wave breaking (LC1) compared to cyclonic wave breaking (LC2) (Thorncroft et al. 1993). Detecting streamers thus allows us to quantify highly transient, finescale excursions of the jet that could be dynamically important for modifying cyclogenesis, but whose effects may not be apparent in monthly or seasonal averages.

Composites of PV 3 days before cyclogenesis (Fig. 5) show large-scale flow features that are consistent with those in the precyclogenesis composites (Fig. 3) and the seasonal-mean circulations (Fig. 4) but provide additional insights. Starting with El Niño, recall that the upstream flow in the Pacific is quite similar for both variants despite the precyclogenesis flow paths over North America being different (Fig. 3, left and center). In the PV composites, we begin to see differences in the ridge–trough pattern that, while subtle, point to dynamical consequences (Figs. 5a,b). During EP El Niño winters, the ridge is tilted southwest–northeast (forward) over the northwestern United States (Fig. 5a), while during CP El Niño winters, the ridge is tilted southeast–northwest (backward) over the Bay of Alaska (Fig. 5b), which becomes clearer from the difference pattern (Fig. 5d). Within the framework of baroclinic life cycles, the forward-leaning ridge in the EP El Niño case exhibits features of anticyclonic (LC1) behavior, which is favorable for the development of southward-extending streamers, while the backward-leaning ridge in the CP El Niño case exhibits features of cyclonic (LC2) behavior, in which there are typically no southward-extending streamers and hence no transient southward movements of the mean flow (Thorncroft et al. 1993).

The actual streamer occurrences fit the baroclinic life-cycle framework. Climatologically, cyclogenesis over the Gulf Stream is preceded by southward streamer excursions in the lee of the Rocky Mountains, seen by comparing streamer detection rates 24 h before all Gulf Stream cyclogenesis events with the DJF seasonal-mean detection rates (Figs. 6a,b). One day before cyclogenesis, EP El Niño winters are also associated with streamer anomalies concentrated in the lee of the Rockies (Fig. 6c), similar to but positioned slightly southwest of those in the full precyclogenesis climatology (Fig. 6a).

FIG. 5. Composite of potential vorticity (shading) on the 320-K isotherm (PVU) for (a) EP El Niño, (b) CP El Niño, and (c) La Niña seasons at 72 h before cyclogenesis over the Gulf Stream region. Gray contours indicate variance of composite sample. (d) Difference between (a) and (b).

FIG. 6. (a) Standardized stratospheric-streamer frequency difference (color shading; difference expressed in standard deviations of the full climatology) on the 320-K isotherm between all precyclogenesis (-24 h) time steps and (b) the seasonal (DJF) streamer frequency climatology (gray shading; percentage of all DJF time steps). Further shown are the standardized stratospheric-streamer differences for (c) EP- and (d) CP El Niño-related precyclogenesis (-24 h) time steps. Black contours in (a), (c), and (d) correspond to 300-hPa wind speed anomalies (m s^{-1} ; negative dashed, positive solid) and orange contours in (b) correspond to the DJF 300-hPa seasonal-mean wind speed. Markers in (a), (c), and (d) correspond to the maxima in precyclogenesis air densities 24 h before Gulf Stream cyclogenesis during EP El Niño (upward triangle), CP El Niño (diamond), La Niña (downward triangle), and for all winter seasons (asterisk; as seen in Fig. 3c).

This close agreement in streamer occurrences between the climatology and the EP El Niño composite is accompanied by an agreement in the probability density distributions for precyclogenesis (-24 h) air [see maxima for all cyclogenesis events (black asterisk) and EP El Niño winters (upward triangle) marked in each map] and in preferred entrance cyclogenesis (Figs. 1a and 3a). In contrast, CP El Niño winters are associated with fewer southward streamer extensions in the lee of the Rockies (Fig. 6d) compared to the precyclogenesis climatology (Fig. 6a) and with a maximum in streamer activity shifted northeastward compared to EP El Niño winters (Fig. 6b). The expected LC2-like scenario would favor transient perturbations and wave breaking north of the mean flow (Thorncroft et al. 1993). The relative difference between the CP and EP El Niño-related streamer occurrences is large and statistically significant at this key time and in this key location (Fig. S2).

La Niña winters follow the climatological pattern, with a southern precyclogenesis flow path and preferred entrance cyclogenesis. In terms of the large-scale circulation, the Pacific jet exhibits some anomalies

(Fig. 3c, right), but the North American stationary trough is similar to climatology (Fig. 4b), and this latter feature seems more important in guiding the upper-level air toward the right Atlantic jet entrance. The trough exhibits very little tilt, which is in agreement with little waviness in the PV composite (Fig. 5c), and hence transient wave development is unlikely to occur during La Niña winters unlike during El Niño winters. Indeed, this is consistent with the lack of transient PV streamers in the lee of the Rocky Mountains 24 h before cyclogenesis (Fig. S3), suggesting that streamer activity is not a prerequisite for entrance cyclogenesis over the Gulf Stream.

In summary, we must consider both the mean circulation and transient perturbations to explain Gulf Stream cyclogenesis during EP El Niño, CP El Niño, and La Niña winters. The key is how these combine to determine the precyclogenesis flow path of upper-tropospheric air that will eventually participate in cyclogenesis events. During EP El Niño winters and La Niña winters, precyclogenesis flow paths are climatologically “normal” (i.e., they guide air into the

FIG. 7. Storm-track differences between EP and CP El Niño winter seasons. (a) Relative fraction of cyclones originating from the Gulf Stream region during (left) EP and (right) CP El Niño winters compared with the full EP and CP El Niño cyclone climatologies, respectively. The dashed box, which follows the eastern coastline of North America, indicates the Gulf Stream region. (b) Cyclone frequency anomalies (shading) during (left) EP and (right) CP El Niño winters relative to the full-winter cyclone climatology (1979–2014). Additional contours show total (i.e., for all cyclones, not only those originating from the Gulf Stream region) cyclone detection rates in EP and CP El Niño winters (from 15% in steps of 10%).

right jet entrance). For EP El Niño winters, there is an additional effect of vigorous transient streamer activity quite far south in the lee of the Rockies (Fig. 6c) that encourages an even more southern precyclogenesis flow path, in agreement with the more anticyclonic (LC1) character of the upper-level wave (Fig. 5a). During CP El Niño winters, the precyclogenesis flow paths are shifted northward compared to climatology, EP El Niño, and La Niña. This is partly due to reduced streamer occurrences in the lee of the Rockies, as well as the more cyclonic (LC2) character of the upper-level wave (Fig. 5b) that inhibits streamer extensions south of the mean flow (Fig. 6d). The precyclogenesis flow hence bypasses the jet entrance to its north, shifting the preferred location for cyclogenesis to the jet exit region. The fact that transient streamer anomalies are important in distinguishing EP and CP El Niño winters also supports the idea of a tropospheric pathway linking the North Pacific and North Atlantic in which synoptic eddies play an important role (Li and Lau 2012; Drouard et al. 2015). Overall, EP and CP El Niño winters are associated with different wave life cycles (LC1 and LC2) and PV streamer activity, and the resulting precyclogenesis flow across North America reflects these differences.

d. Downstream behavior of Gulf Stream cyclones during EP and CP El Niño winters

Coming back to the question of why CP El Niño winters are special in their ability to produce robust European impacts, Fig. 7 shows that the northward shift in preferred cyclogenesis location over the Gulf Stream produces local and downstream impacts over the North Atlantic. During CP El Niño winters, cyclones forming over the Gulf Stream track more northeastward into high northern latitudes. In the northern Nordic Seas, the fraction of all cyclones that originate from the Gulf Stream is 20%–25% during CP El Niño winters but only 2%–3% during EP El Niño winters. During EP El Niño winters, cyclones forming over the Gulf Stream track more zonally across the Atlantic, penetrating farther east into continental Eurasia (Fig. 7a). The fact that Gulf Stream cyclones behave differently during the two El Niño variants affects the entire North Atlantic storm track, producing an overall northeastward extension during CP El Niño winters (Fig. 7b).

4. Summary

We present evidence that tropical Pacific SST variability is associated with shifts in the preferred genesis

position of extratropical cyclones over the Gulf Stream and downstream impacts on the North Atlantic storm track. During EP El Niño and La Niña winters, the preferred region of cyclogenesis over the Gulf Stream is below the jet entrance, as in climatology; during CP El Niño winters, there is more frequent jet exit cyclogenesis that shifts the anchor point of the storm track northeastward. Entrance cyclogenesis seems to be generally favored because the stationary trough over North America tends to guide air on subtropical flow paths toward the jet entrance. For EP El Niño winters, there is also vigorous streamer activity quite far south in the lee of the Rockies of an anticyclonic (LC1) nature; the associated transient southward flow excursions reinforce the subtropical route set up by the stationary trough. For CP El Niño winters, the stationary trough is in place, but tilted backward (southeast–northwest) to promote cyclonic (LC2) conditions. The associated changes in streamer activity and upper-tropospheric wave development produce a northeastward shift of the precyclogenesis flow path during CP El Niño. The precyclogenesis flow bypasses the jet entrance, resulting in the rare seasons with more exit than entrance cyclogenesis. Downstream, Gulf Stream cyclones track farther northeastward into the high latitudes during CP versus EP El Niño winters.

It is uncertain how tropical Pacific SST variability will evolve under future climate change (Stevenson et al. 2012; Kim and Yu 2012; Taschetto et al. 2014), but the results here demonstrate that longitudinal shifts in tropical Pacific SST anomalies will affect the formation and propagation of cyclones over the Gulf Stream. The results indicate possible future changes in heat and moisture transport into higher latitudes by cyclones from the Gulf Stream region, pointing to additional linkages between tropical convection sites and Arctic amplification that remain to be explored (Ding et al. 2014; Feldstein and Lee 2014; Baggett and Lee 2015). The presented dynamics shed light on transient synoptic mechanisms by which tropical Pacific SST anomalies influence the North Atlantic storm track and its anchoring point.

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