Convectively Coupled Kelvin Waves and Tropical Cyclogenesis in a Semi-Lagrangian Framework

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ABSTRACT

This study examines how convectively coupled Kelvin waves interact with the semi-Lagrangian circulation of easterly waves to modulate tropical cyclogenesis. Recent studies have shown that fewer tropical cyclones form in the three days before passage of the Kelvin wave’s peak convection and more develop in the three days thereafter. Separately, other studies have identified the recirculation of moisture and vorticity within easterly waves using a semi-Lagrangian frame of reference. That framework is achieved by subtracting the easterly wave phase speed from the earth-relative winds. This study combines these recent findings by testing whether the equatorial westerlies from Kelvin waves can help close the semi-Lagrangian circulation.

Past studies have shown that Kelvin waves tilt westward with height in the troposphere such that equatorial westerlies build upward from the surface in the days following the convective peak. This study shows that the easterly wave’s semi-Lagrangian closed circulation grows upward as it intersects the Kelvin wave’s westward tilt. The Kelvin wave’s westerly anomalies reach 500 hPa about three days after the convection has passed, which establishes the deep, vertically aligned easterly wave vortex necessary for tropical cyclogenesis. This study focuses on the eastern Pacific, but similar results are found for the North Atlantic. In other basins, the Kelvin wave accentuates the westerlies from the Madden–Julian oscillation and/or the monsoon trough. Given that Kelvin waves often last weeks and circumnavigate the globe, these results may advance long-range tropical cyclogenesis forecasting.

1. Introduction

Decades after Gray (1968), tropical cyclogenesis remains one of the biggest research problems in our field. Many distinct lines of inquiry have deepened our understanding, and this study aims to bridge two of the most recent ones. The first explores a semi-Lagrangian framework that moves westward with the precursor easterly waves (Dunkerton et al. 2009; Montgomery et al. 2010; Wang et al. 2010; Wang and Hankes 2014). The second identifies convectively coupled Kelvin waves and their potential impacts on tropical cyclogenesis (Wheeler and Kiladis 1999; Schreck and Molinari 2011; Ventrice et al. 2012a,b; Schreck 2015). This study leverages both of these developments by examining how Kelvin waves interact with the easterly waves’ semi-Lagrangian circulation.

Early tropical cyclogenesis studies recognized easterly waves as the primary precursors for tropical cyclogenesis, especially in the North Atlantic (Dunn 1940; Riehl 1948; Carlson 1969; Avila and Pasch 1995; Thorncroft and Hodges 2001). These open waves are embedded within the trade easterlies, such that they have no westerly flow on their equatorward side until tropical cyclogenesis. Dunkerton et al. (2009) created a semi-Lagrangian wind field by subtracting the easterly wave’s westward motion from the wind vectors. This framework identifies a closed circulation before genesis that recirculates and aggregates moisture, convection, and vorticity (Dunkerton et al. 2009; Montgomery et al. 2010; Wang et al. 2010; Wang and Hankes 2014).

Once called super–cloud clusters (Nakazawa 1988), convectively coupled Kelvin waves are among the most important synoptic systems in the tropics (Wheeler and Kiladis 1999; Kiladis et al. 2009). Similar large-scale convectively coupled systems like the MJO, equatorial Rossby waves, and mixed–Rossby gravity waves modulate tropical cyclogenesis through their effects on low-level vorticity and deep convection (Liebmann et al. 1994;
Dickinson and Molinari 2002; Frank and Rounty 2006; Schreck et al. 2012). The relationship has been less clear for Kelvin waves, in part because of their 10–20 m s\(^{-1}\) eastward phase speed (Sobel and Camargo 2005; Frank and Rounty 2006; Bessafi and Wheeler 2006). Kelvin waves cannot produce tropical cyclones on their own, but they do interact with other precursors. They can amplify easterly waves over Africa that later become tropical cyclones (Mekonnen et al. 2008; Ventrice and Thornicroft 2013). Kelvin waves also modulate tropical cyclogenesis factors like potential vorticity, vertical shear, ventilation, and moisture (Schreck and Molinari 2011; Ventrice et al. 2012a,b; Schreck 2015).

Schreck (2015) examined the relationship between Kelvin waves and tropical cyclogenesis in every basin. In that study, NASA Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analyses (TMPA, TRMM product 3b42) (Huffman et al. 2007) were filtered (TRMM) Multisatellite Precipitation Analyses (TMPA, TRMM product 3b42) (Huffman et al. 2007) were filtered for Kelvin waves following Straub and Kiladis (2002). The number of tropical cyclones that formed on each day were counted relative to the passage of Kelvin wave’s peak rainfall anomalies (i.e., the convective crest). Consistent with Ventrice et al. (2012b), genesis was inhibited for the three days leading up to the crest and enhanced for three days afterward. These results were surprising since other convectively coupled waves enhance tropical cyclogenesis near their convective maxima (Frank and Rounty 2006; Schreck et al. 2011, 2012).

This study brings together these two recent developments to explore why tropical cyclogenesis is favored after the intersection of an easterly wave and a Kelvin wave’s convection. The semi-Lagrangian framework will illustrate the evolution of the easterly wave’s circulation. It is hypothesized here that the vertical tilt of Kelvin waves may explain the lag between their convection and tropical cyclogenesis. A coherent midlevel vortex is a necessary precondition before convective processes can produce a surface vortex (Nolan 2007; Nolan and Rappin 2008), and easterly waves with a deep, vertically aligned circulation are more likely to develop into tropical cyclones (Wang et al. 2010; Agudelo et al. 2011; Brammer and Thornicroft 2015). The Kelvin wave’s westerly anomalies build upward from the surface to 500 hPa in the three days following peak convection (Straub and Kiladis 2003). As the easterly wave passes through these deepening westerlies, its own semi-Lagrangian closed circulation builds upward until tropical cyclogenesis occurs.

2. Data and methods

Schreck (2015) identified the most favorable lag for genesis relative to Kelvin wave convective crests in each basin (Table 1). Tropical cyclogenesis was defined as the first position in the National Hurricane Center (NHC) and the Joint Typhoon Warning Center (JTWC) best tracks, as obtained from the International Best Track Archive for Climate Stewardship (IBTrACS) (Knapp et al. 2010; Schreck et al. 2014). NASA’s Modern-Era Retrospective Analysis for Research and Applications (MERRA) (Rienecker et al. 2011) was then used to composite wind anomalies relative to a daily climatology to examine the effects of Kelvin waves.

This study builds on those results by producing similar composites in a semi-Lagrangian framework (Dunkerton et al. 2009). Rather than using anomalies from climatology, this study subtracts the estimated easterly wave phase speed from the total zonal winds to transform them into the semi-Lagrangian framework. Figure 1 illustrates this process. Similar to Schreck (2015, his Fig. 6), Fig. 1 shows composite Hovmöllers for the 40 eastern Pacific tropical cyclones that developed 3.00–3.75 days after the Kelvin wave crest.

The dashed line in Fig. 1 indicates the estimated phase speed of 5 m s\(^{-1}\). This line roughly follows the maxima in rainfall (Fig. 1a) and 850-hPa zonal wind (Fig. 1b). Table 1 lists the estimated phase speeds for each basin. The results of this study are insensitive to reasonable variations in these estimates. Other studies (e.g., Dunkerton et al. 2009) calculated the phase speed for each individual wave and subtracted from the zonal winds for that particular storm. The composite averaging used here and the subtraction of the phase speed are both linear operations. The results are, therefore, identical when each individual storm’s phase speed is subtracted before the composing or whether the mean phase speed is subtracted from the composite average. In other words,

\[
\langle U(s, x, y, t) \rangle_s - \langle c(s) \rangle_s = \langle U(s, x, y, t) - c(s) \rangle_s,
\]

where \(U\) is the zonal wind, \(c\) is the estimated easterly wave speed for each storm \(s\), and the brackets indicate

<table>
<thead>
<tr>
<th>Basin</th>
<th>Lag (days)</th>
<th>Storms</th>
<th>Phase speed (m s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastern Pacific</td>
<td>3.5</td>
<td>40</td>
<td>5</td>
</tr>
<tr>
<td>North Atlantic</td>
<td>2.5</td>
<td>29</td>
<td>5</td>
</tr>
<tr>
<td>Western Pacific</td>
<td>0.5</td>
<td>71</td>
<td>5</td>
</tr>
<tr>
<td>North Indian</td>
<td>2.5</td>
<td>19</td>
<td>3</td>
</tr>
<tr>
<td>South Indian</td>
<td>3.5</td>
<td>51</td>
<td>3</td>
</tr>
<tr>
<td>South Pacific</td>
<td>1.5</td>
<td>30</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 1. For each basin, the number of days after the Kelvin wave’s convective crest that produced the most tropical cyclones, the number of storms that form at that lag from 1998 to 2013, and their estimated easterly wave phase speed. Lags are binned such that the +1.5-day bin includes +1.0, +1.25, +1.5, and +1.75 days, for example.
the average over all storms. In this case, $\langle c(x) \rangle_s$ is estimated from the composite Hovmöller (Fig. 1).

The semi-Lagrangian winds are based on the total winds rather than anomalies from climatology. Nonetheless, the statistical significance of the composites is evaluated relative to climatology using Schreck’s (2015) resampling method. Values that are not 95% statistically significantly different from climatology are grayed out. Kelvin-filtered rainfall anomalies averaged $0^\circ–10^\circ$N are contoured every 0.05 mm h$^{-1}$ with wet contours in green and dry in orange. The hurricane symbol denotes the composite time and longitude of genesis. The composites are rotated in time and space relative to each storm’s genesis, so the longitude labels are for the median genesis longitude and are shown only for reference. The diagonal dashed line estimates the easterly wave phase speed at 5 m s$^{-1}$. Comparable to Fig. 6 from Schreck (2015), except the lags on the vertical axis are relative to tropical cyclogenesis rather than to the Kelvin wave crest.

3. Results

a. Eastern Pacific

As in Schreck (2015), Figs. 1a and 1b show tropical cyclogenesis about three days after the strongest rainfall and semi-Lagrangian 850-hPa westerlies passed through the genesis longitude. This delay might seem surprising, since enhanced convection and cyclonic 850-hPa westerlies both favor tropical cyclogenesis. However, the 500-hPa zonal winds shed some light on the paradox (Fig. 1c). Within the enhanced convection, the semi-Lagrangian winds are generally easterly and statistically indistinguishable from their climatological values (gray shading). These easterlies from the equator to $10^\circ$N are associated with unfavorable anticyclonic shear with the prevailing westerlies to the north (e.g., Fig. 3b). After the enhanced convection passes, the Kelvin wave produces significant westerly anomalies (no gray shading), and the tropical cyclone forms within the peak of the semi-Lagrangian westerlies at 500 hPa.

Vertical composites of zonal wind (Fig. 2) illustrate the Kelvin wave’s vertical tilt (contours), which resembles those from previous studies (Straub and Kiladis 2003; Kiladis et al. 2009). The easterly wave positions (vertical dashed lines) are extrapolated from the genesis longitude using the mean phase speed estimated from the composite Hovmöllers (Fig. 1). Four days before genesis (Fig. 2a), the easterly wave lies within an unfavorable environment from the Kelvin wave, which suppresses rainfall and includes anticyclonic easterly anomalies below 500 hPa.

The Kelvin wave begins favoring genesis two days later (Fig. 2b). The easterly wave intersects with the Kelvin...
wave’s enhanced convection and low-level westerly anomalies. The constructive interference of the two waves produces semi-Lagrangian low-level westerlies that are significantly stronger and deeper than climatology. These westerlies extend to 700 hPa, but the Kelvin wave’s midlevel easterly anomalies above that level (blue contours) may limit the vertical growth of the easterly wave.

The Kelvin-filtered westerly anomalies near 500 hPa intersect with the easterly wave on the day of genesis (Fig. 2c). At this point, the Kelvin wave’s convection and low-level westerly winds are ~3000 km to the east. However, the nascent tropical cyclone has deep semi-Lagrangian westerlies where the low-level easterly wave aligns with the midlevel Kelvin wave. The Kelvin wave also enhances semi-Lagrangian easterlies at 200 hPa, which may strengthen the outflow from the storm’s upper-level anticyclone.

Figure 3 shows the evolution of the 850-hPa (left) and 500-hPa (right) semi-Lagrangian winds. Semi-Lagrangian 850-hPa westerlies dominate the eastern Pacific around 10°N throughout the period (Fig. 3, left). Four days before genesis (Fig. 3a), however, the fledgling easterly wave (vertical dash) falls within the easterly phase of the Kelvin wave at 850 hPa (blue contour) where the semi-Lagrangian westerlies are weaker and indistinguishable from their climatological values (gray shading).

Two days before genesis (Fig. 3c), the easterly wave becomes better defined and intersects with the convective (green contour) and 850-hPa westerly (red contour) phases of the Kelvin wave. The strip of westerlies strengthens in the wake of the Kelvin wave’s convection. However, the tropical cyclone does not develop until the Kelvin wave’s convection and 850-hPa westerlies are ~3000 km farther to the east (Fig. 3e).

The easterly wave signal is weaker at 500 hPa (Fig. 3, right column). Consistent with Fig. 2, the semi-Lagrangian westerlies are barely 2 m s⁻¹ on the equatorward side of the easterly wave until genesis (Fig. 3f). They first emerge with the Kelvin wave’s westerly phase two days before genesis (Fig. 3d). The semi-Lagrangian westerlies extend eastward over the next two days when the tropical cyclone forms at the intersection of the westerlies and the easterly wave (Fig. 3f).

Figure 4 shows the evolution of the semi-Lagrangian streamlines and the Okubo–Weiss parameter (Rozoff et al. 2006), which identifies the semi-Lagrangian cyclonic circulations for tropical cyclogenesis (Dunkerton et al. 2009). Two days before genesis (top row), the easterly wave has already developed cyclonic values at 850 hPa where the Kelvin-filtered zonal winds enhance the circulation (Fig. 4a). At 500 hPa (Fig. 4b), however, the Kelvin wave’s easterlies oppose the circulation, which might explain the lack of cyclonic values there. One day before genesis (middle row), the cyclonic Okubo–Weiss parameter strengthens at 850 hPa (Fig. 4c) and begins to extend to 500 hPa as it transitions from the Kelvin-filtered easterlies to westerlies (Fig. 4d). Those westerlies coincide...
with the easterly wave on the day of genesis (bottom row), resulting in a strong cyclonic circulation at both levels.

The Okubo–Weiss parameter simplifies to
\[ -U_x^2 - V_y^2 + 2U_x V_y - 4V_x U_y. \]
In a simplified view of the easterly wave trough, the easterly wave produces \( V_x \), both waves constructively produce \( U_y < 0 \), and the other derivatives are nearly 0. In that case, the first three terms of Okubo–Weiss vanish and the fourth term \( (-4V_x U_y) \) would be positive (cyclonic) and enhanced by the negative \( U_y \) from the Kelvin wave. This term comes from both the vorticity and the \( S_2 \) strain of the combined flow. Figure 4 suggests that cyclogenesis occurs when this interaction happens at 500 hPa.

b. Other basins

This study focuses on the eastern Pacific where Kelvin waves play their largest role in tropical cyclogenesis. Figure 5 uses Table 1 to test these relationships in other basins. The North Atlantic (Fig. 5b) resembles the eastern Pacific (Fig. 5a), albeit with a weaker Kelvin wave signature. In both cases, Kelvin wave’s convection and low-level westerlies are separated from the nascent tropical cyclone. The Kelvin-filtered zonal winds (contours) are weaker in the Atlantic at all levels, especially near 500 hPa, but both composites show the westward tilt. The semi-Lagrangian westerlies (shading) are also shallower in the North Atlantic.

The western Pacific composite (Fig. 5c) shows a strong Kelvin wave, but the tropical cyclone forms near the peak of the Kelvin wave’s convection (Table 1). Western Pacific tropical cyclones often develop near the confluence point of the monsoon trough (Zehr 1992; Briegel and Frank 1997; Lee et al. 2008). In Fig. 5c, the Kelvin wave’s low-level westerlies reinforce the monsoon’s semi-Lagrangian westerlies, which are stronger and deeper than in either the eastern Pacific or the North Atlantic (Figs. 5a,b). They exceed 5 m s\(^{-1}\) up to almost 500 hPa westward of the genesis longitude despite the
Kelvin wave’s easterly anomalies above 700 hPa. Composites for the 4 days leading to genesis (not shown) show the semi-Lagrangian westerlies growing in both depth and intensity as the Kelvin wave approaches.

In the north Indian, south Indian, and South Pacific basins (Figs. 5d–f), the Kelvin-filtered zonal wind anomalies are weaker and less organized. As in the western Pacific (Fig. 5c), the composite storms in each of these basins form with semi-Lagrangian westerlies that extend from the surface to 500 hPa. Schreck (2015) showed that these westerlies are part of the large-scale MJO that are also accentuated by Kelvin waves. Even though the Kelvin-filtered anomalies seem less significant, their time evolution (not shown) indicates that the westerlies strengthen and deepen after the passage of the Kelvin wave’s convection as in the eastern Pacific (Fig. 2).

4. Summary and discussion

Schreck (2015) illustrated that Kelvin waves affect tropical cyclogenesis in all basins. This study uses a semi-Lagrangian framework to understand why Kelvin waves favor tropical cyclogenesis three days after their peak convection. The semi-Lagrangian winds are calculated by subtracting the easterly wave phase speed from the earth-relative winds (Dunkerton et al. 2009). The easterly wave needs to have a deep, vertically aligned cyclonic circulation to focus the convective processes that lead to the development of a surface cyclone (Nolan 2007; Nolan and Rappin 2010; Wang et al. 2010; Agudelo et al. 2011; Brammer and Thorncroft 2015). Vertical composites of these semi-Lagrangian zonal winds suggest that Kelvin waves favor tropical cyclogenesis by deepening the easterly wave’s midlevel circulation. This new finding indicates that the Kelvin waves’ vertical tilt could explain the delay between their convection and tropical cyclogenesis.

As in previous studies of Kelvin waves (e.g., Straub and Kiladis 2003; Kiladis et al. 2009), the Kelvin waves tilt westward such that the westerly anomalies at 500 hPa are ~3000 km to the west of the surface westerlies and peak convection (Fig. 2). Convectively coupled Kelvin waves move eastward at ~15 m s⁻¹, and easterly waves

![Figure 4](image-url)
move westward at $\sim 5 \text{ m s}^{-1}$. The Kelvin wave thus has a phase speed of $\sim 20 \text{ m s}^{-1}$ relative to the easterly wave, and it takes $\sim 1.7$ days for the easterly wave to go from the Kelvin wave’s peak convection to its peak midlevel westerly anomalies.

To verify the role of Kelvin waves in promoting the vertical growth of the easterly waves, similar vertical composites were generated for tropical cyclones that formed without a Kelvin wave interaction (not shown). In these cases, the easterly wave’s semi-Lagrangian westerlies already extended to 500-hPa four days before genesis, contrary to the shallower waves in Fig. 2a. Kelvin waves may primarily affect shallower easterly waves that need help growing upward.

As in Schreck (2015), the eastern Pacific shows the clearest relationship between Kelvin waves and tropical cyclogenesis (Fig. 5). The North Atlantic produces similar patterns (Fig. 5b), but with a weaker Kelvin wave signal. In the remaining basins, the monsoon and/or the MJO provide deep semi-Lagrangian westerlies for tropical cyclogenesis. In these cases, Kelvin waves accelerate the eastward extension of those westerlies.

This study identifies the impacts of Kelvin waves using Fourier filtering of zonal winds, which has limitations. The tropical cyclones themselves can project onto the filters, although less so for Kelvin waves than for other equatorial waves (Schreck et al. 2012; Aiyer et al. 2012). These filters were also designed to capture the

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**Fig. 5.** As in Fig. 2, but for genesis time of storms forming at the most favorable lag relative to the Kelvin wave crests, as defined by Schreck (2015), in each basin following Table 1: (a) eastern Pacific, (b) North Atlantic, (c) western Pacific, (d) north Indian, (e) south Indian, and (f) South Pacific. (a)–(d) Averaged at $0^\circ$–$10^\circ$N and (e),(f) averaged at $10^\circ$S–$0^\circ$.
convective variability with Kelvin waves (Wheeler and Kiladis 1999; Roundy and Frank 2004; Kiladis et al. 2009), and they may be mismatched to the scales of the related circulations (Hendon and Wheeler 2008). Kelvin waves and the MJO are also not always distinct from one another, and their signals often overlap (Sobel and Kim 2012; Roundy 2014). On balance, it is argued that these uncertainties are more likely to underestimate the impact of the Kelvin waves than to inflate them.

This study investigates how Kelvin waves interact with easterly waves during tropical cyclogenesis. However, Kelvin waves also affect the development and intensification of easterly waves outside of the tropical cyclogenesis process (Mekonnen et al. 2008; Ventrice and Thorncroft 2013; Schreck 2015). They are two of the most prominent sources of synoptic variability in the tropics, so their interactions will remain fertile ground for research for years to come.

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