Observations of near-inertial surface currents off Oregon: Decorrelation time and length scales

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Abstract

High-resolution (km in space and hourly in time) surface currents observed by an array of high-frequency radars off Oregon are analyzed to quantify the decorrelation time and length scales of their near-inertial motions. The near-inertial surface currents are dominantly clockwise with amplitudes of 9 to 12 $\mathrm{cm\,s^{-1}}$. However, they appear asymmetric and elliptical as a result of counter-clockwise inertial motions with magnitudes in a range of 2 to 5 $\mathrm{cm\,s^{-1}}$. The decorrelation time and length scales are computed from the decay slope of the near-inertial peak and the spatial coherence in the near-inertial frequency band, respectively. Decorrelation time scales of clockwise near-inertial motions increase from 2 days nearshore (within 30 km from the coast) to 6 days offshore, and their length scales increase from 30 km to 90 km seaward possibly due to coastal inhibition. The local spatial coherence has an exponentially decaying structure for both clockwise and counter-clockwise rotations, and their phases propagate northwestward (offshore) for clockwise and northeastward (onshore) for counter-clockwise rotations.

Observations

Hourly surface currents collected by an array of 11 shore-based HFRs operated by Oregon Sate University, from Loomis Lake, WA (46.43°N) to Crescent City, CA (41.78°N) for two years (2007 to 2008) are analyzed (Figure 1a). The surface vector currents and relevant kinematic and dynamic quantities (e.g., divergence, vorticity, stream function, velocity potential, and deformation rates) are directly estimated on an equally spaced grid of points with 6 km resolution using optimal interpolation.

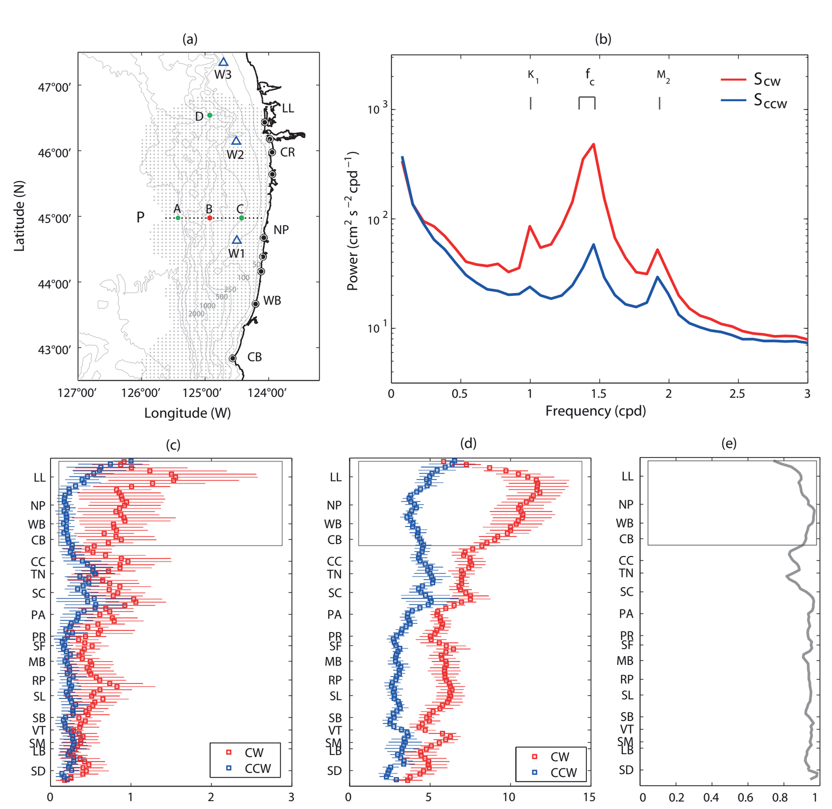

Figure 1: (a) Study area for near-inertial surface currents off Oregon and southern Washington. A gray dotted area denotes the effective spatial coverage at least 90% data availability. Blue triangles (W1, W2, and W3) and dots indicate the NDBC wind buoys (46050, 46029, and 46041) and HFRs, respectively. The estimates of decorrelation time and length scales are presented with examples on grid points A, B, and C along a cross-shore line P and the grid point D. (b) Regionally averaged rotary power spectra of detided surface currents off Oregon and southern Washington. The range of local inertial frequencies and K_1 and M_2 frequencies are indicated. Alongshore distribution of the amplitudes of surface currents over the large-scale US West Coast. (c) at the local inertial frequency (d) in the near-inertial frequency band is presented as the mean (square) and standard deviation (error bar). (e) The fractional data availability (β) of only participating surface currents over two years in the computation, adapted from [1]. A gray box in (c) – (e) indicates the region of Oregon and southern Washington, shown in (a).

The surface currents off the Oregon coast are characterized by variance at low frequency ($|\sigma| \leq 0.4$ cpd), two tidal bands at diurnal (primarily K_1) and semi-diurnal frequencies (primarily M_2 and S_2), diurnal wind and its harmonics, as well as inertial frequency (f_c = 1.35 to 1.47 cpd for 42.5°N to 47.1°N) [e.g., [1]]. The hourly surface current time series are detided by least-squares fitting the major tidal variance at K_1, O_1, P_1, S_2, and M_2 frequencies, but not S_1 frequency, because the amplitude of S_1 tidal currents is much weaker than that of currents driven by diurnal land/sea breezes. There are still peaks around K_1 and M_2 frequencies because the cuspate variance due to modulation of barotropic tides with low frequency energy exist (Figure 1b).

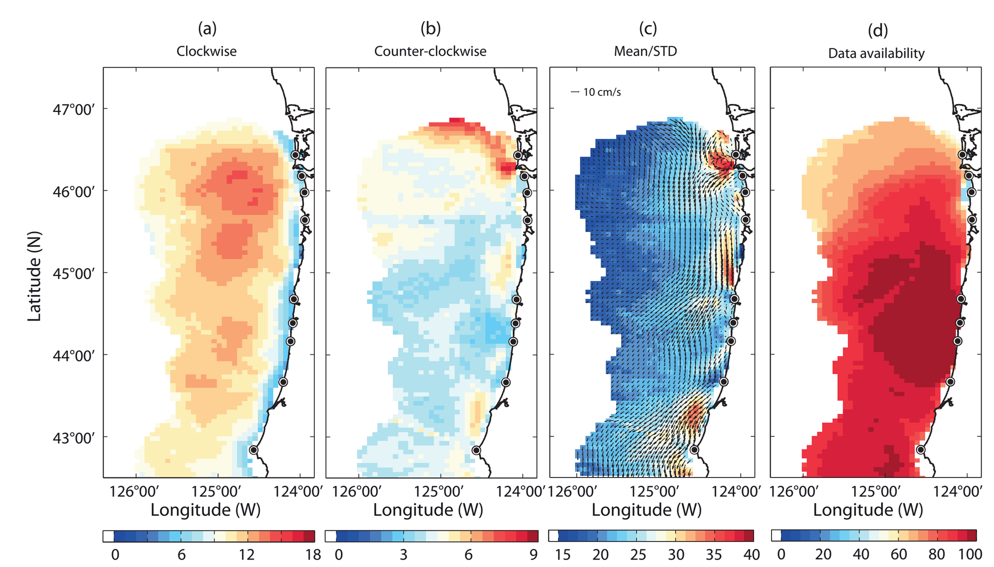

Figure 2: Amplitudes ($\mathrm{cm\,s^{-1}}$) of near-inertial surface currents in (a) clockwise and (b) counter-clockwise directions. (c) Mean (arrows) and standard deviation (STD; colors) ($\mathrm{cm\,s^{-1}}$) of hourly surface currents over two years (2007 to 2008). (d) Data availability of hourly surface currents over two years (2007 to 2008)

Estimates of decorrelation scales

Here we estimate the decorrelation scales in time and space with spectral analysis. The decorrelation time and length scales are computed from the decay slope of the peak (section) and the spatial coherence (section) in the near-inertial frequency band, respectively. The decay slope of the peak can be estimated from the spectra at individual grid points. On the other hand, the spatial coherence should be taken into account in pairs of two grid points. Thus, the near-inertial frequency bands can be defined in slightly different ways ($\widetilde{f}_c$ and $\widehat{f}_c$) (Figure 3).

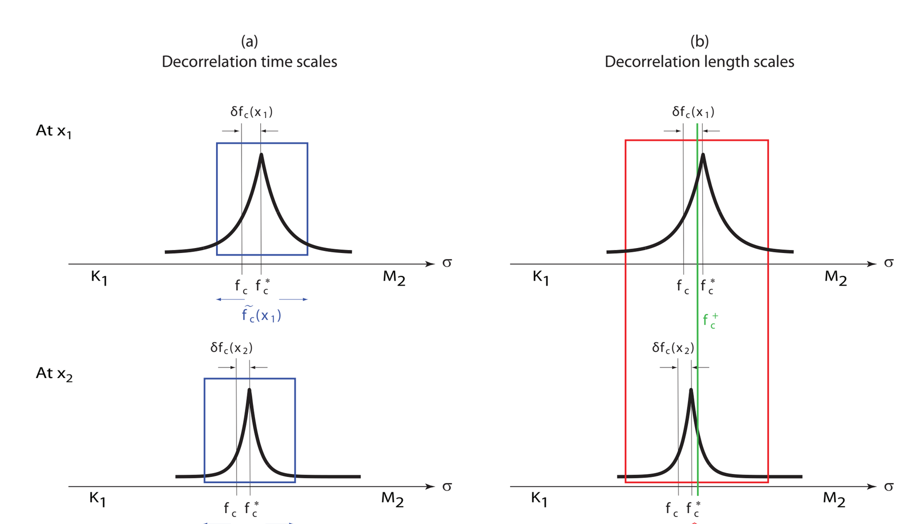

Figure 3: A schematic presentation of two near-inertial frequency bands [$\widetilde{f}_c$ as blue boxes in (a); $\widehat{f}_c$ as a red box in (b)] using power spectra of near-inertial surface currents at two locations ($\mathbf{x}_1$ and $\mathbf{x}_2$). The peak inertial frequency (f_c^*) is a sum of the local inertial frequency (f_c) and a deviation (δf_c). For the estimate of decorrelation time scales, a frequency band ($\widetilde{f}_c$), centered by f_c^* as a function of space ($\mathbf{x}$), is considered. The decorrelation length scales are computed from coherence in a frequency band ($\widehat{f}_c$), which covers near-inertial variance in two locations. Its center frequency (f_c^+; a green line in (b)) is an average of two local Coriolis frequencies [$f_c(\mathbf{x}_1)$ and $f_c(\mathbf{x}_2)$].

Decorrelation time scales

The individual power spectra within $\widehat{f}_c$ are approximated with a σ^{-2} function and a decay slope (λ) (equation 1) in order to quantify the decorrelation time scale (λ) (equation 2).

$$S(\sigma) = \frac{A^2\lambda^2}{1+\lambda^2\left(\sigma+f_c^*\right)^2}, \tag{1}$$

$$c(t) = Ae^{-if_c^* t}e^{-\frac{t}{\lambda}}, \;\; t \geq 0 \tag{2}$$

where A is the constant amplitude in the time domain.

As the peak frequencies of individual power spectra can vary with background vorticity, the fitting with equation 1 should be conducted by following shifted peaks. The time evolution of the stream function (ψ) along a cross-shore grid line P (Figure 1a) shows that the normalized vorticity or rotational tendency is mainly clockwise nearshore (within 10 km from shoreline) and alternates between counter-clockwise during winter and spring and clockwise during summer and fall in the offshore region (Figure 4a).

Figure 4b presents time series of vorticity (ζ) and scaled stream function (ψ/ψ_0; $\psi_0 = 4000\ \mathrm{m^2\,s^{-1}}$) at a grid point B (50 km offshore; Figure 1a), indicated with a black arrow in Figure 4a. Both quantities vary seasonally. In order to present an example of the frequency shift of the inertial peak due to background vorticity, variance of surface currents at trial frequencies (within 0.2 cpd of local inertial frequency) is computed and presented as a function of time in Figure 4c. Although the shifted amount from f_c is not completely the half of background vorticity (ζ), their tendency in time indicates the influence of local vorticity. While vorticity propagations in the cross-shore direction can be identified (Figure 4a), they are not addressed in the scope of this paper.

The clockwise decorrelation time scales vary from 2 (nearshore) to 6 (offshore) days (Figure 5a). Coastal inhibition due to coastline and bottom friction are considered as primary causes of the shorter decay time scale of nearshore near-inertial surface currents [e.g., [2]]. The decorrelation time scales of counter-clockwise near-inertial surface currents are not well determined due to low signal-to-noise ratio (SNR) (Figure 5b). Despite the low SNR, the counter-clockwise near-inertial time scales are much shorter than clockwise ones, which is expected in the Northern Hemisphere. As a complimentary way to determine the decorrelation time scale, the data-derived and model-derived wind transfer functions can be considered.

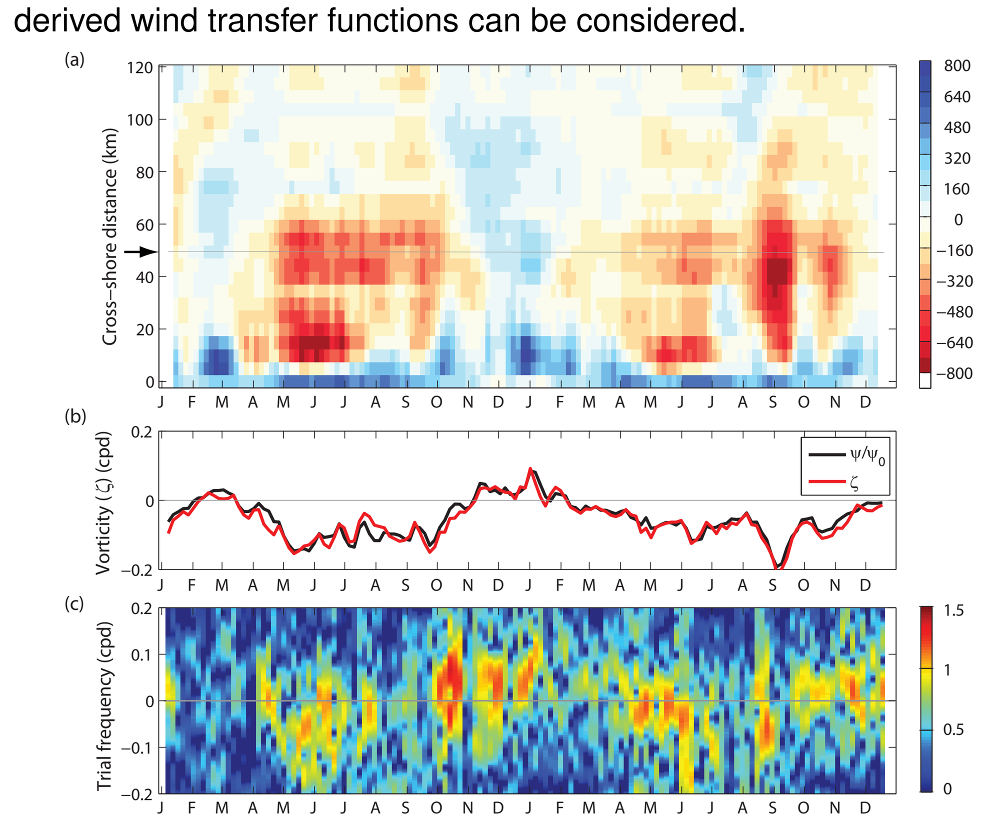

Figure 4: (a) Time evolution of stream function ($\mathrm{m^2\,s^{-1}}$) along a grid line P in Figure 1a. (b) Time evolution of vorticity (ζ, cpd) and scaled stream function (ψ/ψ_0, $\psi_0 = 4000\ \mathrm{m^2\,s^{-1}}$) at the grid point B in Figure 1a. (c) Clockwise variance ($\mathrm{cm^2\,s^{-2}}$, $\log_{10}$ scale) of surface currents at trial frequencies, centered by the local inertial frequency ($f_c = 1.4136$ cpd).

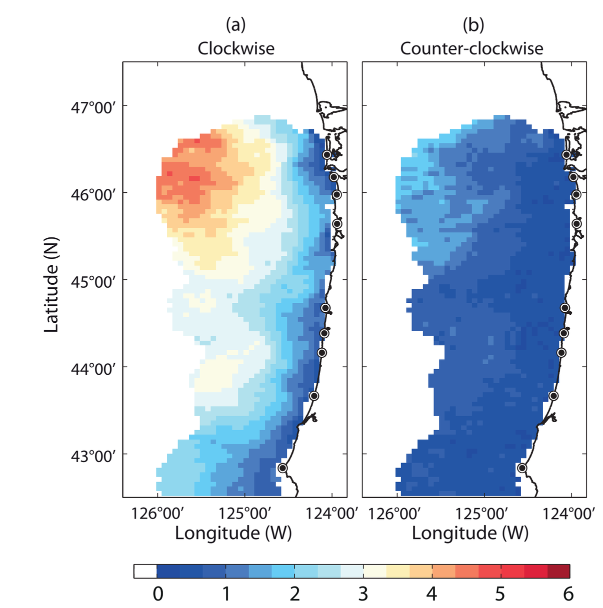

Figure 5: Decorrelation time scales (days) of (a) clockwise and (b) counter-clockwise near-inertial surface currents.

Decorrelation length scales

The decorrelation length scales of near-inertial surface currents are examined with spatial coherence, regarded as the spatial correlation within a specific frequency band:

$$\widehat{c}\left(\Delta\mathbf{x}, \widehat{f}_c\right) = \frac{\langle \hat{\mathbf{u}}(\mathbf{x},\widehat{f}_c)\hat{\mathbf{u}}^{\dagger}(\mathbf{x}+\Delta\mathbf{x},\widehat{f}_c)\rangle}{\sqrt{\langle|\hat{\mathbf{u}}(\mathbf{x},\widehat{f}_c)|^2\rangle}\sqrt{\langle|\hat{\mathbf{u}}(\mathbf{x}+\Delta\mathbf{x},\widehat{f}_c)|^2\rangle}}, \tag{3}$$

where $\hat{\mathbf{u}}$ is the Fourier coefficients of vector current time series and $\langle\cdot\rangle$ indicates averaging over the near-inertial frequency band ($\widehat{f}_c$). To estimate the spatial coherence of near-inertial surface currents at two grid points, a common near-inertial frequency band should be determined (Figure 3b). Although the same bandwidth in both rotations could be applied as was done for the time scale estimate (Figure 3a), that may not guarantee that basis functions of Fourier coefficients computed at two different locations are orthogonal. Thus, the near-inertial frequency band ($\widehat{f}_c$) (Figure 3b) for coherent estimates is defined from the finite frequency axis.

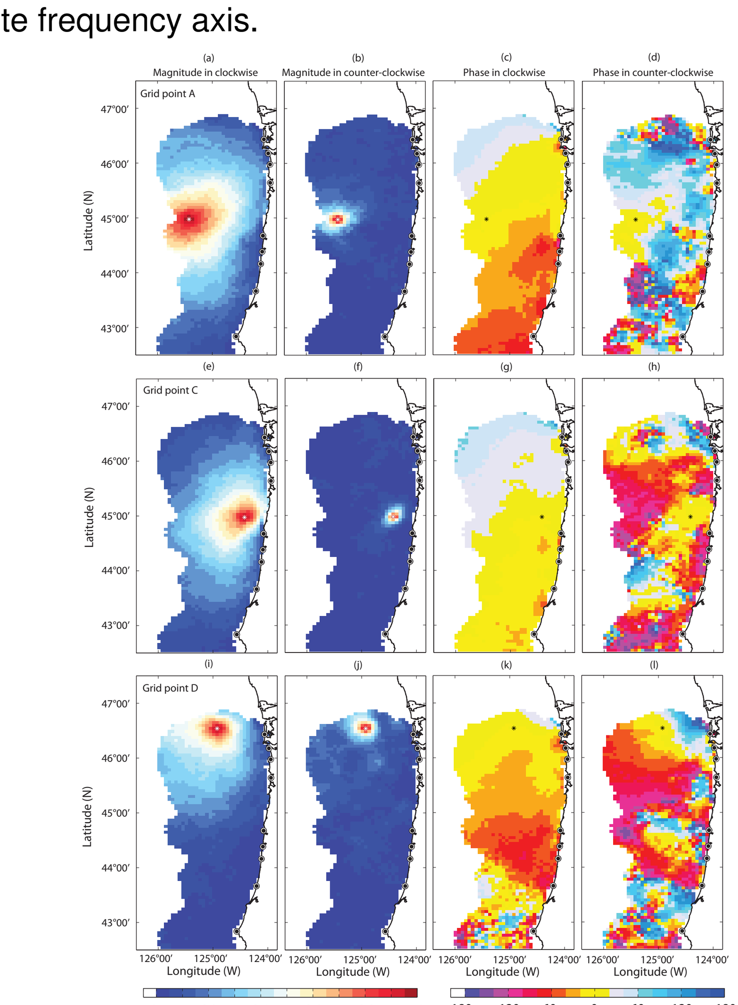

Figure 6: Magnitude and phase (degrees) of coherence of near-inertial surface currents relative to a reference location (A, C, and D in Figure 1a presented with white or black stars). (first column) Clockwise magnitude. (second column) Counter-clockwise magnitude. (third column) Clockwise phase. (fourth column) Counter-clockwise phase. The magnitude is averaged over the near-inertial frequency band, and the phase is computed from a single frequency bin nearby two near-inertial peak. (a) to (d): Grid point A. (e) to (h): Grid point C. (i) to (l): Grid point D.

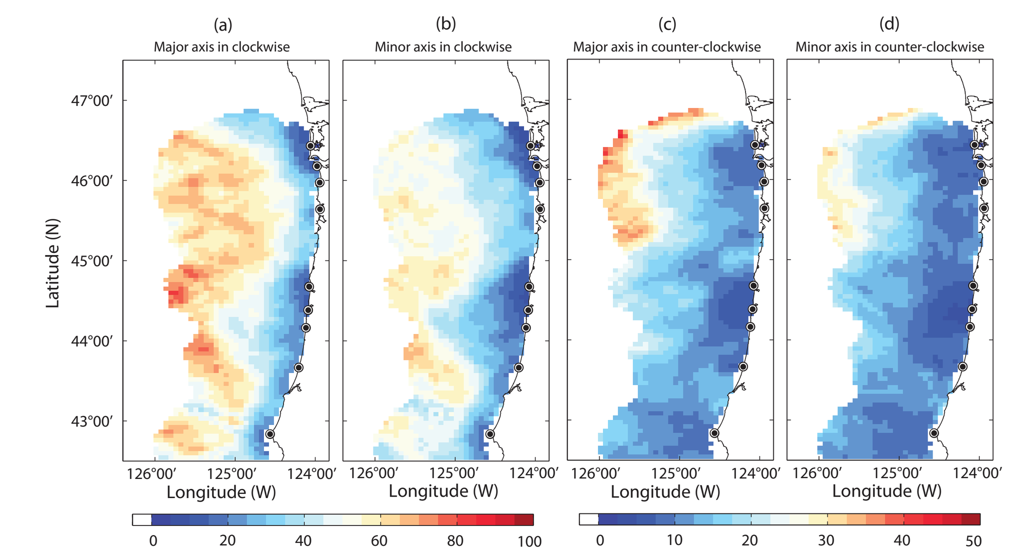

Figure 7: Decorrelation length scales (km) of near-inertial surface currents ($\widehat{f}_c$), fitted into an exponential function. (a) and (b): Length scales on major and minor axes in the clockwise direction. (c) and (d): Length scales on major and minor axes in the counter-clockwise direction.

Concluding remarks

The decorrelation scales of near-inertial surface currents observed by an array of high-frequency radar off the Oregon coast have been investigated. The decorrelation time and length scales are computed from the decay slope of the near-inertial peak and the spatial coherence in the near-inertial frequency band, respectively. In order to increase degrees of freedom, a single time series of surface currents is divided into non-overlapped time series with identical record lengths, and spectral estimates are based on their ensemble average. As the inertial peak is shifted with background vorticity, the decay slopes of the peak are computed following the peak in each chunk of the time series. Decorrelation time scales of clockwise near-inertial motions increase from nearshore (within 30 km from the coast) to offshore from 2 to 6 days, and their length scales have a similar spatial tendency increasing from 30 km to 90 km seaward. The spatial coherence has an exponentially decaying structure for both rotations and their phases propagate northwestward (offshore) in clockwise and northeastward (onshore) in counter-clockwise rotations. The northeastward phase propagation in the counter-clockwise rotation is only observed at the northern domain. These partially poleward propagations may be caused by the positively shifted near-inertial currents due to positive vorticity near the coast. The beta-dispersion effect predicts that near-inertial internal waves are free to propagate equatorward (northward phase propagation), but are restricted in their poleward propagation by the planetary vorticity gradient.

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