AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2013GL057956

Key Points:

- Northeast Pacific striations form as coastal vorticity propagates offshore via beta-plumes
- Vorticity is anchored by coastal geometry, so striations remain stationary
- Striation magnitude is constrained at the shelf by potential vorticity trapping

Correspondence to:
A. Davis,
andrew.davis@gatech.edu

Citation:
Davis, A., E. Di Lorenzo, H. Luo, A. Belmadani, N. Maximenko, O. Melnichenko, and N. Schneider (2014), Mechanisms for the emergence of ocean striations in the North Pacific, *Geophys. Res. Lett.*, *41*, 948–953, doi:10.1002/2013GL057956.

Received 10 NOV 2013
Accepted 18 DEC 2013
Accepted article online 26 DEC 2013
Published online 11 FEB 2014

Mechanisms for the emergence of ocean striations in the North Pacific

A. Davis[1], E. Di Lorenzo[1], H. Luo[1], A. Belmadani[2,3], N. Maximenko[2], O. Melnichenko[2], and N. Schneider[2]

[1]School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, Georgia, USA, [2]International Pacific Research Center, University of Hawai'i at Mānoa, Honolulu, Hawaii, USA, [3]Department of Geophysics, Universidad de Concepcion, Concepcion, Chile

Abstract Recent observations suggest that the mean mesoscale oceanic zonal velocity field is dominated by alternating jet-like features often referred to as striations. Here the generating dynamics of Northeast Pacific striations are explored with a set of 120 year eddy-permitting model simulations. Simulations are conducted with decreasing complexity toward idealized configurations retaining the essential dynamics and forcing necessary for striation development. For each simulation, we diagnose the spin-up of the ocean model and the sensitivity of striation generation to topography, coastal geometry, and wind stress, which modulates the gyre circulation and the nonlinearity of the flow field. Results indicate that Northeast Pacific striations develop predominantly at the eastern boundary and migrate westward in congruence with beta-plumes in both the nonlinear and quasi-linear regimes. Mean striations are governed by coastline geometry, which provides quasi-steady vorticity sources energized by eastern boundary current instabilities.

1. Introduction

Observations have determined that the mean mesoscale oceanic zonal velocity field is dominated by quasi-permanent jet-like features commonly referred to as striations [*Maximenko et al.*, 2005, 2008; *Huang et al.*, 2007; *Ivanov et al.*, 2009; *van Sebille et al.*, 2011; *Buckingham and Cornillon*, 2013]. These features have also been detected in high-resolution ocean models [*Nakano and Hasumi*, 2005; *Richards et al.*, 2006; *Kamenkovich et al.*, 2009] including the Regional Ocean Modeling System (ROMS) [*Huang et al.*, 2007]. Although mechanisms for the emergence of mean zonal jets have been suggested using theory and idealized models [*Rhines*, 1975; *Maltrud and Vallis*, 1991; *Panetta*, 1993; *Rhines*, 1994; *Cho and Polvani*, 1996; *Galperin et al.*, 2006; *Nadiga*, 2006; *Baldwin et al.*, 2007; *Dritschel and McIntyre*, 2008], the dynamics of striations remain uncertain.

Scott et al. [2008] showed that mesoscale eddies follow preferred pathways and so may produce the striated features seen in mean zonal velocity. *Schlax and Chelton* [2008] suggested that striations are an artifact of time-averaging large random mesoscale eddies. *Melnichenko et al.* [2010] showed, however, that eddies contribute to the potential vorticity variance of striations, indicating that they are dynamically distinct. *Hristova et al.* [2008] hypothesized that striations might be related to radiating instabilities of eastern boundary currents (EBCs). *Wang et al.* [2012] showed using a simple single-layer quasi-geostrophic model that radiating modes excited nonlinearly within an EBC do trigger striations.

Centurioni et al. [2008] reconstructed the time-mean map of geostrophic velocities at 15 m depth using drifters and satellite altimetry and found zonal currents connected to permanent meanders of the California Current System (CCS). They proposed that vorticity associated with these meanders radiates Rossby waves that form stationary jets known as beta-plumes [*Rhines*, 1994; *Afanasyev et al.*, 2012; *Belmadani et al.*, 2013].

Here we test this hypothesis with sensitivity experiments using model output. By altering the model bathymetry, we remove the effect of topographic features and a continental slope. We then decrease the strength of atmospheric forcing by an order of magnitude to test the role of nonlinear dynamics, as well as coarsen the resolution of the model to 40 km to test the role of eddy variability. Finally, we replace the eastern boundary coastline with a flat meridional wall to determine the effects of coastal geometry.

Table 1. Model Experiments[a]

Experiment Name	Geometry	Forcing	Resolution
control	Full topography	full	20 km
flat + slope	Flat bottom at 5000 m with uniform continental	full	40 km
flat + slope, weakly nonlinear	shelf along the eastern boundary	full/10	40 km
flat + slope, weakly nonlinear, non-eddy-resolving		full/10	40 km
flat	Flat bottom at 5000 m	full	20 km
flat, weakly nonlinear		full/10	40 km
flat, weakly nonlinear, non-eddy resolving		full/10	40 km
wall	Flat bottom at 5000 m with eastern boundary meridional wall	full	20 km

[a]A description of the coastal and bottom geometry is given for each group.

2. Ocean Model and Experimental Setup

This analysis employs a set of 120 year ROMS integrations [*Shchepetkin and McWilliams*, 2005; *Haidvogel et al.*, 2008; *Curchitser et al.*, 2005] over 180°W–105°W and 9°N–53°N with a horizontal resolution of 20 km and 30 vertical layers. This configuration has captured both the mean and variability of the CCS [*Marchesiello et al.*, 2003; *Di Lorenzo et al.*, 2008; *Di Lorenzo et al.*, 2009]. Vertical diffusion is parameterized according to the Large/McWilliams/Doney scheme [*Large et al.*, 1994]. Forcing is a climatological National Centers for Environmental Prediction (NCEP) wind stress [*Kistler et al.*, 2001] without buoyancy fluxes. NCEP heat fluxes are employed with a nudging toward NOAA extended sea surface temperatures (SSTs) [*Smith and Reynolds*, 2004] in order to avoid drifts in model SST [*Josey*, 2001]. Horizontal boundaries are closed walls, and the control topography is extracted from *Smith and Sandwell* [1994]. Integrations begin from rest with a uniform density profile extracted from the World Ocean Atlas 2005 [*Locarnini et al.*, 2006; *Antonov et al.*, 2006]. Striations are diagnosed using zonal currents at 300 m, where the signature of the gyre circulation is reduced.

The role of topography is explored in a set of experiments (*flat + slope*) (Table 1), in which a uniform bottom depth (5000 m) is prescribed everywhere except along the eastern boundary (and around the Hawaiian and Aleutian islands). Here a uniform shelf slope was applied. The slope was taken from the average continental slope between 30°N and 40°N. Within the *flat + slope* set, the role of nonlinearity was determined by reducing the strength of the forcing by a factor of 10 (*flat + slope*, weakly nonlinear). The role of mesoscale eddies was determined by further coarsening the grid to 40 km (*flat + slope*, weakly nonlinear, non-eddy resolving). In the *flat* runs, sensitivity to offshore topography was determined by removing the continental shelf and prescribing a uniform 5000 m bottom depth. In the *wall* run, the coastlines are replaced with a meridional wall at 125°W. The *control*, *flat + slope*, *flat*, and *wall* integrations are all able to reproduce the gyre circulation (Figures 1a–1d).

3. Spin-Up of Striations From the California Current

Progressive means of 300 m zonal velocities from the *control* run over the first 6, 12, and 120 months (Figures 2a–2c) indicate that striations emerge as zonal plumes generated offshore from notable topographic features, as well as features of the California coastline, consistent with observations [*Centurioni et al.*, 2008].

Progressive averages from the *flat + slope* experiment (using the idealized bathymetry and slope described in section 2) with full forcing and 20 km resolution (Figures 2d–2f), show that in the absence of topographic forcing, striations emerge on similar time scales and have similar magnitude but evince more spatial coherence. This suggests that topography plays a significant but lesser influence on offshore striations, in agreement with South Pacific observations [*Buckingham and Cornillon*, 2013]. It is, however, clear that the primary

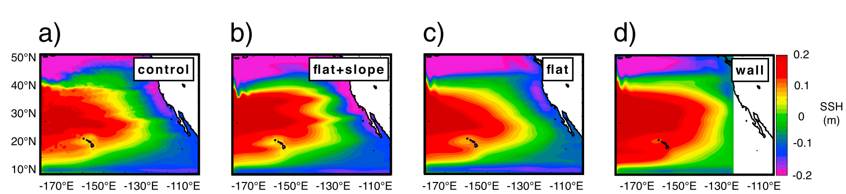

Figure 1. The 120 year means of sea surface height (SSH) from our (a) *control*, (b) *flat + slope*, (c) *flat*, and (d) *wall* experiments.

10.1002/2013GL057956

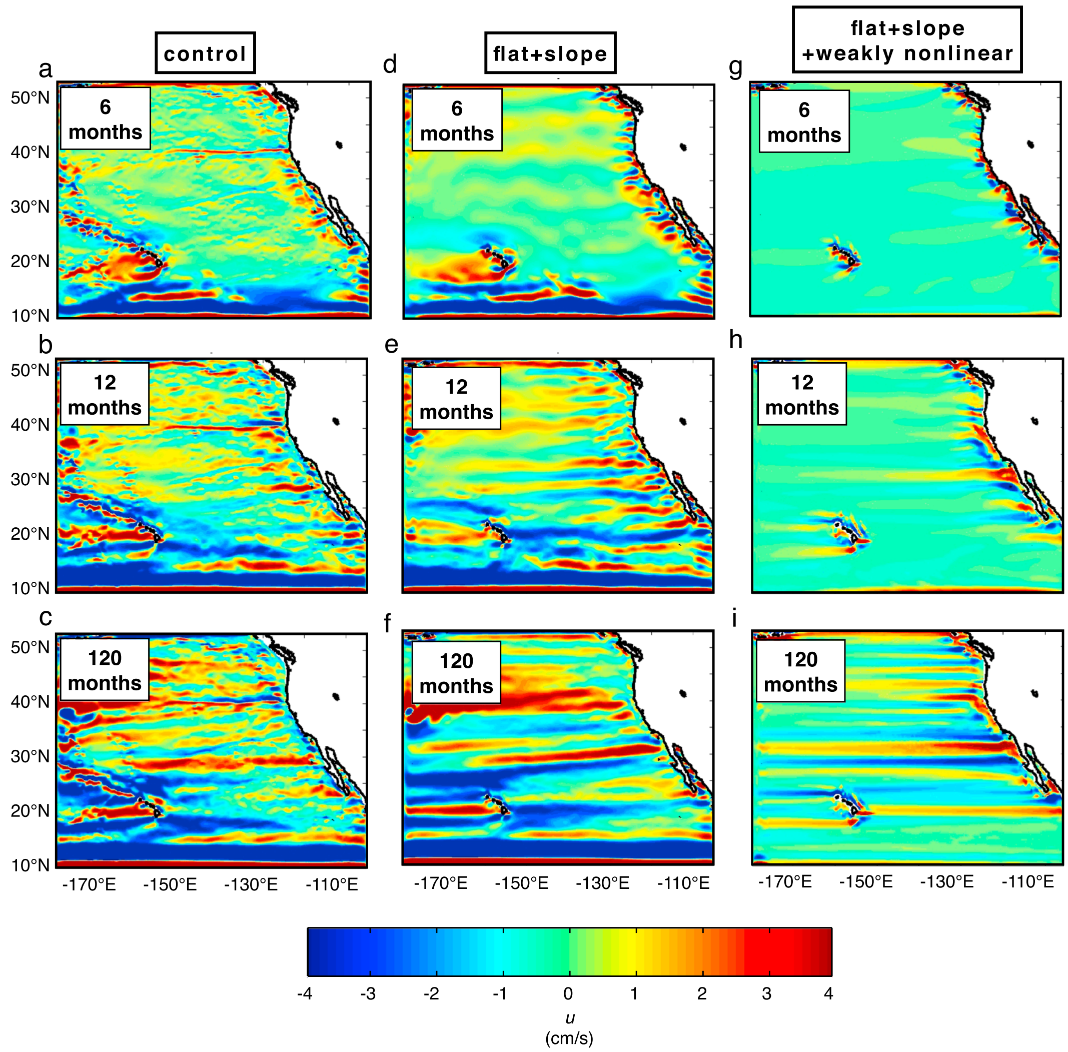

Figure 2. Progressive averages of 300 m depth zonal currents (*u*) at (a) 6, (b) 12, and (c) 120 months from our *control* experiment. (d–f) The corresponding plots for the *flat + slope* case and (g–i) similar plots for the *flat + slope* weakly nonlinear experiment.

source of striation energy is located near the eastern boundary and that striation development is kinematically consistent with beta-plumes.

To determine the sensitivity of striation development to nonlinear background velocity regimes, we examine two additional *flat + slope* experiments, the first in which the magnitude of the wind forcing is reduced by a factor of 10 (i.e., weakly nonlinear) and a second in which the resolution of the model is additionally coarsened to 40 km (i.e., weakly nonlinear and non-eddy resolving). The results of these experiments are indistinguishable visually (not shown), and images are derived from the weakly nonlinear/eddy-resolving case (Figures 2g–2i). Model output still evinces development of apparent eastern boundary beta-plumes. Striations still dominate 300 m zonal velocity and are maintained at a comparable magnitude to that of the full-forcing case. Meanders take longer to develop with the reduced wind energy input (Figures 2e and 2h), and striations are more strongly zonal due to a decreased large-scale circulation.

To evaluate the importance of the continental slope in the formation of striations, we performed three experiments with uniform 5000 m bottom depth and vertical continental boundaries (*flat* experiments; Table 1). When we remove the continental sole in the *flat* experiment, the magnitude of striations decreases to roughly half that of the *control* and *flat + slope* runs (Figures 3a–3c) even though the wind forcing is the same, and the gyre circulation is maintained at the same magnitude (Figures 1b and 1c). The meanders that are sources of vorticity for striations are weaker in the *flat* run (Figure 1c), which may explain the reduced striation

10.1002/2013GL057956

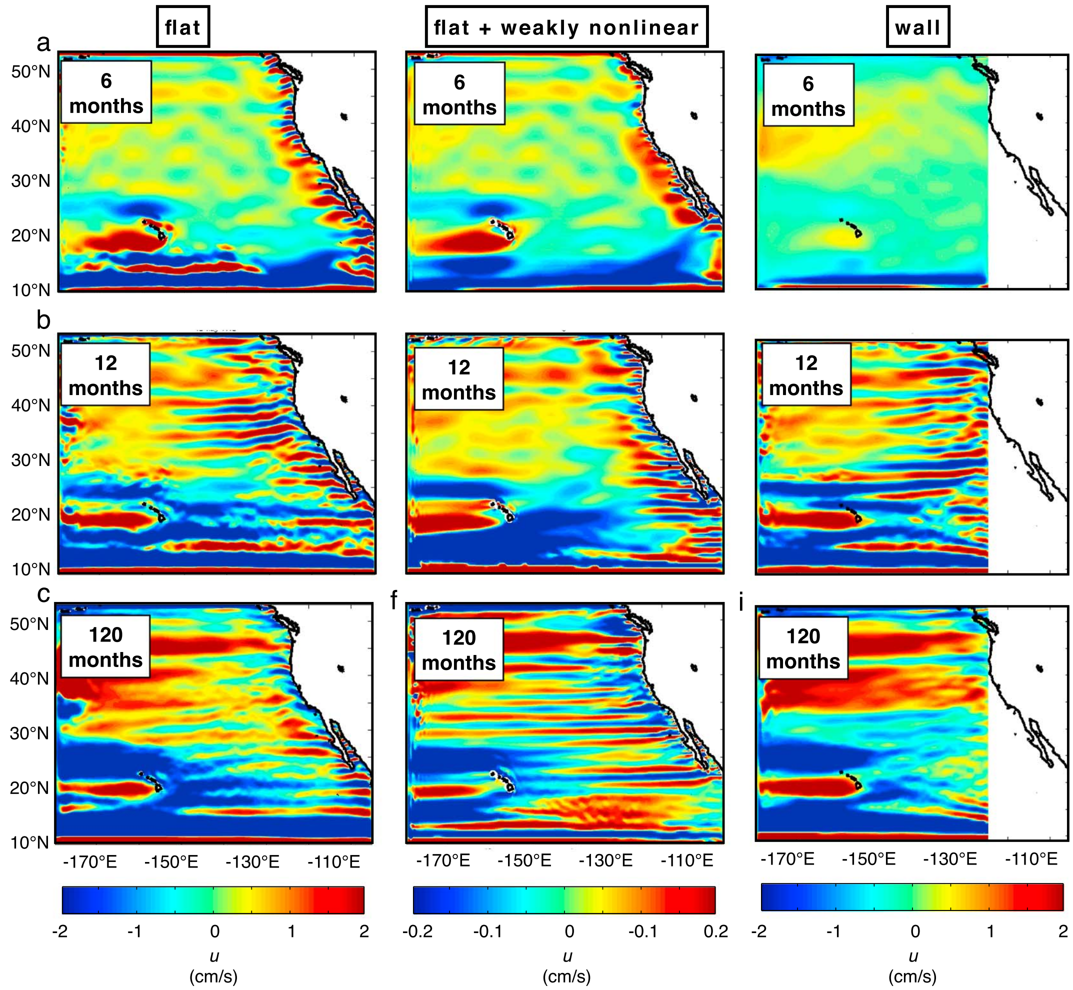

Figure 3. Progressive averages of 300 m *u* at (a) 6, (b) 12, and (c) 120 months from our *flat* experiment. (d–f) The *flat* weakly nonlinear case. (g–i) The *wall* experiment.

magnitude. Continental slopes also impose a dynamical boundary to the offshore propagation of potential vorticity anomalies, so that anomalies from the coast are "trapped" on the shelf and unable to propagate freely offshore until they reach a critical magnitude. Although we do not examine the dynamics of this potential vorticity trapping in detail, we hypothesize that the absence of the continental slope in the *flat* run allows beta-plumes to propagate westward independently of their magnitude. Consistent with this hypothesis, when we reduce the wind magnitude by a factor of 10 in the *flat* weakly nonlinear experiment (Table 1), striation strength is also reduced by an order of magnitude (Figures 3d–3f). This linear response to the wind magnitude is not observed in the *flat + slope* case, where reducing the wind forcing by an order of magnitude only reduces striation strength by a small fraction (Figures 2f and 2i). This leads us to conclude that without a continental slope, striations freely propagate offshore as they develop, whereas in the slope case, anomalies must reach a critical magnitude in order to escape. Despite the slower spin-up of the CCS in the weakly nonlinear *flat + slope* experiment, the magnitude enforced by the slope ensures that striations remain strong in the mean (Figure 2i). The results of the *flat* weakly nonlinear non-eddy-resolving experiments are again visually indistinguishable and are not presented.

The role of coastal geometry was further explored in the *wall* experiments (Table 1) by removing the coastline and setting a wall along the eastern boundary (125°W) (Figure 1d). While the spin-up is characterized by the formation of striations, they are short lived in the mean, and their signature eventually disappears (Figures 3g–3i). Striations are subsumed in the mean because meanders are no longer anchored to coastal features and propagate freely, consistent with the *Wang et al*. [2012] model.

4. Conceptual Model for Striations in the Eastern North Pacific

By analyzing the spin-up of the ROMS model, we showed that Northeast Pacific striations are not necessarily forced by surface fluxes of momentum or buoyancy but can develop from vorticity sources associated with topography and/or instabilities along the eastern boundary, a process for which we propose the following mechanism.

EBC flow is unstable [*Walker and Pedlosky*, 2002; *Hristova et al*., 2008; *Wang et al*., 2012] and generates meanders that are anchored to coastal features [*Batteen*, 1997; *Centurioni et al*., 2008]. The associated vorticity propagates westward as a beta-plume, consistent with observations of striation attachment to CCS meanders [*Centurioni et al*., 2008]. It also agrees with the two most basic observations presented here: that persistent striations are energized within the boundary current as it spins up and that they develop primarily in response to coastal geometry. This progression is most clear in the *flat* experiment (Figures 3a–3c), where jet patterns remain in the absence of bottom topography and continental slope, and in the *wall* experiment, in which permanent striations could not develop without coastal features to anchor vorticity anomalies.

These results strongly suggest that intense striations arise at the coast. The fact that striations emerge in a non-eddying regime indicates that they are unlikely to result solely from time-averaged mesoscale eddy tracks, consistent with recent results from idealized models [*Nadiga and Straub*, 2010] and observations [*Ivanov et al*., 2012; *Buckingham and Cornillon*, 2013]. The extreme contrast in magnitude between the *flat* + *slope* weakly nonlinear and *flat* weakly nonlinear experiments indicates that potential vorticity trapping constrains striation strength.

There are a number of significant idealizations in our model. Climatological wind forcing precludes small-scale winds that may modulate striations [*Chelton et al*., 2004; *Taguchi et al*., 2012]. NCEP winds also produce biases in EBCs [*Colas et al*., 2012; *Cambon et al*., 2013], which may alter stratification and associated coastal instabilities. A purely kinematic treatment is also limited in its ability to determine the wider role of striations in the mean circulation, as well as to generalize to other basins. Further study that focuses on the dynamics and vorticity budgets of striations will be vital in understanding the dynamical balances associated with their generation.

Acknowledgments
This research was partly supported by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), by NASA through grant NNX07AG53G, and by NOAA through grant NA11NMF4320128, which sponsor research at the International Pacific Research Center. Additional support was provided by the NASA grant NNX08AR49G. This is the International Pacific Center/School of Ocean and Earth Science and Technology Publication 1044/9072.

The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

References

Afanasyev, Y. D., S. O'Leary, P. B. Rhines, and E. Lindahl (2012), On the origin of jets in the ocean, *Geophys. Astrophys. Fluid Dyn.*, *106*(2), 113–137.

Antonov, J. I., R. A. Locarnini, T. P. Boyer, A. V. Mishonov, and H. E. Garcia (2006), *World Ocean Atlas 2005*, vol. 2, Salinity, NOAA Atlas NESDIS 62, edited by S. Levitus, 182 pp., U.S. Government Printing Office, Washington, D. C.

Baldwin, M. P., P. B. Rhines, H. P. Huang, and M. E. McIntyre (2007), The jet-stream conundrum, *Science*, *315*, 467–468.

Batteen, M. L. (1997), Wind-forced modeling studies of currents, meanders, and eddies in the California Current System, *J. Geophys. Res.*, *102*, 985–1010.

Belmadani, A., N. A. Maximenko, J. P. McCreary, R. Furue, O. V. Melnichenko, N. Schneider, and E. Di Lorenzo (2013), Linear wind-forced beta plumes with application to the Hawaiian Lee Countercurrent, *J. Phys. Oceanogr.*, *43*, 2071–2094, doi:10.1175/JPO-D-12-0194.1.

Buckingham, C. E., and P. C. Cornillon (2013), The contribution of eddies to striations in absolute dynamic topography, *J. Geophys. Res. Oceans*, *118*, 448–461, doi:10.1029/2012JC008231.

Cambon, G., K. Goubanova, P. Marchesiello, B. Dewitte, S. Illig, and V. Echevin (2013), Assessing the impact of downscaled winds on a regional ocean model simulation of the Humboldt system, *Ocean Modell.*, *65*, 11–24.

Centurioni, L. R., J. C. Ohlmann, and P. P. Niiler (2008), Permanent meanders in the California Current System, *J. Phys. Oceanogr.*, *38*, 1690–1710.

Chelton, D. B., M. G. Schlax, M. H. Freilich, and R. F. Milliff (2004), Satellite measurements reveal persistent small-scale features in ocean winds, *Science*, *303*, 978–983.

Cho, J. Y. K., and L. M. Polvani (1996), The emergence of jets and vortices in freely evolving, shallow-water turbulence on a sphere, *Phys. Fluids*, *8*, 1531–1552.

Colas, F., J. C. McWilliams, X. Capet, and J. Kurian (2012), Heat balance and eddies in the Peru-Chile current system, *Clim. Dyn.*, *39*, 509–529.

Curchitser, E. N., D. B. Haidvogel, A. J. Hermann, E. L. Dobbins, T. M. Powell, and A. Kaplan (2005), Multi-scale modeling of the North Pacific Ocean: Assessment and analysis of simulated basin-scale variability (1996–2003), *J. Geophys. Res.*, *110*, C11021, doi:10.1029/2005JC002902.

Di Lorenzo, E., N. Schneider, K. M. Cobb, P. J. S. Franks, K. Chhak, A. J. Miller, J. C. McWilliams, S. J. Bograd, H. Arango, E. Curchitser, T. M. Powell, and P. Riviere (2008), North Pacific Gyre Oscillation links ocean climate and ecosystem change, *Geophys. Res. Lett.*, *35*, L08607, doi:10.1029/2007GL032838.

Di Lorenzo, E., J. Fiechter, N. Schneider, A. Bracco, A. J. Miller, P. J. S. Franks, S. J. Bograd, A. M. Moore, A. C. Thomas, W. Crawford, A. Pena, and A. J. Hermann (2009), Nutrient and salinity decadal variations in the central and eastern North Pacific, *Geophys. Res. Lett.*, *36*, L14601, doi:10.1029/2009GL038261.

Dritschel, D. G., and M. E. McIntyre (2008), Multiple jets as PV staircases: The Phillips effect and the resilience of eddy-transport barriers, *J. Atmos. Sci.*, *65*, 855–874.

10.1002/2013GL057956

Galperin, B., S. Sukoriansky, N. Dikovskaya, P. L. Read, Y. H. Yamazaki, and R. Wordsworth (2006), Anisotropic turbulence and zonal jets in rotating flows with a beta-effect, *Nonlinear Processes Geophys.*, *13*(1), 83–98.

Haidvogel, D. B., et al, (2008), Ocean forecasting in terrain-following coordinates: Formulation and skill assessment of the Regional Ocean Modeling System, *J. Comput. Phys.*, *227*, 3595–3624.

Hristova, H. G., J. Pedlosky, and M. A. Spall (2008), Radiating instability of a meridional boundary current, *J. Phys. Oceanogr.*, *38*, 2294–2307.

Ivanov, L. M., C. A. Collins, and T. M. Margolina (2009), System of quasi-zonal jets off California revealed from satellite altimetry, *Geophys. Res. Lett.*, *36*, L03609, doi:10.1029/2008GL036327.

Ivanov, L. M., C. A. Collins, and T. M. Margolina (2012), Detection of oceanic quasi-zonal jets from altimetry observations, *J. Atmos. Oceanic Technol.*, *29*, 1111–1126, doi:10.1175/JTECH-D-11-00130.1.

Josey, S. A. (2001), A comparison of ECMWF, NCEP-NCAR, and SOC surface heat fluxes with moored buoy measurements in the subduction region of the Northeast Atlantic, *J. Clim.*, *14*, 1780–1789.

Kamenkovich, I., P. Berloff, and J. Pedlosky (2009), Anisotropic material transport by eddies and eddy-driven currents in a model of the North Atlantic, *J. Phys. Oceanogr.*, *39*, 3162–3175.

Kistler, R., et al. (2001), The NCEP-NCAR 50-year reanalysis: Monthly means CD-ROM and documentation, *Bull. Am. Meteorol. Soc.*, *82*, 247–267.

Large, W. G., J. C. McWilliams, and S. C. Doney (1994), Oceanic vertical mixing—A review and a model with a nonlocal boundary-layer parameterization, *Rev. Geophys.*, *32*, 363–403.

Locarnini, R. A., A. V. Mishonov, J. I. Antonov, T. P. Boyer, and H. E. Garcia (2006), *World Ocean Atlas 2005*, vol. 1, Temperature, NOAA Atlas NESDIS 61, edited by S. Levitus, 182 pp., U.S. Government Printing Office, Washington, D. C.

Maltrud, M. E., and G. K. Vallis (1991), Energy-spectra and coherent structures in forced 2-dimensional and beta-plane turbulence, *J. Fluid Mech.*, *228*, 321–342.

Marchesiello, P., J. C. McWilliams, and A. Shchepetkin (2003), Equilibrium structure and dynamics of the California Current System, *J. Phys. Oceanogr.*, *33*, 753–783.

Maximenko, N. A., B. Bang, and H. Sasaki (2005), Observational evidence of alternating zonal jets in the world ocean, *Geophys. Res. Lett.*, *32*, L12607, doi:10.1029/2005GL022728.

Maximenko, N. A., O. V. Melnichenko, P. P. Niiler, and H. Sasaki (2008), Stationary mesoscale jet-like features in the ocean, *Geophys. Res. Lett.*, *35*, L08603, doi:10.1029/2008GL033267.

Melnichenko, O. V., N. A. Maximenko, N. Schneider, and H. Sasaki (2010), Quasi-stationary striations in basin-scale oceanic circulation: Vorticity balance from observations and eddy-resolving model, *Ocean Dyn.*, *60*(3), 653–666.

Nadiga, B. T. (2006), On zonal jets in oceans, *Geophys. Res. Lett.*, *33*, L10601, doi:10.1029/2006GL025865.

Nadiga, B. T., and D. N. Straub (2010), Alternating zonal jets and energy fluxes in barotropic wind-driven gyres, *Ocean Modell.*, *33*(3–4), 257–269.

Nakano, H., and H. Hasumi (2005), A series of zonal jets embedded in the broad zonal flows in the pacific obtained in eddy-permitting ocean general circulation models, *J. Phys. Oceanogr.*, *35*, 474–488.

Panetta, R. L. (1993), Zonal jets in wide baroclinically unstable regions—Persistence and scale selection, *J. Atmos. Sci.*, *50*, 2073–2106.

Rhines, P. B. (1975), Waves and Turbulence on a beta-plane, *J. Fluid Mech.*, *69*, 417–443.

Rhines, P. B. (1994), Jets, *Chaos*, *4*, 313–339.

Richards, K. J., N. A. Maximenko, F. O. Bryan, and H. Sasaki (2006), Zonal jets in the Pacific Ocean, *Geophys. Res. Lett.*, *33*, L03605, doi:10.1029/2005GL024645.

Schlax, M. G., and D. B. Chelton (2008), The influence of mesoscale eddies on the detection of quasi-zonal jets in the ocean, *Geophys. Res. Lett.*, *35*, L24602, doi:10.1029/2008GL035998.

Scott, R. B., B. K. Arbic, C. L. Holland, A. Sena, and B. Qiu (2008), Zonal versus meridional velocity variance in satellite observations and realistic and idealized ocean circulation models, *Ocean Modell.*, *23*(3–4), 102–112.

Shchepetkin, A. F., and J. C. McWilliams (2005), The regional oceanic modeling system (ROMS): A split-explicit, free-surface, topography-following-coordinate oceanic model, *Ocean Modell.*, *9*, 347–404.

Smith, T. M., and R. W. Reynolds (2004), Improved extended reconstruction of SST (1854–1997), *J. Clim.*, *17*, 2466–2477.

Smith, W. H. F., and D. T. Sandwell (1994), Bathymetric prediction from dense satellite altimetry and sparse shipboard bathymetry, *J. Geophys. Res.*, *99*, 21,803–21,824.

Taguchi, B., R. Furue, N. Komori, A. Kuwano-Yoshida, M. Nonaka, H. Sasaki, and W. Ohfuchi (2012), Deep oceanic zonal jets constrained by fine-scale wind stress curls in the South Pacific Ocean: A high-resolution coupled GCM study, *Geophys. Res. Lett.*, *39*, L08602, doi:10.1029/2012GL051248.

van Sebille, E., I. Kamenkovich, and J. K. Willis (2011), Quasi-zonal jets in 3-D Argo data of the Northeast Atlantic. *Geophys. Res. Lett.*, *38*, L02606, doi:10.1029/2010GL046267.

Walker, A., and J. Pedlosky (2002), Instability of meridional baroclinic currents, *J. Phys. Oceanogr.*, *32*, 1075–1093.

Wang, J., M. A. Spall, G. R. Flierl, and P. Malanotte-Rizzoli (2012), A new mechanism for the generation of quasi-zonal jets in the ocean, *Geophys. Res. Lett.*, *39*, L10601, doi:10.1029/2012GL051861.