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An observational study of oceanic eddy generation mechanisms by tall deep-water islands (Gran Canaria)

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[1] Oceanic eddy generation by tall deep-water islands is common phenomenon. It is recognized that these eddies may have a significant impact on the marine system and related biogeochemical fluxes. Hence, it is important to establish favourable conditions for their generation. With this objective, we present an observational study on eddy generation mechanisms by tall deep-water islands, using as a case study the island of Gran Canaria. Observations show that the main generation mechanism is topographic forcing, which leads to eddy generation when the incident oceanic flow is sufficiently intense. Wind shear at the island wake may acts only as an additional eddy-generation trigger mechanism when the impinging oceanic flow is not sufficiently intense. For the case of the island of Gran Canaria we have observed a mean of ten generated cyclonic eddies per year. Eddies are more frequently generated in summer coinciding with intense Trade winds and Canary Current. **Citation:** Piedeleu, M., P. Sangrà, A. Sánchez-Vidal, J. Fabrés, C. Gordo, and A. Calafat (2009), An observational study of oceanic eddy generation mechanisms by tall deep-water islands (Gran Canaria), *Geophys. Res. Lett.*, *36*, L14605, doi:10.1029/2008GL037010.

1. Introduction

[2] Island eddy generation has been observed at many deep-water tall islands such as the Canary Islands [e.g., *Arístegui et al.*, 1994; *Sangrà et al.*, 2007], the Hawaiian Islands [e.g., *Benitez-Nelson et al.*, 2007], Barbados [*Dietrich et al.*, 1996] and the Philippines [e.g., *Pullen et al.*, 2008]. Island-generated eddies significantly affects ocean biogeochemistry by enhancing nutrient supply and primary productivity [*Arístegui and Montero*, 2005; *Arístegui et al.*, 1997] and thus the efficiency of the biological pump [*Benitez-Nelson et al.*, 2007]. As island-generated eddies can be long-lived structures [*Sangrà et al.*, 2005, 2007], they may modulate the marine system both locally and regionally. Therefore, it is important to study the main eddy generation mechanisms in order to establish the atmospheric and oceanic flow conditions favourable for eddy generation.

[3] Two main mechanisms have been proposed for eddy generation by tall deep-water islands: topographic forcing and wind shear forcing over the island wake. Topographic forcing is related to island boundary-layer detachment when the incident oceanic flow is sufficiently energetic, leading to a wake of successive cyclonic and anticyclonic vortices [e.g., *Pattiaratchi et al.*, 1987; *Heywood et al.*, 1996, *Dietrich et al.*, 1996]. Wind shear forcing is related to the injection of relative vorticity by wind stress curl over the island wake, through the Ekman pumping mechanism [*Barton et al.*, 2000; *Basterretxea et al.*, 2002; *Jiménez et al.*, 2008]. Bathymetry details, the Coriolis parameter and relatively constant upstream stratification may also control Island wake vortices [*Dietrich et al.*, 1996].

[4] *Jiménez et al.* [2008] (hereinafter referred to as J08), studied numerically the relative importance of topographic and wind shear forcing for island eddy generation, using the Island of Gran Canaria as a case study. They concluded that on an *f-plane*, topographic forcing is the main mechanism responsible for eddy generation. They also numerically demonstrated that wind shear acts as trigger mechanism for eddy generation at lower intensities of the incident oceanic flow. Here we present, for the first time, an observational study on the mechanisms of eddy generation by tall deep-water islands, with the focus again the island of Gran Canaria. A secondary objective is to establish the seasonal variability of eddy generation at Gran Canaria, which has still not been investigated.

2. Observational Experiment Setup

[5] Herein, we focus attention on cyclonic eddies because they have a clear signal in the temperature field. In order to monitor cyclonic vortex shedding from Gran Canaria, we deployed a mooring over 2 years (from June 2005 to May 2007) 30 miles southwest of Gran Canaria (27° 29′ 57″N, 016° 15′ 19″W), within the path of the eddies (Figure 1). The mooring was loaded with Aanderaa RCM7/8 current-meters and PPS3 Technicap/IRS sediment traps, at about 150, 275, 500 1000 and 2000 m depth. Maintenance checks were made every six months. During the third six-month period (summer–fall 2006) the mooring was relocated closer to Gran Canaria because of rough seas on the deployment date. Eddy signals were obtained by combining current-meter temperature anomalies with sea surface temperature (SST) and chlorophyll from satellite images. As seen in Figures 2 and 3, negative temperature anomalies and cyclones match well with SST anomalies in satellite images.

[6] To address the importance of topographic forcing, we have calculated the intensity of the incident flow (Canary Current) from two tide gauges located on the northern coasts of the Island of Tenerife and Gran Canaria (Figure 1). Tidal and inertial oscillations were removed by

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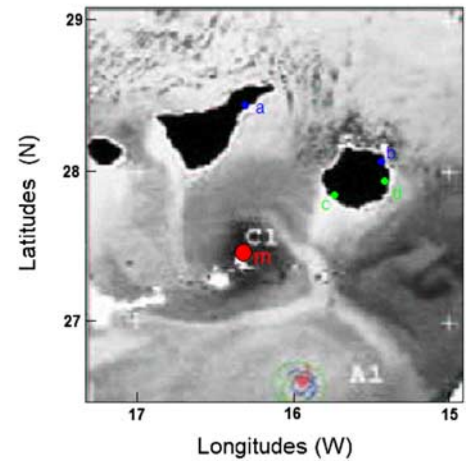

Figure 1. Observational experiment setup. Location of the mooring (m); tide gauge at Santa Cruz de Tenerife (a) and Las Palmas de Gran Canaria (b) and meteorological stations at Puerto de Mogan (c) and Gando airport (d) superposed onto a sea surface temperature satellite image. A cold cyclonic eddy generated by Gran Canaria is marked C1 and a warm anticyclone is marked A1. Colour lines are buoys trajectorie deployed in A1 (see details by *Sangrà et al.* [2005]).

a 28-hour low-pass Fourier filter [*Dick and Siedler*, 1985; *Siedler and Paul*, 1991]. To filter out the inverse barometer effect we have used atmospheric pressure data from meteorological stations near the tide gauges. Geostrophic velocity was calculated from the sea surface height gradient between the islands. The resulting time series were smoothed by applying a three-tidal-cycle low-pass filter. We have also calculated the corresponding Reynolds number:

$$Re = \frac{UL}{A_H}$$

The flow Reynolds number is based on an upstream (Canary Current) velocity U, L (island diameter) = 54×10^3 m, an eddy viscosity $A_H = 100$ m^2 s^{-1} (used by J08).

[7] To estimate the atmospheric forcing we have calculated the wind shear between a meteorological station located on the wind-accelerating flank of Gran Canaria and another located downwind (Figure 1 and auxiliary material Figure S1).[1]

3. Observations

[8] Figures 2 and 3 show temperature anomalies, incident flow, Reynolds number and wind shear time series from our two-year survey. Temperature anomalies allow us to monitor cyclonic eddy generation. Incident flow time series allow us to get an idea of the importance of the topographic forcing in relation with to the intensity of the Canary Current. Finally, wind shear time series, allow us to get a semi-quantitative estimate of the importance of wind shear forcing on eddy generation.

3.1. First Period: Summer–Fall 2005

[9] The negatives temperature anomalies seen in Figure 2a and satellite images indicate five cyclones occurred during the first six month period. Eddy generation events were observed only in summer, coinciding with relatively higher intensities of the incident flow (Figure 2b) and wind shear (Figure 2c). Eddy shedding frequency, as obtained from the time interval between two temperature anomaly maxima, range from two weeks to a month. The Eddy vertical maximum depth signal ranges between 400 and 1000 m (Table 1).

[10] In the particular case of eddy C1 the Canary Current intensity was very low but the wind shear was relatively high (Figure 2c). This suggests that the generation of this eddy is related to wind shear forcing that acts as a trigger mechanism in low incident oceanic flow conditions as pointed out by J08. Coinciding with both low intensity of the incident flow and of wind shear, no eddy generation events were observed in fall.

3.2. Second Period: Winter–Spring 2006

[11] As in the first period, 5 cyclonic eddies are generated during this period, 4 in winter and 1 in spring (Figure 2d). Shedding frequency estimates are similar to the first period. C2 to C4 eddy generation coincides with high-intensities of the incident flow but, with wind-shear as low as in fall 2005 where no eddies were observed. This suggests that topographic forcing alone is sufficient to generate eddies without requiring the additional input of vorticity by wind shear at the island wake, as demonstrated by J08 numerical experiments.

[12] Low incident oceanic flow velocities and wind shear estimated during December of 2005 don't explain the initial negative anomaly associated with eddy C1. However, from December to January the incident flow accelerates sharply, up to 10 cm/s within a week. In early spring, eddy activity decreases, but an increment of the Canary Current and wind shear in April 2006 allows the cyclone C5 to be generated.

[13] The period from December 2005 to April 2006, where wind shear was low, allows estimation of the minimum flow needed for eddy generation by topography alone. This corresponds to a $Re = 50–60$ ($U = 10$ cms^{-1}), which is in accordance with J08 numerical results and laboratory experiments. In the complete times-series there is a time lag, about 10 days, between the increase of the Canary Current and the signal of eddy-related temperature. This is due to eddy spin-up time and the time required for their advection to the mooring position.

3.3. Third Period: Summer–Fall 2006

[14] As in this period the mooring was deployed closer to the island coast, no eddy signals were observed in the mooring data. Eddy presence could be inferred only from SST and chlorophyll images. Similar conditions to 2005 were observed (Figure 3a). Eddy-favourable current and wind shear intensity from mid-spring to late summer allows the generation of 4 cyclonic vortex events, identified both in SST and chlorophyll images (not shown). As in 2005, the geostrophic incident oceanic flow velocity and wind shear increase trough the summer. The Canary Current and wind shear decreases in fall coinciding with no eddy generation. In late fall, an increase of the Canary Current up of to 10 cm/s

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2008GL037010.

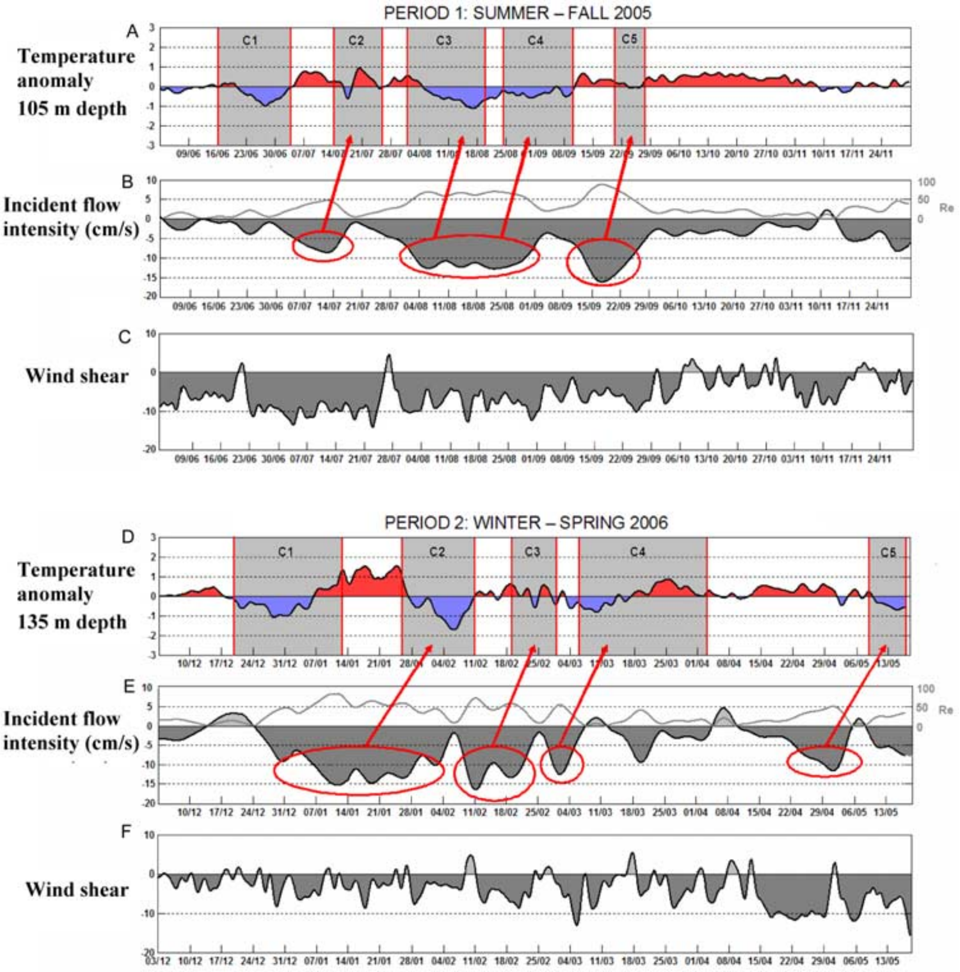

Figure 2. Parameter time series for the first year of data. (a and d) Time series of temperature anomalies as obtained from the mooring. Superposed shaded grey intervals correspond to observed periods of cyclones from SST images. (b and e). Time variation of the intensity of the incident flow (Canary Current) as obtained from tide gauges (right axis). The grey line shows the times-varying Reynolds number (*Re*, right axis). Increments of current intensity associated with eddy generation are shown by red circles, and the corresponding eddy signal in the mooring temperatures anomalies are shown by red arrows. (c and f) Time varying semi-quantitative values for wind shear at the island wake.

generated a new cyclone, C5, in low-wind-shear conditions. During the third week of September and the second week of October, although there were intense wind pulses, no vortex shedding is observed, coinciding with a low incident current. Zonal wind pulses can generate eddies [*Pullen et al.*, 2008] however; this seems not to be the case for wind pulses as in the case of Gran Canaria.

3.4. Fourth Period: Winter–Spring 2007

[15] As in the previous periods, 5 signals of cyclonic eddies have been identified. Only three eddies were observed during winter. For almost all events, good correlations between temperature anomalies and increments of the incident geostrophic oceanic flow were observed. Eddy C1 was generated in low current/high wind shear conditions (Figure 3 and Table 1), suggesting again that wind shear acts as a trigger mechanism when the incident current intensity is too low ($Re < 50$) for eddy generation by topographic forcing alone. During January the wind shear and the Canary Current intensity were very low, and no cyclones were generated. From February to May, wind shear conditions and Canary Current were highly favourable, leading to the generation of eddies C2, C3, C4 and C5.

4. Summary and Conclusions

[16] For the case of the island of Gran Canaria we have observed a mean of ten generated cyclonic eddies per year. Eddies are more frequently generated in summer, coinciding with intense Trade winds and Canary Current. During fall the intensity of the Trades winds and the Canary Current is very low, and no eddy generation was observed. In order to discuss the relative importance of topographic and wind shear mechanisms on eddy generation by tall deep-water islands we have synthesized in Table 1 the main parameters quantifying these forcings for all four periods.

[17] As observed in numerical modelling studies [*Jiménez et al.*, 2008], only topographic forcing may be responsible for eddy generation. This occurs when the impinging flow is intense ($Re \geq 50$) and wind shear (WS) is low (WS < 8 see

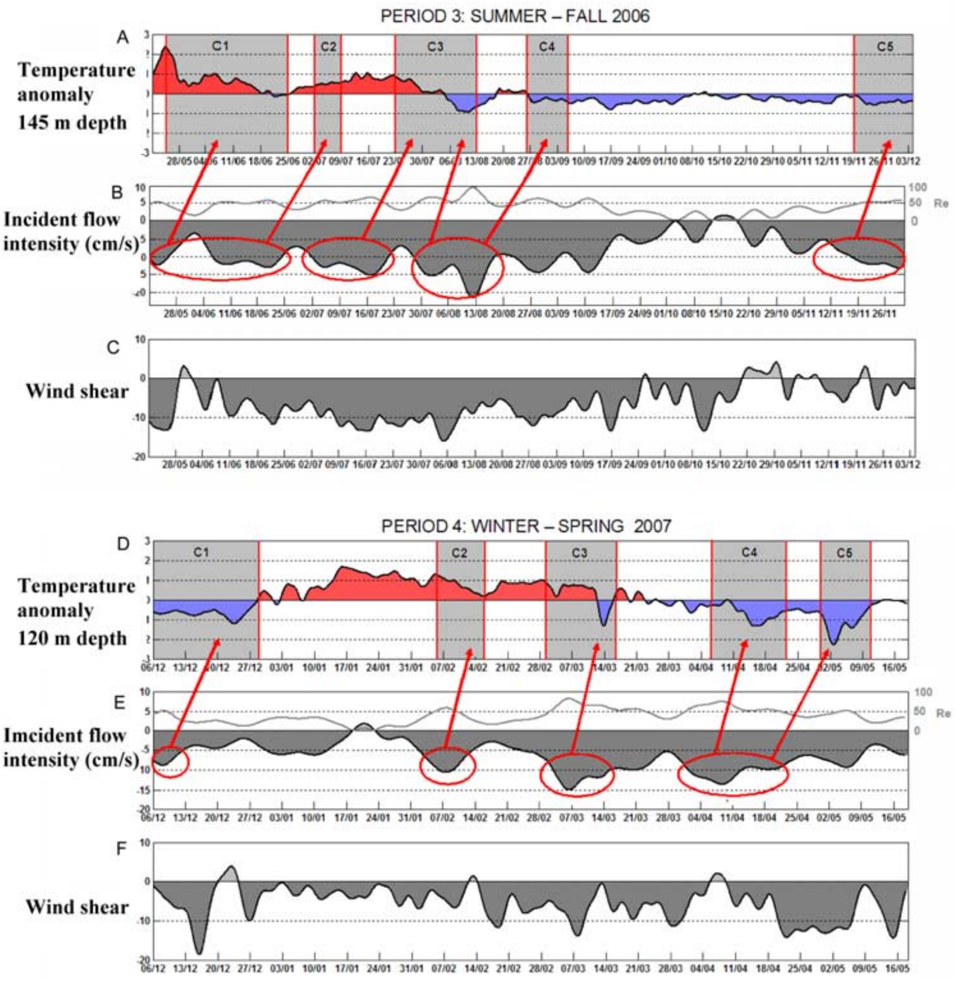

Figure 3. Same as Figure 2 but now for the second year period.

Table 1. Cyclonic Eddy Parameters[a]

Eddy Code	Depth (m)	RE [V ($m.s^{-1}$)]	Wind Shear
	Summer–Fall 2005—Depth = 105 m		
C1	>400	37 [0.5]	8
C2	>400	40 [7.4]	>10
C3	1000	55 [0.1]	10
C4	1000	55 [0.1]	8
C5	<500	65 [0.12]	6
	Winter–Spring 2006—Depth = 135 m		
C1	>500	/	1.5
C2	>500	59 [0.11]	3.2
C3	>500	59 [0.11]	3.7
C4	1000	50 [0.09]	3.2
C5	>500	44 [0.08]	8.3
	Summer–Fall 2006—Depth = 145 m		
C1	/	54 [0.1]	10
C2	/	65 [0.12]	8
C3	/	70 [0.13]	11.6
C4	/	75 [0.14]	9.6
C5	/	54 [0.1]	1.5
	Winter–Spring 2007—Depth = 120 m		
C1	>500	38 [0.07]	8.5
C2	>500	50 [0.09]	3.2
C3	>500	65 [0.12]	6.4
C4	>500	65 [0.12]	5.1
C5	1000	54 [0.1]	9

[a] Depth: maximum eddy depth. Re: mean Reynolds number and corresponding incident flow intensity (*U*), as obtained two weeks prior to eddy generation event. Wind Shear: wind shear at the island wake as calculated from Gando and Puerto Mogan meteorological stations.

Table 1). This is the case for the sumer–fall 2005 eddy C5, the winter–spring 2006 eddies C2, C3, C4, the summer–fall 2006 eddy C5 and the winter–spring 2007 eddies C2, C3, C4. For lower impinging oceanic flow intensities (Re < 50), wind shear acts as trigger mechanism for eddy generation which coincides with J08 numerical results. This occurs when WS is greater equal 8, this being the case for the summer–fall 2005 eddy C1, C2, the winter–spring 2006 eddy C5, and the winter–spring 2007 eddy C1.

[18] Previous observational and numerical studies [*Chavanne et al.*, 2002, *Jiménez et al.*, 2008] show that when wind shear is nearly stationary, two counter-rotating stationary vortices are generated at the island wake. However, when the wind pulsates, wind shear is able to generate eddies that are self-advected westward due to the β-effect [*Cushman-Roisin et al.*, 1990; C. Chavanne, personal communication, 2009]. In our case study, we have not observed this phenomena, probably because the island of Tenerife prevents westward eddy propagation from Gran Canaria, and because the wind forcing is oriented meriodionally instead of zonally, such as is the case for the Philippine Archipelago [*Pullen et al.*, 2008] and the Hawaiian Archipelago [*Chavanne et al.*, 2002].

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References

Arístegui, J., and M. F. Montero (2005), Temporal and spatial changes in microplankton respiration and biomass in the Canary Islands: The effects of mesoscale variability, *J. Mar. Syst.*, *54*, 65–82, doi:10.1016/j.jmarsys.2004.07.004.

Arístegui, J., P. Sangrà, S. Hernández-León, M. Cantón, A. Hernández-Guerra, and J. L. Kerling (1994), Island-induced eddies in the Canary Islands, *Deep Sea Res., Part I*, *41*, 1509–1525, doi:10.1016/0967-0637(94)90058-2.

Arístegui, J., et al. (1997), The influence of island-generated eddies on chlorophyll distribution: A study of mesoscale variation around Gran Canaria, *Deep Sea Res., Part I*, *44*, 71–96, doi:10.1016/S0967-0637(96)00093-3.

Barton, E. D., G. Basterretxea, P. Flament, E. G. Mitchelson-Jacob, B. Jones, J. Arístegui, and H. Felix (2000), Lee region of Gran Canaria, *J. Geophys. Res.*, *105*, 17,173–17,193, doi:10.1029/2000JC900010.

Basterretxea, G., E. D. Barton, P. Tett, P. Sangrà, E. Navarro-Perez, and J. Arístegui (2002), Eddy and DCM response to wind-shear in the lee of Gran Canaria, *Deep Sea Res., Part I*, *49*, 1087–1101, doi:10.1016/S0967-0637(02)00009-2.

Benitez-Nelson, C. R., et al. (2007), Mesoscale eddies drive increased silica export in the subtropical Pacific Ocean, *Science*, *316*, 1017–1021, doi:10.1126/science.1136221.

Chavanne, C., P. Flament, R. Lumpkin, B. Dousset, and A. Betamy (2002), Sacatterometer observations of wind variations induced by oceanic islands: Implications for wind-driven ocean circulation, *Can. J. Remote Sens.*, *28*, 466–474.

Cushman-Roisin, B., E. P. Chassignet, and B. Tang (1990), Westward motion of mesoscale eddies, *J. Phys. Oceanogr.*, *20*, 758–768, doi:10.1175/1520-0485(1990)020<0758:WMOME>2.0.CO;2.

Dick, G., and G. Siedler (1985), Barotropic tides in the northeast Atlantic inferred from moored current meter data, *Dtsch. Hydrogr. Z.*, *38*, 7–22, doi:10.1007/BF02226433.

Dietrich, D. E., M. J. Bowman, C. A. Lin, and A. Mestas-Nunez (1996), Numerical studies of small island wakes, *Geophys. Astrophys. Fluid Dyn.*, *83*, 195–231, doi:10.1080/03091929608208966.

Heywood, K. J., D. P. Stevens, and R. B. Bigg (1996), Eddy formation behind the tropical island of Aldabra, *Deep Sea Res., Part I*, *43*, 555–578, doi:10.1016/0967-0637(96)00097-0.

Jiménez, B., P. Sangrà, and E. Mason (2008), A numerical study of the relative importance of wind and topographic forcing on oceanic eddies shedding by deep water islands, *Ocean Modell.*, *22*, 146–157, doi:10.1016/j.ocemod.2008.02.004.

Pattiaratchi, C., A. James, and M. Collins (1987), Island wakes and headland eddies: A comparison between remotely sensed data and laboratory experiments, *J. Geophys. Res.*, *92*, 783–794, doi:10.1029/JC092iC01p00783.

Pullen, J., J. D. Doyle, P. May, C. Chavanne, P. Flament, and R. A. Arnone (2008), Monsoon surges trigger oceanic eddy formation and propagation in the lee of the Philippine Islands, *Geophys. Res. Lett.*, *35*, L07604, doi:10.1029/2007GL033109.

Sangrà, P., J. L. Pelegrí, A. Hernández-Guerra, I. Arregui, J. M. Martín, A. Marrero-Díaz, A. Martínez, A. W. Ratsimandresy, and A. Rodríguez-Santana (2005), Life history of an anticyclonic eddy, *J. Geophys. Res.*, *110*, C03021, doi:10.1029/2004JC002526.

Sangrà, P., M. Auladell, A. Marrero-Díaz, J. L. Pelegrí, E. Fraile-Nuez, A. Rodríguez-Santana, J. M. Martín, E. Mason, and A. Hernández-Guerra (2007), On the nature of oceanic eddies shed by the island of Gran Canaria, *Deep Sea Res., Part I*, *54*, 687–709, doi:10.1016/j.dsr.2007.02.004.

Siedler, G., and U. Paul (1991), Barotropic and baroclinic tidal currents in the eastern basins of the North Atlantic, *J. Geophys. Res.*, *96*, 22,259–22,271, doi:10.1029/91JC02319.

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