Observations of vortices and vortex Rossby waves in the lee of an island

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Abstract :

A 9-month deployment of high-frequency radio (HFR) current meters and moored ADCPs in the lee of Oahu, Hawaii, gives some dynamical insights in the generation and evolution of vortices in the lee of islands. For mountainous islands lying in relatively strong and steady winds, such as the Hawaiian archipelago in the trade winds, vortices can be generated by Ekman pumping associated with orographic wind stress curls. An anticyclone generated in the lee of Oahu in October 2002 reaches a negative absolute vorticity for 4 days, before quickly decaying and broadening, possibly as a result of inertial instability. A large cyclone, generated in December 2002 in the lee of Hawaii, drifted northwestward and stalled southwest of Oahu in March-April 2003. Vortex Rossby waves developing on its periphery were observed by the HFRs with a northeastward phase propagation, 110 km wavelength and 16 days period.

Résumé :

Un déploiement de 9 mois de courantomètres radio haute-fréquence (HFR) et d'ADCPs mouillés dans le sillage d'Oahu, Hawaii, donne un aperçu sur la dynamique des tourbillons dans le sillage d'îles. Pour des îles montagneuses soumises à des vents relativement forts et constants, comme l'archipèle hawaiien sous les Alizés, les tourbillons peuvent être générés par pompage d'Ekman associé aux rotationnels du vent orographiques. Un anticyclone généré dans le sillage d'Oahu en octobre 2002 atteint une vorticité absolue négative pendant 4 jours, avant de rapidement s'affaiblir et s'élargir, probablement dû à une instabilité inertielle. Un gros cyclone, généré dans le sillage d'Hawaii en décembre 2002, dériva vers le nord-ouest pour s'installer au sud-ouest d'Oahu durant mars-avril 2003. Des ondes de Rossby de tourbillon se développant à sa périphérie sont observées par les HFRs avec une phase se propageant vers le nord-est, une longueur d'onde de 110 km et une période de 16 jours.

Key-words :

vortices ; vortex Rossby waves ; island wake

1 Introduction

The Hawaiian archipelago, isolated in the middle of the Pacific within the North Equatorial Current and trade winds, is an ideal natural geophysical laboratory to study obstacle wakes in rotating stratified flows. We describe here ocean current observations by two high-frequency radio (HFR) surface current meters and moored ADCPs, deployed from September 2002 to May 2003 along the west coast of Oahu (Fig. 1). The currents were low-pass filtered with a cutoff period of 3 days, to filter out tidal and inertial currents ($T_f = 2\pi/f \sim 33$ hours), and subsampled daily. The horizontal resolution is 5 km. The 9-month average circulation consists in a northwestward current, increasing from less than 5 cm/s near the coast to 30 cm/s 60 km offshore, corresponding to a vorticity of $\sim 0.1f$. The dominant winds are northeasterly trade winds, and are affected by the island mountain ranges, yielding a wind stress curl dipole west of Oahu. We focus on the periods between September to November 2002 in Part 1, when the variability was dominated by submesoscale vortices, and between March and April 2003 in Part 2, when the variability was dominated by vortex Rossby waves.

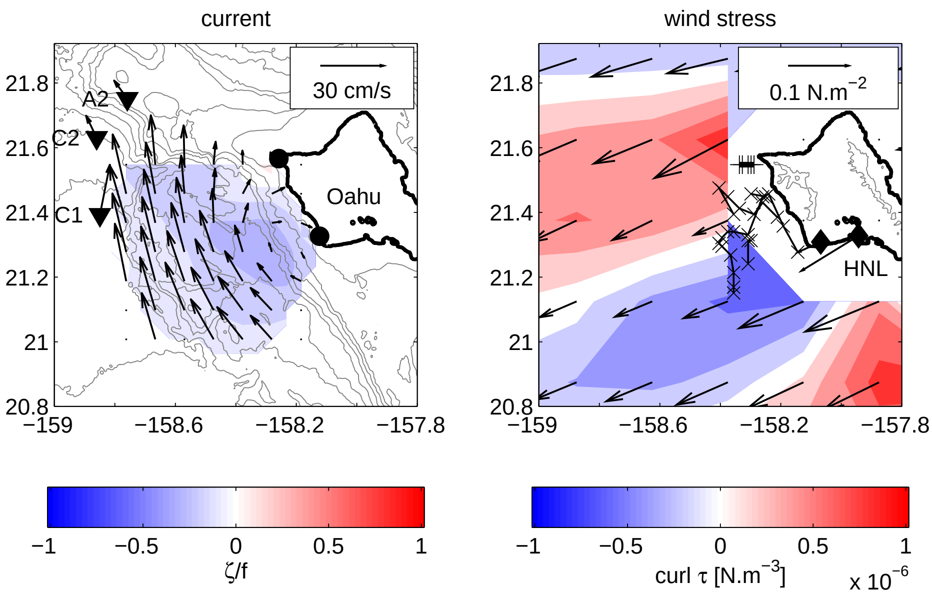

Figure 1: Experimental setup: (left panel) mean surface currents from HFRs and ADCPs (vectors) and vorticity normalized by f (color), (right panel) climatological wind stress from QuikSCAT and airports (vectors) and curl (color), and vortex center tracks during Fall 2002 (thick black line and pluses: cyclone, thin black lines and x-marks: anticyclones, symbols one day apart). Locations of HFRs (circles), moored ADCPs (triangles), and airports (diamonds) are indicated. Topographic contours in gray (every 500 m) and black contour for 0 m.

2 Vortices

2.1 Description

We define a vortex core as a region around a velocity minimum (the vortex center) where vorticity dominates over stretching and shearing deformations:

$$\zeta^2 = (\partial_x v - \partial_y u)^2 > (\partial_x u - \partial_y v)^2 + (\partial_x v + \partial_y u)^2 \quad (1)$$

We define the vortex radius as the maximum distance between the center and the core limits. Vortices with radii ranging from 5 to 50 km, smaller than the first baroclinic deformation radius (∼60 km, Chelton *et al*. (1998)), dominated the low-frequency currents variability from September to November 2002 (Fig. 2). 4 anticyclones were spun-up near the coast (see Fig. 1, right panel) during periods of strong trade winds, in the area of negative wind stress curl, while only one small cyclone was spun-up during a period of weak and variable winds. One anticyclone was particularly strong, its Rossby number reaching 1.1, and remaining above 1 for 4 days. Its vorticity then quickly decayed and its radius increased, before it drifted out of the domain to the southwest.

2.2 Dynamics

Many mechanisms can lead to the formation of vortices in the lee of islands: lateral viscous stress at vertical boundaries, bottom stress, vortex stretching and tilting, and Ekman pumping.

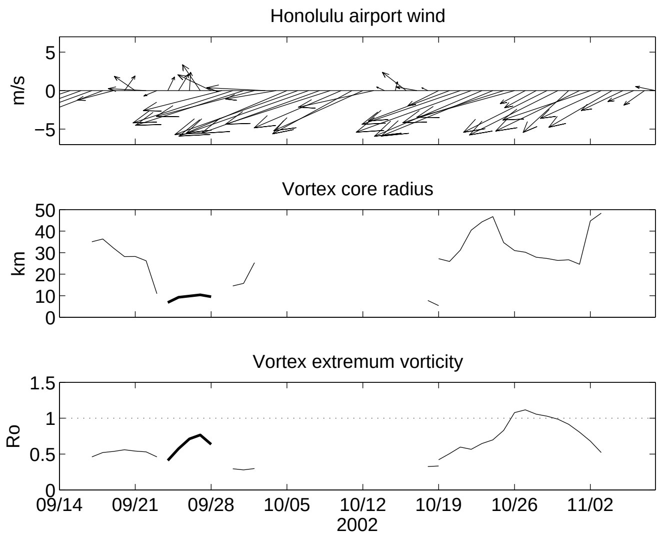

Figure 2: (top panel) 3-day low-pass filtered winds from Honolulu airport (HNL in Fig. 1), (middle panel) vortex core radius, and (bottom panel) vortex Rossby number, defined as the absolute value of the vortex core extremum vorticity divided by f. Cyclones are shown in thick lines and anticyclones in thin lines.

We investigate the latter since a majority of vortices were spun up during periods of strong and steady winds, and that the mean current is weak near the coast and over bathymetry shallower than 2000 m (Fig. 1). Positive (negative) curl to the northwest (southwest) of Oahu drives Ekman upwelling (downwelling) which can generate cyclones (anticyclones) (Chavanne *et al.* (2002)). During the spin-up phase of the strong anticyclone, $\frac{\partial \zeta}{\partial t} \sim 5.4 \times 10^{-11} s^{-2}$. Using the linear vorticity balance (neglecting the beta effect):

$$\frac{\partial \zeta}{\partial t} = \frac{curl \tau}{\rho H} \tag{2}$$

where ρ is density of water and H depth of no motion, taken as 400 m from observations at mooring C1, we obtain a required wind stress curl of $\sim 2.2 \times 10^{-5} N.m^{-3}$, which corresponds to the average curl over the spin-up period estimated from the airport observations. Therefore Ekman pumping can explain the vorticity growth of the strong anticyclone.

The observation of the dominance of anticyclones over cyclones, albeit not statistically significant due to the low number of vortices observed, may be simply due to the limited extent of the observational domain, missing the cyclones to the north.

As conjectured by Sipp and Jacquin (2000), an incompressible inviscid 2D flow with closed streamlines is prone to centrifugal instability if the sign of the absolute vorticity $\zeta + f$ changes somewhere in the flow. The absolute vorticity of the strong anticyclone is shown in Fig. 3 at its peak (on Oct 27, 2002). It does change sign in the core of the vortex, suggesting that the rapid decay and broadening of the vortex a few days later may be due to centrifugal instability. Following Kloosterziel *et al.* (2007), we estimate an upper bound on their growth rate to be $\sim$3.5 days. Although it takes longer for the instability to affect the entire vortex, this estimate was derived for a barotropic vortex. For baroclinic vortices, the instability is allowed to grow faster (R. Kloosterziel, personal communication).

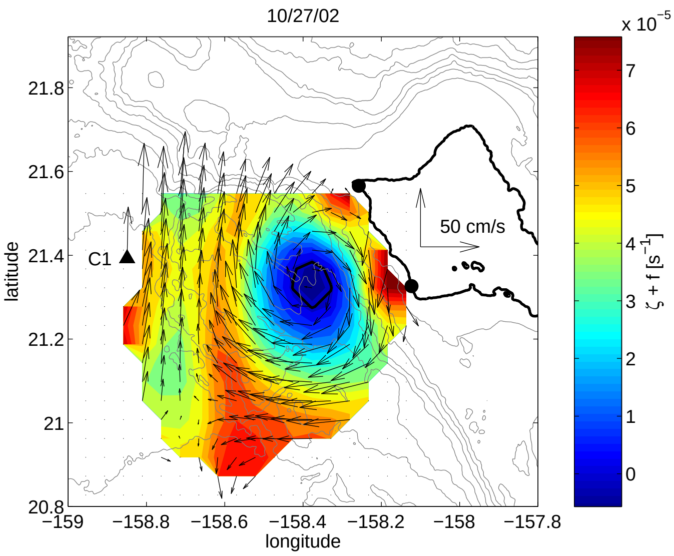

Figure 3: Surface currents on Oct 27, 2002 (arrows) and their absolute vorticity $\zeta + f$ (color). The zero contour is shown in black.

3 Vortex Rossby waves

3.1 Description

From March to April 2003, the low-frequency currents variability is dominated by vorticity waves, as captured by the first mode of a complex EOF analysis of the vorticity in the time domain (Fig. 4), which accounted for 54 % of the variance. The waves have a median wavelength of 110 km, a median propagation direction of 69 degrees ccw from east, and a median period of 16 days, corresponding to a phase speed of 8 cm/s. Their vertical structure is revealed by the first EOF mode of the currents observed at A2 (not shown), which accounted for 80 % of the variance. They are surface-intensified, with an e-folding depth of 225 m and maximum vertical shear at 80 m, corresponding to $5.8 \times 10^{-4} s^{-1}$ for surface currents of 35 cm/s. The currents reverse direction at ~800 m, 300 m deeper than the first normal mode reversal depth, and vanish at the bottom.

A snapshot on Apr 9, 2003 (Fig. 5) shows the spatial structure of the currents and vorticity at a particular phase of the wave, within the broader context of mesoscale currents in the Hawaiian archipelago, as derived from altimetry (Ducet *et al.* (2000)). Vorticity crests of ~0.6 f were aligned parallel to the island chain, corresponding to alternating northwestward/southeastward currents of 35 cm/s amplitude, and propagated toward the northeast. A large cyclone of ~100 km radius, which originated in the lee of the Island of Hawaii in December 2002, was sitting between 110 and 190 km southwestward of Oahu during spring 2003.

3.2 Dynamics

Due to the eastward component of their phase propagation, these waves cannot be purely planetary Rossby waves. Barotropic and bottom-trapped topographic Rossby waves can have an eastward phase propagation if the bottom slopes downward to the north (opposing the β effect), but the surface intensified baroclinic modes always have a westward phase propagation, isolating themselves from the topographic effect by moving a node in the horizontal velocity to the bottom (Rhines (1970)), as observed at A2. The large cyclone radial gradient of vorticity

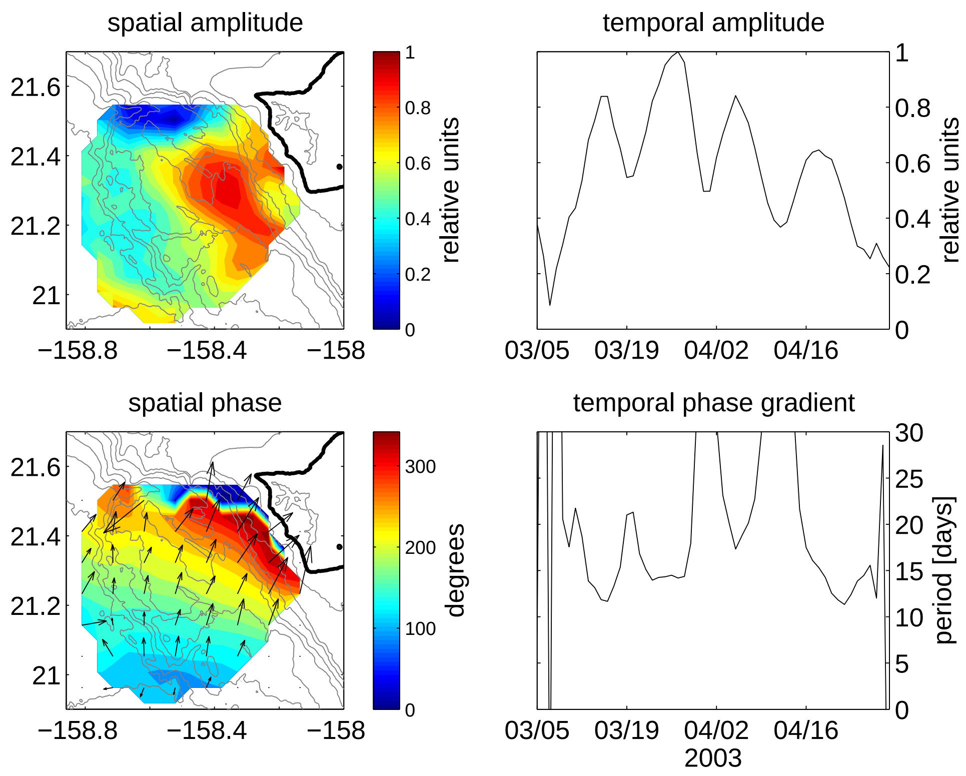

Figure 4: Spring 2003 vorticity complex EOF 1: (left panels) spatial and (right panels) temporal structures of (top panels) amplitude and (bottom panels) phase and phase gradient, i.e. wavenumber (left, arrows) and period (right).

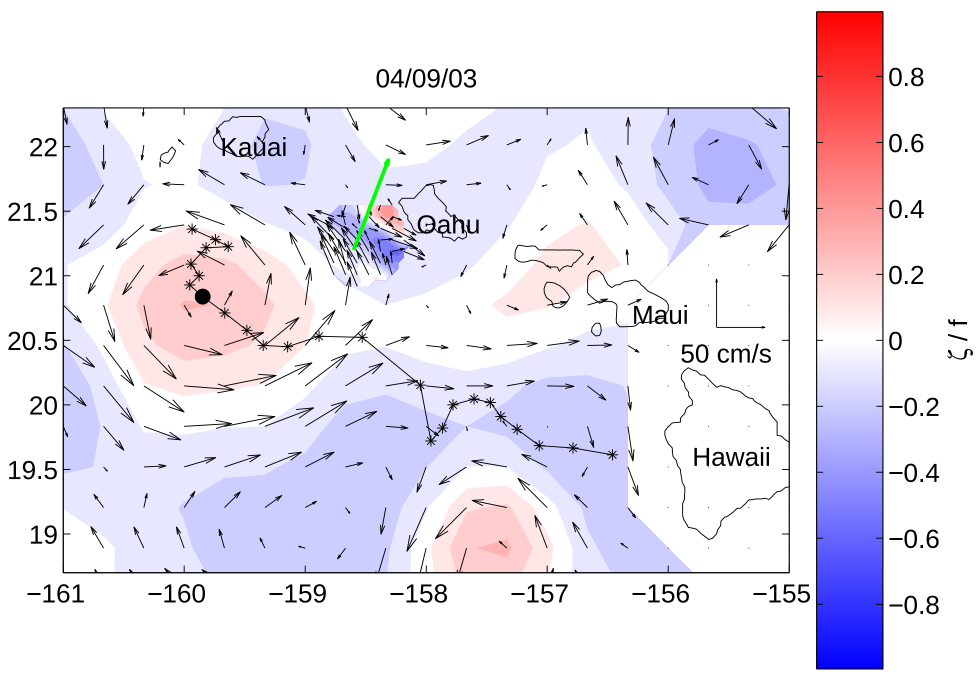

Figure 5: Surface currents on Apr 9, 2003 (arrows) and their vorticity normalized by f (color) from altimetry and HFRs. The green arrow shows the direction of phase propagation of the vortex Rossby waves. The cyclone's track is shown as a solid black line, with stars every 7 days, and a dot for the center's location on Apr 9, 2003.

enables the existence of vorticity waves called vortex Rossby waves. Their dispersion relation is (Montgomery and Kallenbach (1997)):

$$\omega = n\Omega + \frac{n\zeta'}{R(k^2 + n^2/R^2)} \tag{3}$$

where n is the azimuthal mode number, Ω is the angular velocity of the vortex at the radius R, ζ' is the radial gradient of the vortex relative vorticity, and k the radial wavenumber. The frequency is dominated by the first term (Doppler shift), and so is the radial phase speed ω/k, which is outward for positive k (corresponding to a trailing spiral), explaining the eastward component of phase propagation seen in the HFRs observations. We infer the vortex characteristics from an azimuthal average of the observed vortex and evaluate them at the radius going through the middle of the observational domain of the HFRs. Using the wavenumber obtained by the complex EOF analysis, projected in the radial direction from the vortex center, equation (3) yields a period of 30 days for mode number 1 and 15 days for mode number 2, close to the periods obtained from the EOF analysis.

4 Conclusions

HFRs observations with 5 km resolution reveal the existence of energetic current variability on scales typically not resolved by altimetry: submesoscale vortices with radii ranging from 5 to 50 km and vortex Rossby waves with $\sim$100 km wavelength. These oceanic features have finite Rossby numbers that can reach above one, leading to inertial instability for anticyclonic vortices. They are surface-intensified and strongly sheared in the vertical. These characteristics should be taken into account when considering the propagation of inertial and internal waves in the ocean.

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