The "von Karman vortex street" to the west of Big Island

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Abstract
Satellite-tracked drifting buoy data and altimetry data are used to study the active vortex field to the west of Big Island. A pair of vortices were observed at the trajectory of buoy in 1995. The westward propagation of the vortex pair is studied in detail by reproducing the loops of each vortex. The orbital period and radius of the pair of vortex are determined to be 10–11 d and 58–68 km. Two arrays of contra-rotating vortices are displayed in the average sea surface height anomaly (SSHA) field to the west of Big Island. Based on the calculation of the fluid dynamical parameter, the "von Karman vortex street" is proved to be generated to the west of Big Island as the North Equatorial Current impinges upon Big Island from the east. Finally, the analysis of the buoy trajectories in a decade contributes to the conclusion of the pattern of VKVS in a statistical view.

Key words: von Karman vortex street, buoy trajectory, sea surface height anomaly, Big Island

1 Introduction

Hawaiian Islands as a chain of islands, with Big Island as the biggest constituent, lie near the northern part of the North Equatorial Current (NEC). The velocity of the westward currents in the south of the Hawaiian Islands exceeds 25 cm/s and the average velocity of the NEC is 17 cm/s (Qiu et al., 1997). Strongly influenced by the Hawaiian Islands, especially by Big Island, the NEC to the east of Big Island detours when it impinges upon the island and two sorts of elongated vortices appear to the west of the island (Qiu et al., 1997). The region to the west of Big Island is the place where the active vortex field exists. Since Pazert (1969) initially described the cyclonic and anti-cyclonic vortex events in this region in detail, more studies have begun to focus on them (Wyrtyk, 1982; Mitchum, 1995; Flament et al., 2001; Holland and Mitchum, 2001; Lumpkin and Flament, 2001).

The eastward countercurrent to the west of the Hawaiian Islands is caused by the effect of the Hawaiian Islands on the trade wind and the NEC and by the local ocean–atmosphere interaction (Xie et al., 2001; Liu et al., 2003). Except for the oceanic response to wind-stress curl caused by the effect of Hawaiian mountains, the NEC impinges upon the islands and a westward-traveling ocean vortex street is generated in the ocean and acts to intensify the eastward countercurrent in the west of the Hawaiian Islands (Liu et al., 2003). But this opinion is based

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on the numerical experiment results from a 2.5 layers ocean model in which the Hawaiian Islands are treated as a whole island.

Up to now nobody has verified the existence of a westward traveling oceanic "von Karman vortex street" (VKVS) to the west of Big Island, based on the observational data, however, with the analysis of the data from satellite-tracked drifting buoy and altimeter data from ERS–1, ERS–2 and TOPEX/POSEIDON satellites, a pair of westward propagating vortices to the west of Big Island are described in Part 2. The SSHA filed is shown in Part 3 to indicate the VKVS to the west of the island. The assumption of the existence of VRVS is proved theoretically in Part 4. Then, the following part focuses on the existence of VRVS from long term observation data. Finally, the temporal variability of VKVS and the relationship between the VKVS and the Hawaiian Lee Countercurrent (HLCC) is discussed in Part 6.

2 The buoy trajectories

As a partnership between the Global Drifter Center (GDC) and Meteorological Laboratory and the Marine Environmental Data Service (MEDS) of the Canadian Department of Fisheries and Oceans, numbers of drifting buoys were deployed in the ocean from 1979 as the standard of the World Ocean Circulation Experiment (WOCE) Surface Velocity Program (SVP) (Niller et al., 1995). Buoys are attached to drogues and released into the ocean at 15-m depth. Satellite-tracked buoy data are collected every 6 h and the available data in our study are from 1979 to 1998.

The buoys encounter strong vortices to the west of Big Island of Hawaii. Two remarkable trajectories of buoys, numbered 9922298 and 7711698, are observed (see Fig.1). They both originated from Big Island on August 1st in 1995 and drifted westward. It is well observed that in the region west of 157°W, the northern buoy trajectory acts as a westward propagating cyclonic vortex, while the southern trajectory is a propagating anticyclonic vortex (see Fig. 1a). To visualize the propagating course of the vortices, based on the drifting buoy data, we reproduce the vortices in the frame of translating reference for the cycloid, resulting from the superposition of a rotation and a translation (Kennan and Flament, 1995). The radius is estimated by the half-width of Gaussian least square fitted to each loop of the vortex.

Figure 1b displays the orbital period during the propagation of the vortex pair and the orbital period is the temporal span of the buoys around the rotating center of the vortex. As in Fig. 1c, it can be seen clearly that the cyclonic and anticyclonic vortices have almost the same period with alternate longitude in each transition and thus can be classified as the vortex pair. The vortex pair appears off the western coast of Big Island (between 158° and 157°W) with an orbital period of 7.5~8.0 d. After that, as the vortex pair is propagating westward, the period increases to 10~11 d and then does not change. The radii of the loops of the vortex pair are displayed in Fig 1c. Cyclonic and anticyclonic vortices have nearly an equal size with radii ranging from 58 to 68 km.

To examine the characteristics of the spatial distribution of the vortices in a broader region and verify the assumption of the VKVS, we introduce another data set in the following part.

3 Spatial distribution of SSHA to the west of Big Island

The satellite altimeter data, used in this study, are obtained from the MSLA products merged with ERS (35-d repeat orbit periods) and TOPEX/POSEIDON (T/P) (10-d repeat
orbit periods) data sets. The ERS products are generated as a part of the “Joint analysis of ERS–1, ERS–2 and TOPEX/POSEIDON altimeter data for oceanic circulation studies”. MSLA products are available at 10-d intervals, with a 0.25°×0.25° resolution for the period.

Vortices to the west of Big Island are readily observable based on the SSHA field, because the negative SSHA is usually corresponding to the cyclonic vortex, and vice versa. The SSHA fields have the advantage of being able to display the instantaneous vortex spatial distribution over the buoy trajectories in determining the pattern of the VKVS. In the successive comparison of the SSHA fields during August–December of 1995, the vortices propagate westward about 0.45° of longi-

Fig. 1. Trajectories of the drifting buoys 9922298 and 7711698 between August and December 1995 (a), orbital period of the buoy around the center of the vortex (b) and radius of the vortex inferred from the orbit of the buoy (c). Both in b and c, the crosses represent cyclonic vortices and the dots represent anticyclonic vortices.
tude in 10 d and the relative velocity $\mu$ of vortices is 5.7 cm/s. The distance between two successive cyclonic (anticyclonic) vortices is 5.0–5.5 longitudes. But there is a problem that the SSHA fields are terminated by the signal of the intraseasonal variation resulting from intraseasonal variation of wind stress and buoyancy flux with the period shorter than 120 d and the VKVS could hardly be observed obviously as a whole from the SSHA field in each 10 d. Then we averaged SSHA fields during 28th August and 26th December of 1995 during 120 d span (Fig. 2) and at the same time efficiently reduced the intraseasonal variation signals of SSHA.

![Image](image-url)

Fig. 2. Mean SSHA, derived from satellite altimeter data during August 28-December 26 of 1995. The solid contours denote positive SSHA, indicating the anticyclonic vortex while the dash contours denote negative SSHA, indicating the cyclonic vortex (contours in 2 cm).

It is well displayed that the meridional distribution of SSHA to the west of Big Island is almost inverse in the north and south of 18°N. There are 5 negative SSHA cores against the northern negative area with an amplitude of 2~6 cm, while 4 positive cores against the southern positive area with a larger amplitude of 8~12 cm. According to the relationship between the vortex and the SSHA, the symmetrical vortex arrays of inverse vorticity are determined to the west of the island. The northern array of the vortices is composed of 5 cyclonic vortices mostly at 19.5°N zone and the southern array of 4 anticyclonic mostly at 17.5°N zone. The altimetric radii are bigger than the orbiting radii in Fig. 1c for the buoy remaining trapped in the core of vortex at all time (Flament et al., 2001). It is estimated from the figure that the lateral spacing $b$ between vortices is about 2 latitudes and the longitudinal spacing $a$ between vortices is 5.2 longitudes by averaging the distance between the successive vortices in both arrays. Figure 2 suggests the distinct characteristics of the pattern of VKVS.

But it is still questionable whether the vortices to the west are the result of the NEC detouring while it impinges upon Big Island from the east and the two series vortices are the VKVS or not?

4 Verification of the VKVS

It is well known that the vortex street is formed in the wake of a body, of which the generation condition is that the Reynolds number $Re$ is larger than the critical value, $Re_{cvs}$ of generating the VKVS, that is,

$$Re = \frac{U_0 d}{v} > Re_{cvs},$$

(1)

where $d$ is the representative width of the body; $U_0$ is the free-stream velocity; and $v$ is the kinematics coefficient of friction.
We have compiled all the available satellite buoy data in the region from 156° to 146°W, 17° to 22°N, spanning the period between August and December 1995. The irregularly spaced trajectories are interpolated to a grid of 0.5°×0.5° with the Kriging method. Following the quality check procedure from the two-step scheme described by Hansen and Poulain (1996), we average the velocity in the belt of 19°–20°N and get the average westward velocity of 20 cm/s, which is taken as the velocity $U_0$ of the NEC, towards Big Island from the east. Then, take the diameter $d$ of the circumbore of the irregularly shaped island as the representative of the body width. It is computed to be 140 km. With the value of $v$ taken as 0.011 4 cm/s , the Reynolds number in the case of NEC detoured by Big Island is 246, and it is larger than $Re_{CVS}$ of 60 (Bachelor, 1994). So the condition of generating the VKVS is satisfied in our interested region during August and December 1995.

Additionally, based on the relative velocity $u$ of vortices, the free-stream velocity $U_0$, and the longitudinal spacing $a$ between vortices and the representative diameter $d$ of the body in the former sections, we calculate the Strouhal number defined as

$$St = \frac{1 - u/U_0}{a/d}. \quad (2)$$

Then the Strouhal number is calculated to be 0.175 and it is close to the universal Strouhal number with a uniform value of 0.18 throughout the Reynolds number range (Tsutomo, 1997) and confirms the pattern of VKVS to the west of Big Island.

Based on the corrected Strouhal number, we are able to continue to compute the vortex shedding frequency defined as

$$f = \frac{U_0 - u}{a}, \quad (3)$$

and the period of the vortex shedding $T = 1/f = 46$ d. From Part 2 the shedding of the vortex can show that the center of the cyclonic vortex goes across the section 160°W on the 292nd day and the successive anticyclonic vortex of buoy 7711698 on the 338th day, just 46 d later. Therefore, the vortex to the west of Big Island belongs to the VKVS.

In his review paper, in 1960 Wille pointed out that no array of vortices is stable to any order of disturbance higher than the first order $b/a=0.281$. It would seem very likely that the vortex street could exist at high Reynolds number of turbulence. But the fact is that vortex street does exist beyond the suspicion on the von Karman stability condition. Many authors have measured the value of $b/a$, and it is between 0.20 and 0.40 (Bearman, 1967) while in the case of Big Island during August–December 1995 the spacing ratio $b/a$ is 0.38. It is within the range of practical stability condition of the vortex street.

Another criterion for stability was proposed by Kronauer (1964), which states that the vortex street adjusts itself into the configuration of minimum CDS. It is defined as the associated vortex street drag coefficient of a given vortex velocity $u$. In our study $b/a=0.38$, the stability criterion of Kronauer is satisfied when $u/U_0=0.284$, and from the observations of the case of drifting buoy and SSHA fields, $u/U_0=0.285$, that is, it is fairly consistent with the theoretical result. Therefore, it is concluded that the VKVS is generated and stable to the west of Big Island in accordance with various conditions and the stability criterion of the fluid dynamics.

5 Analysis of long-term observation data

Although the pattern of VKVS to the west of Big Island in 1995 is determined through the analysis of the satellite drifting buoy data and SATELITE altimeter data, it is only an example. To study
the vortex distribution in a long run, we have examined all available buoy data in the region (15°–23°N, 180°–150°W) for 10 a period (from 1989 to 1998) and reproduced the vortices by means of the methodology in Section 2.

In Fig. 3, two arrays of contra-rotating vortices appear to the west of the island. They are symmetric to the latitude of the island. It is similar to the analytical result about drifting buoy (reference is IPRC Newsletter), but they did not mention the VKVS in this newsletter. The north array consists of 58 loops of cyclonic vortices (thin) and the southern array of 68 loops of anticyclonic vortices (thick).

As a whole, vortices in the cyclonic array are as large as those in the anticyclonic array (see Fig. 4) with radii ranging from 40 to 80 km. However, the variances in the amplitude of the radii can be interpreted by the fluctuation of the velocity of NEC east of the island. Several bigger anticyclonic vortices are located to the west of 165°W. They result from the merging of vortex pairing in an unstable anticyclonic shear flow with radius doubling to more than 80 km (Flament et al., 2001).

6 Summary

The objective of our study is to reveal and understand the characteristics of the VKVS to the west of Big Island. As a result of the detouring of the NEC, while it impinges upon the island from the east, pattern of the VKVS is to form to the west and propagates westward. In the region less affected by the island, west of 158°W, there is the vortex pair with the orbital period of 10–11d and the radius of 58–68 km. The average SSHA field presents general distribution of the vortices in a region broader than that covered by the trajectories. The obvious feature of the SSHA field is that there are two symmetrical arrays of cyclonic and anticyclonic vortices similar to the pattern of the vortex street. The lateral spacing between vortices is about 2 latitudes and is 5.2 longitudes. To prove the VKVS, we continue to examine the VKVS parameters of fluid dynamics in the case of our study and the theoretic result is well consistent with our observation. Finally, the conclusion of the VKVS about the west of Big Island is confirmed by the analysis of 10 a period surface buoy data in a statistical view.

As pointed out in many studies (Qiu and Durland, 2002; Liu et al., 2003) that there is an
eastward flow to the west of Hawaii (HLCC). It has a certain relation to the VKVS, because there is an eastward current between the two vortex arrays at the latitude of 19°N and then it intensifies the HLCC. On the other hand, the HLCC, acting as the border of the cyclonic and anticyclonic vortices, stabilizes the circulation of the region.

This study is mainly concerned with the characteristics of VKVS, observed from the satellite-tracked buoy trajectory data and then ascertained by the analysis of the satellite altimeter data. But how the VKVS changes and develops is still a problem, and this allows future studies for the response of the VKVS to the ocean–atmosphere interaction.

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